code	ISAP 1st Conference - Titles & Abstracts
01000	**International Conference on the Structural Design of Asphalt Pavements - Proceedings, preliminary pages** *n/a* This document contains the preliminary pages of the Proceedings for the 1st International Conference. The Table of Contents gives a good overview of the structure of the conference and the papers presented (and discussion thereon).
01001	**International Conference on the Structural Design of Asphalt Pavements - Proceedings, introductory pages** *n/a* This document contains the introductory pages of the Proceedings for the 1st International Conference, including an outline of the Sessions of the conference.
01002	**Report on Session I - AASHO Road Test and Performance Criteria** *Moderator: J.W. Turnbull* A moderated discussion of the papers presented in Session I. Performance of Flexible Pavement W. N. Carey, Jr., Assistant Director for Research Paul E. Irick, Research Statistician, Highway Research Board, AASHO Road Test Staff Performance of Treated and Untreated Aggregate Bases A. C. Benkelman, Flexible Pavement Research Engineer Harold M. Schmitt, Assistant Flexible Pavement Engineer, Highway Research Board, Aasho Road Test Staff R. Ian Kingham, Engineer-Observer, Canadian Good Roads Association, AASHO Road Test Staff Application of AASHO Road Test Results to the Design of Flexible Pavement Structures Wallace J. Liddle, U.S. Bureau of Public Roads Thickness Design Relationships for Asphalt Pavements F. N. Finn and J. F. Shook, The Asphalt Institute, College Park, Maryland Analysis of AASHO Test Data by The Asphalt Institute L. J. Painter, The Asphalt Institute, College Park, Maryland
01003	**Performance of Flexible Pavement in the AASHO Road Test** *W. N. Carey, Jr., Paul E. Irick* Pavement performance relationships developed at the AASHO Road Test have already been presented in great detail in the Highway Research Board reports on the project. In the limited time available here, it is our aim to summarize the material on flexible pavement performance contained in these reports. We hope that this will serve to bring the rationale used at the Road Test to engineers who may not find time to study the reports in detail. We shall begin with a sample of the performance data, then tell briefly how the data were summarized by means of empirical equations. After the equations have been given for flexi- ble pavement performance, we shall show a few of the many curves that can be plotted from the equations. We shall also describe the apparent characteristics of structural deterioration noted in the Road Test flexible pavements under traffic.
01004	**Performance of Treated and Untreated Aggregate Bases** *A. C. Benkelman, Harold M. Schmitt, R. Ian Kingham* There were three major experiments included in the study of flexible pavement performance at the AASHO Road Test, the factorial, the special base, and the paved shoulder experiment. Of the three, the factorial experiment was by far the most comprehensive. It included study of sections in the four major loops having three levels of surfacing thickness, three levels of base, and three levels of subbase thickness, a 3 x 3 x 3 factorial. In loop 2 (the light axle load loop), only two levels of subbase thickness were employed in a 3 x 3 x 2 factorial. In this experiment, the materials composing the asphaltic concrete surfacing, the crushed stone base course, and the sandy gravel subbase were uniform throughout, as was also the embankment soil on which the pavement was laid.
01005	**Application of AASHO Road Test Results To The Design of Flexible Pavement Structures** *Wallace J. Liddle*

This paper outlines the methods utilized by the AASHO Operating Committee on Design in applying the results of the AASHO Road Test to the design of flexible pavements.

The pavement serviceability-performance concept used to analyze Road Test data, is accepted as the basis of the design procedures that have been evolved. Also, the equations, that have been reported as the findings of the Road Test are accepted and used without modification as to basic form. It has been necessary, however, to make certain assumptions in applying the Road Test equations to mixed traffic conditions and to those situations where soils, materials, and climate differ from those that prevailed at the test site. Each adjustment is explained as it is encountered in the development of the design procedure.

The primary and first stated objective of the AASHO Road Test was:
"To determine the significant relationships between the number of repetitions of specified axle loads of different magnitude and arrangement and the performance of different thicknesses of uniformly designed and constructed asphaltic concrete . . . surfaces on different thicknesses of bases and subbases when on a basement soil of known characteristics."

Another objective was:
"To develop instrumentation, test procedures, data, charts, graphs, and formulas, which will reflect the capabilities of the various test sections; and which will be helpful in future highway design, in the evaluation of the load-carrying capabilities of existing highways and in determining the most promising areas for further highway research."

01006

Thickness Design Relationships For Asphalt Pavements
F. N. Finn , J. F. Shook

Thickness design relationships for asphalt pavements have been developed using data from the AASHO Road Test. A design equation relates the thicknesses of the layers of a pavement structure to design life, expressed as applications of loaded axles, and to laboratory-soaked CBR test values for the subgrade soil.

The basic relationship between design and load applications was derived from AASHO Road Test data. Extension of the basic relationship required consideration of the scatter in the data and the properties of the relationship in the region beyond Road Test experience. Current state highway design methods were relied upon to verify the extrapolations presented.

It was shown that the structural components (surfacing, base and subbase) could be treated as a linear combination of equivalent thicknesses of each layer. It was concluded that one inch of asphalt concrete surfacing or asphalt base was equal to two inches of a good crushed stone base and 2.67 inches of subbase.

Subgrade support was evaluated with the laboratory-soaked CBR test procedure. It was demonstrated that the AASHO Road Test subgrade soil had a CBR value of 2.5. Extension to include other CBR values was made using the current Asphalt Institute design method.

Mixed traffic was evaluated in terms of equivalent applications of an 18-kip single-axle load. Conversion factors were developed from the basic relationship derived from the AASHO Road Test data.

01007

Analysis of AASHO Test Data by The Asphalt Institute
L. J. Painter

This paper presents a group of equations which describe the asphalt pavement performance results from the AASHO Road Test. The present serviceability index has been used as a measure of pavement performance in this analysis. The analysis consists of equations relating the serviceability index to traffic rate, applied axle load and pavement thickness. The equations are easily used for solution of thickness design problems or for estimating the remaining useful life of in-service highways. The effects of applied load have been accounted for in a manner permitting the evaluation of mixed-traffic situations. The effect of the Illinois environment has been evaluated, and the probable way in which other environments would affect pavement performance is pointed out. Also indicated is a means of studying and adjusting for the effect of other subgrade soil strengths. Very deliberate efforts were made to eliminate from the analysis any possible biases arising from the specific conditions of time, traffic rate, Initial serviceability, etc., prevailing at the Road Test during testing. These are extraneous influences compared to the more basic engineering limitations such as soil strength, materials and methods of construction.

Report of Session II - Road Tests, Field Studies, and Performance Crlteria
Moderator: A.C. Benkelman

A moderated discussion of the papers presened in Session II.

01008	British Full-Scale Pavement Design Experiments A. R. Lee and D. Croney Road Research Laboratory, Harmondsworth, Middlesex, England Pavement Evaluation Studies in Canada Special Committee on Pavement Design and Evaluation, E. B. Wilkins, Chairman, Canadian Good Roads Association, Ottawa 4, Canada Michigan Pavement Performance Study for Design Control and Serviceability Rating W. S. Housel, The University of Michigan, Ann Arbor, Michigan Controlled Tests of Mixed Loads on Flexible Pavements A. A. Maxwell, R. G. Ahlvin, and D. N. Brown U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi An Alternate Analysis of the Present Serviceability Index L. J. Painter, The Asphalt Institute, College Park, Maryland
01009	**British Full-scale Pavement Design Experiments** *A. R. Lee , D. Croney* Adequately controlled full-scale road experiments are essential to the development of any reliable method of pavement design. In Great Britain such experiments are normally carried out on heavily trafficked public roads. Advantage is taken of road improvement schemes such as major realignments or dualling projects so that the experimental sections are laid on newly prepared subgrades and not on foundations which have already been subjected to traffic stresses. The procedure followed has been similar in all cases. Each site is used to investigate the performance of one or more base materials under various types and thicknesses of bituminous surfacing. A series of short sections of length 100-200 feet long are laid, in which the thicknesses of both base and surfacing are varied above and below the values expected from previous experience to be satisfactory. The performance of the sections is judged primarily on the deformation caused by traffic, and the degree of cracking which develops. The paper summarizes the results from five of the larger experiments at present under observation. The main conclusions reached are as follows: (1) Pavements surfaced with rolled asphalt wearing courses deformed less than equivalent pavements surfaced with open-textured coated macadam. In this respect 1-1/2 inches of rolled asphalt was equivalent to about 4 inches of coated macadam when laid on unbound or lightly bound bases. (2) Rolled asphalt bases performed better than unbound, cement-bound or open-textured coated macadam bases. For heavily-trafficked trunk roads, a thickness of base of at least 8 inches was required when any of the latter base materials was used under a 4-inch asphalt surfacing. The thickness of base could be reduced to about 5 inches when rolled asphalt was used as the base material. (3) With bound bases beneath an asphalt surfacing the over-all thickness of pavement required was less than the thickness indicated by the C.B.R. method of pavement design. Maintenance at periods of about four years was found to be necessary on pavements surfaced with open-textured bituminous materials, even where the over-all thickness of pavement was greater than that indicated by the C.B.R. method. The performance of soil cement, lean concrete and bituminous-bound bases appears to depend critically on the grading of the aggregate and on the binder content, and particularly on the way in which these factors determine the density of the compacted materials. Insufficient evidence has so far been obtained on this matter, and further experiments are now in progress to investigate it further.
01010	**Pavement Evaluation Studies in Canada - Part I** *E. B. Wllkins* This paper attempts to summarize the procedures and results of the co-operative pavement investigation program started in Canada in 1958. The paper is offered as a committee presentation as all members contributed to the information contained herein. For convenience, the paper is divided into four parts. Part I contains an outline of the pavement investigation program. It describes the pavement design problem in Canada, the formation of the Committee and the objectives of the Committee's work. It indicates the philosophy and approach adopted in the investigations, wherein the basic data is

	developed through a study of existing rigid and flexible pavements in service on the main highway systems. The three-stage investigation plan, together with the standardized procedures for data collection, testing and data processing, are described. The unique features of the program which include the method of rating pavement performance and the method of evaluating the strength of a section of pavement are presented in some detail. Part II of the paper deals with pavement deflection testing procedures. The standard CGRA Benkelman Beam rebound deflection testing procedure which is used in all Canadian flexible pavement investigations is described. Data supporting this procedure is discussed and significant factors to be considered in carrying out such tests are noted. Several modifications to the standard Benkelman Beam are described. Both theoretical considerations and practical field data are used to substantiate that the CGRA Benkelman Beam rebound deflection test results are a valid measurement of pavement strength. Data are presented to show the influence of wheel load and pavement temperature on rebound deflection measurements. Part III deals with the results of some special studies and the application of certain findings. A method of design for strengthening existing flexible pavements is described. Data are presented to show the influence of shoulders on flexible pavement strength. Data from the evaluation of the load-carrying capacity of special base course materials are presented. Information is discussed showing the use of the Benkelman Beam in evaluating pavement failures for maintenance purposes. The influence of frost action on pavement strength and performance is discussed. Data on the seasonal variation in the load-carrying capacity of flexible pavements are presented. Part IV of the paper deals with the analysis of pavement performance data collected during 1959 and 1960. Pavement performance, design, age, loading, strength and environmental data from several thousand sections of flexible pavement in all parts of Canada have been collected under stage 1 of the investigation program, The information for each of these sections has been recorded on punch cards and stored at a central data processing center. Multiple regression analyses have been performed on a" electronic computer to relate flexible pavement performance with the principal variables affecting it. Results are presented and discussed which illustrate some of the Committee's findings to date, while plans for further work are indicated. The volume of pavement inventory data collected during 1961 is far greater than the combined data for 1959 and 1960. The completed 1961 data was received by the central computation center in February 1962 and will be included in the analyses to be carried out during the spring of 1962. It is hoped that further results will be available at the time of the International Conference in August 1962.
01011	**Pavement Evaluation Studies in Canada - Part II** *E. B. Wllkins* The Benkelman Beam apparatus was developed at the WASH0 Road Test in Idaho in 1953 in order to measure pavement deflections occurring under typical test vehicle wheel loadings. The test gained quick recognition among pavement investigators due to its relative ease of operation, speed and economy in obtaining deflection data. During meetings in 1958 and 1959 of the Special Committee on Pavement Design and Evaluation of the Canadian Good Roads Association it was decided to secure extensive pavement deflection information employing the Benkelman Beam apparatus. A careful review of previous work by committee members indicated that revisions and standardization would be necessary to the procedure being employed in order to achieve more reproducible results. Additional research was, therefore, undertaken during the spring and summer of 1959 to enable the development of a test procedure which would be satisfactory to the Committee. In order to clarify this presentation, the method of test developed at the Idaho Road Test has been termed the WASH0 procedure, while the proposed method adopted by the Special Committee on Pavement Design and Evaluation is designated as CGRA procedure.
01012	**Pavement Evaluation Studies in Canada - Part III** *E. B. Wllkins* Special studies have been undertaken in conjunction with stages 1 and 2 of the investigation. In certain cases additional information has been required to establish standard procedures within the Committee. There has also been a requirement for immediate approximate solutions based on preliminary data to some of the problems under investigation. When all the pertinent information has become available, modifications may be required, especially in connection with the design procedures. The studies detailed in the following section have been found to be useful to the Committee.
01013	**Pavement Evaluation Studies in Canada - Part IV** *E. B. Wllkins* The purposes of stage 1 of this Pavement Investigation Program, together with the methods for collecting and summarizing the inventory data, were explained in Part I of this paper. Part IV is confined to the presentation of some typical results obtained from the analysis of the pavement Inventory data to date. Before presenting these results it is important to re-emphasize the uses and

limitations of the data from which they were derived. The uses of the pavement inventory data may be summarized as follows:

1) The data may be used to isolate and evaluate the relative effects of the principal variables on the performance of pavements. This may be accomplished through multiple regression analysis with performance as the dependent variable and such factors as rebound deflection, age, traffic and climate as the independent variables.

2) Blocks of data may be selected from the pavement inventory for special evaluations. As the pedological soil classification of the basement material defines the subgrade strength quite accurately, sections constructed on the same pedological soil type may be selected to compare rebound deflection and thickness or to determine the effects of shoulder type on the performance of pavements of equivalent design.

3) The pavement inventory data provide a permanent, concise record of the design of all pavement sections in the highway system as well as of the performance and rebound deflections values at a given time. The inventory can thus be repeated periodically to trace the actual performance and rebound deflection histories of sections.

4) The inventory data may be used to estimate pavement life.

et cetera. . .

01014 **Michigan Pavement Performance Study for Design Control and Serviceability Rating**
W. S. Housel

The Michigan Pavement Performance Study is a cooperative research program conducted by the University of Michigan and sponsored by the Michigan State Highway Department and the U.S. Bureau of Public Roads. The general pavement research program has been in progress since 1946, when the University took over Willow Run Airfield. Preliminary projects were initiated with other sponsors from the transportation industry joining the Highway Department and University in a joint effort. Over a period of some 15 years, the investigation has included extensive pavement condition surveys of pavement at Willow Run Airfield and on highway pavements throughout Michigan.

The objective of the study has been to develop quantitative measures of pavement adequacy for the primary purpose of correlating design and performance and to provide a basis for gauging serviceability. Pavements are built for the purpose of providing durable riding quality for the safety, convenience and comfort of the highway user. Major factors which affect the life and serviceability of a highway pavement are its structural characteristics as related to the vehicle loads to which it is subjected and the uncontrolled variables of environment. It was felt that the integrated result of all these factors, both controlled and uncontrolled, could be measured by changes in the pavement profile (roughness) and structural continuity (cracking pattern). These two factors were selected as the quantitative counterparts of riding quality and durability, the two most important attributes of a highway pavement.

A truck-mounted profilometer was built to accurately record pavement profiles; provision was made to record pavement cracking. In the past four years that the equipment has been in operation, some 9500 miles of pavement profiles have been recorded and analyzed. As a result of this investigation, a number of significant relationships have been developed.

01015 **Controlled Tests of Mixed Loads on Flexible Pavements**
A. A. Maxwell, R. G. Ahlvin, D. N. Brown

Traffic of 10,000-, 25,000-, and 50,000-lb single-wheel-load test carts was applied to a test section constructed of a well-graded crushed limestone on a weak clay subgrade to study the effects of mixed traffic on flexible pavements. Deflection, deformation, density, and CBR were measured at specified intervals of test traffic.

Test results indicate that occasional application of overload traffic will shorten the useful life of flexible pavements in proportion to the magnitude of the overload traffic; occasional drastic overloads will not necessarily result in immediate pavement failure.

01016 **An Alternate Analysis of The Present Serviceability Index**
L. J. Painter

This paper accepts the present serviceability concepts which have been developed by Mr W.N. Carey, Jr., and Dr P.E. Irick as presented in Highway Research Board Bulletin 250. Two features of the equations presented by Carey and Irick have proven troublesome to engineers within The Asphalt Institute. First, the equations are so arranged that it is possible to obtain PSI values greater than 5.0 or less than 0.0. Since the Rating Panel was restricted to a range from O-5, we believe that the equations

should likewise be restricted. Second, the initial constants associated with the two pavement-type equations were different, implying that one pavement type could be built to a higher initial serviceability than another. The equations presented in this paper have overcome these two objections without sacrificing the accuracy of estimate. The equations developed by Carey and Irick also include a unique transformation of the principal independent variable, slope variance. Equations presented in this paper are limited to more conventional transformations.

Some information is also included relative to the relationship between the Bureau of Public Roads roughometer measurements and slope variance measurements of the AASHO Road Test-type profilometer.

Alternate present serviceability equations have been developed for both rigid and asphalt pavements. The measurements required are identical to those for the Carey and Irick equations except spalling has been added to the rigid equation.

01017 **Report on Session III - Theoretical Developments Related to Structural Design of Asphalt Pavements**
Moderator: William H. Goetz

A moderated discussion of the papers presented in Session III.

Note on a Method of Analysis for Pavements
J. Bachelez, Ingenieur en Chef de L'Aeroport de Paris
G. Jeuffroy, Societe Anonyme Pour la Construction et 1'Entretien des Routes, Paris, France

Fatigue Characteristics of Bitumen and Bituminous Mixes
P.S. Pell, University of Nottingham, Nottingham, England

Model Study of Stresses in Asphalt Pavements
Dr. Bh. Subbaraju, Central Road Research Institute, New Delhi, India

Continuation of Study on the Theoretical Design of Flexible Pavements Based on Shear Strength
William L. Hewitt, Cornell University, Ithaca, New York

Behavior of Asphaltic Concrete Diaphragms to Repetitive Loadings
R.A. Jiminez and B.M. Gallaway, Texas Transportation Institute, College Station, Texas

The Bearing Capacity of Asphaltic Concrete Carpets Surfacing
E. Shklarsky and M. Livneh, Israel Institute of Technology, Technion City, Israel

Shear Loads on Pavements
E.S. Barber, U.S. Bureau of Public Roads, Washington 25, D.C.

Analyses of Road Test Data Using Procedures Developed in U.S. Army Corps of Engineers Accelerated Traffic Tests
C.R. Foster, National Bituminous Concrete Association, College Station, Texas

General Analysis of Stresses and Displacements in Layered Elastic Systems
R.L. Schiffman, Rensselaer Polytechnic Institute, Troy, New York

01018 **Note on a Method of Analysis for Pavements**
J. Bachelez, G. Jeuffroy

The purpose of this paper is to consider the possibilities of analysing a road structure by means of a simiplified elastic theory, on the basis of experimental results obtained from the WASH0 Road Test.

01019 **Fatigue Characteristics of Bitumen and Bituminous Mixes**
P. S. Pell

Details are given of a laboratory investigation into the fundamental fatigue properties of bitumen and bituminous mixes. Tests were carried out in two different types of machine, rotating bending under constant stress amplitude, and oscillating torsion under constant strain amplitude, to Investigate the effect of such factors as temperature, speed of loading, bitumen content of the mix, void content, surface finish, rest periods, and rate of crack propagation.

Fatigue tests on sandsheet specimens carried out under constant amplitude bending stress at various temperatures between -13.5 deg C and +25 deg C show that the material exhibits fatigue properties over wide ranges of stress and that for a particular temperature and speed of loading the relationship between the logarithm of the stress and the logarithm of the number of cycles of loading to cause failure is linear between 10^4 and 10^8 cycles. The life under constant stress amplitude tests is highly

dependent on the temperature, a low temperature giving a longer life at a particular stress; it is also dependent to some extent on the speed of loading. However, taking into account the stiffness of the material which depends on temperature, speed of loading, rheological characteristics, and composition of the mix, it has been found that when the logarithm of the strain, calculated as the stress amplitude divided by the stiffness, is plotted against the logarithm of the number of cycles to failure, all experimental results at different speeds and temperatures for one mix lie with a certain amount of scatter about one straight line. It appears, therefore, that the fatigue life is primarily controlled by the magnitude of the applied strain and not by the stress, and that the effects of temperature and speed of loading can be accounted for by their effect on the stiffness of the specimen.

The results of fatigue tests on sandsheet specimens under constant amplitude torsional strain at different temperatures between -20 deg C and +40 deg C confirmed the bending results, but at the higher temperatures under this type of loading the fatigue life includes a considerable crack propagation time, the rate of propagation depending on the stress at the tip of the crack. Examination of the fatigue cracks and failure surfaces showed that in nearly all cases failure originated on the principal tensile plane.

Similar results have been obtained for mixes containing different amounts of aggregate but as the quantity of aggregate in the mix is reduced so the life for a given strain increases, suggesting that the criterion of fatigue crack initiation in bituminous mixes may be one of tensile strain in the bitumen present in the mix.

Tests on bitumen alone at various temperatures both in bending and shear also gave comparable results on the basis of tensile strain, but under certain conditions, particularly at low stresses, the measured fatigue life Includes a considerable length of time necessary to propagate the crack or cracks sufficiently to terminate the test. Unlike sandsheet specimens, bitumen alone showed beneficial effects of rest periods particularly at higher temperatures.

01020

Model Study of Stresses in Asphalt Pavements
Dr. Bh. Subbaraju

In order to obtain a better understanding of stress conditions existing in asphaltic concrete surface layers of highway and runway pavements, a model of a thin asphaltic concrete slab, 23 inches long, 21-1/2 inches wide and 2-1/2 inches thick was prepared. The slab was supported on a soil base of ML material (Unified Soil Classification System) contained in a 25-1/2 inches by 23-1/2 inches by 23 inches wooden box.

The load was applied to the model pavement slab either through a 3-3/4 inches diameter by 1/2 inch thick circular steel bearing plate or through a hard rubber wheel of 4 inches diameter attached to the head of a Universal testing machine.

Strains were measured at different parts of the slab using strain gauges of the equiangular rosette type. The strain data obtained from about 700 strain measurements were reduced to principal stresses and shear stresses.

The results obtained in this study indicate the presence of rather large tensile stresses in the slab and must therefore, be given careful consideration in the design of asphalt pavements. Under the conditions of the experiments, the maximum stress in the asphaltic concrete pavement could be computed very closely by an equation given in this paper.

01021

Continuation of Study on the Theoretical Design of Flexible Pavements Based on Shear Strength
William L. Hewitt

Study of the theoretical design of flexible pavements based on the shear strength properties of the components of the pavement structure is continued in an attempt to correlate the design procedure with engineering practice and to develop curves which will simplify the design procedure. Test constants used in design are angle of internal friction and cohesion, which should be determined on the bearing material as it will be found under service conditions. In the case of soils and untreated aggregate bases consideration must be given to moisture content and density; whereas, for bituminous mixtures the quantity and type of bituminous material, density, voids, temperature, and rate of loading of the test specimen will influence shear strength constants.

In comparing the theoretical design procedure developed by the writer with that used by the Texas Highway Department, It is found that the basic equation gives thickness of pavement suitable for only moderate roadway traffic and that a traffic factor or safety factor must be applied to adjust for traffic volume. The range of traffic factors is from 1 to 2, corresponding to traffic volumes of moderate to heavy.

An indirect comparison with the Hveem Stabilometer method of thickness design indicates that the

theoretical procedure gives reasonable values for moderate traffic, indicating the need for a traffic factor for heavy traffic. The indirect comparison is made possible through the development of a relationship between angle of internal friction and resistance value, R.

Design curves are developed for each of four wheel load categories with a traffic factor of 1.0. For the 10,000 pound dual wheel load design curves are given also for a traffic factor of 2.0. It is hoped that the convenience of the design curves will stimulate interest in the design of flexible pavements on the basis of the shear strength properties of the pavement components.

01022 **Behavior of Asphaltic Concrete Diaphragms to Repetitive Loadings**
R. A. Jiminez , B. M. Gallaway

This paper presents data on the behavior of asphaltic concrete slabs subjected to repetitive loadings in the laboratory. The specimens, 17-1/2 inches in diameter, were produced in the laboratory by a special molding procedure and also were obtained by coring from existing roads in the State of Texas. An apparatus was built which loads the test specimen with forces that vary sinusoidally with time, clamps the specimen about its periphery, and gives the specimen support of uniform magnitude on the bottom surface.

Several loading and mixture variables were investigated to determine their effects on the flexibility and endurance to repeated loads of coarse sheet-asphalt mixtures. The results of the investigation show expected findings that (a) resistance to repetitive loads is a function of specimen thickness, (b) different types of asphaltic concrete have different degrees of endurance to repetitive loads and (c) thicker specimens are not capable of bending as much as the thinner ones.

01023 **The Bearing Capacity of Asphaltic Concrete Carpets Surfacing**
E. Shklarsky, M. Livneh

Evaluation of the bearing capacity of asphaltic concrete carpets constitutes a fundamental problem in the design of pavements. Literature abounds with papers on this problem, approached either from an empirical or a theoretical viewpoint. Particularly important in this field is the work of McLeod based on a theoretical approach similar to the calculation of the bearing capacity of soil under static loads, with the strength parameters, (namely the cohesion and the internal friction angle) and the plastic mechanism of rupture, taken into account. However McLeod's calculations do not include the fact of the strength being anisotropic.

In this paper, the basis for the bearing capacity calculation is the author's suggested modification of Coulomb's rupture theory in which the internal friction angle is isotropic and the cohesion anisotropic. In the light of this modified theory, and with the aid of the appropriate laws of the theory of plasticity, bearing capacity formulae can be derived for the following three cases: (a) thick carpets; (b) thin carpets over a non-rigid base; (c) thin carpets over a rigid base. These formulae take into account the friction between the contact surfaces of wheel and asphaltic concrete and between the asphaltic concrete underside and the upper surface of the base, and utilize the values of the anisotropic cohesion and isotropic angle of internal friction of both carpet and base material.

The main conclusions arrived at from the theoretical considerations in this paper, show the following factors affecting the bearing capacity of an asphalt carpet (a) Anisotropy factor. In all cases where it is greater than unity the bearing capacity is reduced. It is clear that disregarding this factor leads to overestimation of the bearing capacity. (b) Braking stresses. Although the cohesion of the material is higher in braking than at rest, the former state remains the most critical, and practical experience supports this. (c) Strength of the base in carpets over a flexible base. A small increase in the cohesion of the base material greatly increases the bearing capacity, as does increasing the thickness of the carpet. (d) Coefficient of friction between the carpet and a rigid base. When the coefficient of friction is small, this case may be more critical, than that of a flexible base. Here, too, increasing the thickness of the carpet increases the bearing capacity for inclined loading but reduces it for vertical loading.

Naturally, only practical tests in the field can provide final confirmation of the conclusions; pending such confirmation they can, it is hoped, serve as a satisfactory means of estimation.

01024 **Shear Loads on Pavements**
E. S. Barber

Stress analysis of pavements is often based on normal loads alone; however, there are shear loads that should not be ignored. This paper considers two sources of applied shear stresses - those produced by a pneumatic tire under a vertical load and those caused by a component of the total load parallel to the surface of contact, generally considered horizontal.

When a vertical load is applied to a pneumatic tire on a horizontal surface, shear stresses acting toward the center of the loaded area are produced on the surface of contact. By numerical combination of concentric rings of shear stress, the vertical normal stresses produced by a uniform distribution of

inward acting shear stresses over a circular area are calculated and graphed.

The vertical normal stress under the center of a circular area to which various distributions of inward acting shear stresses are applied is also shown. For vertically loaded pneumatic tires, measured stresses are generally somewhat greater than those calculated from the vertical load. The effect is most important at shallow depths and should be considered in studies of effect of pavement thickness on transmitted stresses.

Shear stresses in one direction between tire and pavement surface may be produced by various means, such as longitudinal grades, super-elevation, starting, stopping, and horizontal curves. Interior vertical normal and horizontal shear stresses caused by a uniform shear stress in one direction applied to a circular area are calculated and related to similar stresses from applied normal loads. The horizontal shear stress is especially important in the stability of layered systems, where the bond between layers may be critical.

The effect of horizontal load components in reducing bearing capacity is evaluated. When horizontal and vertical stresses are applied together, their combined effect must he considered in any analysis of bearing capacity.

Under static loads, which are often critical for design because of creep, an exact analysis of stresses must include the inward acting shear stresses peculiar to pneumatic tires. When acceleration or deceleration produce strong horizontal loading components, critical stresses are greatly increased and bearing capacity is greatly decreased when compared to vertical loading over the same time. Either of these conditions is more critical than a vehicle moving at constant velocity along a horizontal tangent.

01025

Analyses of Road Test Data Using Procedures Developed in U.S. Army Corps of Engineers Accelerated Traffic Tests
C. R. Foster

When a flexible pavement system is loaded, each layer deforms elastically and non-elastically. Nonelastic deformations are the concern in most methods of flexible pavement design. Non-elastic deformation can be of two types: (1) a change in shape with no change in volume; or (2) a change in shape accompanied by a change in volume. The first is shear deformation and the second is compaction.

In the analysis of the several accelerated traffic tests conducted by the U.S. Army Corps of Engineers on flexible pavements it was necessary to separate the effects due to shear deformation and compaction and to make separate analyses. Also, separate procedures were developed to provide designs against shear deformation and compaction.

Shear deformation occurs when a layer is overstressed and for any given loading condition the primary variables are the strength of the layer being considered and the thickness above it, All existing flexible pavement designs are concerned primarily with thickness. In the analysis of thickness requirements as indicated by the Corps of Engineers accelerated traffic tests and by actual airfield performance it was found necessary to consider the in-place strength of the layer being studied. Also, since the available data for any one condition of loading were limited it was found desirable to develop methods of expressing the loading conditions in dimensionless values so that all the available data on thickness versus strength could be compared simultaneously.

This paper reviews the dimensionless methods developed in the analysis of the Corps of Engineer accelerated traffic tests for thickness and illustrates the use of these methods with the WASH0 test results, The compaction that develops in a given layer in a flexible pavement structure under load is primarily a function of: (1) the soil type, (2) the loading, and (3) the depth from the point of load application to the layer. The variability produced by differences in soil types has traditionally been treated in a semi-dimensional manner by expressing the degree of compaction in terms of the maximum unit weight obtained in a standard laboratory compaction test. In the analysis of the compaction requirements as indicated by Corps of Engineer accelerated traffic tests, methods of expressing loading conditions in dimensionless numbers were developed so that simultaneous comparisons could be made of the compaction-thickness relationships for all available data. These are reviewed in this paper.

The paper points out that although the developments were based on airfield pavements they are applicable to road test data.

01026

General Analysis of Stresses and Displacements in Layered Elastic Systems
R. L. Schiffman

The design and analysis of flexible pavements requires a knowledge of the stresses and displacements due to a variety of surface loading conditions.

This paper presents a general theory for the analysis of elastic layered systems. The current state of knowledge is reviewed. General formulations of the effect of layering are developed. Analytical procedures are developed for the consideration of general distributions of normal and tangential surface loads, and axi-symmetric and slightly inclined rigid plates.

01027 **Report on Session IV - Theoretical Developments Related to Structural Design of Asphalt Pavements**
Moderator: Robert G. Hennes

A moderated discussion of the papers presented in Session IV.

The Explicit Solution of the Equations of the Elastic Deformations for a Stratified Road Under Given Stresses in the Dynamic Case
Andree Bastiani, Dr. in Mathematics, Paris, France

A Fundamental Approach to the Design of Flexible Pavements
K. R. Peattie, Shell Research Limited, Thornton Research Center, Chester, England

Theoretical Concepts Applied to Asphalt Concrete Pavement Design
F. N. Finn and E. L. Skok, Jr., The Asphalt Institute, College Park, Maryland

Applications of Layered System Concepts and Principles to Interpretations and Evaluations of Asphalt Pavement Performances and to Design and Construction
Donald M. Burmister, Columbia University, New York 27, New York

The Response of Linear Viscoelastic Materials in the Frequency Domain with Emphasis on Asphaltic Concrete
Hratch S. Papazian, Ohio State University, Columbus 10, Ohio

A Structural Design Procedure for Pavements
R. F. Baker, Ohio State University, Columbus 10, Ohio

Viscoelastic Behavior of Asphalt Concrete Pavements
Carl L. Monismith and K. E. Secor, University of California, Richmond, California

The Application of Elastic Theory to Flexible Pavements
A. C. Whiffin And N. W. Lister, Road Research Laboratory, Harmondsworth, Middlesex, England

Analysis of Viscoelastic Pavements Subjected to Moving Loads
K. S. Pister and R. A. Westmann, University of California, Berkeley 4, California

Use of Galerkin's Method for the Study of Static and Dynamic Behavior of Road Structures
R. Lattes, J. L. Lions, J. Bonitzer, Laboratoire Central des Ponts et Chaussees, Paris (XVe), France

Designing Flexible Road Pavements
G. Schnitter and R. Jenatsch, Swiss Federal Institute of Technology, Zurich, Switzerland

01028 **The Explicit Solution of the Equations of the Elastic Deformations for a Stratified Road Under Given Stresses in the Dynamic Case**
Andree Bastiani

A road is considered as an elastic stratified body in a three dimensional space. It is assumed that each layer is a homogenous material, characterized by its Lame elastic constants (or its Young modulus and Poisson ratio) and its density. The system of partial differential equations which determine in the i-th layer and in function of the time the displacement components is solved under the following conditions: For $t = 0$, displacement components and their partial derivatives in t vanish; for $t > 0$, stress components are known functions on the free surface and, at the points of contact of two layers, the displacements and stresses are the same if computed in the upper or lower layer.

First, we solve the problem of finding the solution of the system in the i-th layer, knowing displacement or stress components at the upper or lower surfaces. For this, the notion of function is generalized using the Ehresmann local structures and the differential system is considered as a system of equations for the new objects; by an integral transformation the system is reduced to a system of linear equations. By solving this system, we obtain relations between the integral transforms of the displacement and stress components at the upper and lower intersurfaces of the i-th layer as well as at the upper surface of the last layer.

Assuming the displacement components known on the free surface, the integral transforms of the stress and displacement components are computed on the second intersurface as functions of these parameters. These quantities are also computed as functions of the displacement components at the

last intersurface. By writing that the solution is the same in both cases, we are led to a system of linear equations, the solutions of which are the integral transforms of the displacement components at the free surface and at the last intersurface. From these, we deduce the solutions of the initial equations.

The solutions are obtained in the form of ordinary integrals containing the given stress components. These integrals can be computed with a computing machine or approximated by elementary functions (the approximation depends on respective sizes of the parameters).

The regularity conditions imposed for the given stresses are practically not restrictive; in particular, strain and stress components are not supposed to be harmonic.

Examples: stresses produced by a vibrating machine or by the movement of a vehicle.

01029

A Fundamental Approach to the Design of Flexible Pavements
K. R. Peattie

The increasing use of unconventional road structures, such as those incorporating greater thicknesses of bitumen-bound layers, emphasizes the need for a better understanding of the contribution which each layer makes to the strength of the whole structure and for the development of thickness design procedures based on fundamental considerations. Most existing methods for determining the thicknesses of roads are empirical and do not take into account the different load-spreading abilities of base materials and cannot be extended to cover new conditions of loading without extensive field trials.

The basis of the theoretical treatment is the assumption that a real road structure may be represented by a series of elastic layers lying on a semi-infinite elastic mass. Traffic loads are assumed to be applied to the layered system as stresses uniformly distributed over a circular contact area.

The stresses and strains in such a structure may be obtained by solving the general elastic equations applying to the behaviour of elastic layered systems. Rigorous solutions of the stress and deflection equations have now been published for a wide range of the parameters involved in three-layer systems.

When calculating stresses, strains and deflections it is necessary to know the elastic properties of the materials in each layer. The moduli of soils and granular base materials may be determined in the field by vibrational techniques. An approximate relationship is available connecting the values of Young's modulus of such materials with their California Bearing Ratio values. The moduli or stiffnesses of bitumen-bound road materials may be measured in the laboratory, and are dependent on temperature and traffic speed.

The critical quantities in a flexible road structure are considered to be the vertical compressive stress at the surface of the subgrade and the horizontal tensile strain at the bottom of the bituminous layer.

A relationship between the permissible value of the vertical stress in the subgrade and the CBR-value of the soil has been developed from an analysis of road structures which are known to be satisfactory in practice. Because of the predominantly repetitive nature of the loading applied to roads considerable attention has been given to the fatigue behaviour of bituminous road mixes. It has been suggested that the principal tensile strain is critical in this respect and a relationship connecting the value of this strain with the number of load applications causing failure has been obtained.

A suitable design for a flexible pavement may be obtained by assuming the layers to be of certain thickness and calculating the values of the critical stresses and strains developed in this structure by the design load. These thicknesses are then adjusted, to bring the values of the critical stresses and strains within the permissible limits. The construction of design charts which can be used more directly and rapidly is described.

01030

Theoretical Concepts Applied to Asphalt Concrete Pavement Design
F. N. Finn, E. L. Skok jr.

In this paper we have attempted to show how stresses and strains computed from the elastic theory can be related to the performance of an asphalt concrete pavement. To make correlations between stresses, strains and performance, it was necessary to (1) enumerate the solutions which are available; (2) estimate the properties of the materials to be used in the pavement structure for the conditions in the field; (3) combine the material properties and the loading conditions with theory to obtain the stresses and strains theoretically produced by each application of load; and (4) correlate these stresses and strains to some measure of the performance of the pavement system.

It was decided to use the equations presented by Burmister and developed by others for the two-layer and three-layer system because they represented solutions for layers which are "fully elastic." In order to use the elastic layered system theory for analysis, the components of a pavement were assumed to

be elastic (have a constant modulus of elasticity). Consideration of the magnitude and duration of the stresses imposed on a pavement system by normal highway loads leads us to believe that stresses calculated from the elastic theory are proportional to the actual level of stress in a pavement system, With one application of a load, an adequate pavement will rebound almost completely, although in many cases permanent deformations occur after a number of applications. We feel, therefore, that a section can be treated elastically with each load application. When the visco-elastic theory is made more workable, it may provide a better approximation to the actual stresses and permanent deformations occurring in a pavement system.

The paper reviews the use of present methods for determining strength coefficients of the various components in a pavement section. These methods are used to establish proper "working" moduli of the materials. If the materials are tested at a stress-strain level close to that imposed on a pavement structure (which would be near the origin of stress-strain curve), the stress-strain ratio can be used as a modulus of elasticity, and the determination of theoretical stresses and deflections of various load and design conditions can be based on that value. In most cases for an adequate design, the strain level was low; therefore, a close approximation to an elastic condition can be assumed. "Working" moduli are determined for the pavement components at the WASH0 and AASHO Road Tests using plate load tests, deflection tests and some vibratory triaxial data on the pavement materials. These "working" moduli were then used to compute stresses in the various sections of the WASH0 and AASHO Road Test.

For correlation of stresses with field performance, it was assumed that accumulated transverse permanent deformation would be correlatable with the vertical stresses imparted to the subgrade (ZZ2) and shear stresses in the layers. Also, because cracking occurs primarily in the surface layer, the tensile radial stresses in that layer (RR1) were considered to correlate with cracking or disintegration in the surface layer. The serviceability concept as used at the AASHO Road Test because of its definition incorporates both cracking and accumulated permanent deformation: therefore, it was correlated with the vertical stress on the subgrade which was considered to be a measure of the general stress level in the pavement system. Mathematical formulae were developed to show these various relationships.

Although the relationships in the paper cannot as yet be used to design an asphalt concrete pavement section, we have attempted to show that the elastic theory can be used as a possible performance model. To set up the proper relationships, it will be necessary to work further to establish proper "working" moduli for the pavement components. We do not propose that the use of the elastic theory will result in a completely rational design, but by using the elastic theory in this manner, it is possible to relate the load on the pavement to the strength of the components in a more rational way than is now possible by most existing design procedures.

It is hoped that the advantages of using a theoretical approach to the design of an asphalt pavement have been shown and that further planned studies will be directed toward verifying these relationships.

01031 **Applications of Layered System Concepts and Principles to Interpretations and Evaluations of Asphalt Pavement Performances and to Design and Construction**
Donald M. Burmister

The significant determination of the "in-place" strength properties of the component layers and of the deflection and shear performances of a layered pavement system must be the major objectives of testing and of analyses. A layered pavement system is inherently a preconditioned and prestressed structure formed in place by systematic heavy rolling to incorporate definite density and strength properties in each layer and to prestress each layer to stresses greater than any anticipated service loading conditions. Equally important and effective is the shear strength continuity and mechanical bond incorporated at each interface and throughout the layers to form an integral prestressed pavement structure.

The distribution of vertical stresses in a layered system discloses the increased load-spreading capacity and reduction in stressed imposed in the subgrade layer with increase in the ratio of the effective moduli of the component layers. But increased vertical stress gradients through the reinforcing layers bring into action a shear stress build-up through the reinforcing layers, which may become critical to the point of initiating a breakdown of a pavement structure. The critical nature of shear stress conditions is due to the fact that they are essentially deflection-dependent and that they increase with stiffness of the pavement system. These shear stress conditions can be alleviated by multi-layer construction with smaller jumps in moduli ratios and by somewhat increased thickness of reinforcing layers, so as to maintain the desired deflection performances of the layered pavement system.

The only practical, effective, and satisfactory method of evaluating the "in-place" layer moduli of the component layers, and the deflection performances of a layered pavement system is by means of systematic comparable series of prototype load bearing tests. The principles and methods of evaluation of layered pavement systems are presented, making use of deflection and shear stress influence curves. Such evaluations provide the basic information for design of multi-layer pavement systems and over-all thickness to limit deflections and shear stresses sufficiently below critical values to insure the integrity and long service life of layered pavement systems under repeated load conditions.

Two cases have been analyzed - the Hybla Valley Test Track Data, and the WASH0 Road Test Data. The results are presented in two graphs showing the "in-place" layer moduli, the deflection performances, and even more important the degree of constructional excellence and actual uniformity achieved. These findings are discussed and they have important implications with regard not only to necessary modifications of design criteria, but also to essential modifications in construction methods and sequences, in order to attain and to insure the necessary high standards of excellence in construction demanded for modern expressway systems. The spread in the quality of construction disclosed by these evaluations is too large to be considered acceptable, and the average of construction is too low compared with the potential excellence evident from these analyses, which could be consistently achieved in construction. The evaluations have shown that inferior deflection performances were due principally to local constructional conditions of inferior shear deformation characteristics in granular subbase and base course construction. Methods for "proof testing" each pavement component before acceptance should be developed and used as a planned supervision part of construction in order to insure a uniformly high standard of constructional excellence.

01032

The Response of Linear Viscoelastic Materials in the Frequency Domain with Emphasis on Asphaltic Concrete
Hratch S. Papazian

Pavement design and performance is discussed in the light of material response, and the need for mapping the mechanical properties of engineering materials is emphasized. The fundamental rheological problem of determining the functional relationship between stress, strain and time is stated, and the rheological equation of state of a general viscoelastic material is introduced in terms of the equations relating the isotropic and the deviatoric components of the state of stress to the dilatational and the distortional components of the state of deformation.

The general stress-strain equations of linear, viscoelastic materials are defined in the frequency domain in terms of algebraic coefficients which are functions of frequency. These coefficients are complex numbers whose magnitude and phase, at any given frequency, depend on the properties of the material. They are named the complex moduli of the material, and are shown to be fundamental material constants which are independent of testing procedures or boundary conditions. Analytical and graphical procedures are presented for obtaining the complex moduli of a material experimentally. These are based on a series of dynamic tests covering a wide range of frequencies, or a single static test covering a wide range of time. The first gives magnitude and phase of the complex modulus at each frequency used, while the second method yields an analytical expression for the modulus as a continuous function of frequency.

These methods are applied to determine the complex elastic modulus E*, and the complex transverse modulus T*, of asphaltic concrete, which, at levels of stress sufficiently low compared with its ultimate strength, and for small strains, is shown to act as a linear, viscoelastic material. Both sinusoidal-stress dynamic tests, and constant-stress static tests are performed on several mixes at various temperatures, and a good correlation is obtained between the results of the two types of tests.

In the case of an isotropic, linear viscoelastic material, it is shown that two independent complex moduli, such as E* and T*, are sufficient to describe its response in full. However, to relate the mean normal stress to the mean normal strain, and the deviatoric stress tensor to the deviatoric strain tensor, two other complex moduli are defined, namely, the complex bulk modulus K*, and the complex shear modulus G*; and formulas are presented for obtaining them in terms of the other two independent complex moduli. By means of a mechanical analogy, these moduli are interpreted as the impedances of mechanical models, made up of elastic and viscous elements, whose constants are easily found.

The general stress-strain equations of the linear, viscoelastic body in the frequency domain are shown to be identical in form with the classical stress-strain equations of the elastic body in the time domain and to include them as a special case. Methods are presented for transforming the relationships from the frequency domain back to the time domain.

Variations in the components of the elastic moduli are studied in terms of response of the material under stress, and as a means for the evaluation and comparison of pavement materials. Finally, applications to pavement design and performance studies are outlined.

01033

A Structural Design Procedure for Pavements
R. F. Baker

An approach to the structural design of pavements is advanced based upon published solutions to the elastic theory two-layer and three-layer problem and upon the use of viscoelastic principles. It is suggested that the distributional effects of pavement components and the stresses throughout the system can be approximated using the elastic theory if applicable load rates and load duration are utilized in the testing procedures. The concept of complex moduli as advanced by Papazian are considered of particular importance in evaluating the pavement components.

The behavior of the components under stress is outside the elastic theory insofar as measurable permanent deformations or cracking occurs. The term "failure" of a material is ambiguous and the term "response" is preferred because the "failure" of a pavement structure is a serviceability-economic decision not based upon any specific level of material behavior.

The importance of the ratio of elastic moduli in defining stress levels is emphasized according to the theory, moving vehicles tend to develop higher flexural stresses and lower subgrade pressures than do static loads. Thus, moving loads are a more severe test of the pavement layers, while static loads produce a more rigorous test of the subgrade.

The load distribution effects of a pavement component will not be greater than indicated by the elastic modulus. Thus, the quality of a surface or base course from a load distribution perspective is defined by its modulus of elasticity (assuming Poisson's Ratio is constant). However, since stress is defined by the ratio of moduli, the "quality" of a base course in terms of load distribution varies with the stiffness of the overlying and underlying materials.

Continued work in evaluating stress and performance, and additional solutions to the elastic theory layered system will improve the suggested approach. The method is considered a higher level approximation than is currently in use and an evolutionary step in the ultimate use of the viscoelastic approach.

01034 **Viscoelastic Behavior of Asphalt Concrete Pavements**
Carl L. Monismith, K. E. Secor

A brief review of research on the viscoelastic behavior of asphalts and asphalt mixtures is presented demonstrating the time-dependence of the stress vs. strain characteristics of these materials. Together with this review, discussion of the applicability of analyses utilizing this time-dependent behavior in assessing the performance of asphalt concrete pavements is presented.

Based on analysis of data of the various investigations, two simple linear viscoelastic models were selected and their suitability evaluated by four types of triaxial compression tests on one asphalt concrete mixture, namely: (1) creep, (2) stress relaxation, (3) constant rate-of-strain, and (4) repeated axial load. Initially it was hoped to eliminate the effects of lateral pressure in these tests. However, data for deviatoric stress and strain are presented which preclude the use of such an approach.

From the triaxial compression tests, it was ascertained that the simplest model for asphalt concrete required at least four elements in order for it to demonstrate instantaneous elastic deformation, retarded elastic deformation and viscous flow. Data are presented illustrating that this model will, in the majority of cases, predict with a reasonable degree of accuracy the time-dependent behavior of asphalt concrete in the four types of tests over a range in load conditions, lateral pressures (0 - 250 psi) and temperatures (40 deg F - 140 deg F). Variations of the viscoelastic properties for these conditions are also presented together with a discussion of their significance. Thus this phase of the research produced a basic system of data relating the stress-strain-time characteristics of a particular asphalt concrete.

Using the data developed from the triaxial compression tests, solutions were developed for the time-dependent deflections of a viscoelastic plate on an elastic foundation for static loading. Static plate loading tests were performed on 4 ft by 4 ft slabs of the same asphalt concrete mixture resting on an elastic foundation composed of 1600 springs over a range in temperatures (40 deg F - 140 deg F) and at different levels of stress. Comparisons of the predicted and measured time-dependent deflections are presented. In general, the measured and computed deflection profiles had the same general shape and time-dependence, but the measured values had magnitudes considerably greater than those given by theory with the deviations between the two sets of values increasing with increased temperature. A discussion of the probable sources of difference between the slab test data and the theoretical predictions is included.

One of the major discrepancies between theory and actual behavior appeared to be the assumption of equal properties in tension and compression of asphalt concrete for slow rates of load application. Thus data are presented for tension and compression creep tests at 77 deg F which illustrate differences in the time-dependent properties. Data are also presented for bending creep tests on the same specimens which indicate that the divergence in tensile and compressive properties is time dependent.

Using the results of the bending creep tests, a modified theory is presented and the slab test results at 77 deg F are reanalyzed using this theory accounting for the differences in tensile and compression properties. Considerable improvement between the theoretical predictions and actual slab test data is obtained. Thus it would appear that for static loading, at least, viscoelastic theory may be required to predict the behavior of asphalt concrete pavements.

01035 **The Application of Elastic Theory to Flexible Pavements**
A. C. Whiffin, N. W. Lister

Amongst other things, a road should spread wheel loads so that the repeated stresses applied to the soil subgrade become too small to compact the soil appreciably or cause it to fail in shear, while the road itself should not experience stresses leading to failure of any of its layers.

The present methods of pavement design are ad hoc in character and based upon experience of the behaviour of different types of road over a wide range of traffic and soil conditions. A more reliable method of design might be developed on the basis of the dynamic stresses produced in the road by moving vehicles, the stress/deformation characteristics of the layers in the road under repetitive loading, and the variation of these properties with time. The present paper reviews the position, but it is not yet possible to present a technique for designing roads from this information.

Several theories for computing stresses and deflections in multi-layered elastic systems have been developed and are reviewed. That devised by Burmister appears to fit the conditions applying in a flexible road. Diagrams are given showing how the various stresses in a multi-layer road vary with the dynamic elastic moduli of the layers and their thicknesses, the curves being based on an analysis of the computations performed by Acum and Fox. The vertical stress at the soil/base interface under a moving wheel rises with increase of the elastic modulus of the soil. This stress falls with increase of the elastic modulus or thickness of the road base or surfacing. A road base of high elastic modulus has good load-spreading properties, but this is accompanied by high horizontal tensile stresses in the base near to its interface with the soil. Some road bases, although having the high elastic modulus necessary for good load-spreading characteristics, do not have sufficient tensile strength to withstand the stresses generated within them and failure occurs.

A review is given of the information available concerning the dynamic elastic moduli of road-making materials and shows that much more information is needed, It has so far proved difficult to devise in situ tests for determining the moduli of bitumen or tar-bound materials at the rates of loading applying to traffic conditions.

Values of the dynamic elastic moduli have been obtained for some of the materials in roads where measurements have been made on the dynamic stresses generated in the subgrade. Reasonable agreement then occurred between the measured and computed values of the dynamic stress. The measurements of stress showed that, of the base materials tested so far, rolled asphalt appeared to have the best long term load-spreading properties. When any of the layers of the road contained tar or bitumen, the dynamic stress applied to the soil rose with increase of the temperature of the road. The stresses were found to be proportional to wheel load.

Before data on stresses and deflections can be used in pavement design, detailed information is required on the behaviour of the layers under the conditions of repeated stress to which they are subjected in a road. Asphalts have been studied, but little work has been done on mixes of high void content such as bitumen macadam or tarmacadam, while no information is available on the fatigue properties of road bases. Measurements of the deflections of roads under moving vehicles will eventually lead to information concerning the elastic moduli of the layers. The Benkelman Deflection Beam is being used in several countries to assess the quality of a road, the measurements being made when subgrades are normally in their weakest condition. Results obtained so far indicate that the magnitude of deflection criteria depend on the intensity of the traffic using the road, the type of subgrade and the type and thickness of base and surfacing. The most important factors seem to be the type of the base material and the traffic intensity. The elastic approach outlined in the paper may never give a complete design method, but it is already being used to analyze road failures and a typical example is outlined in detail.

01036 **Analysis of Viscoelastic Pavements Subjected to Moving Loads**
K. S. Pister, R. A. Westmann

The linear elastic analysis of flexible pavements subjected to time-independent stationary loads has received extensive attention in recent years. No attempt will be made to review the literature which has developed; a brief summary may be found in (1). The adequacy of such analysis applied to flexible pavements is contingent upon, among other factors, whether or not the layers of a pavement cross-section may be regarded as linearly elastic. Recent laboratory studies (2) have demonstrated that the structural section (asphalt concrete) of flexible pavements exhibits viscoelastic behavior.

Stationary loads (for example, parked vehicles) produce time-dependent deformation in a vlscoelastic pavement. A single load or a series of load applications causes an accumulated displacement or strain condition that may produce permanent deformation or failure by cracking. The analysis for such problems can be carried out in a manner parallel to the elastic analysis by uslng the elastic viscoelastic correspondence principle. Typical examples of such analysis for stationary loads applied to viscoelastic plates on elastic as well as viscoelastic foundations may be found in (3) and (4). The deformation produced by a number of loads distributed over an area can be obtained by superposition as in the corresponding elastic problem. It should be noted that the relationship between temperature and viscoelastic mechanical properties, as described in (1) and (2) is of fundamental importance in this type of problem.

In the sequel two factors which have not received much attention in the application of elastic or viscoelastic theory to pavement analysis will be discussed. The first concerns the effect of moving loads on a vlscoelastic pavement, while the second Involves improving the analysis by including the possibility of different mechanical properties in tension and compression.

01037 **Use of Galerkin's Method for the Study of Static and Dynamic Behavior of Road Structures**
R. Lattes, J. L. Lions, J. Bonitzer

The main purpose of the work presented in this communication was to set a method for computing Stresses and deformations in road structures submitted to time-varying loads, including dynamic phenomena such as wave propagation and reflection, resonance, etc. . . . Conventional method used by Burmister and others is not applicable in this case, and one must use other techniques.

Galerkin's method presents many advantages:

1. It is well fitted to use of electronic computers.

2. It is applicable to dynamic loading cases as well as to static ones.

3. It allows stresses and deformations to be computed in a great many points (one hundred for instance) of the road structures without excessive increase of the cost.

4. Cost of computations does not increase very much as the number of layers of the structure increases.

5. Calculations are made in a Cartesian system of coordinates which allows simple calculation of stresses and deformations even when loaded areas are not of simple forms. Also it is expected the method could be extended to cases of horizontally limited structures.

6. Viscoelastic properties of certain layers can be taken into account. Presented model uses simple Voigt models, but more complex models, giving better approximation of viscoelastic properties of materials, could be as well used.

Finally, it seemed useful to compute not only stresses and deformations, but also their derivatives relating to elastic and viscoelastic parameters characterizing road layers.

01038 **Designing Flexible Road Pavements**
G. Schnitter, R. Jenatsch

This report deals with the design of road pavements. It was prepared in connection with an inquiry by the Swiss Federal Board of Road and River Engineering to VAWE (Laboratories for Hydraulic Research and Foundation Engineering). as well as with studies and literature research conducted at VAWE.

The design of the rigid pavement can today rely on uniform methods. The basic factors, such as the behaviour of the building material and the mechanics of the pavement acting as a slab, are governed by relatively simple rules and can be regarded as fairly settled.

As regards the design of the flexible pavement, however, so far no uniform method has become established. The fact that the properties of the bituminous binders vary with temperature and loading period, and also the wide variety of the products available have so far defeated a clear determination of the key factors essential for the design of flexible structures. Though there are various designing methods, these are largely based on the personal experience and preference of their inventors.

Accordingly, the present report chiefly gives a survey of the terms and key factors used. Moreover, it gives a description and a critical comparison of the principal designing methods at present applied to flexible pavements.

Reference is made to the effect of dynamic factors on design. Finally, the method of design used by VAWE is described.

01039 **Report on Session V - Strength Evaluatlon of Pavement Structure Elements**
Moderator: H. Bolton Seed

Effects of Compaction and Subgrade Stabilization on Deflections and Performance of Virginia Pavements
F. P. Nichols, Jr., Virginia Council for Highway Investigation and Research, University of Virginia, Charlottesville, Virginia.

Time-Dependent Deformation of Clay Soils Under Shear Stress
Manrique Lara-Thomas, Ohio State University, Columbus 10, Ohio

Basic Material Properties for the Designof Bituminous Concrete Surfaces
Emil R. Hargett, South Dakota State College, Brookings, South Dakota

Resilience Characteristics of Subgrade Soils and their Relation to Fatigue Failures in Asphalt Pavements
H. B. Seed, C. K. Chan, and C. E. Lee, University of California, Berkeley, California

A Study of the Repeated Load Strength Moduli of Soils
H. G. Larew And S. B. Ahmed, University of Virginia, Charlottesville, Virginia

The Effect of Resilience-Deflection Relationship on the Structural Design of Asphaltic Pavements
F. N. Hveem, E. Zube, R. Bridges, and R. Forsythe, Division of Highways, Sacramento 19, California

Dynamic Testing as a Means of Controlling Pavements During and After Construction
W. Heukelom and A. J. G. Klomp, Koninklijkc/Shell-Laboratorium, Amsterdam, Netherlands

Analysis of Flexible Airfield Pavements by Surface Plate Loading
Philip P. Brown, Bureau of Yards and Docks, U.S. Navy, Washington 25, D. C.

The Structural Behavior of Flexible Pavement - An Analysis of Rigid-Plate Bearing Tests on Full-Size Test Sections
A. C. Benkelman and S. Williams, Phvsical Research Division, U. S. Bureau of Public Roads, Washington 25, D. C.

Dynamic Testing at the AASHO Road Test
L. W. Nijboer, Koninklijke/Shell Laboratorium, Amsterdam, Netherlands
C. T. Metcalf, Shell Oil Company, Martinez, California

Resiliency of Base Rock
O. A. White, Oregon State Highway Department, Salem, Oregon

Finnish Road Structures and the Use of Wedges Against Frost Heaving
0. A. Taivainen, Faculty of Technology, Oulu University, Oulu Finland

01040 **Effects of Compaction and Subgrade Stabilization on Deflections and Performance of Virginia Pavements**
F. P. Nichols Jr.

The major effort of one of the Sections of the Virginia Council of Highway Investigation and Research has been directed toward ascertaining some of the more important factors affecting the performance of flexible pavements. The performance histories of well over 100 typical Virginia pavements have been observed carefully since 1954. In 1958, a specially designed test project was built, and another is scheduled for completion in 1962. Measurements have been made, using the Benkelman beam, of the deflection characteristics of many of these pavements. Average deflections under a 9,000-lb dual wheel on certain pavements have been found as low as 0.010"; on others the average has approached 0. 100", with individual readings of over 0.150". Since many of the weaker pavements were more costly to build than some of the stronger ones, it has been felt imperative to look into the reasons for the weaknesses.

The two most noticeable factors associated with the weakness of the pavements observed have been (1) inadequate compaction within the structure and (2) inadequate subgrade support. From the first experimental project it appears that high deflections can be minimized more effectively by improving compaction of the structural components than by increasing the thickness of asphaltic concrete in the same total structural thickness. But on more recently constructed projects an even more striking reduction in deflection has resulted from substituting subgrade stabilization for select borrow as the lowest course in the pavement structure.

Some of the deflection data on which the above statements were based are summarized graphically in this paper. Advantages of subgrade stabilization are listed along with certain practical considerations to be made before choosing this method of design. Also, recommendations for the application of the research findings to the design of future pavements are shown in a table, These recommendations, if adopted, should result in major savings in initial construction costs in comparison with rigid slab designs and with some recent flexible designs involving greater thicknesses of black base than those tabulated.

01041 **Time-dependent Deformation of Clay Soils Under Shear Stress**
Manrique Lara-Thomas

Soil-deformation theories have always constituted one of the most difficult obstacles for the development of a more rational approach to the solution of interaction problems in soil mechanics. Traditionally, approaches based on theory of elasticity and on theory of plasticity have been used in the solution of certain soil mechanics problems, as per Terzaghi and Jurgenson. More recently, the

	approach based on the theory of viscoelasticity has gained more and more popularity among researchers working in the field. The viscoelastic approach is based on the general concepts of the science of rheology, or the science of flow. Briefly, the theory assumes that the mechanical behavior of real materials can be approximated by a certain combination of the behavior of two ideal bodies: the ideal elastic body and the ideal viscous body. Thus, in a very general sense, the mechanical behavior of any real material can be determined by a particular equation or set of equations giving a relation between the components of the stress and strain tensors, and also between the components of the rate of stress and strain tensors. The purpose of the study was: (1) To investigate the deviatoric rheological properties of certain cohesive soils under creep tests. (2) To apply concepts of the viscoelastic theory in the analysis of the results. (3) To develop procedures to fit rheological models to experimental data. (4) To investigate whether the materials tested exhibited linear viscoelastic behavior. (5) To study the effect of load repetition on the properties described above.
01042	**Basic Material Properties for the Design of Bituminous Concrete Surfaces** *Emil R. Hargett* This paper emphasizes the growing need for a flexible pavement design procedure that is based on the engineering properties of highway materials or material combinations. This rational design approach is recommended as a replacement for the empirical design methods that are now in use by highway and airport engineers. The engineering properties of primary concern are shearing resistance, elastic properties, and fatigue resistance. These engineering properties are then used to explain the stability and performance characteristics of bituminous concrete surfaces. A new method of tension and compression testing is described and the test results explained in view of our needs for basic design data. This method of tension and compression testing enables the research and design engineers to evaluate the stability of bituminous concrete in terms of basic strength components. Shearing resistance and angle of internal friction may be obtained graphically from a Mohr diagram plotted from tension and compression test data. Averages of the test results obtained from a limited amount of testing are included. The application of these test data to a rational design approach is discussed briefly. This paper advocates the collection and evaluation of data regarding basic material properties as a means of upgrading the design methods now in popular use.
01043	**Resilience Characteristics of Subgrade Soils and Their Relation to Fatigue Failures in Asphalt Pavements.** *H. B. Seed, C. K. Chan, C. E. Lee* A laboratory test, involving the application of repeated axial stress to soil samples in triaxial compression cells, is described and its application for predicting the resilient deflections of plates, under repeated loading conditions, is demonstrated. It is shown that the resilient modulus of a compacted clay varies with the number of stress applications, the time interval between compacting and loading the soil, the stress intensity, the method of compaction, the compaction density and water content and changes in density and water content after compaction. The relationship of these effects to soil structure is discussed. The marked increase in resilient deformations which may result from compaction in the field to a degree of saturation exceeding about 85 per cent and, for relatively inexpansive soils, the desirability of compacting to degrees of saturation not exceeding about 80 per cent, in order to minimize resilient deformations, are indicated. The marked reduction in resilient deformations resulting from slight increases in compaction density are also shown. Evidence is presented to show that the resilience characteristics of a soil compacted with pneumatic rollers in the field are very similar to those of laboratory samples prepared by kneading compaction; however, the properties of field samples which attain a high degree of saturation by moisture absorption after compaction to a low degree of saturation are best simulated either by duplication of these conditions in the laboratory, or by compacting the soil directly to the final condition by static compaction. The resilience characteristics of the subgrade soils in the WASH0 and AASHO Test Roads are evaluated. It appears that the AASHO Test Road subgrade is perhaps a particularly resilient soil at high degrees of saturation and that the conditions and method of construction may have led to somewhat higher resilience characteristics throughout the project then would result from more conventional construction procedures. Finally, considerations in selecting a resilient modulus for incorporation in elastic theories for layered systems are presented.

01044 **A Study of the Repeated Load Strength Moduli of Soils**

H. G. Larew, S. B. Ahmed

This paper presents the results of a laboratory study of the stress-strain relationship for three fine grained soils under the action of both gradually applied and repeated loads.

The method used to obtain the repeated load, triaxial test, stress-strain curves is believed to be original. Each of these repeated load stress-strain curves was obtained by subjecting a series of identical soil samples to varying levels of repeated deviator stress and then measuring the resulting equilibrium deformation or strain for each level of repeated deviator stress. These values of repeated deviator stress and resulting equilibrium strain were then used to plot the repeated load stress strain curve.

Stress-strain curves were obtained by both conventional (gradually applied load) and repeated load triaxial tests and the resulting deformation moduli were compared at various levels of compaction, molding moisture content and density.

For the three soils studied, it was found that the repeated load deformation modulus was normally less than the modulus obtained in the conventional triaxial test. In the case of the sand-clay material this difference between gradually applied and repeated load moduli was as great as 100 per cent. For a given level of compactive effort both gradually applied and repeated load moduli decreased with increasing molding moisture content for all soils, although the rate of decrease was less for the sand-clay soil.

For a given compactive effort the ratio of the gradually applied load modulus to repeated load modulus was affected to varying degrees by changes in molding moisture content. The effect of molding moisture content upon this ratio was more pronounced in the case of the sand-clay soil where the ratio of Es/Er attained a value of 2 at higher moisture contents at both high and low levels of compactive effort. For the other two soils studied this ratio varied from about 1 to 1.5.

These results seem to indicate that a soil deformation modulus obtained from the conventional or gradually applied load triaxial test on even a nonrepeated load plate bearing test will not properly reflect the action of a soil under a pavement, for example, where the soil will be subjected to repeated loads. Some current methods of pavement design based upon a deformation modulus obtained from conventional triaxial tests or plate bearing tests may need to be restudied and revised to more properly reflect the action of repeated loads.

01045 **The Effect of Resilience-Deflection Relationship on the Structural Design of Asphaltic Pavements**

F. N. Hveem, E. Zube, R. Bridges, R. Forsythe

Since 1938 the State of California has measured transient pavement deflections over a wide variety of pavement structural sections in order to better understand and cope with the problem of fatigue cracking in bituminous pavements.

In 1955, based upon the results of deflection measurements from 400 electronic gauge units on 43 projects, limiting deflection values for the prevention of fatigue cracking in the design life of a bituminous surfacing were presented by the California Division of Highways for a variety of structural sections. Since that time, these criteria have been used as a guide for the determination of the adequacy of existing pavements and the magnitude of necessary reconstruction.

In order to introduce the deflection factor into design criteria, a device known as the resiliometer, has been under development by the Materials and Research Department since 1946. This instrument subjects a 4 inch diameter by 4 inch high soil specimen to cyclic dynamic loads of varying intensities of 0 to 50 pounds per square inch. The resilience test value is the net volumetric compression and rebound resulting from these loads. Considerable time and effort was expended in modifying the resiliometer in order to increase test sensitivity and reproducibility and in making qualitative resilience appraisals of different soil types from throughout the State.

In 1960, a program aimed at the correlation of laboratory resilience measurements with field deflection data was initiated as the first step toward the incorporation of the test soil resilience value into the flexible pavement design procedure. Twenty-five sampling locations from California highways and the AASHO Test Road were included in this study.

At each test area, field deflection measurements were made with the Benkelman Beam and truck (15,000 lb. single axle load). The sampling locations selected (based primarily on the range and consistency of the deflection measurements obtained) were sampled to a depth of 30 inches. Undisturbed samples obtained from each element of the structural section were tested in the resiliometer at the air pressures appropriate to the depths at which the samples were taken based upon a modification of the Boussinesq equation. Where undisturbed samples were not obtainable, the soils

were recompacted in the laboratory and tested at field moisture and density.

A plot of the resilience summations for each sampling location vs. field deflection is shown in the report. The result reflects an encouraging trend toward correlation and, with future samplings should provide a tie with pavement performance suitable for the establishment of resilience design criteria. Utilization of this relationship will be based upon adjustment of a proposed structural section to reduce the pavement deflection, predicted from the results of laboratory resilience tests on preliminary samples to a tolerable minimum.

A design example involving resilience test data is shown.

The results of resilience tests on remolded "sensitive" soils after curing periods of varying length are also presented.

01046 **Dynamic Testing as a Means of Controlling Pavements During and After Construction**
W. Heukelom, A. J. G. Klomp

As the mechanical properties of bituminous pavements depend essentially on the temperature and the duration of the loading period, the time factor must not be neglected in testing pavements. Therefore a method has been developed for dynamic investigations of roads and runway constructions. A heavy mechanical vibrator generates alternating forces of a few tons (with a frequency 5 to 60 c/s) which enable dynamic deflection measurements to be made. Furthermore the velocity of the propagated waves can be measured. A light electrodynamic vibrator produces waves of lower penetration power (at higher frequencies up to 3000 c/s), of which the wave velocity can be measured. From the wave velocities found in various construction layers the dynamic moduli of elasticity can be calculated.

Various theories give the possibility to calculate the deflection of layered systems when the E-moduli are known. So the E-moduli derived from wave propagation measurements were found to tally with the deflections measured under the vibrations of the heavy machine.

The measurements can be carried out at any stage of construction. Measurements on soils can be regarded as the first step in road design. Test data give indications about the necessity to improve the subgrade. From the elastic properties an idea of the values of the permissible vertical soil pressure can be deduced.

From measurements on soil improvements and bases it was found that the degree to which layers of unbound materials can be compacted depends to a large extent on the reaction of the subsoil. In general the observed E-moduli are not higher than 1-1/2 to 2-1/2 times the E-values of the underlying material. On poor soils, however, there is a tendency for the modular ratio to be somewhat higher.

To explain these findings, equilibrium stress conditions for granular materials have been considered and compared with computed stresses under the load of traffic.

Bound materials show higher E-values, which are only slightly dependent on the nature of the underlying material. Dynamic testing of materials in the laboratory has yielded data on typical wearing-course materials such as asphaltic concrete.

Dynamic measurements on total road constructions can serve to check whether the finished road meets the requirements specified in the design.

Variations of the properties of the successive layers of the road construction, resulting from compaction, changes in water content, freezing, thawing and cracking could be observed.

01047 **Analysis of Flexible Airfield Pavements by Surface Plate Loading**
Philip P. Brown

This paper describes the results of several series of plate loading tests made on the surface of airfield pavements with varying size plates. The data is analyzed by the Burmister Theory of the two layer pavement system to determine the effective elastic moduli (E1 and E2) of pavement and subgrade respectively. The elastic modulus of the subgrade is compared in some instances with that determined by loading directly on the subgrade soil.

Analysis of the data show that for those pavements loaded, which in all cases had been subjected to traffic for several years, the effective subgrade modulus computed from surface loading is considerably greater than that determined by loading directly on the subgrade. Conversely, the effective elastic modulus of pavement material (surfacing, base and subbase) is considerably lower than has previously been indicated.

The data also show clearly that the deflections of the pavement under small radius loadings are governed largely by the properties of the pavement materials, while deflections under large radius

loadings are determined primarily by the subgrade properties. The importance of this factor to design for high pressure tires is discussed.

A method of using surface plate load data to determine the required thickness of flexible overlay to support increased wheel loadings is presented. This procedure utilizes the test plot of load versus radii (for a specific deflection) as an influence curve, and applies to instances where the overlay material has the same modulus as the existing pavement material. When superior overlay material is used, the procedure must be supplemented by the layered system analysis.

01048

The Structural Behavior of Flexible Pavement - An Analysis of Rigid-plate Bearing Tests on Full-size Test Sections
A. C. Benkelman, S. Williams

The paper concerns part of a comprehensive field investigation conducted to obtain fundamental relations between load and thickness of flexible pavement by static-load testing of full-size, specially constructed test sections at Hybla Valley, Virginia.

The test sections consisted of a 3, 6, or 9 inch thickness of bituminous concrete surface course on 6, 12, 16 or 24 inch granular base courses constructed on a uniform clay soil embankment; also, 3, 6, and 12 inch bituminous concrete courses laid directly on the clay soil.

Loads were applied repetitiously through circular steel plates of various diameters to the surface course, the base course, and the subgrade of each of the test sections. Most of the data were obtained by either of two procedures, namely, the Accelerated Test and the Repetitional Test. Briefly, the former test consisted of the application and release of three loads of increasing magnitude followed by the application of a continuously increasing load. The latter test consisted of the application and release of loads of 16, 32, 48 and 64 psi, followed by 75 applications of an 80 psi load.

The effect of the loads was obtained by measuring both the deflection and the recovery of each of the pavement structure components and the subgrade simultaneously.

Flexible pavements in service whose design is structurally adequate to carry the prevailing traffic must act essentially in an elastic manner. It was found in the Repetitional Test series that for certain limiting loads applied on the surface of the pavement, the supporting subgrade acted wholly elastic between about the 10th and the 75th or final application of load. It was considered that these loads were safe loads for the conditions of the test. For the criterion thus established, it was found that the thickness of pavement structure (3-inch bituminous concrete surface plus granular base) required to support a unit load of 80 psi, without producing detrimental or nonelastic movement of the subgrade, varies approximately as the total load to the 0.4 power.

Other findings of the investigation include:
1. The subgrade soil when load-tested directly through rigid plates never developed the same degree of elastic action as when the load was distributed to it through the overlying pavement structure.

2. A consistent and orderly interrelation of the effect of unit load, diameter of test plate, and pavement structure thickness was found.

3. For average surface course temperatures in excess of about 75 deg F, the granular base course appeared to be more effective in supporting load applied through a rigid plate than an equal thickness of bituminous concrete; for temperatures below this level the bituminous concrete surface was the more effective of the two pavement components.

4. The surcharge provided by the bituminous surface course appeared to have little effect upon the ability of the base course to support load applied through rigid plates. Likewise, the surcharge provided by the surface plus base course had little effect on the load supporting capacity of the subgrade.

5. The unit load supported by the subgrade soil at a given deflection decreased at a diminishing rate with an increase in size of loaded area up to that of a plate 64 inches in diameter, the maximum size tested.

01049

Dynamic Testing at the AASHO Road Test
L. W. Nijboer, C. T. Metcalf

The Road Vibration Machine was recently employed to measure pavement properties of the AASHO Road Test in northern Illinois. Dynamic measurements were made on pavement sections ranging in thickness from 11 to 19 inches, over a frequency range from 8 to 2500 cycles/second. These measurements showed that:

1. The stiffness of asphalt pavements is greatly influenced by seasonal changes.

2. Softening of the subsoil is the main factor influencing the reduction of stiffness during spring breakup.

3. When the quality of base and subbase is impaired, pavement failure is imminent.

4. The critical stiffness level for satisfactory performance is approximately 100 ton/cm.

5. Seasonal recovery seems to take place, but its magnitude needs further investigation.

6. Recovery is speeded up by traffic, but some damage from repeated loading also occurs.

7. There is good agreement between measured stiffnesses and stiffnesses calculated from velocity measurements.

8. The stiffness of pavement sections containing black (asphalt-stabilized) bases is very high.

01050

Resiliency of Base Rock
O. A. White

The purpose of this project was to investigate by laboratory tests the resilient properties of natural materials used for highway base construction. Further, should these aggregates be found to have resilient properties other than characteristic stress-strain relationships of solid material, the purpose was to determine the degree of resiliency and the effect of gradation, moisture content, compaction, and applied load on resiliency.

01051

Finnish Road Structures and the Use of Wedges Against Frost Heaving
O. A. Taivainen

Frost heaving is a serious technical problem in road building in Finland. The severe winter, frost susceptible ground and the high ground water level all are hazards and difficulties.

The thickness of base and subbase courses of gravel roads has been about 85-95 cm. since 1930-1950 and from 1954, 50-80 cm. For the 1930-1950 period when no consideration was made for the frost susceptibility of soils, roads generally showed considerable frost heaving, especially in the end of rock cuts and earth cuts. The detrimental effect of frost heaving has increased since modern Finnish roads have been covered with flexible pavements. The pavements have been broken and traffic problems have resulted. Since 1954, pavement has thickness of 5 cm.; base course, 20 cm.; and subbase course 25-55 cm. according to soils' frost susceptibility.

Because of these facts modern Finnish roads use wedges for paved surfaces. In Sweden wedges have been used since 1949: In Finland the Administration of Roads and Waterways (ARW) in 1955 issued instructions for building of wedges, and in 1956 supplementary instructions were given.

The wedges are used in Finland on the border of rock cuts, where embankments and cuts meet and where soil changes and on the each side of
culverts, when the ground is frost susceptible soil. The measurements of wedges are shown on the figures 1, 2, 3, 4, 5 and 6.

The effects on the paved roads have been studied only during two winter periods. Observations of considerable frost heavings have generally
not been made, because the paved roads are situated in South Finland, where the winter freezing index has been relative low. But in North Finland, where the freezing index is high, a few observations have been made.

01052

Report on Session VI - Design and Construction Influence on Structural Behavior of Asphalt Pavements
Moderator: Dr Gordon D. Campbell

A moderated discussion of the papers presented in Session VI.

Structural Section Drainage
H. R. Cedergren, California Division of Highways, Sacramento 14, California
W. R. Lovering, The Asphalt Institute, Sacramento, California

The Extension To Practice Of A Fundamental Procedure For The Design Of Flexible Pavements
G. M. Dormon, Shell International Petroleum Company Limited, London, England

The Application of Pedology to Flexible Pavement Design in Wisconsin
Dr. R. H. Keyser, University of Santa Clara, Santa Clara, California

Structural Design of Flexible Pavements in North Carolina

L. D. Hicks, North Carolina State Highway Commission, Raleigh, North Carolina

An Investigation of Flexure Cracking on a Major Highway
G. L. Dehlen, National Institute for Road Research, Pretoria, South Africa

Design of Flexible Pavements Considering Mixed Loads and Traffic Volume
W. J. Turnbull, C. R. Foster, and R. G. Ahlvin, U.S. Army Engineers, Waterways Experiment Station, Vicksburg, Mississippi

German Experiences in the Construction of Hot-mixed Asphalt Bases
Dr. H. W. Schmidt, Esso A. G., Moorburger Strasse 16, Hamburg, Germany

Development and Structural Design of Asphalt Pavements In Germany
Dr. Walter Becker, Esso A. G., Hamburg, Germany

California Method for the Structural Design of Flexible Pavements
F. N. Hveem And G. B. Sherman, California Division of Highways, Sacramento 19, California

01053 **Structural Section Drainage**
H. R. Cedergren, W. R. Lovering

Water that cannot freely drain out of pavement bases is always a serious threat to the integrity of pavements. Excess water and poor drainage almost always lead to pavement failure.

The continued serviceability of any pavement depends upon prevention of the accumulation of excess water at all levels within the structural section and in the underlying basement soil. Standard practice should provide balanced designs in relation to the porosity or permeability of the "roof" of the structural section (the wearing course), the permeability and seepage potential of the "basement" soil beneath the structural section and the capabilities of the section for removing water. In this paper some methods are presented that make possible the development of reasonably balanced designs with drainage layers "built-in" as an Integral part of the section. The importance of having drainage layers with adequate permeability is given special emphasis to demonstrate the value of layered drainage systems incorporating a protective layer of filter material and a drainage layer of coarse crushed rock or lean open-graded asphalt mix. The ability of open-grated asphalt mixes to transmit water may be verified by observing the flow of water which occurs at the edges of open-graded wearing courses immediately after rains.

It is pointed out that damage should be thought of in developing the over-all cross-sections of pavement. The paper discusses over-all design in relation to trench sections and full-width drainage.

01054 **The Extension to Practice of a Fundamental Procedure for the Design of Flexible Pavements**
G. M. Dormon

Solutions of fundamental elastic equations are used to determine the stresses and strains developed in the layers of a road structure. Structures strong enough to carry defined traffic loads are designed by adjusting the thickness and properties of the various layers so that the stresses and strains developed at critical points in the structure are within permissible limits.

The elastic properties which unbound soils and granular base materials develop in situ are limited by their ability to maintain equilibrium under load stress conditions (e.g., tensile stresses), and the moduli of successive layers are in consequence determined primarily by the "geometry" of the system. For mathematical convenience all granular base layers are considered to act as a single layer for which the "effective" modulus, assumed uniform over the whole thickness will generally vary only between about 1.5 and 4 times that of the subgrade. The stiffness modulus, and breaking properties of the bitumen-bound layers will vary with time and temperature of loading. For practical conditions, however, a limiting low value of the stiffness modulus exists in situ at high service temperatures, which is governed by the mix composition. Deformation of the structure is controlled by limiting the vertical compressive strain in the subgrade and granular base, This will usually be greatest at high service temperatures for constructions incorporating thick bitumen-bound layers, or at thaw temperatures if the subgrade is frost-susceptible. Brittle and fatigue fracture of the bitumen-bound layers are governed by the tensile stress at low temperatures and the tensile strain respectively in the bottom of the layer.

On the basis of these considerations, the relative influence of the thickness and properties of the construction layers on the critical stress conditions is assessed and it is shown that the over-all advantage of a dense bitumen-hound layer over a granular layer of the same thickness will increase as their thicknesses increase. The risk of cracking of the bitumen-bound layer is found to be influenced only to a small extent by the thickness of the granular layers, but to depend mainly on the properties of the subgrade and the thickness of the bitumen-bound layer. Fatigue fracture is for example, more likely to occur on weak subgrades (particularly during thaw periods) and a small increase in the thickness of

a dense bitumen-bound layer will considerably reduce the risk in this respect. Provisional design curves have been drawn up which show, for any particular subgrade, alternative constructions with dense bitumen-bound and granular base layers, meeting specific design requirements for motorways. The design thicknesses are in reasonable agreement with practical experience and lend support to the applicability of the theory and its usefulness for indicating performance trends in both conventional and unusual constructions.

01055 **The Application of Pedology to Flexible Pavement Design in Wisconsin**
Dr. R. H. Keyser

The paper is a portion of a research project which developed into the following closely interrelated problems:

(1) The development of procedures and solutions to highway engineering problems, utilizing principles and data of both pedology and soils engineering, and,

(2) The development of principles and formulae relating the design of flexible pavements to the many variables associated with Wisconsin soil conditions and climate.

Approximately 360 Wisconsin pedological soil series are grouped under 124 major series units which are based on the relationships of their engineering properties, drainage, topographic and geologic features, pedological classification units, and engineering uses. The relationships were established by field Investigations as well as laboratory test results on approximately 420 soil samples. The Pedological soil series descriptions have been rewritten to stress the engineering aspects of each series.

Theoretical and empirical concepts of flexible pavement designs were utilized to develop a family of pavement design curves. The validation of the semi-empirical curves was checked by field investigations of pavement performance which attempted to relate pavement composition, thickness, and traffic volumes to subgrade conditions. Approximately 175 subgrade soil samples were tested to aid in the analysis of the subgrade conditions.

Based on tests on many soil samples from different locations, on field investigations, and on the sciences of Pedology and Soil Engineering, recommendations for solutions to highway engineering soil problems are summarized in tables and figures.

Flexible pavement design curves have been developed indicating effects of commercial traffic, soil series, and climatic influences. The curves are developed from data obtained from theoretical and practical concepts of flexible pavement designs, and from field investigations of pavement performance.

01056 **Structural Design of Flexible Pavements in North Carolina**
L. D. Hicks

This paper outlines in some detail the development of a method for the thickness design of flexible type pavements in North Carolina. The method may be considered a more or less rational approach to a problem that has been solved in the past by empirical methods or by guess, in that the total thickness of the pavement and its components may be determined by a procedure that takes into account the effect of traffic loads and strength characteristics of paving materials and subgrade soils.

The design wheel load may be selected from a statistical analysis of traffic data, which has been expanded for future increase, or the selection may be made on a basis of an estimate of the daily average number of vehicles of a certain type and weight, based on traffic data, that will use the pavement over a given number of years. This latter method of selection is currently used in North Carolina.

The distribution of the pressure below the surface of contact induced by the design wheel load is a determining factor in designing the total thickness of a flexible pavement, as well as the thickness and quality of its components. The Boussinesq theory of pressure distribution was used to compute the vertical pressures beneath dual wheel assemblies designed to carry loads of 4,000, 5,000, 6,000, 6,500, 7,000, 8,000, 9,000, and 10,000 pounds. The computed pressures are shown in curve form to depths of 30 inches.

The strength of the subgrade soil, base course material, and bituminous pavement mixture can be determined by any reliable method. At the present time North Carolina is using the CBR test for measuring the bearing capacity of subgrade soils and base course materials. The CBR values are converted to pounds per square inch bearing capacity by a conversion curve included in the paper. A factor of safety of 2.5 is applied to the bearing capacity of subgrades to obtain the design bearing value. Bituminous paving mixtures are designed by the Marshall Method and the Hubbard-Field Method, depending upon the type, to specified stabilities.

The paper includes several examples of design to illustrate the method.

01057

An Investigation of Flexure Cracking on a Major Highway
G. L. Dehlen

The paper describes investigations of extensive "chicken net" cracking of the surfacing of a major road in South Africa. Benkelman Beam tests, in which both curvature and deflection were measured, indicated that the cracking was due to excessive flexing of the surfacing under traffic. A contributory cause was probably the relatively low flexibility of the surfacings. Possible reasons for the severe curvatures were investigated, concentrating on the base and subbase which are the layers on which curvature is most dependent, Permeability tests, artificial wetting of the surfacing, and boreholes through the structure revealed that excess water in these layers was not generally a cause of the severe curvature. A method of measuring Young's moduli of the foundation layers in the field with a specialized plate bearing test was developed, and this revealed that the subbases were generally low in Young's modulus, and that this deficiency could be regarded as the cause of the severe curvatures, and thus as a second contributory cause of the cracking.

A number of possible remedial treatments were studied in full-scale trials on the road. Thin resurfacings studied to date have not been satisfactory, cracks reappearing soon after laying. Some types of 4 inch overlay have brought about a considerable reduction in flexure, and would probably prove satisfactory solutions in practice.

It does not appear that adequate warning of such failure is given by existing design methods. Studies have been begun to improve knowledge in this regard and, if necessary, to develop an additional complementary procedure for design in the future.

01058

Design of Flexible Pavements Considering Mixed Loads and Traffic Volume
W. J. Turnbull, C. R. Foster, R. G. Ahlvin

Load repetition is now widely recognized as a significant parameter in pavement design. With this recognition comes the added problem of combining mixed loads to arrive at a measure of traffic volume usable for design.

The Corps of Engineers has developed criteria relating loading and strength of material (CBR) to design thickness required. These criteria are used in design of airfield pavements for a reasonable use life. The Corps has also developed a relation between design thickness required (in percentage) and load repetitions. This relation is used in design of military airfields for short-term use, in evaluating effects of short-term use of existing airfields by overload aircraft, and in recent designs for the more intensive load repetitions attendant to channelized traffic of heavy, bicycle-type landing gear aircraft.

This paper reports rather extensive developments by which the principles and relations embodied in the criteria relating loading, strength, and thickness and those relating thickness and load repetitions have been further extended and combined to provide a revised method of design for highway pavements. The method provides means for combining any composition or distribution of loading and treating any intensity of use from that of a perimeter road, highway shoulder, or residence drive to that of the most heavily traveled turnpike or freeway. The method also provides means of designing for essentially light traffic with a mingling of very heavy traffic, such as might be experienced at remote missile sites, and it permits accommodation of any desired design life.

In summary, the revised pavement design method includes development of curves showing the number of repetitions of a basic 18,000-lb, single-axle, dual-tire load equivalent to one operation of any of a range of loads from passenger cars to very heavy trucks. It also includes development of design relations for the basic 18,000-lb single-axle load in terms of CBR, thickness, and load repetitions. The first-mentioned development permits the collective evaluation of the effects of any composition of traffic and for any desired pavement-use life. The second-mentioned development provides curves from which design thickness can be determined for the total equivalent operations of the basic load arrived at in the first development. The method provides a positive treatment of load repetitions and obviates the need for selection of a single design load to represent an entire range of light to heavy loads.

01059

German Experiences in the Construction of Hot-mixed Asphalt Bases
Dr. H. W. Schmidt

First, the development of hot-mix asphalt bases in Germany since 1955 is reviewed. The main reasons for the successful introduction of this new type of base construction are outlined. Experiences on test roads, development of suitable test methods and design criteria are discussed briefly which have led to tentative specifications for hot-mix asphalt bases published in 1960.

A short review is given on the structural design of asphalt pavements with an asphalt base course in Germany. Experiences gathered in the construction of hot-mix asphalt bases during the last 6 years are presented. It is shown how the favorable results obtained have influenced the establishment of standard design models for asphalt pavements.

Six different asphalt base course projects built from 1956 to 1958 are described in detail. These projects include the construction of new Autobahn stretches and of sections on expressways, city streets and highways for various traffic conditions. Details given on these projects comprise the structural design and cross-section applied, the location and length of the project, the subgrade conditions, the machinery used, the composition and properties of the different layers from frost blanket to wearing course, the preparation and laying of the asphalt mixes and the behavior of the finished pavement under the existing traffic loads. Information is also presented on the reconstruction of rigid Autobahn sections using asphalt pavements and hot-mix asphalt base courses. Cross-sections applied on the Koeln-Frankfurt Autobahn in 1958 are discussed. Reference is made to tentative specifications published in 1958 recommending two methods of reconstruction.

In conclusion, the application of hot-mix asphalt bases for rigid types of pavements on new Autobahn stretches and on airfields is briefly described.

01060 **Development and Structural Design of Asphalt Pavements in Germany**
Dr. Walter Becker

After a description of the historical origin of the German road network the paper initially outlines the development of traffic and road construction during the last 12 years since the Federal Republic of Germany was founded in 1949. For the continuous improvement of the existing Federal and State roads of about 130,000 km length asphalt construction methods have been applied to a large extent. Now about 82% of these roads have a bituminous pavement.

Owing to the steady increase in the number of motor vehicles, primarily of heavy trucks, it soon became evident that a renewal of the wearing surfacings was not sufficient but often the roads had to be renewed entirely. In this connection it was recognized that the base is of special importance for the performance of the road. In particular, it was necessary to replace the handpacked stone base, until then preferably used, by other construction methods which are technically better and which can be carried out more economically by employing machinery.

In order to find suitable base construction methods a number of test roads were built in Germany during the last 10 years. The paper describes these test roads briefly and Indicates the results already available,

Subsequently the paper outlines according to what viewpoints asphalt roads for heavy traffic are presently constructed in Germany. There does not exist an officially recognized thickness design procedure. When designing a pavement the experiences gained with existing roads of various thicknesses and their behavior under traffic are taken as a basis. From this basis there developed rules as to how a pavement has to be designed to withstand a certain traffic load. All roads have to be provided with a frost blanket of an appropriate thickness, unless a frost-proof subgrade exists. On a frost-susceptible subgrade road structures in Germany are generally built at least 70 cm thick. The frost blanket is the balance remaining after the deduction of the thicknesses of the base course and the surfacing.

In recent years specifications for the subgrade, the base and the surfacings of asphalt pavements have been issued, which the paper explains in detail. These specifications also indicate the thicknesses considered necessary for each construction method under a specific traffic load. The total thickness of a road structure in Germany is the sum of these individual thicknesses requirements. Respective tables have been compiled and included in the paper.

The continuous efforts for standardizing road construction methods have resulted in a restriction of possible variants contained in the Federal Specifications for the various types of construction. For instance, it has been decided to use a standard design model for "Autobahnen". Also some States of the German Federal Republic introduced standard design models for the Federal and State roads constructed by them; these standard design models are based on the experiences the respective States have meanwhile collected and take account of special local conditions. The paper furnishes information on such standard design models.

01061 **California Method for the Structural Design of Flexible Pavements**
F. N. Hveem, G. B. Sherman

This paper discusses briefly the problem of structural design of flexible pavements, the factors that influence performance and the variables that can be measured with existing tests. The problem of design in pavement structures is broken into three phases: (a) traffic; (b) the resistance of the underlying soils to deformation; and (c) tensile strength of the pavement structure.

A method is shown for converting mixed truck traffic into a single number, called the Traffic Index, which indicates the relative destructive effect of traffic. The statistical approach is used to evaluate traffic. A large sample of trucks are weighed and average axle weights determined for trucks of various

axle groupings. From these average axle figures, constants are determined which can be applied to various axle load groups to determine the Equivalent Value in terms of 5000-pound wheel loads. From the EWL (Equivalent Wheel Load) calculations based on the number and weight of trucks expected to use the road, a Traffic Index may be determined. The Traffic Index is directly proportional to the thickness of structure needed to carry the anticipated traffic.

The factor which measures the resistance of a soil or granular base to deformation is determined by the Hveem Stabilometer and is known as "Resistance Value."

The paper discusses the effect of cohesion (tensile strength) upon the performance of the pavement. Included in this phase of the paper is a discussion of equivalency of asphalt concrete in terms of inches of gravel or stone base. Data from our study of the AASHO Test Road is shown which indicates that the equivalency varies with the load of the vehicle and the strength of the asphalt mixture.

A design formula is proposed, which is as follows:

Thickness of Structure = [0.080 (Traffic Index) (90 - Resistance Value)] / (Cohesiometer Value)^O. 2

The paper discusses modifications in the California Design Formula which might be made as a result of the study of the AASHO Test Road data. Charts showing correlation with the Test Road performance are included. The formula shows a possible coefficient of correlation of 0.97 and a standard error of estimate of +/- 1.5 inches.

The paper also briefly discusses the variability of correlation statistics depending upon which layer or layers are corrected to accommodate the error.

The primary and important advantages of the California formula are:

1. The California procedure utilizes numerical values derived from physical tests of the layered system consisting of the basement soil, the subbase, base and pavement.

2. The method recognizes the effects of both structural strength and surcharge effect of the pavement and base layers.

3. The California method recognizes the effect of load repetition, individually and in combination, as well as weight and provides a logical means for converting miscellaneous traffic wheel loads to a single number, the Traffic Index, which number bears a direct linear relationship to the thickness of pavement structure required.

4. The California method has been in use for approximately 13 years and has demonstrated that it can accommodate wide variations in the type of soil, type of base and type of pavement as well as variations in wheel loads and the number of load repetitions. It also shows excellent correlation with the Test Road data on flexible pavements.

01062

Report on Session VII - Design and Construction Influence on Structural Behavior of Asphalt Pavements
Moderator: William S. Housel

A moderated discussion of papers presented in Session VII.

Hot-mixtures of Calcareous Soil-Sand-asphalt Type
E. A. Gonella and J. J. Font, Vialidad National, Buenos Aires, Argentina

Development in the Design and Construction of Bituminous Surfaced Pavements in the State of Victoria, Australia
A. H. Gawith And C. C. Perrin, Country Roads Board, Victoria, Australia

Asphalt Pavement in Southwestern Santa Fe Province, Argentina, with Fine Local Materials
L. M. Zalazar, Southern University and University of Buenos Aires, Buenos Aires, Argentina

Design, Construction and Evaluation Criteria of Flexible Asphalt Pavement for Airports in Italy
Giorgio Moraldi, Libero Docente in Tecnica, Delle Fondazioni E Costruzioni in Terra, Roma, Italia

The Use of Pavement Deflections in Asphalt Pavement Overlay Design
E. Zube and R. Bridges, Division of Highways, Sacramento 19, California

Jet Aircraft Runway Resurfacing
Wayne A. Thompson, Dictrict Public Works Office, U.S. Navy, San Bruno, California

Effect of Surface Color on Thaw Penetration Beneath an Asphalt Surface in the Arctic

C. W. Fulwinder And G. W. Aitken, U.S. Army Cold Regions Researchand Engineering Laboratory, Hanover, New Hampshire

Research Future of The AASHO Road Test Facility
W. E. Chastain And J. E. Burke, Illinois Division of Highways, Springfield, Illinois

Soil Stabilization with Cutback Asphalt in Southern Brazil
L. M. Zalazar, Southern University and University of Buenos Aires, Buenos Aires, Argentina
P.C. De Castro, State Highway Department of Rio Grande Do Sul. Brazil

The Application of Engineering Economy Studies to Asphalt Pavement Design
H.E. Riggs, Stanford Research Institute, Menlo Park, California

01063 **Hot-mixtures of Calcareous Soil-Sand-Asphalt Type**
E. A. Gonella, J. J. Font

This report has been developed from laboratory and field tests, related with the design of reinforcements of old pavements near Buenos Aires, Argentina. These overlays were built with hot-mixtures of calcareous soil-sand-asphalt type.

Two main purposes have been studied. First, the design of the overlay thickness that must be used to restore the old pavement on the basis of the measurement of Benkelman deflections. Second, to correlate the behaviour under traffic of a base course built of these hot-mixtures with laboratory stability test.

Dealing with the first scope, some experimental sections have been built of calcareous soil-sand asphalt reinforcements on failed pavement and the Benkelman deflections measured before and after the overlay was laid.

The decrease of deflection has shown the relative effectiveness of the reinforcement. Taking into account the over-all conditions, efforts have been made to determine the required thickness of the overlay once a given decrease of deflection has been established from an initial deflection. Proceeding with the second purpose, the behaviour of a test road has been watched where a base of the mixture referred to had been built. The factors of structural design of this road were checked and the Benkelman deflections measured from time to time. The quality of the hot-mix base was checked with Hveem and Marshall Stability tests. It was found to be a very good base, with an R Stabilometer value of 82.

Finally, some comments on the characteristics of the mixture used are made. The successful use of this mixture must be pointed out because of the great savings that have been made considering the fact that stone aggregates were not economically available within short haulage distances.

01064 **Development in the Design and Construction of Bituminous Surfaced Pavements in the State of Victoria, Australia**
A. H. Gawith, C. C. Perrin

The paper by way of introduction outlines the successful application of a policy of stage construction in developing a sealed road system to carry the traffic of the time in the years prior to the 2nd world war. Most pavements were constructed without much scientific design, in the knowledge that they would be maintained and strengthened as the need arose. Developments in the design of sealed pavements of greater durability, demanded by the rapid increase in motor traffic after the war, are described. As the result of some limited experience during the war the California Bearing Ratio method of design was adopted as that most applicable.

Factors which were taken into account in estimating pavement requirements from the CBR of the subgrade included consideration of the total weight of traffic expected to be carried during the designed life of the pavement as the equivalent repetitions of a 5,000 lb. wheel load modified by factors for vehicle placement on the pavement, and local climatic conditions, The chart evolved in 1945 for pavement thickness design by this method is reproduced, together with a simplified chart produced in 1949 after assembling all the factors into a single formula in terms of the number of commercial vehicles using the roadway at the time, the average annual raInfall, and the CBR of the subgrade at 95% modified AASHO compaction. To facilitate the evaluation of more soil samples without carrying out the actual CBR tests, relationships have been established between the CBR of a soil, the simple Atterberg Tests and the Group Index. Formulae for estimating the CBR from these relationships are given in the paper.

The use of various "in situ" bearing or penetration tests, as an alternative to the CBR test for estimating the CBR of the soil is referred to. These include the Proctor Needle, the Static Cone Penetrometer developed in Holland, and a Dynamic Cone Penetrometer based on a Swiss original, and relationships between values obtained with these implements and the CBR are suggested.

Current design practice makes use of the curves produced by the Road Research Laboratory of Great Britain, and these are included in the paper. The curves suggest a pavement thickness for traffic falling within certain groups, for certain CBR values of the subgrade which have been either established in situ or estimated by some other method. Where CBR values are estimated in the laboratory they are modified to take into account the annual local rainfall.

A tentative formula for estimating the additional thickness required to strengthen an existing pavement, deduced from the deflection of the pavement as measured by the Benkelman beam, is suggested, The paper makes reference to the relative values of various materials used in the pavement, and tabulates suggested design CBR values for materials having certain characteristics of grading, plasticity, etc., together with the minimum cover required over these materials.

The paper concludes with a reference to construction practices in the State of Victoria and the predominant use of light bituminous surfacing, the success of which, on pavements carrying quite high traffic volumes, has been due not only to the detailed attention paid to the design and application of the surface treatment, but to the construction compaction, and subsequently, the traffic compaction of the pavement prior to its bituminous treatment.

01065 **Asphalt Pavement in Southwestern Santa Fe Province, Argentina, with Fine Local Materials**
L. M. Zalazar

The design of asphalt pavements in the region of Santa Fe Province presents many difficulties, because of the type of soil profile, the heavy rainfall, which in normal years reaches 50 inches, and the flat topography which seriously retards drainage. These conditions require a strong pavement to support the medium-heavy traffic of Santa Fe's main highways, but the lack of coarse materials in the Province introduces another difficulty which is hard to overcome at a reasonable cost.

We have described such a region in a previous publication. It belongs to zone 2 which is one of the five typical soil profiles in Argentina. The southwestern portion of Santa Fe, wherein we have developed the design described in this article, is the best portion of the Province and is shown in the shaded area on Figure 1. Although it is an area in which there are no coarse materials like the whole of Santa Fe, sand is available in a few localized river deposits and this sand generally is composed of round polished particles. The soil profile of southwestern Santa Fe is of the typical Chermoziem type. The first horizon is a black humus silty soil good for agricultural purposes but undesirable for pavement design, The second horizon is a heavy clay, a product of the illuviation process, and retains moisture tenaciously. The third horizon is composed of the best soil of the profile with a loess soil as a parent material.

Proceeding westerly, the C or third horizon improves very much in its properties, being a sandy loam at our starting point at about the middle of the Province and becoming a pure sandy loam at the border of Cordoba Province at the extreme west. Design for asphalt pavements in this area becomes a problem of soil stabilization using soils of the C horizon for bases and subbases and a blacktop of surface treatment or preferably a bituminous mat in view of local traffic conditions. The available fine sand would permit the granular stabilization of the loess as a first step, constituting some advantage in a place of many difficulties. However, the fine round sand particles cannot provide the required internal friction. Consequently, the granular portion of the mixture has been improved by blending the local sand with sharp angular coarse sand hauled from an average of 200 miles. This process has been considered unavoidable for the base course where internal. . .

et cetera

01066 **Design, Construction and Evaluation Criteria of Flexible Asphalt Pavement for Airports in Italy**
Giorgio Moraldi

The paper describes the experience acquired in Italy with the design of flexible airport pavements and the materials employed in the different layers, the studies performed on the behaviour of subgrades and pavements under load, pavement evaluation criteria and resurfacing.

1. For the design of total pavement thickness both FAA. and CBR design diagrams are used, but they should be adopted with caution, as for Italian soils they may lead to very different results.

2. The prescriptions for the materials to be employed in the base and subbase courses differ according to their behaviour under compaction. To assure a convenient bearing capacity even in saturated conditions, not only a low plasticity index is requested, but also definite minimum soaked CBR values. Adequate compaction is controlled by means of density tests, and for coarse grained materials by means of the modulus of deformation value, assessed with plate bearing tests using small plates.

3. Research on the behaviour of subgrades, base courses, and finished pavements by means of plate bearing tests have been performed by late Prof. Maresca, by Mr. Quaranta and by the writer. Maresca

proposed a new method of interpretation of repeated plate bearing tests, in which the elastic and the plastic components of the deflection are evidenced. He has also defined a critical bearing capacity which corresponds to a sudden rise in the curve of the increments of plastic deformations. Quaranta has shown that the bearing capacity of different base and surface course layers is not only a logarithmic function of the thickness of the layer, but for each material reaches an upper limit which depends on the bearing capacity of the underlying layer. He has also given a simple formula to evaluate the ratio between the bearing capacity of an asphalt pavement and the bearing capacity of the base course. The author has shown that the validity of the well-known linear relationship between the deflection and the number of load repetitions not always holds true, as there seems to exist a fatigue limit of the structure evidenced by a non-linear relationship. He therefore invalidates the possibility of extrapolating the results of repeated plate bearing tests, and advocates the adoption of a simple conventional test based on a single cycle of load application followed by other three-load repetitions.

4. Experience on resurfacing of rigid pavements with asphalt overlays has shown that the presence of an intermediate layer of open graded bituminous concrete 7 cm thick, placed between the old pavement and the new one, is very effective in avoiding reflection cracks.

01067

The Use of Pavement Deflections in Asphalt Pavement Overlay Design
E. Zube, R. Bridges

Many miles of highway constructed during the past 30 years are in need of realignment, widening and blanketing as modern traffic demands increase. There are other projects which have become badly cracked well before the design useful life has been reached. State, county and city highway engineers are, therefore, annually faced with selecting those projects most in need of the various improvements since financing does not permit all deficient highways to be reconstructed. Although a decision as to the type and extent of an improvement is sometimes arrived at on the basis of laboratory tests of in-place materials, the selection of the thickness of asphalt blanket is frequently based on the experience of engineers assigned the task.

This report describes an approach used in California on some 25 projects in arriving at the required thickness of asphalt blanket using the results from field deflection tests performed on existing pavements. A brief description of testing equipment is provided along with a testing procedure now in use.

Also provided in the report are limiting critical deflection values based upon a 15000 pound single axle load for different types of construction, and traffic conditions usually associated with the primary highway system. Experience on the deflection damping capabilities of different layer thicknesses of asphalt mixtures, cement treated bases and aggregate bases is discussed. Graphs of actual deflection results obtained from highway construction are provided which show the deflection attenuation properties of each material. Although the deflection results are not definitive, they do suggest that, for the conditions of test, crushed gravel bases reduce deflections in order of 0.001 to 0.002 inches per inch of base thickness, asphalt mixtures at 70 deg F to 100 deg F reduce deflections 0.002 to 0.004 inches per inch and cement treated bases reduce deflections 0.003 to 0.005 inches per inch of applied thickness. The initial deflection of an existing pavement is very important in determining how much one inch of any material will reduce the deflection. For example, at deflection levels of 0.100 inches each inch of overlay is capable of reducing the deflection by several thousandths of an inch. At deflection levels of 0.010 inches an inch of overlay has a minute and sometimes unrecordable effect.

From this study a method is developed for selection of type of overlay with a chart of equivalent thicknesses of gravel required versus initial deflections. Also provided are some examples of application of the method.

01068

Jet Aircraft Runway Resurfacing
Wayne A. Thompson

The paper describes the background, history, design, and construction features of a resurfacing project at the Naval Air Station, Alameda, California where heavy loads and high tire pressures relative to the operation of jet aircraft are of prime concern. Because the Asphalt Institute has made extensive studies concerning airfield pavements and particularly asphalt concrete pavement design they were invited by the Navy Department, Bureau of Yards and Docks to assist the Navy in any way they could to insure an adequate design.

Plate load tests, penetration tests of the old pavement surface and a study of the original construction features governed the selection, use of materials and thickness of the overlay design.

Design features were worked out cooperatively by the Asphalt Institute and Navy personnel. Features that were particularly noteworthy and debatable are: The use of all crushed rock for coarse and fine aggregate; all limestone dust for mineral filler (passing no. 200); 40-50 penetration for grade of asphalt; 98% of Marshall for in-place density.

Special emphasis was placed on control during construction with representatives from the Asphalt Institute participating by invitation. A field laboratory especially constructed for the job and assistance from specialists in the field of pavement construction with added inspection help were special features to insure adequate control. Pre-construction conferences and training also contributed to the over-all emphasis on insuring a good job. Batching operations, laydown operations, and rolling operations were carefully inspected and regulated by those concerned and experienced in Airfield Pavement Construction.

Continuing research is a part of the over-all study to determine the feasibility of using asphalt concrete for similar projects relative to reinforcing old pavements and construction of new pavements to withstand heavy loads and high tire pressures. The Naval Civil Engineering Laboratory, Port Hueneme is conducting the surveillance program assisted by the Twelfth Naval District, Public Works Office. The tests included:
(a) Unconfined compression tests at 77 deg F.
(b) Density.
(c) Penetration of Asphalt Cement.
(d) Air permeability.
(e) Maintenance costs.
(f) Traffic.

The paper concludes that although the construction work was very successful and the pavement is now functioning very well under the loads and pressures imposed it will take several years to determine the rate of hardening of the asphalt and whether or not it is possible to build a flexible pavement which will remain sufficiently flexible to resist cracking caused by small deflections of the pavement surface under the loads of small high pressure tires.

01069

Effect of Surface Color on Thaw Penetration Beneath an Asphalt Surface in the Arctic
C. W. Fulwinder, G. W. Aitken

This paper presents the results of a study conducted to determine the reduction in thaw penetration obtained by painting an asphalt runway pavement white at Thule Air Force Base, Greenland.

This study was one phase of an over-all program conducted by the Corps of Engineers to study the design and construction of pavements in the arctic and subarctic. A description of the site, complete with meteorological and soil data, is furnished and the investigational program conducted to study the pavement at Thule is outlined. The results obtained in 1953-1954 from a small, white-painted test area on an asphalt taxiway at Thule indicated that a reduction in depth of thaw of up to 1.8 feet was effected by painting the surface.

A thirteen hundred foot section of the main runway, where thawing into the subgrade had caused pavement subsidence, was painted white in July 1959 to permit further study of a white-painted asphalt surface and to reduce thaw penetration. The paint used was Prismo R/W white traffic paint with ground pumice mixed with the paint as a texturizing material. The paint was applied by 36-inch-wide, truck-mounted spray bars and was dry to the touch in 30 minutes.

Comparison of the subsurface temperature observations obtained under the white-painted runway area with those obtained under unpainted sections of the runway show that a reduction in thaw penetration of 1.5 feet was obtained in 1959 under the white-painted area even though almost one-third of the thawing season had elapsed prior to completion of the painting. Analysis of the 1960 subsurface temperature data showed the reduction in thaw penetration attributable to the white-painted surface to be approximately 2 feet. In both 1959 and 1960, thaw did not penetrate into the subgrade beneath the white-painted pavement.

Additional factors evaluated in the course of this investigation included the effects of normal traffic on the durability of the paint, the reactions of flight and operations personnel to the white-painted surface and any unusual maintenance problems which could be attributed to the white-painting program.

It is concluded that painting the runway surface prevented occurrence of further settlement, thereby eliminating the costly maintenance formerly required in the subsidence area. Further observations will be made to determine the continued effectiveness with time in reduction of thaw penetration.

01070

Research Future of the AASHO Road Test Facility
W. E. Chastain, J. E. Burke

The first, and perhaps major objective of the AASHO Road Test was:

"To determine the significant relationships between the number of repetitions of specified axle loads of different magnitude and arrangement and the performance of different thicknesses of uniformly designed and constructed asphaltic concrete, plain Portland cement concrete, and reinforced Portland cement concrete surfaces on different thicknesses of bases and subbases when on a basement soil of

known characteristics."

This first objective asked for relationships between pavement performance and pavement design variables for various axle loads.

A new concept was developed during the Road Test to define pavement performance, and the test results with respect to this objective were expressed by formulas that show the relationships that were found to exist.

The AASHO Road Test pavement experiment design was based on scientific statistical principles. Test sections were selected and located in a manner to provide unbiased estimates of the effects of traffic of known loading and frequency of application on the performance of pavements of specific designs. The structural sections of the major experiment relating to asphalt pavements comprised a a complete factorial experiment wherein the design factors were surfacing thickness, base thickness, and subbase thickness.

Within the space and funds available, only a few variables could be studied thoroughly. The experiment was designed to investigate these particular variables. In general, the variables selected for study were those of prime importance which could not be studied conveniently by other means.

et cetera

01071 **Soil Stabilization with Cutback Asphalt in Southern Brazil**
L. M. Zalazar, P. C. De Castro

"Soil-Asphalt" is a type of physico-chemical stabilization of soils according to Dr. Winterkorn. It has been considered in the past as a structure for use in base courses on secondary roads. At the present time and following the modern techniques, "Soil-asphalt " in different ways becomes an important structure for heavy duty pavements as it was pointed out by H. G. Nevitt and other outstanding technicians. By increasing the asphalt content and using friable or sandy soils it becomes very close to a "sand-asphalt" or "sand shell-asphalt." That is not the type of mixture which will be the matter of the present paper.

We will consider it as the stabilization process, i.e. a process that provides stable structures with a low percent of bitumen content through a cutback asphalt, an asphalt emulsion or, following very modern developments, using Asphalt Cement in a "foamed state." If the asphalt content increases to values of the order 6% plus in terms of pure asphalt cement we are in the field of "asphalt mixes" (sand-asphalt, sand shell-asphalt, etc.), which may serve as pavement base courses when they have the required internal friction for such structure. The lubricating action of asphalt combined with the possible water content gained through time in service reduces the internal friction in terms either of CBR (Porter), "R" value (Hveem), Shearing Strength (McDowell), etc.

01072 **The Application of Engineering Economy Studies to Asphalt Pavement Design**
H.E. Riggs

There is a definite need for state highway departments to recognize the importance of designing and employing a logical decision-making process, based on economics, in selecting between alternative design or engineering proposals. Without proper decision-making machinery, the impact of much of the research and technological advances noted at this conference can be negated through uneconomic decisions. The purpose of this paper is to present a general discussion of engineering economy principles and to illustrate the use of these principles in selecting between alternative asphalt pavement designs. The purpose is not to evaluate the relative economics of specific technical alternatives, but rather to describe a rational, economic method of comparing and evaluating any set of technical designs. The approach is applicable not only to the selection of alternative designs for a single pavement type, but also to many other design and administrative decisions.

In conducting economy studies, it is necessary:
(1) to define the alternatives between which a decision is to be made;
(2) to identify and define those factors that may cause differences in the costs of the alternatives and to eliminate from consideration all factors that will be the same no matter which design is ultimately chosen; and
(3) to convert all factors to a common dollar basis and make a comparison over time, considering the time value of money through the use of compound interest.

The economic comparison of designs that are expected to provide equivalent pavement service Over time is relatively easy; bids or estimates will provide factual information regarding the cost of constructing the pavement structure specified by each design. The more usual circumstance--and the more difficult one to analyze--arises when different pavement designs can be expected to provide different service experience. For example, one design may permit a reduction in maintenance cost, or a lengthening of the time period until resurfacing is required; another design may require a second stage

	of construction at some future date. Thus, alternative designs may involve not only different expenditures for initial construction but also differing patterns of expenditures over time-and it is both the present and future expenditures that must be compared, recognizing that money has a time value. With specific reference to asphalt pavement designs, engineering economy techniques are singularly appropriate for use in evaluating the economic implications of stage construction and of over-design of the asphalt pavement structure. A graphic method of analysis employing hypothetical numerical examples is used to illustrate the application of engineering economy to these two specific design situations.
01073	**Report on Session VIII - Summation of Principles of Structural Design of Asphalt Pavements** *Chairman: Francis N. Hveem* Chairman: Francis N. Hveem, Materials & Research Engineer, California Division of Highways Presentation of Summation Reports by Moderators Session I - AASHO Road Test and Performance Criteria W.J. Turnbull Session II - Road Tests, Field Studies, and Performance Criteria A.C. Benkelman Session III - Theoretical Developments Related To Structural Design of Asphalt Pavements William H. Goetz: Session IV - Theoretical Developments Related To Structural Design of Asphalt Pavements Robert G. Hennes Session V - Strength Evaluation Of Pavement Structure Elements H. Bolton Seed Session VI - Design and Construction Influence on Structural Behavior of Asphalt Pavements Gordon D. Campbell Session VII - Design and Construction Influence on Structural Behavior of Asphalt Pavements William S. Housel Floor Discussion Closing Statement: Session Chairman
01074	**Listing of 1st Conference Participants** *n/a* An alphabetica listing of 1st conference participants, with their full names, affiliations and addresses.
01075	**Index of Conference Participants** *n/a* An alphabetical lsiting of authors and contributors, with page references.

code	ISAP 2nd Conference - Titles & Abstracts
02000	**Preliminary Pages and Table of Contents** *n/a* This document contains the preliminary pages of the Proceedings for the 2nd International Conference. The Table of Contents gives a good overview of the structure of the conference and the papers presented (and discussion thereon).
02001	**Report on Session I & Chairman's Opening Address** *Chairman: Willaim N. Carey* The Opening Address, followed by a moderated discussion of the papers presented in Session I. The Measurement of Highway Pavement Performance B. G. Hutchinson Thickness Determination of Flexible Highway Pavements for Mixed Loads and Traffic Volume M. Livneh and E. Shklarsky Design of Subsurface and Surface Against Detrimental Compaction and Shear in the Finished Structure J. L. McRae Flexible Airport Pavement Design and Performance G. Y. Sebastyan A Method for Strengthening Flexible Pavements J. Lassalle and S. Langumier Developments in the Application in Practice of a Fundamental Procedure for the Design of Flexible Pavements G. M. Dormon and J. M. Edwards Prediction of Pavement Deflections from Laboratory Tests C. L. Monismith, H. B. Seed, F. G. Mitry, and C. K. Chan The Computation of Road Deflections under Impulsive Loads from the Results of Vibration Measurements M. E. Szendrei and C. R. Freeme Analysis of Deflection Data from the AASHO Test J.M. Kirk Consideration of Calculated Strains at Various Depths in Connection with the Stability of Asphalt Pavements W. Heukelom and A. J. G. Klomp The Behavior of Asphalt Pavements under Variable Repeated Loads P. Ferrari Evaluation of Applicability of AASHO Road Test Results to Corps of Engineers Flexible Pavement Design Criteria W. J. Turnbull, R. G. Ahlvin and D. N. Brown
02002	**The Measurement of Highway Pavement Performance** *B. G. Hutchinson* Until more appropriate models of pavement behaviour are developed, the measurement of the performance of pavements under actual service conditions provides the only realistic basis for assessing new pavement designs. In fact systematic field performance measurements provide the only source of information for evaluating the validity of any newly formulated models of pavement behaviour. Conditions such as these dictate that rigorous and universally applicable techniques be developed for measuring highway pavement performance. A number of attempts have been made over the years to formulate objective measures of pavement performance. In general all of these attempts measured some aspect of the pavement surface distortion in the form of an index of roughness. Hveem has made an excellent survey of the types of equipment used to measure or estimate pavement roughness and the techniques used to analyze and interpret the data.

While many miles of highway pavement have been surveyed with one or other of the instruments described by Hveem, no rational method of profile interpretation has been developed with the exception of the A.A.S.H.O. Road Test formulation reported by Carey and Irick.

This paper explores the formulation of apavement performance measure from a systems oriented approach. The driver functions are examined and existing knowledge on human response to motion is reviewed in order to establish the critical human parameters of the system. A tracking task is described and the results of a field experimental program are given.

02003 **Thickness Determination of Flexible Highway Pavements for Mixed Loads and Traffic Volume**
M. Livneh , E. Shklarsky

The design of the thickness of flexible pavements is not accomplished at present by one unequivocal method, however, this is not the place to describe the many methods of calculation that are in use. The differences between them arise both from the multiplicity of ways of evaluating the strength of pavement layers and from the many ways of evaluating the serviceability of the pavement.

One accepted method is that of the U.S. Corps of Engineers based on evaluation of the strength according to the CBR scale. Since this method of the U.S. Corps of Engineers is particularly suited to the calculation of pavement thickness for runways, there is special interest in the development of a method of extending this method for use in determining the thickness of highway pavements. Obviously such an extension should include highway pavement thickness calculation formulae equivalent to those of the U.S. Corps of Engineers as a special case while also providing an appropriate method of calculation for mixed traffic, which is the actual case on the roads. This paper presents the above mentioned extended formulae after first developing the settlement relationships which enables the required translation of the U.S. Corps of Engineers method to highway pavements. Additionally, the paper presents a method of calculating pavement thickness for mixed traffic loads also based on the above mentioned settlement relationships.

02004 **Design of Subsurface and Surface Against Detrimental Compaction and Shear in the Finished Structure**
J. L. McRae

This paper presents a concept for design of new pavement or evaluation of existing pavements encompassing requirements for compaction to equilibrium under the anticipated vertical stress in each structural member, (i.e., subsurface and surface layers) and avoidance of detrimental shear in any member of the pavement. A factor of safety with regard to shear failure, expressed as the ratio of shear strength, at an appropriately selected value of strain, to the theoretical maximum shear stress is introduced.

Illustrative examples are given in which the Gyratory Testing Machine (GTM) is used to evaluate the compaction and shear characteristics of the various structural elements, including an illustration of the use of the Gyratory Testing Machine (GTM) shear data in the original Prandtl Formula to predict the bearing resistance versus shear strain relationship for the surface course of a flexible pavement.

Discussion of environmental conditions has been purposely avoided in this paper in the interest of brevity. It is recognized that the test specimens should be subjected to environmental conditioning prior to testing. The nature of such conditioning will, of course, vary depending upon the anticipated conditions for any particular geography and weather.

02005 **Flexible Airport Pavement Design and Performance**
G. Y. Sebastyan

Increasing aircraft traffic loading intensity and density necessitates a continual review of the design methods for flexible pavement used in civil engineering practice.

Developments in flexible pavement design methods during the past few years tend to follow two general directions.

Empirical and semi-empirical flexible pavement thickness design analyses have given place to design methods developed on the basis of the rationalization of empirical knowledge by measuring, correlating and expressing design variables involved using statistical methods and analysis.

The AASHO Road Test and the work of the Canadian Good Roads Association (CGRA) Pavement Design and Evaluation Committee are two excellent examples of this approach.

The other direction in the development of flexible pavement design methods is the rational design approach based on determining and limiting the stresses or deflections generated in the subgrade and the pavement structure under the superimposed load as evaluated by the theory of elasticity.

As an introduction to the subject, some of the problems and difficulties encountered in Department of Transport's design work which made use of the various empirical, semi-empirical and rational methods will be discussed in the light of the data and experience collected by the Department.

02006

A Method for Strengthening Flexible Pavements
J. Lassalle, S. Langumier

In the present paper, the Authors aim at presenting an experimental method which can be used, in strengthening work on flexible pavements, to evaluate the desired thickness of asphalt mix overlay.

They have not dealt with the following points: Why use a strengthening overlay?
When this must be done?
because these points must take into account criteria which are outside the method itself.

This paper is divided into four parts:
- Principle of the method;
- Practical application of the method;
- Examination of four points of special importance; - Possibilities evolved in the method.

02007

Developments in the Application in Practice of a Fundamental Procedure for the Design of Flexible Pavements
G. M. Dormon, I. M. Edwards

The corresponding paper at the first conference outlined the application to practical conditions of a fundamental design approach, In this paper progress made since that time in extending the basic curves for practical application is summarised, and the results reviewed in the light of full scale experience and further mathematical and laboratory investigations. The evaluation of existing pavements and the design of airfield pavements are briefly discussed.

02008

Prediction of Pavement Deflections from Laboratory Tests
C. L. Monismith, H. B. Seed, F. G. Mitry, C. K Chan

Asphalt concrete pavements must be designed so that the thickness of the pavement structure is sufficient to prevent not only excessive permanent deformations (rutting or plastic flow), but also cracking of the asphalt concrete surfacing. In recent years this latter form of distress has increased in significance in that it has occurred in a number of otherwise well-designed pavements which exhibit no permanent deformations (ruts) in the regions of distress. This form of pavement distress has been well described by Hveem; it occurred in the WASHO Road Test and was present in the AASHO Road Test, at least in the loops subjected to the intermediate axle loads.

This load associated cracking of the pavement has been attributed to fatigue failure of the surfacing resulting from repeated traffic stresses over a period of time. The California Division of Highways and more recently several other agencies, have measured the deformation and rebound occurring innumerous pavement sections and have found a close correlation between the occurrence of cracking and the magnitude of the transient pavement deflections. However, as indicated by the California data it is necessary to consider not only the absolute value of deflection as a damage determinant but also the number of repetitions of load, since in a number of instances, cracking has only developed after large numbers of load repetitions producing potentially damaging deflection.

The prevalence of this form of pavement distress has created a need for methods of predicting the transient deformations of a pavement in order to assess the magnitude of the stresses and strains developed in the surfacing which in turn appear to determine the fatigue life of the pavement. In a general way, it is to be expected that stresses or strains in the asphalt surfacing will increase with the magnitude of pavement deflection, but they are also dependent on the curvature of the deflected surface. However, methods for predicting deflection would be a valuable first step in solving the problem of preventing fatigue failures in pavements.

02009

The Computation of Road Deflections under Impulsive Loads from the Results of Vibration Measurements
M. E. Szendrei, C. R. Freeme

The impedance method of vibration testing of roads has been under investigation for a number of years at various research laboratories. Up to the present time no satisfactory general mathematical theory exists by which the field results may be evaluated, although a number of attempts have been made in this direction and have been successful in solving some special cases.

In order to interpret field measurements a more practical approach has been followed by postulating a "mechanical model" with a number of frequency independent parameters, suggested by the shape of the experimental curves.

Although vibration tests are carried out using sinusoidal forces only, it is possible to analyse a force impulse, such as applied by a moving wheelload, by Fourier techniques and, by combining the relevant impedance value with each frequency component of the pulse, a method has been found by which the resultant road response to the force impulse may be estimated.

Measurements were taken with the equipment consisting of an inverted electromagnetic vibrator supported by a spring on a 1 ton cylinder. The cylinder makes contact with the road through a steel plate 30 cm in diameter. The applied sinusoidal vertical force is measured by a calibrated geophone fixed to the vibrator, while the resultant velocity is measured by a similar calibrated geophone located centrally near the top of the 1 ton mass. This method was first suggested by Thrower but the present equipment has been modified by the addition of the 1 ton mass to lower the natural resonance of the road-equipment system to more realistic frequencies.

02010 **Analysis of Deflection Data from the AASHO Test**
J. M. Kirk

The proceedings from the International Conference on the Structural Design of Asphalt Pavements in Ann Arbor, 1962, shows the great interest in the use of the theory of elasticity for the interpretation of test results and for the design of flexible road structures. The basic idea is that different materials have different load-spreading abilities, and that these differences are due to differences in Young's modulus, which can be calculated from results of static or dynamic tests on the materials, by the use of the theory of elasticity.

The numerous results from the AASHO Road Test offers a good opportunity to check if this assumption of elastic behaviour of road materials can be used for the design of road structures, and the following pages contain an analysis of some deflection data from the AASHO Road Test.

02011 **Consideration of Calculated Strains at Various Depths in Connection with the Stability of Asphalt Pavements**
W. Heukelom, A. J. G. Klomp

A new computer program developed by A. Jones enables the calculation of stresses and strains at various depths and radial distances from the center of a single wheel load, following the theory of elasticity. Some of the results have been used to consider the initial strain and change in thickness of asphalt layers under and around single and double wheels. In addition, a simple concept of plasticity has been used to estimate the permanent strain and change in thickness after removal of the load. The qualitative trends shown are compared with experience gained in practice.

Some attention is also given to a statistical treatment of wheel loads in Dutch practice and to the thickness design of entirely bituminous road structures intended to carry a given traffic on subgrades of variable CBR value.

02012 **The Behavior of Asphalt Pavements under Variable Repeated Loads**
P. Ferrari

The most modern method of asphalt pavement constructions consists in making the carpet, binder, and base course with asphalt mixture, so that these three layers as a whole constitute a single plate resting on the sub-base, which latter is generally formed with compacted granular material. This type of pavement may undergo deterioration and even ruin through various causes, depending on the nature and conditions of the subgrade, weather conditions, and particularly heavy loads passing thereon.

However, even when all the above factors have been into account in the design, and the pavement has been properly constructed, it has been observed that, if traffic is heavy and intense, the pavement keeps well for a certain period of time, but subsequently cracks begin to appear on the carpet, at first of limited length and depth, which in time deepen and extend to large areas of the pavement, taking on the characteristic aspect of a net.

With the loss of its two important properties of monolithicity and impermeability, the efficiency of the pavement appears completely impaired.

Without leaving out of consideration the alterations brought about by ageing and weathering on the properties of the asphalt cement, the chief factor in causing the formation of cracks has been traced, in the last few years, to a "fatigue" phenomenon due to repeated loads; consequently, in the design of pavements, this phenomenon has been - in a wholly empirical way - taken into consideration, by increasing the thickness in direct proportion with the anticipated increase in repeated loads. In effect, since the true nature of fatigue phenomena in asphalt mixtures was unknown, it has been thus far impossible to evaluate their qualitative and quantitative importance for the purposes of resistance to repeated loads. This gap in basic knowledge takes on an even greater importance in the so-called "rational" methods for the calculation of pavements, whose basic hypothesis on the physical properties of asphalt mixtures do not take into account the element of material fatigue.

On the basis of some experiments conducted at the Experimental Laboratory of the Institute of Road, Railway, and Airport Constructions of the University of Naples on asphalt concrete samples submitted to repeated alternating bending stresses, this paper deals with a theory which should make possible to identify the factors which cause fatigue failure in the asphalt mixture, through the study of alterations in the stress distribution and structure of the material brought by repeated loads. It is thus possible to determine the pavement features which have a greater weight on said phenomenon, and thereby to influence same for the purpose of improving pavement behavior.

02013 **Evaluation of Applicability of AASHO Road Test Results to Corps of Engineers Flexible Pavement Design Criteria**
W. J. Turnbull, R. G. Ahlvin, D. N. Brown

Various approaches were investigated in an effort to use the results of the AASHO Road Test completed in 1961 to validate or modify present Corps of Engineers (CE) flexible pavement design criteria. The AASHO Road Test results are not directly applicable for use in improving existing CE design criteria because sufficient data were not obtained during application of test traffic to determine material strength conditions, especially at failure.

The present serviceability index method of evaluating pavement performance, developed by the AASHO Road Test staff, appears to have considerable merit in quantitatively assessing pavement condition. However, the specific variables for which objective measurements are taken for use in this method of evaluation are not those normally considered in pavement design.

The various approaches followed in attempting to relate the pattern of behavior represented by the AASHO Road Test results to the pattern inherent in the CE design procedures are explained and comparisons are shown. Mathematical patterns seem to be strongly parallel, but the specific field measurements needed to draw a direct comparison are lacking.

02014 **Report on Session II - Theoretical Treatment of Structural Design of Asphalt Pavements**
n/a

A moderated discussion of the papers presented in Session II.

Analysis of Stresses and Displacements in a Three-Layered Viscoelastic System
J, E. Ashton and F. Moavenzadeh, Massachusetts Institute of Technology, Cambridge, Massachusetts

Dynamic Phenomena in Pavements Considered as Elastic Layered Structures
A. Avramesco, Laboratoire Central Des Ponts et Chaussees, Paris, France

Stresses and Displacements in Viscoelastic Layered Systems under Circular Loaded Areas
Y. H. Huang, Council of Highway Investigation and Research, Charlottesville, Virginia

The Theory of Viscoelastic Two-Layer Systems and the Conception of its Application to the Pavement Design
K. Ishihara, University of Tokyo, Tokyo, Japan
T. Kimura, Tokyo Institute of Technology, Tokyo, Japan

Stress-Strain Law for Viscoelastic Flexible Pavement under Temperature Variations
A. B. KU, University of Detroit, Detroit, Michigan

The Analysis of Pavements under Arbitrary Loading
A. L. Yettram, C. A. O'Flaherty and M. E. Fleming, The University of Leeds, Leeds, England

Deflection of Viscoelastic Medium Due to a Moving Load
W. H. Perloff, Purdue University, Lafayette, Indiana
F. Moavenzadeh, Massachusetts Institute of Technology, Cambridge, Massachusetts

Stresses and Displacements in Elastic Layered Systems
J. Verstraeten, Centre De Recherches Routieres, Brussels, Belgium

Stresses in Layered Systems under Static and Dynamic Loading
A. Waterhouse, Bradford Institute of Technology, Yorkshire, England

Stress and Displacement in an Elastic Mass under Semi-Ellipsoidal Loads
J. L. Sanborn, University of New Hampshire, Durham, New Hampshire
E. J. Yoder, Purdue University, Lafayette, Indiana

Predicting Performance of Bituminous Surfaced Pavements
R. D. Barksdale, Georgia Institute of Technology, Atlanta, Georgia
G. A. Leonards, Purdue Universiv, Lafayette, Indiana

02015

Analysis of Stresses and Displacements in a Three-Layered Viscoelastic System
J. E. Ashton, F. Moavenzadeh

This study presents an analysis of the surface deflection of a three-layered linear viscoelastic half-space under a uniformly distributed normal circular loading. The method of solution involves replacing the elastic constants in the known elastic solution (due to Burmister) by the hereditary integral forms of the stress-strain relationships. This method of analysis was selected largely because such stress-strain relationships can be used to realistically represent the viscoelastic behavior of the real materials involved over broad time intervals. In the analysis presented, the geometrical variables are separated from the time dependent variables. It is shown that the geometrical variables can be handled in a manner identical to Burmister's solution, while the time dependent variables can be handled with convolution integrals.

02016

Dynamic Phenomena in Pavements Considered as Elastic Layered Structures
A. Avramesco

The results concerning the moving load given in this paper will probably appear as the most important. But it is the whole of dynamic phenomena in elastic layered structures which is tackled with - and also the meaning and the limits of the elastic approximation of roads. The analysis does not always go as far as the establishment of numerical results: however, the numerical transcription of the method is being now carried out on almost the whole of the phenomena described here. It has seemed that the qualitative results on one hand and the quantitative values already obtained on the other hand, justified this account.

The idea of calculations will be recalled, but the reader is strongly advised to refer to the noted work*, where are given the procedures of integration, and almost every bibliographic reference; also, the case of "torsion" may appear as of purely theoretical interest: but it allows to underline the essential features of the phenomena so simply that it has been thought necessary to include it in this paper and it is already studied experimentally in France for the testing of roads.

Formulas or equations have been written only either when they allow to conceive how the mathematical method works, or to precise a physical result. The reader interested in complete developments is again asked to refer to the noted paper* for calculations and references.

---

* A. Avramesco: Dynamique des structures elastiques stratifiees Annales des Ponts et Chaussees Janvier-Fevrier,1966.

02017

Stresses and Displacements in Viscoelastic Layered Systems under Circular Loaded Areas
Y. H. Huang

This paper is concerned mainly with the analysis of stresses and displacements in viscoelastic layered systems. The analysis is based on the elastic-viscoelastic correspondence principle in which the Laplace transform is applied to replace the time variable with a transformed variable and thus change the viscoelastic problem into an associated elastic problem. The solution of the associated elastic problem, when transformed back into the real time variable, will give the desired viscoelastic solution.

Two methods, one based on a direct method of Laplace inversion and the other on an approximate method of collocation, were developed to determine numerically the stresses and displacements in two and four-layer systems made of linear viscoelastic materials.

Numerical solutions involving both simple and complicated cases are presented, and the significance of these solutions is discussed.

02018

The Theory of Viscoelastic Two-Layer Systems and the Conception of its Application to the Pavement Design
K. Ishihara, T. Kimura

The result of analysis for viscoelastic two-layer systems developed formerly by the senior author was reexamined and supplemented by some additional numerical result. In order to incorporate the theory into the practical application, a conception was introduced along with a method that enables the viscoelastic constants of a substance to be determined in accordance with the time of loading at which a pavement is subjected to an external load. With the use of the proposed theory, the effect of vehicle speed on the pavement behavior was analyzed for the test data of the AASHO road test. The proposed conception which reveals a qualitative coincidence with the actual data suggests a direction towards a. dynamic design of pavement.

02019

Stress Strain Law for Visoelastic Flexible Pavement under Temperature Variations
A. B. Ku

In the analysis of flexible pavements, theoretical calculations usually fail to predict actual pavement performance accurately. Although the deviation may attribute to various causes. One of which, we believe, is the oversimplication of the mathematical model representing the pavement body.

In this paper, we shall endeavor to propose more realistic stress-strain relationships and concern ourselves with the effect of temperature and viscoelasticity on these relationships.

02020 **The Analysis of Pavements under Arbitrary Loading**
A. L. Yettram, C. A. O'Flaherty, M. E. Fleming

A general method is proposed for the analysis of a pavement which consists of a thick, rectangular slab on an elastic foundation and is subjected to any arbitrary normal loading. The foundation is assumed to be of the Winkler type while the flexural, transverse shear and transverse compressive stiffness of the slab are all taken into account. Furthermore the true finite nature of the system is considered.

Analytically, the method involves developing the variational approach to problems in elasticity to deal with the complete slab and foundation system.

Computationally, the use of polynomial expansions is proposed to describe the independent variable (the distribution of the loading) and also the dependent variables (the distributions of transverse shearing forces, bending moments and torque, rotations and deflections in the slab). This technique results in a set of linear simultaneous equations in the polynomial coefficients, and the solution of this set then enables the dependent variables to be calculated at any location, as required.

02021 **Deflection of Viscoelastic Medium Due to a Moving Load**
W. H. Perloff, F. Moavenzadeh

Rational design of a pavement which will properly perform its function requires knowledge of the stresses and deflections of the pavement system. The majority of stress analysis problems which have been solved in the past have assumed an homogeneous, isotropic, time-independent, linear elastic material (BOUSSINESQ, 1885; BURMISTER, 1943, 1956). It is probable that linear elastic behavior has been most frequently assumed primarily because of the reduction in mathematical complexity which results from such an assumption.

Recently it has been shown, however, that, for highway pavement materials, the assumption of time independent behavior is not even approximately correct (PISTER and MONISMITH, 1960: PAPAZIAN, 1961; HOUSEL, 1959: SCHIFFMAN, 1959). In order to more appropriately characterize the response of such materials, various time-dependent constitutive equations have been formulated. One of the simpler types of such equations describes the behavior of linear viscoelastic materials. This type of equation can be written in several forms, one of which is (LEE, 1960). In his equation (a sub r) and (b sub r) may be functions of time, space and even temperature. However, linearity requires that (a sub r) and (b sub r) be independent of stress and strain. Assumption of homogeneity and isotropy eliminates the dependence of (a sub r) and (b sub r) on location and orientation of stress within the medium, and greatly simplifies the analysis. It is also often desirable to express Lee's equation as two equations in which dilational (volumetric) and deviatoric (shearing) effects are separated.

02022 **Stresses and Displacements in Elastic Layered Systems**
J. Verstraeten

The expressions of the stresses and displacements are derived in the general case of elastic layered systems subjected, on a circular area of their upper horizontal surface, to the action of one of the following stresses:
- a uniformly distributed shear stress, directed in one direction;
- a uniformly distributed shear stress, directed towards the center of the circular area;
- a uniformly distributed vertical stress.

The derivations are made under the assumption that the superposition of the three above-mentioned stresses represents the action of a vehicle wheel on the upper surface of the surfacing course.

Starting from the derived theoretical formulas of the stresses, numerical calculations are performed in the particular case of four-layered systems with continuous interfaces. . " These calculations permit to draw general conclusions relevant to pavement design.

02023 **Stresses in Layered Systems under Static and Dynamic Loading**
A. Waterhouse

The purpose of this paper is two-fold.

1. Briefly to outline existing methods of the design of flexible pavements leading up to a brief historical introduction to the mathematical analysis of elastic layered systems. It presents a finite element

approach to this problem and treats salient points involved in detail. Certain matrices are quoted in sufficient detail to enable the stiffness matrices for the elements to be calculated. No results are presented at this stage but work is proceeding to compare the finite element analysis first with the Boussinesq theory and second with the results presented by Peattie and Jones. The effect of rigid inclusions in the mass is being studied and it is hoped that figures will be available by August 1967.

2. To describe experimental work involved in the determination of axial stresses in two-layer and three-layer systems, vertically below the central axis of a circular load. The measurements also involve a continuous record of surface displacement and applied load and the determination of relative 'E' values. Loads are applied statically and dynamically.

02024 **Stress and Displacement in an Elastic Mass under Semi-Ellipsoidal Loads**
J. L. Sanborn, E. J. Yoder

The purpose of this study was to devise a numerical solution for theoretical stresses and displacements in a soil mass due to non-circular loads of non-uniform distribution. The analysis was based on theory of elasticity and previous investigations of the configuration of wheel loads.

The study was composed of three parts:
1) to write a program for a digital computer, which could be used directly or with minor modifications for any given load distribution,
2) to use that program to develop charts of vertical stress and displacement for a reasonable approximation of usual tire loads, and
3) to compare effects of uniform circular and non-uniform, non-circular loads.

Stresses were considered to be distributed according to Boussinesq theory which assumes a homogeneous isotropic elastic mass. No attempt is made to account for the effects of the layered structure of flexible pavements. Several investigators have described solutions to two and three layer problems. However, since a primary function of this program is to provide a basis for comparison of effects of non-uniform loads with the conventionally assumed uniform circular loads, the work was restricted to the simpler homogeneous case which has been the assumption adopted by other investigators in a large portion of the earlier work.

02025 **Predicting Performance of Bituminous Surfaced Pavements**
R. D. Barksdale, G. A. Leonards

Current theoretical approaches to flexible pavement design may be divided into two categories:
(a) ultimate strength methods, which attempt to consider failure mechanisms, and
(b) analyses of stresses and strains based on elastic theory, which attempt to predict (and hence control) failure mechanism and provide an approach for calculating subgrade stresses as a basis for avoiding failure mechanism.

Thus, progress has been made toward the development of a suitable tool to predict pavement performance. However, changes in material properties under the action of repeated loadings accompanied by permanent deformations and a redistribution of stresses with time cannot be evaluated using elastic theory.

The purpose of this paper is to extend the basis for predicting pavement performance to include repeated loads and time dependent material properties that can be evaluated from laboratory tests. The analysis of pavements using elastic, multi-layered theory is also extended to include numerical solutions of four-layer pavement systems.

02026 **Report on Session III - Structural Design of Asphalt Pavement - Soil Conditions and Construction Methods**
Moderator: Hector C. Calderon

A moderated discussion of the papers presented in Session III.

Field Application of the Resilience Design Procedure for Flexible Pavement
J. L. Beaton, E. Zube, and R. Forsyth, State of California Highway Transportation Agency, Sacramento, California

The Design and Evahration of Asphalt Concrete Pavements Using Continuous Waves
W. H. Cogill, University of New South Wales, Kensington, Australia

The Influence of Compaction Methods and Condition on the Structural Behavior of Compacted Subgrades
H. E. Wahls and L. J, Langfelder, North Carolina State University, Raleigh, North Carolina

Structural Effect of Restraint Layer on Subgrade of Low Bearing Capacity in Flexible Pavements

T. Yamanouchi, Kyushu University, Fukuoka, Japan

Experiences With the Use of Wedges Against Frost Heaving
0. A. Taivainen, University of Oulu, Oulu, Finland

Considerations on the Structural Number
H. Takeshita, Chuo University, Bunkyo-Ku, Tokyo, Japan

Measurement and Interpretation of the Elastic Compressibility of Subgrades and Its Relation to the Behavior of Asphalt Pavements
C. Ruiz, Graduate School, Highway Engineering, Buenos Aires, Argentina

Soil-Cement Properties Determined by Repeated Loading in Relation to Bases for Flexible Pavements
J. K. Mitchell, University of California, Berkeley, California
Chih-Kang Shen, Loyola University, Los Angeles, California

Structural Design of Asphalt Pavements With Local Materials for Heavy Loads
L. M. Zalazar, Graduate School, Highway Engineering, Buenos Aries, Argentina

02027 **Field Application of the Resilience Design Procedure for Flexible Pavement**
J. L. Beaton, E. Zube, R. Forsyth

Since 1960 the California Division of Highways has been utilizing pavement deflection measurements as a guide for the determination of the structural adequacy of existing pavements and the magnitude of necessary reconstruction. In order to introduce the deflection factor into flexible pavement design at the preliminary stage, a device known as the resiliometer has been developed by the Materials and Research Department. This instrument subjects a 4" diameter by 4" high soil specimen to cyclic dynamic loads with intensities varying from 0 to 50 lbs. per sq. in. In 1960 a program aimed at correlation of laboratory resilience measurements with field deflection data was initiated as the first step toward incorporation of the test soil resilience value into the flexible design procedure. Twenty-five sampling locations from California highways and the AASHO test road were included in this study, The results of What is considered to be a successful field correlation program were presented at the 1962 International Conference on Flexible Pavement Design.

This paper reports on subsequent studies initiated for the purpose of utilizing the pavement deflection-resilience correlation in practical design situations. It includes a description of the development of a method for selecting design moisture content and density of preliminary samples and establishment of a curing period between fabrication and testing of sensitive" soils. Upon establishment of these test criteria, 40 preliminary samples from 21 different projects were tested and analyzed utilizing design moisture content and density criteria. After completion of construction, the roadways subject to analyses were tested for transient deflection in order to determine the relationship between predicted and actual field deflection utilizing established design criteria. A coefficient of corelation of 0.86 with a confidence band ranging from 0.73 to 0.92 was obtained. Averaging the results of two or more samples from a single roadway increased the correlation coefficient to 0.93. Field trial data are presented, along with examples of the design procedure.

02028 **The Design and Evaluation of Asphalt Concrete Pavements Using Continuous Waves**
W. H. Cogill

Asphaltic concrete pavements are layered structures, in which the highly stressed zone near the surface transmits and spreads the vehicle load to the lower layers. The wearing surface must offer resistance to abrasion. Also, it must possess elastic stiffness in order to enable the lower courses to be stressed less highly: this permits the use of material having poorer bearing qualities for the lower layers.

It has been shown by Burmister, and by Cumming & Gerrard that, if the elastic constants at various depths in such a structure are known, the stresses can be calculated in the layers under any given configuration of surface load. This paper is concerned with the determination and meaning of elastic constants in layered media of this kind.

02029 **The Influence of Compaction Methods and Condition on the Structural Behavior of Compacted Subgrades**
H. E. Wahls, L. J. Langfelder

In order for current design procedures and compaction specifications to provide for satisfactory subgrades, several fundamental assumptions must be valid. The strength parameter utilized in pavement design is assumed to depend on the density of the soil and to be unaffected by other factors such as compaction method and molding water content, Consequently, the strength value corresponding to a given field density is assumed equivalent to the laboratory strength value for the same compacted density. Furthermore, it is assumed that the behavior of the soaked laboratory sample is an adequate indicator of potential environmental effects. Also, the particular strength index utilized in the design

procedure is assumed to be a significant measure of potential material performance. Finally, the typical control procedures imply that the optimum compaction conditions for field construction are equivalent to the optimum conditions determined in the standard laboratory tests.

It is the intent of this paper to review, on the basis of current knowledge, the validity of the preceding assumptions. Because the bulk of the available information regarding strength or strength indices for compacted solids is based on laboratory data rather than field data, the initial phase of paper will review the factors that have been shown to affect the shearing resistance of laboratory-compacted samples. Next the available data correlating laboratory and field behavior will be considered. Also, limited data on the influence of field environmental conditions and traffic on subgrade performance will be presented. Finally the implications of the data that is being reviewed to current laboratory testing procedures will be discussed.

02030 **Structural Effect of Restraint Layer on Subgrade of Low Bearing Capacity in Flexible Pavement**
T. Yamanouchi

This paper treats of the results of various studies, including theoretical calculation by elastic approximation, laboratorial loading experiments made on the model pavement in a concrete box of 1.4 x 1.4 m cross section and 1.0 m depth by continuous repetition of loading about 100,000 times upon a loading plate in diameter and in-situ road experiment, aimed to prove that, in the case of flexible pavement on the subgrade of low bearing capacity, the pavement of total thickness which is considerably thin in structure compared with that of conventional progressive system is rendered serviceable by placing a restraint layer on the subgrade. The structural effect such as this is supposed to be due to the distortion resistance and/or the prevention of subgrade intrusion by the restraint layer.

As the materials for restraint layer in this study, the following items were adopted:
(1) Soil-cement method,
(2) Method by low pressure polyethylene net.

02031 **Experiences With the Use of Wedges Against Frost Heaving**
O. A. Taivainen

Observations have been made regarding frost heaving in road construction in which wedges have been used for preventing the effects of frost. This report deals with the observations made, and the practical experience gained, with the use of the wedges for preventing frost heavings in Finnish roads during the last few winter seasons.

The investigated spots have been in frost-susceptible ground, the road-parts in question being situated on both sides of culverts. The following cases have been investigated:
- culverts without any transition wedges,
- culverts with short irregular wedges, filled with sand,
- - culverts with long regular sand wedges, and
- a wedge filled with insulating lightweight aggregate.

Observations have been made regarding the changes in the roads, and particularly with respect to the grades in the winter as well as in the summer time. Some special observations regarding the depth of freezing and the temperatures in the structures of the road have also been made, when sand and lightweight aggregate have been used as insulating material in the wedges.

The investigation has produced as a result a proposal for the shape and the dimensions of the frost displacement wedge for culverts, and as a result of this proposal certain viewpoints regarding its use have also been presented.

02032 **Considerations on the Structural Number**
H. Takeshita

In Japan, the most widely used method for designing of flexible roads is the CBR method. The determination of the total thickness by means of CBR design curve is reasonably satisfactory in practice, but the questions have arisen on the thickness design of each layer by this method due to the different load distributing abilities of the materials to be used. At present as to the structural design method intensive field trials are going on in order to justify these new concepts.

This paper attempts to show the considerations concerning flexible roads, as the following items:

1. The tentative relations between structural number, wheel load and CBR were obtained from the field investigations.

2. The coefficient of relative strength "a" seems to be correlative with the modulus of deformation of the material.

3. By the use of the results obtained, the cause of cracking of the asphalt pavement on the National Highway Route No. 17 was analysed.

02033 **Measurement and Interpretation of the Elastic Compressibility of Subgrades and Its Relation to the Behavior of Asphalt Pavements**

C. Ruiz

The asphalt pavements of the national and provincial roads of Argentina which carry a very heavy and intense traffic frequency, show alligator cracking as their most common failure. This alligator cracking is not accompanied by deformation of the transverse or longitudinal profiles of the pavement when they are first formed. As from the early investigations by Nijboer and Van der Poe1 (1952), and the experimental observations by Hveem (1955), it is accepted that what causes alligator cracking is that the fatigue due to the repeated and excessive elastic deflections of the structure under transient loads, reduces the tensile strength of the asphaltic layers until they finally crack. The measurement of elastic deflections and particularly of their curvature, has turned to be the simplest and most practical means of evaluating the present state of the pavements in service and of establishing the possibility of development of the cracking under discussion, when these deflections are related to the frequency and intensity of the loads and to past experience.

Modern design methods directly or indirectly based on the elastic layers theory and on experience, tend to achieve that the stresses and strains due to the transient loads, anywhere in the structure, be compatible with the characteristic of the materials under any service condition, somehow or other bearing in mind the effect of fatigue. Whatever the point of view, we arrive at the conclusion that the elastic behaviour of a structure under loads, essentially depends upon the harmony between the critical tensile stress in the lower zone of the upper asphaltic layers and the other critical vertical stress at the level of the inferior bearing layers.

The elastic behaviour of the structure requires that in the inferior noncemented layers, and especially in the subgrade, the vertical stress that reaches them does not cause shearing stresses, which surpass the strength of the material controlled by the lateral support. It should be remembered that in dealing with compressible materials, the vertical reaction related to the recoverable reduction of the volume, can fundamentally control the elastic deflections of a structure, and, consequently, control the development of the fatigue of the asphaltic layers responsible for its cracking.

02034 **Soil-Cement Properties Determined by Repeated Loading in Relation to Bases for Flexible Pavements**

J. K Mitchell, Chih-Kang Shen

Ranges of values for the strength, strain at failure and resilient modulus have been determined for two soil-cements in the laboratory using repeated load compression and flexure tests. Resilient moduli in flexure may range from 100,000 to several million psi. Corresponding moduli in compression may be several times these values. The actual values for a given soil-cement may be sensitive to variations in density, water content and applied stress intensity, depending on soil type or whether the soil-cement is loaded in compression or flexure. Property values determined using the repeated loading test may be significantly different than those obtained using static loading procedures.

Flexible pavement sections containing soil-cement base courses are analyzed using allowable stresses and strains and modulus values determined from the repeated loading tests. Combinations of asphalt concrete and soil-cement base thickness are found which, for a range of subgrade strengths, limit critical stresses and strains in the pavement sections to acceptable values. The conditions examined are 1) tensile strain at the bottom of the asphalt layer, 2) vertical compressive strain in the subgrade, 3) tensile stress in the soil-cement, and 4) tensile strain at the bottom of the soil-cement layer, Surface deflections are also examined.

It is shown that if a "weak" soil-cement base (E = 100,000 psi) is used over a weak subgrade, design may be controlled by either subgrade compressive strain or tensile stress in the base. On stronger subgrades the subgrade compressive strain controls. For a "strong" soil-cement base (E = 1,000,000 psi) the design is controlled by tensile stress in the base for all subgrade strengths if surface deflections are not critical.

It is shown that no single value of equivalency, in terms of inches of granular base required to provide the same subgrade protection as one inch of soil-cement, exists, but that the equivalency depends on the modulus of the soil-cement, modulus of the subgrade, and thickness of the asphalt layer. Previously reported equivalency value of 1.5 to 3.3 fall well within the range predicted by the analysis.

The analyses presented in this paper are intended primarily to show how soil-cement bases can perform a valuable load carrying and distributing function in a pavement section. Before the results of such studies can be used for design purposes, however, more information is needed concerning fatigue characteristics of soil-cement, cracking and other weathering effects that may develop in the field, and the suitability of the laboratory repeated loading tests for prediction of stresses and deflections in the

field.

02035 **Structural Design of Asphalt Pavements with Local Materials for Heavy Loads**
L. M. Zalazar

A deep analysis is made in the present paper about pavement design in the Northeastern zone of Argentina within the National Route No. 12 between Corrientes City, Province of the same name and Posadas, Province of Misiones. The project will permit to link both capitals through a new paved road along almost 227 km divided into 4 Sections.

The zone belongs to a subtropical region with warm climatic conditions and heavy rains over the whole year, but reaching peak figures during spring. Rainfall on the past Spring-Summer (1965-1966) from October 1, 1965, up to April 30, 1966, made one of the highest figure of the century with a total of 1.726 mm (68 inches) for the mentioned period of seven months. Also the Parana River which flows at the north of the route marked on March 2nd the second great flood of the century, being the maximum on 1905, producing many troubles in the ground affecting the drainage of the zone which normally run off to the river.

Drainage is always a problem due to the extreme flatness of the natural ground which contains an excellent black "top soil" for agricultural purposes, used most in the cultivation of rice. This fact means an important factor against the good behaviour of pavements, because of the moisture accumulation on the top of the soil profile and moisture accumulated within.

02036 **Report on Session IV - Structural Components of Asphalt Pavements - Dynamic and Fatigue Properties**
Moderator: Robert F. Baker

A moderated discussion on the papers presented in Session IV.

RheologicaI Behavior of Asphalt Pavings Under Traffic
0. Andersson, National Swedish Road Research Institute, Stockholm, Sweden

An Experimental Investigation of the Stresses, Strains, and Deflections in a Layered Pavement Structure Subjected to Dynamic Loads
S. F. Brown and P. S. Pell, University of Nottingham, England

The Surface Wave Method
R. Jones, E. N. THrower, and E, N. Gatfield, Road Research Laboratory, Berks, England

Field Measurement of Dynamic Elastic Moduli of Materials in Flexible Pavement Structures
C, T. Metcalf, Shell Oil Company, San Francisco, California

New Developments in Vibrations Techniques
L. W. Nijboer, Rijkswaterstaat Rijkswegenbouwlaboratorium, Delft, Netherlands

Vibratory Study of Stabilized Layers of Pavement in Runway at Randolph Air Force Base
A. A. Maxwell and A. H. Joseph, Waterways Experiment Station, Vicksburg, Mississippi

Deformability, Fatigue, and Healing Properties of Asphalt Mixes
P. Bazin and J. Saunier, Compagnie de Raffiage Shell Berre, Paris, France

Results of Fatigue Tests on Different Types of Bituminous Mixtures
J. M. Kirk, Asfaltindustriens, Oplysningskontor, Copenhagen V, Denmark

Fatigue of Asphalt Pavement Mixes
P. S. Pell, University of Nottingham, England

Effect of Asphalt Aging on the Fatigue Properties of Asphalt Concrete
B. A. Vallerga, F. N. Finn, and R. G. Hicks, Materials Research and Development, Oakland, California

The Behavior and Performance of AsphaIt Pavements with Lime-Fly Ash-Aggregate Bases
E. J. Barenberg, University of Illinois, Urbana, Illinois

02037 **Rheological Behavior of Asphalt Pavings Under Traffic**
O. Andersson

Under the influence of traffic, road pavements suffer deformations, which to a certain degree of approximation can be treated as elastic. In fact all the layers, especially those containing bituminous materials, exhibit viscoelastic properties, even under load pulses of quite short duration. A more accurate analysis of the behavior of the pavement under traffic loading therefore requires consideration

of the viscoelastic response of asphaltic concrete to load pulses of short duration,

The present paper deals with measurements of the compression of wearing courses under a wheel moving at different speeds and at different axle loads and also similar measurements in a road under normal traffic. The properties of asphalt concrete have also been studied by analysis of stress relaxation and creep data of laboratory specimens recorded after different rates of compression and loading.

02038 **An Experimental Investigation of the Stresses, Strains, and Deflections in a Layered Pavement Structure Subjected to Dynamic Loads**
S. F. Brown, P. S. Pell

When the research project now being carried out at Nottingham University was launched, there appeared to be two important gaps in the laboratory experiment contribution to flexible pavement design. Firstly it was clear that an attempt should be made to measure in-situ strains as well as stresses and also that more comprehensive results should be obtained not only in the subgrade, but also at the interfaces and in the upper layers of the pavement. It was also thought that the system should be subjected to dynamic load similar to that which occurs in practice in a road pavement.

The approach has been to build up a three layer system investigating first a single layer, a clay subgrade, then a two layer system incorporating a granular base layer and finally the complete structure after the addition of a bituminous surface.

This paper is concerned with results from the first two of these systems, the two layer results being less complete and generally of a more preliminary nature than those for the single layer.

The main aim of the work has been to check the validity of linear elastic theory as applied to, firstly a homogeneous semi-infinite mass (Ahlvin and Ulery), and secondly a two layer system (Jones). In order to do this, stresses and strains have been measured within the pavement at various depths and radii and on sufficient planes to determine, by superposition, stress and strain conditions at a particular point. In addition, values of in-situ modulus and Poisson's ratio have been calculated from the results.

02039 **The Surface Wave Method**
R. Jones, E. N. Thrower, E.N. Gatfield

The surface wave method is being developed as a non-destructive means of measuring the elastic properties, and where possible the thickness, of the various layers of a road. Continuous vibrations are generated at the road surface, and measurements are made of the wavelength and velocity of the waves which travel along the road surface. The measurements are usually made at a number of specific frequencies to derive the experimental dispersion curve, i.e., relation between the measured velocity and wavelength, which is subsequently analysed to obtain the required information.

The present paper describes work in progress at the Road Research Laboratory, England, on some aspects of the method. The experimental technique employs frequencies within the range of 25 c/s to 30,000 c/s, and emphasis is placed upon manual and computer aids used to derive the experimental dispersion curves from the initial data. Recent work on the basic theory indicates how theoretical dispersion curves can be calculated for most types of road structure. Inversion of the dispersion curve to give unique solutions for elastic properties and layer thicknesses is possible only in rare cases, notably single layers of concrete or cement-bound materials. Inversion of the dispersion curves for other cases is possible if some of the parameters, layer thicknesses for example, are known.

To provide an adequate check on the theory, models of roads are being tested. Experimental dispersion curves obtained in two-dimensional models with one or two superficial layers give excellent agreement with theoretical dispersion curves calculated from independent measurements of the elastic properties and thicknesses of the uniform materials i.e. aluminum alloy, Perspex and linoleum, used in the models.

The paper also gives a brief account of the practical uses which have been made of the Surface Wave Method at the Road Research Laboratory. The thickness, elastic properties and strength properties of concrete and cement-bound layers have been derived, and a modified technique using one frequency only has been developed for studying variations of quality of cemented road layers. Possible extension of these applications to other materials is discussed. Other applications have included investigations to follow changes in the properties of road bases of granular, cement-bound and bituminous materials with time and traffic.

02040 **Field Measurement of Dynamic Elastic Moduli of Materials in Flexible Pavement Structures**
C. T. Metcalf

In the interest of gaining added experience and further background in the use of dynamic testing techniques on regular highway pavements, a series of wave propagation (velocity) measurements has been accomplished on two prominent field projects in the United States. Testing was completed using the small, high frequency vibration equipment. investigation of these pavements by the non-destructive,

dynamic principles has added to the information on the properties of some special experimental base materials as well as on the properties of the regular materials used in conventional highway constructions. Further insight has also been obtained on the analytical methods which can be employed to evaluate the results.

Tests at Colorado's experimental base project were made to investigate the properties of pavements containing relatively thick layers of asphalt stabilized sands in the base course. Results here showed that it was necessary to adopt a separate method of analysis - other than the past conventional approach - to evaluate those pavements containing thick layers of asphalt-treated base. Temperature was also found to exert a significant influence on results.

In other tests at Minnesota's extensive field design project, velocities we obtained on a wide variety of materials contained in pavements in the regular highway system throughout the state. Again it was found that analysis of the data was dependent on the particular type of pavement involved: pavements with thick requiring different techniques than those with thin surfaces.

02041 **New Developments in Vibrations Techniques**
L. W. Nijboer

The paper deals with vibration phenomena in a road construction. The theories, developed by Jones (R(oad) R(esearch) L(aboratory), England, are discussed, both for the case of a single slab of bound material, and for a compound slab, consisting of two layers. His theories cover the case of "no friction" between the two layers and the case of "no slip."

The measuring technique is elucidated and the mathematics applied in the analysis of vibration phenomena are discussed. Experiments carried out on a single slab (c.q. cement concrete and asphalt on a granular base) and on compound slabs (asphalt on lean concrete, asphalt on sand-cement, asphalt on blast furnace slag) and asphaltic concrete on an asphaltic base are discussed. The latter covers one case of "no friction" (asphalt on lean concrete), the other experiments represent cases of "no slip."

Means to control the correctness of the analysis of the vibration measurements are discussed. Two classes of materials are distinguished, viz. hydraulically bound materials (cement bound material, blast furnace slag) and bitumen bound materials. It is indicated that the value of the Young's modulus of the first group of materials is independent of frequency, whilst for the second group the rules by which the frequency influences the E-value is elucidated.

For the material of the bituminous layer the concentration of the mineral aggregate in the layer (Cv) is used as a criterion. The value of Cv can be determined from vibration measurements and from an analysis of the material. A second means of control by comparing measured and calculated R-values (Spring constant of the structure) is discussed.

The paper gives a survey of values of the Young's modulus obtained in the field on hydraulically bound materials and the values of Cv on bituminous bound materials and points to some discrepancies for the cement bound material. Calculations show that for some existing roads in the Netherlands the radial stress at the bottom of the second layer will be 80% higher in the case of "no friction", than in the case of "no slip," demonstrating the constructional advantages of a "no slip" construction over "no friction."

02042 **Vibratory Study of Stabilized Layers of Pavement in Runway at Randolph Air Force Base**
A. A. Maxwell, A. H. Joseph

The basic purpose of this paper is to demonstrate a method of nondestructive testing of pavements in an actual prototype structure where it is desired to evaluate changes in strength with time of the various layers making up a flexible pavement. The reconstruction and strengthening of a runway at Randolph Air Force Base was chosen to illustrate a prototype condition. For the particular runway discussed in this paper, three procedures were utilized in improving the load-carrying capabilities. These were:
(a) thickening the overall pavement,
(b) improving the quality of the individual layers, and
(c) increasing the strength of two of the layers by the use of lime as a stabilizing agent.

The basic discussion in this paper centers about the last-named item, primarily because it was felt that there would be a distinct change in strength with time as a result of the addition of lime. In order to record possible changes in strength, it was decided to utilize the method of nondestructive testing described herein in an effort to evaluate the strength changes with time, particularly with respect to lime stabilization. It is of course recognized that changes in strength might be brought about by other factors, and certainly these will not be ignored in yearly evaluations. It is planned to carry on this study for several years longer.

02043 **Deformability, Fatigue, and Healing Properties of Asphalt Mixes**
P. Bazin, J. Saunier

The ever-increasing traffic necessitates a constant improvement in road quality. The bituminous mix, the main purpose of which was to impermeabilize and improve the surface quality, is becoming more and more important as a load carrier in the road structure.
Under these circumstances, it appears extremely necessary to obtain a method, which can rationally determine the thickness of the mixes to be used.

At present, numerous methods have been proposed: they are usually based on the elastic characteristics of the utilized material. In the case of flexible pavements, this is only an easy approximation; in fact, the mechanical properties of bituminous mixes depend on the temperature and the time of loading, which deforms them.

In order to broaden our knowledge in this field, we have designed and manufactured a laboratory apparatus, which enables us to study the deformability and behaviour under repeated load of the bituminous mixes, under conditions which are equivalent to those of their utilization on the road.

In this article are contained the description of the utilized apparatus, in addition to the results concerning the determination of the complex modulus and the fatigue caused by bending. This article additionally contains an attempt to correlate the fatigue provoked by this apparatus and that caused by a loaded wheel rolling on a bituminous carpet.

Finally, after having studied the relative influence of several parameters (nature of bitumen, void-content, etc. . .) on the bending and fatigue, the first results are given of a study on the healing of mixes after rupture and on their recovery ability, after a fatigue period, which has not yet caused noticeable cracking.

02044 **Results of Fatigue Tests on Different Types of Bituminous Mixtures**
J. M. Kirk

In the last ten years, a number of rational design methods have been developed, based upon the usual engineering principle that the calculated stress in the different materials used, must not exceed a certain permissible stress, which depends upon the properties of the material.

This increases the need of knowledge of the strength of the materials used in road construction. As far as bituminous mixes are concerned, a number of workers have investigated the fatigue strength by various methods and Pell gives a review of this research. The most important general findings are that for a given mix, the fatigue strength - that is the number of loadings to failure - will depend upon the strain, while temperature and speed of loading is of negligible importance, as found by Saal and Pell, and further that the fatigue strength depends upon the bitumen content of the mix as stated by Pell. A number of tests, which have been carried out in order to obtain a more general picture of factors, which influence the fatigue strength are described in the following.

02045 **Fatigue of Asphalt Pavement Mixes**
P. S. Pell

At the first Conference in 1962 it was generally accepted that fatigue was one of the possible causes of surface cracking. This conclusion followed the observations made at the WASHO and AASHO Road Tests as well as many other contributions made by different agencies over the last twelve years. The results of full scale road trials have also shown that bituminous bound bases performed better than other base materials investigated and these facts have led to the investigation of rational methods of design which take into account the structural properties of the various pavement components. A rational method of design must incorporate strength considerations and by the very nature of the problem fatigue strength is one of the factors which should be taken into account.

Irrespective of design methods, however, there can be little doubt that under traffic loading the layers of a flexible pavement structure are subjected to continuous flexing and the possibility of fatigue cracking exists under these conditions. With the advent of larger wheel loads in conjunction with heavier traffic it is likely that fatigue considerations will assume greater importance in the future for the economic design of asphalt pavements.

These developments have led to research into the fatigue behaviour of asphaltic mixtures being carried out in a number of different countries. It is not proposed in this paper to review in detail the present information available in this field as this task has recently been done elsewhere but to report the work carried out at Nottingham University since the first conference.

Before giving details of the tests and their results a few comments will be made on the relevant facts which have emerged from earlier work as it is hoped that this will assist the assessment of the experimental results and an understanding of the importance of the various factors involved.

Possibly the greatest difficulty in interpreting fatigue test results arises from the fact that they are influenced by the method of testing. Generally testing methods fall into one of two types, either

"controlled stress" when the loading is in the nature of an alternating stress of constant amplitude, or "controlled strain" when the loading is in the form of an applied alternating strain or deflection of constant amplitude. The influence of the type of test is well illustrated by considering the effect of stiffness on the fatigue life of identical specimens tested by both methods.

02046 **Effect of Asphalt Aging on the Fatigue Properties of Asphalt Concrete**
B. A. Vallerga, F. N. Finn, R. G. Hicks

A laboratory study of the effect of asphalt aging on the fatigue properties of asphalt concrete has been conducted. Fatigue tests using artificially aged asphalts with penetration values of 63, 53, 37, and 15 (after mixing) and refinery produced unaged asphalts with penetration values of 65, 48, 28, and 9 (after mixing) were carried out under constant bending stress load conditions at one temperature and one rate of loading.

The fatigue test results for each asphalt were interpreted with the aid of three-layered theory for three typical roadway structural sections. The variables included in this analysis were surface stiffness (E1), base stiffness (E2), and surface and base thickness.

The results of the interpretation confirmed the hypothesis presented in reference (1) that artificially aged asphalts impart better fatigue properties to asphalt concrete than unaged asphalts at comparable consistencies. In addition, it was shown that for equivalent pavement designs the thickness of the surface layer and the magnitude of the base modulus significantly affect the fatigue life of asphalt concrete.

02047 **The Behavior and Performance of Asphalt Pavements with Lime-Fly Ash-Aggregate Bases**
E. J. Barenberg

It is the purpose of this paper to examine the field performance of several pavements with pozzolanic materials, and to compare the estimated strength of the pavement in the field with the required strength or thickness indicated by the proposed design procedure. A total of 16 pavements are examined in this study. These include pavements with both light and heavy traffic, and both overdesigned and underdesigned pavements. Only pavements which have been in service for more than 6 years were considered in this study.

This presentation is divided into three parts: First is a review of the properties of pozzolanic materials. Included in this review will be the proposed design procedure and the rationale behind the proposed procedure. Next is the review of the field performance of the pavements with pozzolanic base materials. Finally a brief discussion of the significance of the findings and recommendations for changes in the procedure are presented.

The pavements considered in this study were selected from several parts of the country to make the study more representative, Since it was not feasible for the author personally to collect all of the data, specific information was required from various contractors, materials suppliers, and industrial organizations. Much of the data presented herein are in response to these requests.

02048 **Report on Session V - Evaluation of Properties of Structural Components in Asphalt Pavements**
Moderator: K. Wester

A moderated discussion on the papers presented in Session V.

Stress and Strain Measurements in Experimental Road Sections Under ControlIed Loading Conditions
K. H. Gusfeldt and K. R. Dempwolff, Deutsche Shell A. G., Wilhelmsburg, West Germany

Observed and Calculated Strains at Various Depths in Asphalt Pavements
A. I. G. Klomp and TH. W. Niesman, Koninklijk/Shell Laboratorium, Amsterdam, Netherlands

Testing Flexible Pavements Under Normal Traffic Loadings by Means of Measuring Some PhysicaI Quantities Related to Design Theories
L. W. Nijboer, Studie-Centrum Wegenbouw, Arnhem, Netherlands

Deflection Prediction in Prototype Pavements
J. R. Morgan, University of Melbourne, Victoria, Australia
J. C. Holden, County Roads Board of Victoria, Victoria, Australia

AnaIysis of the Elastic Behavior of Flexible Pavement
H. Y. Fang, Lehigh University, Bethlehem, Pennsylvania
J. H. Schaub, West Virginia University, Morgantown, West Virginia

EvaIuation of El Toro Airfield by Layered Theory

J. P. Nielsen, U. S. Naval Civil Engineering Laboratory, Port Hueneme, California

Viscoelastic Properties of Bituminous Mixtures
G. Sayegh, Laboratoire Central des Ponts et Chaussees, Paris, France

The Effects of the Rheological Properties of Asphalt on Strength Characteristics of Asphalt Concrete
W. L. Hewitt and F. 0. Slate, Cornell University, Ithaca, New York

A Practical Approach to Flexible Pavement Design
F. P. Nichols, Jr., National Crushed Stone Association, Washington, D.C.

L.C.P.C. Studies on Pavement Design
J. Bonitzer and PH. Leger, Laboratoire Central des Ponts et Chaussees, Paris, France

02049 **Stress and Strain Measurements in Experimental Road Sections Under Controlled Loading Conditions**
K H. Gusfeldt, K. R. Dempwolff

In the course of the last ten to twenty years many theoretical and empirical methods for dimensioning roads and airfields have been devised. For practical application most of these methods were adopted either reluctantly or not at all. The reason for this is probably that the designing engineer is not sure whether the theoretical criteria governing stress and strain tally with actual conditions under traffic load.

In earlier trials it has been found that some 80% of the forces brought to bear are absorbed by the pavement itself. A method was developed to measure stress and strain through the complete thickness of the structure. Preliminary tests made with strain gauges embedded in carrier blocks revealed that a simple, linear relationship existed between tyre pressure and horizontal strain in the road.

Following these promising preliminary trials we set ourselves the task of ascertaining stress and strain in all three dimensions under controlled loading conditions with a single wheel. In doing so, as many factors as possible were simplified and kept constant, for instance, both acceleration and deceleration on the test section were deliberately avoided. The object of these trials was solely to study the strain and stress pattern itself. Repeated tests served to verify the measurements under varying temperature, speed, and load conditions. Fatigue tests were deliberately segregated from the test track and transferred to the laboratory along with the determination of the strength values.

On the basis of these preliminary tests the experimental road was so dimensioned that the wheel exerts pressure on the centre line of the test area and no edge effects distort the strains and stresses. The experimental road, moreover, readily permitted variations in the road construction, built on a scale of 1 : 1. It was thus possible to avoid any change in the strain and stress conditions which might be caused in a scaled-down model.

02050 **Observed and Calculated Strains at Various Depths in Asphalt Pavements**
A. J. C. Klomp, TH. W. Niesman

After some tentative laboratory experiments on a model road investigations were started on roads with thick asphalt pavements. Electric resistance strain gauges were attached to the surface of the various asphalt layers. With the aid of these gauges the strains under the rolling wheels of a vehicle can be determined at various depths in an asphalt pavement. The quantities thus obtained were compared with quantities calculated on the basis of elastic theory. The Young moduli of elasticity to be introduced were determined by dynamic testing.

02051 **Testing Flexible Pavements Under Normal Traffic Loadings by Means of Measuring Some Physical Quantities Related to Design Theories**
L. W. Nijboer

In an introduction the paper discusses the arguments that led to the conclusion that it is necessary to carry out full scale road tests to be able to form an opinion on the practical value of various calculation methods.

Properties of materials as well as differences between the load system used in the mathematical approach and the real wheel load are elucidated.

It is pointed out that as a first stage in this study a simple construction (two layer system) and a simple load system (single wheel) have to be preferred for the experimental investigation. Conditions of testing were chosen in such a way that a single construction thickness sufficed as variation in the properties of the chosen all bituminous construction could be obtained by testing over the four seasons at different temperatures.

The measuring techniques are elucidated as the strain gauges at various levels and the optical deflection

technique used present YEW developments. Details of the construction and of the loading system are given. The properties of the materials have been determined both in the field by in situ measurements (vibration technique) and in the laboratory, and the properties during the test runs are discussed.

From existing mathematical methods for the elastic design theory graphs have been prepared for use of handling and with a view to simplify application, both for the Burmister method and for the "slab" method (Jeuffroy).

The results of measurements under the centre of loading are discussed and a comparison is made for all the physical properties measured between measured data and calculated values according to the two methods. From the results conclusions are drawn as to the correctness by which the elastic theories are able to predict actual stresses, strains and deflections in the road construction under traffic. The results of some measurements to determine the influence on the lateral position of the wheel are discussed.

02052 **Deflection Prediction in Prototype Pavements**
J. R. Morgan, J. C. Holden

Under the sponsorship of the Australian Road Research Board the University of Melbourne is carrying out research into stress and strain distributions in pavement structures. One indication of the present lack of knowledge of the behaviour of pavements is the inability to predict surface deflections even in simple pavements from laboratory tests. This paper describes an approach to the problem whereby surface deflections in a single-layer system acted on by .a static uniform flexible load are predicted from strain measurements in triaxial samples of the material tested under stress conditions representative of those within the mass.

Tests were carried out on an air-dry graded sand contained in a tank 6 ft x 6 ft x 4 ft-8 inches high. The surface was loaded by a 10-inch diameter flexible membrane to a maximum pressure of 30 psi and deflections were recorded under both initial and repeated applications of the load. Stresses in both the vertical and horizontal direction were measured using miniature earth pressure cells. The measured stresses at representative points along the centre-line were applied to 4 inch diameter by 8 inch high samples and the strains measured. These strains were then integrated to compare with the surface deflection measured in the sand tank.

The paper describes the special techniques used to calibrate the pressure cells. These were found necessary to overcome the problem of apparently statically inadmissible stress ratios reported by previous investigators. Methods used to measurs axial and radial strains in the triaxial samples to an accuracy of +/- 0.0002 inches are also described.

The results indicate that surface deflections in the prototype pavement under first-cycle loading can be predicted reasonably well, although the method is not suitable as a design technique because of the refined experimental measurements required. The stress measurements indicate that the simple Boussinesq elastic theory is inadequate, particularly for prediction of radial stresses, It is suggested that consideration of anisotropic material behaviour would lead to better stress prediction in real materials.

02053 **Analysis of the Elastic Behavior of Flexible Pavement**
H. Y. Fang, J. H. Schaub

Analysis of the elastic behavior of flexible pavement as measured by the rigid plate load test and the Benkelman beam deflection test results is reported. The experimental data for these tests were obtained from the AASHO Road Test, Ottawa, Illinois. The fundamental relations between pavement deflections and environmental variables are discussed. The correlations between pavement deflection and the strength of pavement components and subsurface conditions are presented.

A simple equation based on the elastic theory is developed. The modulus of subgrade reaction, K, can be easily estimated by use of the equation if the thickness of the pavement components and pavement surface deflection as measured with the Benkelman beam are known. An equation using nondimensional techniques based on methods of dimensional analysis is developed for analyzing the results of Benkelman beam deflection tests on flexible pavement.

It is concluded that there is a close agreement, theoretically and experimentally, between the Benkelman beam and conventional test methods. It is suggested that the Benkelman beam could be adopted for general use for the evaluation of pavement performance and structural design of flexible pavements at a savings of considerable time and money.

02054 **Evaluation of El Toro Airfield by Layered Theory**
J. P. Nielsen

The techniques of the layered pavement method for the design of flexible pavements has been used to evaluate the El Toro Marine Corps Air Station, El Toro, California. This evaluation has produced in-situ moduli of deformation for all components of the flexible pavements. These in-situ moduli have been

correlated with the depth of the various layers, field density, field moisture, and soil types. A brief description of the geologic setting of the station is included.

02055 **Viscoelastic Properties of Bituminous Mixtures**
G. Sayegh

In order to develop rational design methods for flexible pavements, knowledge of viscoelastic properties of bituminous mixtures is needed. Within the domain of linear behaviour, viscoelastic properties can be defined through complex moduli, creep or relaxation functions.

At the Laboratoire Central des Ponts et Chaussees, several methods have been developed over the past five years in order to study these properties in the case of bituminous mixtures. They provide rheological models and corresponding analytical expressions utilizable for the design of bituminous pavements.

The characteristics we chose are complex moduli (Young's modulus and shear modulus) and Poisson's ratio, determined from vibration methods. The main reason for this choice is that it allows experimental conditions resembling those prevailing in actual pavements under traffic loads. Creep tests were used too in order to cross-check and extend results from dynamic experimentation to very low frequencies or slow deformations.

In the first part of this paper we shall discuss results obtained with a bituminous concrete of the so-called "Le Mans" type (used for the wearing course of the racing circuit of Le Mans). A rheological model and analytical expressions for the complex moduli and Poisson's ratio will be derived.

In the second part we shall discuss results obtained with other types of bituminous mixtures and try to draw some general conclusions about the behaviour of bituminous mixtures in the range of linear (small) deformations.

Finally we shall compare results of in situ measurements with those of laboratory experiments. It will be seen that it is possible to predict the performance in situ from laboratory experiments.

02056 **The Effects of the Rheological Properties of Asphalt on Strength Characteristics of Asphalt Concrete**
W. L. Hewitt, F. O. Slate

In the design of asphalt pavements, consideration should he given to the stresses imposed on the pavement and the ability of the pavement to resist these stresses. A major concern in the design of an asphalt concrete surface course is the vertical stress transmitted to the surface from tire contact, Also to be considered are those stresses in the surface which result from shrinkage and expansion with variations in temperature. An asphalt pavement surface will be subjected to compression, flexure, and tension stresses under varying conditions of load and environmental conditions.

For this investigation, asphalt concrete test specimens were prepared in the laboratory using limestone aggregate of one gradation at an asphalt content of 5.5 percent, based on the total weight of the mix. Five asphalts were used: three were from Venezuelan crudes and had penetrations of 70, 94, and 173; and the other two were of penetration grade 85-100, one from Rocky Mountain crude and the other from California crude. The effects of asphalt viscosity on the compressive strength of asphalt concrete at 80 and 140F, and at a rate of deformation of 0.05 inch per minute, were evaluated. Triaxial specimens were tested at zero and at 30 pounds per square inch lateral confinement. Also, the influence of rate of loading on the compressive strength of asphalt concrete at 80F was investigated. The data were analyzed to determine pavement resistance to tire contact pressure.

Modulus of rupture for mixtures using each type of asphalt was determined at 40 and 80 degrees F. In addition, specimens were subjected to repetitive loading in flexure at a deformation of plus and minus 0.005 inch from the neutral axis, and the modulus of rupture was determined after 1,000 and 100,000 load repetitions. The influence of repetitive loading on flexural strength is shown.

The influence of asphalt viscosity on the tensile strength and deformation of asphalt concrete was investigated. For each type of asphalt, specimens were tested in tension at 0, 20, 40, and 60F, and at a rate of loading of 0.002 inch per minute. The effect of rate of loading on the tensile strength of asphalt concrete at 0 and at 40F was investigated.

Instrumentation and test procedures are described. The application of the results of this investigation to aspects of asphalt pavement design is discussed.

02057 **A Practical Approach to Flexible Pavement Design**
Frank P. Nichols, Jr.

The results of the AASHO Road Test are discussed with emphasis on the variability in published

equivalency values for the several types of material included in that experiment. In spite of this variability, certain weighted average values have become considered as constants and are used as coefficients of relative strength in pavement design procedures patterned after the 1961 AASHO Interim Guide.

This paper points out the fallacy of constant equivalency ratios and cites the fact that, even on the same project, the relative strength ratio between the same two materials varies with the magnitude of load and, most particularly, with depth below the surface.

A more practical approach to a universal design procedure is proposed. Every design would include provisions for:
(1) permanently firm, non-resilient support at the subgrade level, to be assured where necessary by means of chemical stabilization,
(2) a base course affording stability without brittleness, and
(3) a binder-surface combination of high stability with adequate cohesion to resist horizontal shear stresses from acceleration and deceleration.

Thicknesses would be essentially standard for standard materials under standard traffic loadings. Although minor thickness adjustments might be made where only non-standard materials are available, all three components should still be present, and overall thickness should be great enough to prevent overstressing the roadbed soil beneath the lowest improved layer.

The appendix contains a brief summary of the latest deflection and performance data from experimental sections on Virginia highways. The design recommendations are largely based upon these data.

02058 **L.C.P.C. Studies on Pavement Design**
J. Bonitzer, Ph. Leger

Since the First Conference the Laboratoire Central des Ponts et Chausees (L.C.P.C.) has investigated various aspects of the structural design of pavements, which are discussed in this paper, following indications about the practical concerns at their origin.

Engineers are concerned about more exact design of new pavements to support heavy traffic, and particularly motor-road pavements. They are concerned too about a detailed evaluation of the destructive effects of traffic according to axle load, speed, and environmental effects. French law allows single axle loads up to 18 t, much heavier than other countries (except Belgium), and one is concerned about the advantages and disadvantages of the situation - and the very important problem of highway strengthenings. French highways are frequently broad enough for the present traffic, but insufficiently thick for the actual loads they must support.

The total length of highways that should be strengthened either by a bituminous surface course, or by a layer of cement-treated or granulated slag-treated material is at least 20,000 km for the national road system (one quarter of the whole system). It is comprehensible that such a problem played a major role in the planning of our research program.

Little information of immediate practical application about strengthening problems can be found in the AASHO-Road Test. Thus, it is necessary to evaluate the quality of the pavement to be strengthened from measurements, essentially deflection measurements (or, more generally speaking, measurements of the mechanical response to a load application). Devices like the Benkelman beam allow one to make relatively few deflection measurements per day, and are no longer adequate, for experience shows that static deflexions are frequently highly scattered about their mean, with standard deviations up to 1/4 of the mean, or even more; therefore it is necessary to make a great number of measurements. This is the purpose of the Lacroix-deflectograph. On the other hand, mean static deflection of a pavement section does not suffice to characterize fully the quality of this section. There may be road sections of poor load-bearing ability with very low deflections. Also, deflection shows seasonal variations, which are different for different structures.

Moreover, in the case of bituminous pavements, it depends on temperature and, as shown by experimental results, on vehicle speed. This makes it necessary to vary measurement conditions, to perform measurements with time-varying loads, and, on the other hand, to try to derive from deflection data certain intrinsic characteristics whose direct measurement would be difficult, such as Young's moduli of pavement materials. We were led to think that it would be useful to focus attention not only on peak deflections, but on the whole deflection profile, and especially on the radius of curvature in the neighborhood of the peak deflection. This also explains why we have concerned ourselves with all kinds of methods of mechanical testing of pavements, as well as with mathematical models allowing us to compute deflections from intrinsic characteristics of the structures.

Suitable criteria for pavement failure conditions are needed. One of the major teachings of the AASHO-Road Test was confirmation of the fact that pavement failure was due to fatigue by repeated load applications. However this statement poses more questions than it solves. The paper outlines some of

the questions.

02059

Research and Reality - Banquet Address
John C. Kohl

RESEARCH AND REALITY

Banquet Address before the Second International Conference on the
Structural Design of Asphalt Pavements at Ann Arbor, Michigan, August 9, 1967
by
John C. Kohl, Executive Secretary
Division of Engineering, National Research Council, Washington, D.C.

02060

Report on Session VI - Asphalt Treated Bases - Properties and Performance
Moderator: Prof. Giorgio Moraldi

A moderated discussion on the papers presented in Session VI.

Pavement Deflections From Laboratory Tests and Layer Theory
B. S. Coffman, Ohio State University, Columbus, Ohio

The Properties, Behavior and Design of Bituminous-Stabilized Sand Bases
J. S. Gregg, G. L. Dehlen, and P. J. Rigden, National Institute for Road Research, Pretoria, South Africa

Load Transmission Characteristics of Asphalt Treated Base Courses
C. L. Monismith, R. L. Terrel, and C. K. Chan, University of California, Berkeley, California

A Field Experiement of Asphalt-Treated Bases in Colorado
R. I. Kingham, The Asphalt Institute, College Park, Maryland
T. C. Reseigh, Colorado Department of Highways, Denver, Colorado

Mechanical Properties of Asphalt Pavement Materials
B. F. Kallas and J. C. Riley, The Asphalt Institute, College Park, Maryland

Hot Mixed Sand Asphalt Bases in Oklahoma
B. C. Hartronft, State of Oklahoma Department of Highways, Oklahoma City, Oklahoma

The Use of Asphalt Pavement Structures in the Australian Environment
A. J. Scala and E. J. Dickinson, Australian Road Research Board, Victoria, Australia

02061

Pavement Deflections From Laboratory Tests and Layer Theory
B. S. Coffman

The behavior of a flexible pavement system under loading represents a complex problem and is dependent on many variables. For simplicity, loading conditions may be divided into three classes:

(1) Moving loads under which the pavement response is essentially elastic.

(2) Stationary loads under which the pavement response is a complex function of time-dependent stresses and strains.

(3) Acceleration loadings which can impose shear and/or normal forces on a pavement.

A major problem in predicting deflections under such loadings is in defining the response of each of the load-supporting materials using laboratory or field derived properties. Once found, however, such defining properties may be used to describe the stress-strain-time characteristics of the pavement under any wheel loading.

This study was directed at an attempt to interpret the results of in-situ deflection measurements on a theoretical basis for loading class 1, and to some extent, 2. The pavement studied was a short section of U.S. 62 running north and slightly east of Columbus, Ohio. This pavement, a four lane divided highway, was constructed in the summer of 1963 and the materials used in constructing the pavement were sampled at the time of construction and tested in the laboratory. Tests were performed on each material over the range of temperatures or densities and moisture contents expected in the field.

For field deflection data, reference rods were placed in the pavement at nine locations and periodic measurements were made during 1964 and 1965. As a part of these measurements the temperatures of the asphaltic concrete layers were determined and the pavement was trenched to determine the moisture content and density of the subbase and upper subgrade as well as the thicknesses of the pavement layers.

The objective of these field tests was to define the material conditions existing at the time of each deflection measurement. With material conditions defined by the field tests, and using the lab test data, it was possible to calculate theoretical deflections for the different loading conditions with the layer elastic theory.

Thisis a report of comparisons between the resulting calculated and measured deflections. In a larger sense it is a test of the validity of the concept of combining individually determined time-dependent moduli to represent the material and loading conditions to be found in flexible pavements.

02062 **The Properties, Behavior and Design of Bituminous-Stabilized Sand Bases**
J. S. Cregg, G. L. Dehlen, P. J. Rigden

Bitumen-stabilized sand could be a suitable road base-course material in large areas of Southern Africa where no hard aggregates are available. The progress in a research project aimed at developing a method of design for bitumen-sand bases is described.

An intensive laboratory study was carried out on one representative bitumen-sand mixture. Triaxial tests carried out over a range of temperatures and a wide range of strain rates revealed that the strengths of the mixture could be expressed in terms of the Coulomb relationship. While the angle of friction phi remained fairly constant, the c-intercept varied in an orderly manner with strain rate and temperature, the effects of which could be combined using the time-temperature superimposition concept. Tensile strengths measured in direct extension varied more rapidly with rate of strain and temperature, but could again be combined using the superimposition concept. Repeated load triaxial tests carried out with various stress intensities and durations indicated that the modulus of resilient deformation was inversely related to the ratio between the major and minor principal stresses.

A field study was carried out on eight sections of road in South West Africa with various compositions of 6-inch thick bitumen-sand base. Relationships were found between the deformations which had occurred under traffic and the in-situ CBR, in-situ vane shear strength, and bearing capacity determined from triaxial tests on cores of the stabilized base. Very little deformation was observed beneath stationary trucks with 7000-lb wheel loads, Although more deformation might have occurred during the warmer season. The strengths associated with satisfactory performance were very much less than those specified for conventional granular base-courses. Plate bearing tests indicated that the moduli of resilient deformation of the bitumen-stabilized bases were of the same order as those of conventional unbound granular bases, so that it was unlikely that the use of these bases would permit reductions to be made in the thickness of cover to the subgrade relative to the design cover with an unbound base. Mixtures having dense gradings were generally found to have higher strengths and moduli of resilient deformation than mixtures lacking in fine material. The study is continuing.

02063 **Load Transmission Characteristics of Asphalt Treated Base Courses**
C. L. Monismith, R. L. Terrel, C. K. Chan

In the past decade, deflection has come into widespread use as a means of measuring the expected performance of pavements. If deflection could be predicted, by applying a suitable theory with appropriate material characteristics, and compared with the ever-increasing body of knowledge relating deflection to performance,avaluable step could be taken in the efficient design of pavements and the economic utilization of paving materials.

Because of the widespread interest generated by the AASHO Road Test in asphalt-treated bases, and because of limited availability of data on the characteristics of certain asphalt-treated materials (primarily those treated with asphalt emulsions and liquid asphalts), this investigation was undertaken. Specifically, the paper describes:
1) laboratory measurements of the properties of asphalt-treated materials,
2) methods whereby the laboratory data can be used to predict pavement deflections within the framework of suitable theory, and
3) comparisons between predicted deflections and measured deflections in prototype pavement structures with base courses consisting of materials treated with asphalt cement, asphalt emulsion, and liquid asphalt.

From these analyses, a method is suggested whereby layer equivalencies can be established for specific situations through suitable laboratory tests on appropriately conditioned materials, and through analysis of systems representative. at least to a degree, of pavement structures. However, it is emphasized that no one equivalency can be applied to a specific material; moreover, for the emulsion and liquid-asphalt-treated materials, the equivalencies would appear to change during the initial period after placement because of curing.

02064 **A Field Experiment of Asphalt-Treated Bases in Colorado**
R. I. Kingham, T. C. Reseigh

Twenty test sections were constructed in 1965 near Pueblo, Colorado to determine thickness

requirements for two hot mix sand-asphalt bases. For comparative purposes an asphalt concrete base and an untreated crushed gravel base were included in the experimental design. Each asphalt base was built in three thicknesses with no subbase and a common surfacing thickness. The untreated base was built in one thickness according to the Colorado design procedure. Some thicknesses were replicated and the experiment was partially repeated over a second soil type.

The road was opened to traffic in the spring of 1965. The paper reviews the performance of the test sections through the spring of 1966. The Present Serviceability Index Concept developed at the AASHO Road Test was used to judge performance. Measurements have been made with both the CHLOE Profilometer and the Bureau of Public Roads Roughometer.

The load response characteristics of the various base types were determined using the Benkelman Beam for deflection measurement. In addition, a measure of the curvature of the pavement was made with the Dehlen curvature meter developed in South Africa. Beam deflection data were used with layered system theory to determine elastic moduli for the various asphalt base types. The moduli showed excellent agreement with those determined in the laboratory for similar temperature conditions and a loading frequency of one cycle per second. Theory and inferred moduli were used for asphalt bases to derive thickness-deflection relationships for average surfacing and base temperatures observed in the field. Such relationships provide one means of obtaining equivalent thicknesses of different materials when critical deflection values become available.

02065 **Mechanical Properties of Asphalt Pavement Materials**
B. F. Kallas, J. C. Riley

This paper presents results of studies on the mechanical properties of the materials constituting the various layers of an experimental asphalt base project constructed by the State of Colorado. The initial investigations reported herein are part of a continuing Asphalt Institute program of studies on asphalt bases, and on the structural design of asphalt pavements.

Relationships between applied forces acting on the various paving materials and resultant deformational response were developed by several laboratory testing procedures. Sinusoidal stresses varying in magnitude and frequency were applied axially to unconfined cylindrical asphalt paving mixture samples at several temperatures. The resultant axial strains were measured and dynamic complex moduli were determined. Values of Poisson's ratio for these materials were determined by similar testing procedures. Repetitive triaxial tests were made on untreated granular base and subbase, and on the subgrade soil. Repeated short duration deviator stresses were applied to triaxially confined specimens and the resultant recoverable or resilient axial deformations were measured. From these tests resilient deformation moduli were determined for varying confining pressures at several levels of deviator stress. Repetitive flexure tests were also made on asphalt paving mixture beam samples. Repeated controlled short duration loads were applied to beam specimens and the resultant dynamic deflections of the beam were measured. Stiffness moduli were determined from results of these tests.

In addition to strength moduli, standard test data were obtained and are reported on the materials incorporated In the experimental project.

The strength moduli determined by the laboratory tests are used to calculate pavement deflections according to N-layer elastic theory. A computer solution developed by Chevron Research Company Is used for these computations . Generally, the calculated deflections for all asphalt base course test sections are lower than Benkelman beam deflections measured on the Colorado Experimental Base Project.

02066 **Hot Mixed Sand Asphalt Bases in Oklahoma**
B. C. Hartronft

With a background of experience with the soil asphalt roads and based on information obtained from South Carolina and their experience with hot mixed sand asphalts the Oklahoma Highway Department embarked on a program utilizing local sand materials for construction of flexible bases of the hot mixed sand asphalt type on the interstate and primary system of highways. This base is a mixture of graded sands and asphaltic cements processed through a hot mix asphalt plant and laid with the conventional asphalt laydown machine.

As of July, 1966 over 200 miles of two lane pavement have been constructed with hot mixed sand asphalt base as well as about that many miles utilizing this material for overlay and widening.

The remainder of this paper will be concerned with results of various testing on five different projects over a period of approximately four years. An attempt will be made to describe the components of the base, the apparent effect of the surfacing, the variation in the physical properties of the asphaltic cement, and the load carrying capacity of the pavement structures.

02067 **The Use of Asphalt Pavement Structures in the Australian Environment**

A. J. Scala, E. J. Dickinson

An assessment of the use of asphalt bound granular materials as a structural element in Australian road and airfield pavements is made.

At present, these materials are applied as surface courses to pavements at airports and in urban areas and they are relatively expensive. Research is in progress to compare their behaviour with that of natural and crushed granular materials now generally used as the structural element.

Some results of the continuous measurement of temperature at various depths in the layer of asphaltic concrete at a site near Melbourne, are given.

Model experimental sections have been laid at one site to compare the load spreading properties of the two types of base material and, by surface and subgrade deflection combined with subgrade stress measurements, their relative behaviour is demonstrated.

02068 **Report on Session VII - Structural Performance of Asphalt Pavements**
Moderator: Malcolm D. Armstrong

A moderated discussion of the papers presented in Session VII.

Performance Studies of the Mexico City International Airport
L. M. Aguirre, D. Sanchez, and M. Zarate, Secretaria De Obras Publicas, Mexico, D.F.

U.S. Navy Experience with the Performance of Asphalt Pavements Subjected to High Pressure Aircraft Tires
P. P. Brown and C. E. Rhodes, Department of the Navy, Washington, D.C.

Use of Viscoelastic Concepts to Evaluate Laboratory Test Results and Field Performance of Some Minnesota Asphalt Mixtures
L. J. Gardner, Standard Oil Company of California
E. L. skok, Jr., University of Minnesota, Minneapolis, Minnesota

The Behavior of Flexible Pavements Under Moving Wheel Loads
N. W. Lister and R. Jones, Road Research Laboratory, Berks, England

A New Method in Correlation Study of Pavement Deflection and Cracking
Kuang-Yuan Kung Taiwan Highway Bureau, Republic of China, Taiwan, China

Long Term Deflection Study of an Exceptionally Maintenance Free Pavement
A. Lee, Maryland Road Commission, Brooklandville, Maryland
S. Williams, Bureau of Public Roads, Washington, D.C.
W. G. Mullen, North Carolina State University, Raleigh, North Carolina

The Lacroix L.C.P.C. Deflectograph
E. Prandi, Laboratoire Central des Ponts et Chaussees, Paris, France

Recent Full-Scale Flexible Pavemenl: Design Experiments in Britain
G. F. Salt, Road Research Laboratory, Berks, England

Field Performance Studies of Flexible Pavements
Pavement Design and Evaluation Committee, Canadian Good Roads Association, Ottawa, Canada

02069 **Performance Studies of the Mexico City International Airport**
L. M. Aguirre, D. Sanchez, M. Zarate

The flexible pavements of the Mexico City International Airport have had a very special performance, due to the peculiar characteristics of the subsoil. The objective of the present paper is to make a brief exposition of the performance exhibited by such pavements, and the experiences obtained from an experimental section which, apparently, solves the observed problems and is intended to be used in the construction of future runways.

02070 **U.S. Navy Experience with the Performance of Asphalt Pavements Subjected to High Pressure Aircraft Tires**
P. P. Brown, C. E. Rhodes

Since the early 1950s, the U.S. Navy has been operating high performance carrier jet aircraft on its training and fleet support stations. These aircraft utilize tires with inflation pressures which have steadily increased with the gross aircraft weights and restrictions on the size of landing gear. Operational pressures now exceed 400 psi.

This paper describes typical operations at several Naval Air Stations, the criteria to which flexible pavements have been constructed, and the performance of these pavements. In general, there are many well constructed high quality flexible pavements performing well under these high tire pressures at Naval Air Stations. Limited failures have occurred in areas of concentrated landings and of marginal quality materials and construction.

The paper also describes the procedures used by the Navy for assessing the suitability of flexible pavements for use by aircraft with high pressure tires.

02071 **Use of Viscoelastic Concepts to Evaluate Laboratory Test Results and Field Performance of Some Minnesota Asphalt Mixtures**
L. J. Gardner, E. L. Skok Jr.

In 1963 and 1964 fifty test sections were set up on highways throughout Minnesota. Their purpose is to use the findings and concepts of the AASHO Road Test to study the design and performance of asphalt pavements under in-service environment and traffic conditions. At the Road Test relationships between load and pavement thickness were established for one set of embankment materials and for controlled traffic. In this investigation an attempt is being made to expand these relationships to other embankment materials and mixed traffic in Minnesota.

The following testing has been done on these test sections in the field: (1) fractional plate load testing with in-place moisture and density determination of each layer, (2) determination of Benkelman Beam deflections, rut depth, and cracking for each section and (3) determination of the roughness index and present serviceability rating for each section. Items (2) and (3) are being run about once per year on each of the test sections. The roughometer index is used along with the rut depth and cracking to determine a present serviceability index periodically. The trend of the PSI with traffic will define the performance of the test section.

The following laboratory tests were performed on all 50 embankment soils: Atterberg limits, standard moisture-density, gradation, stabilometer R-values, and California Bearing Ratio tests. The granular bases and subbases have had the first four above-mentioned tests run on them plus CBR and triaxial tests on a selected number of them. A special study was made on the granular materials and it was found that the R-value test adequately classified the strength characteristics of the bases and subbases.

Extractions were made of the asphalt surface and base mixtures, and penetration, softening point, and ductility tests are being performed on the recovered asphalt. Four-inch cores of the bituminous materials have also been taken from each test section to determine density, cohesiometer, and modified tensile strength of the mixture. The cohesiometer and modified tension did not give very meaningful results. It was felt that the asphalt mixtures could be evaluated better if a nondestructive test could be devised which used a loading condition close to the magnitude of a wheel load. A repetitive type test was also considered preferable over a static test. This also involved evaluation of the mixture based on the viscoelastic rather than elastic or rupture theory.

In 1964 a study under the sponsorship of the Asphalt Institute was started at the University of Minnesota to try to develop a practical laboratory test for asphalt mixtures using some of the viscoelastic concepts developed at Ohio State University and the University of California. The goal of this work is to run tests on mixtures cored from the 50 test sections and compare the performance of these mixtures in the field with the stress-strain properties of the samples.

Both constant stress tests and repeated load tests have been made on a number laboratory prepared mixtures and, at the writing of this paper, the project at the University of Minnesota is at the stage of initial testing of some of the asphalt cores. Minimal meaningful comparisons with performance are only possible at present because most of the test sections have not as yet failed. The apparatus has been developed and a number of laboratory mixtures have been tested under different magnitudes of vertical and lateral pressures with one temperature.

This paper will cover the theoretical considerations, the apparatus developed for testing the mixtures, the test results and effects noted, and the results of the tests on field cores made up to the present time.

02072 **The Behavior of Flexible Pavements Under Moving Wheel Loads**
N. W. Lister, R. Jones

The ability to predict the pattern of transient stress-deformation behaviour of a road under moving wheel loads, which is a necessary step to developing a rational method of pavement design requires simplifying assumptions to be made regarding the loading conditions, interfacial contact between layers and the uniformity and rheological properties of the materials in the road. Convenient empirical formulae have been developed for some components of interfacial stress and surface deflections for two and three layer elastic systems. These have been used to examine the errors arising from differences between real and assumed conditions in the shape of the tyre contact area and the distribution of stress on the road surface. For the tyres examined the assumption of a circular loaded area defined by the

wheel load divided by the inflation pressure was found to be a satisfactory approximation in the elastic analysis.

Dynamic loading effects generated by vertical motion of the wheel passing over surface irregularities has been shown to produce up to 35 per cent higher (or lower) surface loads than the nominal (static) wheel load on experimental sections of poor riding quality from an unladen test vehicle travelling at 15 m.p.h. In addition, variations of up to 40 per cent were recorded in the vertical component of stress in the subgrade beneath the same type of construction attributable to variations of nominally the same materials; the largest variations were observed beneath a crushed stone base and the smallest beneath uncracked cement-bound bases. The effects of dynamic loading and variability of materials are usually inter-related, and suggestions are made for further studies under normal traffic conditions.

Difficulties of defining the appropriate elastic moduli of soils, unbound materials and bituminous materials for use in the elastic analysis are discussed. Comparisons are made of the measured values of the surface deflection and the vertical component of stress in the soil with those calculated using moduli deduced from vibrational experiments. Suggestions are made for further experimental work to remove some of the present uncertainties.

02073 **A New Method in Correlation Study of Pavement Deflection and Cracking**
Kuang-Yuan Kung

Most methods for pavement deflection study are based on the magnitude of deflection; some are based on the radius of curvature; a few others are on the basis of "Bending Index." The writer found a new method based on 'Slope of Deflection." In this paper, various methods are discussed and compared with one another. The 'Slope of Deflection" method is derived from a typical deflection curve, by means of basic principles of the 'Strength of Materials. " Results of field tests and observations on test highways are used to verify the reliability of the method. A distinct relation between slope of deflection and pavement cracking is presented, for the test roads on Virginia highways a slope around 0.75 x 10^(-3) being the maximum allowable. Among the 40 test projects in Virginia, 39, both with and without stabilization in subbase, follow the criteria. One test road consisting of a more rigid base, is the only exception.

The correlation between flexible pavement deflection and pavement performance has been studied for many years, Many experiments were carried out in this field. Most of them were run on the basis of the magnitude of deflection; some were on the basis of "Radius of Curvature." Still a few others on the basis of "Bending Index." Each has its specialty. However, the results do not agree either on the basis adopted or on the conclusions stated. . Furthermore, none of them can be free from inconsistencies to a satisfactory degree. Therefore which one is the best still can not be certain.

The writer found a new method based on "Slope of Deflection" which is derived from a typical deflection curve by means of basic principles of the "Strength of Materials." . This new method is not only sound in theory but also strongly supported by field tests and observations on Virginia test highways. This paper will first discuss the existing methods for comparison purpose, and then the writer's new method "Slope of Deflection." Finally two suggestions for securing more accurate data in field measurements are also discussed.

02074 **Long Term Deflection Study of an Exceptionally Maintenance Free Pavement**
A. Lee, S. Williams, W. G. Mullen

Beginning in 1955 a cooperative research program was undertaken by the Maryland State Roads Commission with the Bureau of Public Roads to study the deflection behavior of selected existing flexible type pavements by utilizing the Benkelman Beam technique that was developed at the WASH0 Road Test. This work continues, and an interim report was issued in July, 1965. Previously, two papers by Lee in 1956 and by Williams and Lee in 1957 had been published relating progress and tentative interpretation of results. A third paper by Mullen, Clingan and Paulis summarizing and interpreting results over a ten year period was published in 1966.

In 1960 the study was expanded to include observations on newly completed flexible pavements in addition to existing pavements selected in 1955. At that time the entire study was included as a project under the HPS-HPR program of the Bureau of Public Roads. Each year all newly completed flexible pavements have been added to the program so that initial deflection observations are available.

In the fall of 1963, a physical sampling investigation of the pavement layers, base and subgrade of one of the pavements in the original study, U.S. 40 between Frederick and Hagerstown, was undertaken. Analysis of the behavior of another of these pavements, I-70S between Frederick and Rockville, has been reported under a separate study.

A number of interesting findings have resulted from the over-all study. Included are observations that spring deflections are higher than fall deflections, outer wheel path deflections are higher than inner wheel path deflections. and, most significant, for the range of pavement thickness encountered in

Maryland, the magnitude and dispersion of deflections may be grouped into different categories according to subgrade soil types.

The over-all findings hold true for U.S. 40 West, the pavement that is the subject of this paper. In addition, the continuous good performance of this pavement may be attributed to adequate structural thickness and to an unusually well-protected subgrade. Subgrade protection has been afforded by an impervious bituminous concrete surface course coupled with good longitudinal drainage.

02075 **The Lacroix L.C.P.C. Deflectograph**
E. Prandi

Among other means of investigating pavement deformability, deflection measurements with a given load are a simple and handy one. Deflection expresses overall behavior of the pavement. Applied to conventional structures, it remains the main deformability criterion, though it is certainly desirable to complete a pavement description by other characteristics, such as:
- layer thicknesses
- strength and stiffness of materials
- volume of traffic
- environmental conditions, etc.

The Benkelman beam was used for the first investigations on pavement deformability. It possesses, it seems to us, two main drawbacks:
- its precision is limited
- the rate of operation is low: in our experience, 50 to 80 measurements per day with a well trained crew.

The use of the so-called JYC optical deflectometer allowed of only limited improvements. In 1956, M. Lacroix attempted to design an apparatus which would be able to perform a large number of deflection measurements per day, Teamwork, including agencies of the Service des Ponts et Chaussees (Dordogne, Maine-et-Loire) and the LCPC resulted in the development of several successive prototypes, the first of which was already able to perform 7,000 to 8,000 measurements per day.

A deflectograph includes:
- A truck travelling at approximately constant slow speed, with a rear axle load of 13 tons;
- A measurement beam, which is analogous to a Benkelman beam. This beam rests on the pavement during measurement and is automatically shifted from one point of measurement to the next.
- A measuring and recording system converting displacement of the tip of the probe arm of the beam into an electrical signal.

The main original feature of the deflectograph is the intermittent displacement of the beam, which allows measurement to be performed during rest periods.

On standard apparatus (about 20 now in operation), the influence lines of the deflection for each measurement point is photographically recorded. A digital recording system, using a magnetic tape, was recently tried.

02076 **Recent Full-Scale Flexible Pavement Design Experiments in Britain**
G. F. Salt

The paper by Lee and Croney presented at the first International Conference on the Structural Design of Asphalt Pavements in 1962 described five full-scale pavement design experiments which had been constructed in Great Britain between 1949 and 1960 and gave the principal results from each.

Since 1960 six further experiments have been constructed, investigating the performance of materials which have recently come into common usage in the country, and examining in more detail points of doubt or anomaly arising from previous work. These experiments were mentioned as proposals for future work in the original paper, and this contribution thus constitutes an extension to it.

The paper first describes the changes which have taken place since 1962 in the procedures adopted at the British Road Research Laboratory for carrying out this work and then goes on to give details of the six new experiments.

Detailed results are given for only one of these as the remainder have not yet been in service long enough for measurements to be significant. The possible implications of some of the early measurements are, however, briefly discussed.

02077 **Field Performance Studies of Flexible Pavements**
Pavement Design and Evaluation Committee

This paper attempts to summarize the results of the co-operative pavement investigation program in

	Canada which have been attained since the Conference in 1962. The paper is offered as a Committee presentation as all the members contributed to the information shown. Extensive regression analyses on the Stage 1 pavement inventory indicates the significance of age and strength on pavement performance. The regression equations are most significant at pavement ages of 6 to 11 years. Extensive data is shown for loss of strength during the spring of pavements subject to frost action. Regression analyses were not successful in predicting the loss of strength. Uniform and non-uniform pavements are described together with data showing the improved performance and reduced thicknesses that are achieved with uniform pavements. Small weak areas are associated with non-uniform pavements. A design method for new pavements is outlined together with construction control methods based on Benkelman tests. Construction control methods to attain uniformity are emphasized as being supplementary to design and equally important.
02078	**Report on Session VIII - Summary Session** *Moderator: F. J. Benson* A moderated discussion of the Moderators' summary reports on Sessions I through VII. Terminal Remarks by Prof. W.S. Housel, Chairman, Executive Committee.
02079	**List of Registrants** *n/a* An alphabetical list of conference contributors and their affiliations.
02080	**Index of Contributors and Discussors** *n/a* An alphabetical list of conference contributors and appropriate page references.

code	ISAP 3rd Conference -- Titles & Abstracts
03000	**3rd International Conference on the Design of Asphalt Pavements - Volume 1 - Preliminary pages and Table of Contents** *n/a*
03001	**The Bearing Capacity of Pavements with Frost Retarding Layers. A Test Road Study** *Olle Andersson, Bjorn Orbom, Goran Ringstrom* For an extensive study of frost penetration and bearing capacity of roads with frost retarding layers of different composition and different thickness and surrounded by different types of bases and sub-bases a test road was built in western Sweden in 1966-67. During the construction period and the following year the various layers were followed up by measurement of dynamic elastic modulus by the wave propagation method, and several sections were subjected to repeated plate loading applying up to 50000 loads at each point in order to study the fatigue properties. For investigation of the development of bearing capacity the test road under traffic is followed up by measurements each year implying plate bearing tests, levelling, cross profile and longitudinal profile by the CHLOE profilometer. Most frost penetration retarding materials caused an increase in rebound deflection and did in some cases cause a disastrous permanent deflection, which necessitated rebuilding. Some materials had no detectable influence upon the permanent deflection. The serviceability index as measured by the CHLOE meter decreased faster on some sections having insulating layers but showed in some sections a slower decrease than on the reference sections. The dynamic elastic modulus of the base course increased during the first year by more than 30% also in those having insulating layers beneath. The test road will be followed up for several years to come but has already given positive results for the frost protection aspect of road design.
03002	**The Measurement of Traffic Axle Load Distributions for Pavement Design Purposes** *J. E. B. Basson. G L. Dehlen, R. G. Phillips, P. J. Wyatt* One of the required inputs for the design of new pavements, or of overlays to existing pavements, is accurate data on the axle loads of the traffic they will carry. Estimation procedures based on visual traffic counts together with the results of earlier axle load measurements made with loadometers or static weighbridges are sometimes employed to obtain such data for the present traffic. As the variables associated with the conversion of traffic counts to axle loads at a particular location include the commodities carried, the type of vehicle, the season, and police control of illegal axles, such an estimation procedure cannot be expected to render acceptably accurate results at all locations. By means of traffic surveys the effects of some of these variables have been quantified. These surveys have revealed that there is no estimation procedure which does not result in significant inaccuracies in the design thickness of a pavement. By contrast, the direct measurement of axle load distributions, using one of several dynamic weighing techniques, reduces the errors in the evaluation of present traffic to negligible proportions, and is considered to be the approach most suitable for pavement design purposes.
03003	**Ste. Anne Test Road - Flexible Pavement Design to Resist Low Temperature Cracking** *R. A. Burgess, O. Kopvillem, F. D. Young* Low temperature transverse cracking of bituminous pavements is a form of pavement distress prevalent in Canada and the northern United States. This distress induces a deterioration in pavement performance through spalling, heaving or settling at the cracks and reduces pavement service life. In 1967, a test road, designed and instrumented for the investigation of this problem, was constructed at Ste. Anne, Manitoba, This road incorporated twenty-nine test sections involving a number of different bituminous mix materials, pavement structures and subgrade types, believed to be potentially important in the study of transverse cracking. After five years of service, the following conclusions can be drawn with respect to the relative performance of the test sections: (1) Pavements incorporating high viscosity type asphalts and softer grade asphalts exhibit a greater resistance to transverse cracking. (2) Pavements with thick asphalt bound layers exhibit a lower frequency of transverse cracking. (3) The type of subgrade influences the frequency of transverse cracking. (4) The asphalt content of the mix, in the range of one percent below Marshall optimum to one-half percent above Marshall optimum does not appear to be significant in affecting pavement transverse cracking frequency. A laboratory study was conducted in conjunction with the field programme to investigate the possibility of correlating laboratory predicted fracture temperatures with the actual field performance of the St. Anne test sections. Predicted fracture temperatures were determined by calculating that temperature at which accumulated thermal stresses exceed the tensile strength of the compacted mix. Additionally, since the tensile properties of an asphalt binder are proportional to the tensile properties of a mix made with that binder, the possibility of predicting pavement field performance by a knowledge of binder properties alone was investigated. Accumulated thermal stresses of the binders and their mixes were calculated from their respective stiffness moduli at one-half hour loading time (cooling rate} over the appropriate temperature range. Accumulated thermal stress and breaking stress (tensile strength) were plotted as a function of temperature. The predicted fracture temperature is the intercept of these curves. Comparison of the laboratory and field results revealed that there is an excellent correlation between the laboratory predicted fracture temperatures of the binder and mix and the temperature of initial cracking of the asphaltic pavement in the field. For practical purposes, therefore, the tendency of an asphaltic pavement to crack can be predicted by a knowledge of the binder stiffness modulus at low temperatures and long loading time. Conversely, the binder, or mix, stiffness parameter may be used as a pavement design criterion to alleviate the transverse cracking problem. These research findings would also imply that it is necessary to be more selective in the use of materials and pavement designs with due consideration being given to their performance under the prevailing climatic conditions.

03004 **The Response of Asphalt Pavements to Low Temperature Climatic Environments**
J. T. Christison, K. O. Anderson

The response of asphalt pavements to environmental conditions is well recognized, but not easily quantified. Variations in temperature , particularly freezing conditions, may result in non-traffic load associated distress. Analyses of several pavement systems in Western Canada where continuous temperature records were collected, has yielded specific information on temperature gradients and time variations at various depths throughout the pavement structures.

To extend this information to other climatic areas, a computer program has been developed that utilizes a finite difference method to predict the thermal regime within pavement systems. The necessary input parameters for the program are the thermal properties of the component layers and readily available meteorological data. Comparisons of predicted and recorded temperatures have shown excellent agreement.

Calculated temperatures throughout the asphalt concrete surface layer, together with laboratory evaluation of fracture strength have been used to predict the pavement susceptibility to thermally induced fracture. Results of field studies support the analysis technique described.

03005 **A Study of Subgrade Moisture Conditions in Connection with the Design of Flexible Pavement Structures**
T. Y. Chu, W. K. Humphries, S. N. Chen

In the structural design of flexible pavements, the supporting power of subgrade soils should be evaluated on the basis of anticipated moisture conditions. It is, therefore, necessary to predict subgrade moisture conditions and to simulate these conditions in performing laboratory tests for subgrade evaluation. In this study, field investigations were conducted at selected sites in South Carolina for determining subgrade moisture variations under existing pavements. Findings from these investigations were utilized In the development of laboratory procedures for treating subgrade soil specimens in order to simulate anticipated moisture conditions. While laboratory investigations reported in this paper were carried out in connection with a particular type of subgrade evaluation test, the procedures developed for specimen treatment may be adapted to other types of test for similar purposes.

03006 **The Influence of Climatic Factors on the Structural Design of Flexible Pavements**
D. Croney, J. N. Bulman

Current design standards for flexible pavements in Britain are based on the results of full-scale road experiments extending over 20 years. The influence of seasonal and climatic factors is taken into account by such a protracted period of observation. In extending the use of the standards to other climatic environments or in applying methods of structural analysis to them, the influence of climate on the performance of the various elements of the pavement needs to be appreciated.

The first part of the paper considers the influence of climate on the strength of soil foundations. Recent research in the field of soil mechanics is used to isolate three broad subgrade moisture conditions based on rainfall, evapo-transpiration and the position of the water-table. The role of vapour transfer in influencing subgrade strength is also discussed.

High temperatures reduce the modulus of the bituminous elements of the pavement and again the effects of this on the stress regime are discussed. Augmented vertical stresses in the subgrade, as well as a loss of stability in the bituminous material may lead to increased deformation under traffic during hot weather. However, the ability of the materials to accept higher levels of strain reduces the risk of cracking under these conditions.

Sub-zero temperatures normally lead to a much increased modulus both in bituminous materials and subgrades. The transfer of water into the subgrade during the downward progress of the zero isotherm will however reduce the elastic modulus of the subgrade drastically immediately ofter the thaw. The implications of this on pavement stresses must be considered.

Published data have been used to estimate for four soil types and for two granular sub-base and base materials the probable effect on strength of a wide range of climatic conditions. Strengths are expressed in terms of CBR or elastic modulus. Used in conjunction with structural design procedures these values will give some indication of the influence of climate on pavement thickness requirements.

03007 **The Classification of Traffic for Pavement Design Purposes**
E. W. H. Currer, P. D. Thompson

03007.pdf
For the structural design of new pavements the information available about traffic is normally restricted to census data obtained from visual counts. Such counts are made in Britain at about 4-yearly intervals on a national basis, but for major projects supplementary studies will normally be required. It has been usual practice to differentiate between private cars, light commercial vehicles (delivery vans of estimated unladen weight not exceeding 1.5 tonnes), heavy commercial vehicles and public service vehicles. The total of heavy commercial and public service vehicles only has been used in the past for structural design purposes. More recently however it has been recognised that the axle-load spectrum of the commercial traffic is of major importance.

An electronic weighbridge suitable for installation in the carriageway surface was developed many years ago and effort is now directed towards the production of an alternative capacitor-type pad which can be placed on the carriageway surface. Equipment of the former type has been used to obtain the axle-load spectrum of the traffic on existing roads, but the cost precludes its use for routine survey purposes. The objective of research in this field in Britain has been to determine by limited surveys mean spectra for commercial axles appropriate to different classes of road, e.g. industrial motorways and major trunk roads, rural major roads, secondary rural roads and roads in residential areas. A summary of results to date is given in the paper. Typical spectra obtained in this manner are converted to an equivalent number of standard 8200 kg (18,000 lb) axles per 100 commercial axles, using the A.A. S. H.O. equivalence factors.

In using this approach, to evaluate from the commercial traffic flow the cumulative number of equivalent 8200 kg (18,000 lb} axles carried by a particular carriageway lane during the design life of a pavement, two other pieces of information are required:-

(1) the average number of axles per commercial vehicle
(2) the distribution of commercial traffic between the carriageway lanes.

Studies of these two factors have recently been made in Britain and the results are summarised in the paper.

03008 **A Contribution to the Establishment of Design Loads for the Thickness Design of Flexible Road Pavements**
H. Keller

Theoretical and empirical research is constantly producing new ideas on flexible pavement design, but these are not being incorporated in the principles used in actual practice for assessing useful design loads. This report is designed to draw attention to research that has been done on the specification of service load data for roads in the Federal Republic of Germany. It also outlines the work that remains to be carried out in the future.

It lists initially the requirements that are currently made for loading data for flexible pavement design and indicates possible ways of simplifying data presentation.

The report deals with surveys already carried out on service loads: starting with the pattern of stress distribution between truck tires and carriageway surface, it discusses vertical axle loads assessed in permanent surveys as well as sample and indirect surveys. It also deals with the data required on loading periods and loading points.

Explanatory measurement examples are cited for various characteristics of truck traffic, Finally, the report takes current loading data requirements and available data as a basis for indicating what still has to be done in flexible pavement design research to establish design criteria for the service loads of roads.

03009 **The Transient and Long Term Performance of Pavements in Relation to Temperature**
N. W. Lister

At the present stage of development of a structural method of design applicable to British conditions it is possible to model the transient stress-strain behaviour of several types of flexible pavement with some confidence whereas progress in solving the more complex problem of the long term behaviour of pavement materials and subgrades under repetitive loading is understandably slower. It is therefore of value to try to relate levels of transient stress and strain generated within the road directly to their observed long term behaviour.

Most British pavements tend to deteriorate by deformation of the road surface followed by cracking at a relatively late stage. Elastic analysis of a pavement with a rolled asphalt surfacing and base indicates the critical nature of stress-strain conditions at high temperature and these are related to the development of deformation in an experimental road section under traffic, nearly all of which took place under high temperature conditions.

Full-scale repeated loading tests carried out in a Road Machine under controlled conditions of wheel load and temperature on a pavement with a crushed stone base are described. The results again demonstrate the critical importance of temperature in determining deformation behaviour and indicate the existence of a critical value of vertical stress in the subgrade above which subgrade deformation occurs.

03010 **A Model Utilizing Climatic Factors for Determining Stresses and Deflections in Flexible Pavement Systems**
Charles R. Marek, Barry J. Dempsey

In this paper, a model for determining the stresses and deflections at various locations in a multi-layered flexible pavement system as a function of load, climatic exposure conditions, and material characteristics is described. Application of the model to a flexible pavement section at the AASHO Road Test and comparison of theoretical stresses and deflections with measured stresses and deflections at various times during the life of the section is made. The comparisons relate the applicability of the model for pavement analysis.

The model combines a heat-transfer model for evaluating frost conditions and temperature-related effects, with an elastic layer model for stress and deflection determination. The heat-transfer portion of the model was derived from one-dimensional, forward-finite-difference, heat-transfer theory. This portion of the model was used to generate temperature profiles and frost-line locations in the pavement system at a specified time, It was designed to include many input parameters such as short-wave radiation, long-wave radiation, convection, and air temperature. Other factors considered are physical properties and thermal properties of the pavement materials including unit weight, moisture content, material classification, thermal conductivity, heat capacity, and latent heat. The model was developed so that appropriate thermal properties of the pavement materials are used depending on whether or not an unfrozen or frozen state exists. In addition, it can be easily expanded to include newly developed parameters. The model has been programmed for computer solution.

The stresses and deflections at various locations in a multi-layered flexible pavement system were determined based on Burmister's elastic layer theory. A computer routine, developed by Chevron Research Corporation and modified to work on the University of Illinois' computer system, was employed for solution.

Modular values and layer thicknesses were established based on layer interface location, frost-line location, and layer condition (frozen or unfrozen). Stiffnesses of the asphaltic concrete surface and binder layers were determined by use of the procedure developed by Van der Poel and revised by Heukelom and Clomp. A correction for air content when in excess of three per cent, as suggested by Van Draat and Sommer, was also employed. Average layer stiffnesses for the surface and binder layers were determined and utilized for computation of stresses and deflections in the system at a specified time.

Using the model, theoretical stresses and deflections for Section 581 from the AASHO Road Test were computed for the period of July 1, 1959 to June 30, 1960. Comparisons were then made between theoretical and measured stress and deflection values to substantiate the applicability of the model for theoretical analysis of pavement systems.

03011 **German Experiences with the Replacement of Granular Frost Blankets by Other Types of Construction**
H. Proksch

During the years 1954 - 1970 numerous research projects and experiments were carried out in Germany in order to investigate by which means granular frost blankets customarily used for 40 years may be substituted by other types of construction. The studies being undertaken involved comparative experimental field projects using asphalt membrane envelopes, full-depth asphalt pavements and bituminous and plastic thermal insulating layers as well as extensive laboratory investigations,

The paper describes the experimental projects in detail and reports the results already available of measurements of subsoil moisture content, frost penetration depth, thermal properties of the bituminous and elastic materials used and of load bearing characteristics applying plate bearing tests, dynamic load tests and the Benkelman Beam.

03012

The Effect of Climatic Factors on Benkelman Beam Deflections in the Melbourne Area of Victoria, Australia
A. Ratnarajah

A programme of testing to evaluate the effects of seasonal climatic variations on pavement deflections as measured by the Benkelman Beam was initiated in March 1969 jointly by the Australian Road Research Board and the Country Roads Board, Victoria. The areas selected for testing were all in the vicinity of Melbourne. In order to minimize the effects of variations in subgrade type, groups of sites in geologically similar areas were selected. Five such areas were chosen. The frequency of testing was approximately monthly for the first twelve months and two monthly thereafter.

Results to date indicate that ambient temperature as such has no effect on the subgrade that is measurable in this investigation. Rainfall however has a measurable effect on the subgrade. Its effect on Benkelman Beam deflections is tied in with the effects of the permeability of the subgrade and with the surface drainage conditions at the site. The effects of evaporation of water from the ground surface would be to reduce the amount of water falling on the surface that would otherwise percolate into the pavement and subgrade. No attempt has been made to evaluate this effect.

The tests have given some basis on which a correction factor to the observed deflections may be applied in certain situations when the deflection testing is not carried out at the time the subgrade is at its weakest.

03013

Prediction and Observation of the Performance of a Flexible Pavement on an Expansive Clay Subgrade
B. G. Richards, R. Gordon

For an experimental section of road pavement in the Darling Downs, Queensland, investigations carried out earlier on a highly expansive clay subgrade suggested an ultimate equilibrium subgrade suction of the order of 350 p.s.i. or 6 per cent dry of optimum moisture content (OMC) for standard AASHO compaction. During and after construction, rapid drying in the vicinity of the edges of the sealed pavement caused serious longitudinal shrinkage cracking at the edge of the seal in less than 12 months. Subsequent seasonal rainfall entering these cracks led to serious deformations and loss in surface shape and, in many cases, to shear failure. Practical methods are suggested which may overcome these problems.

A laboratory programme was devised to investigate the volume change characteristics and repeated loading 'resilient' moduli as functions of subgrade suction and initial compaction. The results indicate that for an expansive clay subgrade, the volumetric and vertical strain can be linearly correlated with the logarithm of the suction over the suction range considered. The compacted material is also isotropic with the vertical strain being exactly one third of the volumetric strain.

The repeated loading 'resilient' moduli are very sensitive to suction and the logarithm of the moduli can also be linearly correlated with the suction logarithm. From the "Shell Rational Method" design charts for lightly trafficked roads, these correlations are found to have a variation of pavement thicknesses from 15 in. at the equilibrium suction to over 4 in. at OMC depending on compaction conditions.

Finite element analyses have been made for deformations due to volume changes under changing subgrade moisture conditions and the deformations due to an 18,000 lb axle loading with moisture and stress dependent material properties. These theoretical predictions have been compared with preliminary field observations obtained from the experimental sections. Both the predicted and observed behaviour are in general agreement and clearly indicate the important influence of subgrade moisture on the performance of a pavement built on expansive clay subgrades in a semi-arid environment.

03014

Effects of Environment on Pavement Temperatures
R. H. Williamson

Climatological considerations are of considerable importance in the design, construction and maintenance of both rigid and flexible pavements.

This paper describes some of the deleterious effects of warm environments on road pavements and presents ways in which both empirically obtained long-term temperature data and theoretically evaluated temperature variations in multilayered structures may he related to practical engineering problems.

The motivation for, and evaluation of, a simulation model which will predict pavement temperatures using finite difference techniques is presented, and the advantages of using such a model for the acquisition of relevant data on pavement temperatures enumerated.

Pertinent areas in which the mechanisms of heat transfer are not well understood are outlined and some existing concepts questioned.

03015

Laboratory Evaluation of Rutting in Base Course Materials
Richard D. Barksdale

A method is presented for evaluating the relative performance of unstabilized base course materials with respect to rutting and is then used in the evaluation of a number of materials. A general method is also proposed for calculating rut depth occurring in flexible pavements, The proposed methods make use of the plastic axial strains obtained from the repeated load triaxial test.

Cylindrical specimens 6 in. in diameter and 12 in. in height of crushed stone and soil-aggregate mixtures were placed in a conventional triaxial cell and subjected to 100,000 load repetitions using a constant confining pressure and a triangular stress pulse.

Stress-strain curves giving the relationship between deviator stress, confining pressure and plastic axial strain were constructed for each material studied using the repeated load test results. The concept of a rut index was proposed which can be calculated making use of the plastic stress-strain relationship, and is approximately proportional to the rut depth that will occur in the base after a desired number of load repetitions, The rut index appears to offer a practical laboratory method for evaluating the relative performance of base materials used in pavements having similar structural configurations.

An evaluation of the test results using the rut index approach indicates that under good conditions of drainage and proper maintenance of the pavement surface, carefully selected blends of 20 percent soil and 80 percent stone should perform satisfactorily. Soil aggregate blends having properties similar to the materials tested should probably not be used at all under poor drainage conditions, and 40-60 blends should not be used even under good conditions of drainage. The results further indicate that only a sufficient amount of fines should be used in a crushed stone base to permit proper compaction if the amount of rutting in the base is to be minimized. Furthermore, even though the specified gradation and density may be the same, bases constructed from aggregates obtained from different sources may exhibit different rutting characteristics.

A general engineering method for estimating the rut depth in a flexible pavement after a desired number of load repetitions was proposed which utilizes nonlinear Layered theory, the plastic stress-strain response of the component materials, and a hyperbolic, plastic stress- strain law. Field verification is now needed of both the proposed rut index and the general method for predicting rut depth.

03016

Stiffness of Pavements Characterized by the Dynamic Modulus Evd - Definition of Dynamic Plate Loading
G. Baum

The deformation properties of unbound pavement layers are studied by means of static plate loading tests. Attempts to use static plate loading on the surface of bituminous pavement layers failed on account of the properties of viscoelastic bituminous road materials,

This paper describes that static plate loading can be replaced by defining a dynamic plate loading test. This is done by substituting sinusoidal forces for the static step forces produced by the load plates.

The sinusoidal forces are generated by an unbalance vibration machine and set a road surface in vibrational motion (and/or, depending on the test to be made, any surface of a pavement layer). The generated vibrations are related to various parameters.

To characterize the vertical deformations at a point of measurement the theory of simple linear vibration systems is used.

The investigations have brought out that only one of the constants derived from the technique of vibration gives sufficient technical information to be a valid test data. This is a spring constant which is applicable to frequencies exceeding 20 to 40 Hz (higher frequency domain).

By means of the dynamic theory of the elastic half-space the dynamic deformation value, E(sub vd), is calculated from the spring constant.

Pavements are considered as one-layer systems. In addition, by measuring the velocity of surface waves at low frequencies the effective modulus, E(sub 2), of the subgrade of pavements is determined. And by the use of the Burmister theory the effective modulus of elasticity, E(sub 1,b), of the "upper layer" (pavement) with a thickness of h is calculated from E(sub vd) and E(sub 2).

The systematic procedure of the investigation is thoroughly described. For lack of space, however, references are used to complement the description. Finally, full particulars on the procedure can be found in the description of 26 test sections of the road experiment "Grunbach" (Germany) especially designed for base course testing.

03017

Fatigue Tests on Pavements by Pulse Generators
H. Behr

For the study of the Optimum thickness design Of pavements and the selection Of suitable road materials many approaches have been used ranging from purely theoretical calculations to observations of road experiments under heavy test traffic with special trucks. The paper describes the basic considerations which have led to finding still another way by the use of simulative fatigue testing roads in a laboratory.

The equipment (pulse generators) installed at the Bundesanstalt fur Strassenwesen (BAST) - Federal Road Research Institute - is explained in detail. The results of an analysis of the pattern of loading produced by truck tires and pulsed loading are compared to prove the similarity of the most important load criteria.

Seventeen fatigue tests have been made by means of the pulse generators described in the paper. Each comprised 600,000 to 1,000,000 passages per track (30 cm) on the test sections built. The simulative loadings correspond to moving wheel loads of 3 - 10 Mp (approx. 30 - 100 N). The results obtained hitherto are relative to 9 selected pavements with bases of dry-bound crushed stone and asphalt-coated gravel varying in thickness, as well as to special designs with heat insulating layers of plastic foam. The bearing properties of these structures under dynamic loading are defined and the behaviour of roads subjected to fatigue tests described.

Special attention is paid to permanent surface deformations, since, in a way, this characteristic is a very interesting criteria for the description of riding quality and rutting. An attempt is described to establish an approximative law for permanent deformations in relation to the magnitude of loading and the number of load repetitions. The dependency on

the load is expressed by deformation coefficients.

With the reservations that the laws still have to be placed on more secure foundations by results of further fatigue tests, load equivalents have been calculated.

The load equivalents are a first step towards calculating the effect of mixed traffic, i.e., various load quantities in random sequence. In addition the real test acceleration produced by fatigue tests can be determined on the basis of load equivalents relative to a road under traffic.

Before more detailed data can be stated, results from further fatigue tests must be waited for. The future program of research is briefly outlined.

03018

Assessing the Properties of Materials for the Structural Design of Pavements
J. Bonnot

At the present time, knowledge concerning the mechanical properties of materials has not progressed as rapidly as pavement design methods, and the conventional tests used for selecting the composition of pavement mixes are not directly related to the mechanical characteristics affecting their performance in the pavement. The Laboratoires des Ponts et Chaussees have undertaken the development of a series of tests allowing the basic properties of pavement materials to be fully defined.

For the gravel treated with hydraulic binders used in the base course, the modulus of elasticity, which is required for calculating the distribution of stresses and strains in the pavement, is determined from the stress-strain curve obtained during direct tensile testing. The values obtained are characteristic of very rigid materials.

The risk of fatigue failure is examined by means of fatigue bending tests; the observed behaviour is very different from that of asphaltic materials and this has major consequences on pavement design. The risk of cracking by shrinkage is examined from strain failure under direct tension, or by means of special tests in which the prevented thermal shrinkage process is reproduced in the laboratory. The spacing between the cracks may be estimated from the breaking strength under direct tension.

For asphaltic materials, the moduli values necessary for calculating the distribution of strains and stresses in the pavement are given by the complex modulus test. Other modulus values may be obtained through the relaxation test or from stress-strain curves obtained during the direct tensile test. Master curves of these different moduli are compared. The risk of fatigue failure is examined by means of fatigue bending tests with the imposed strain.

Failure strength and strain data under direct tension are also given, and this test is compared with the Brazilian test. The tensile and compression test allows the determination of variations in cohesion and internal friction with the loading rate and with temperature.

Resistance to rutting in asphaltic materials is also examined by means of creep tests under compression, or by a test based upon the wheel tracking test.

03019

Applied Rheology of Asphalt Mixes - Practical Application
G. Chomton, P. J. Valayer

The rheological properties of asphalt mixes are usefully studied when they emphasize the durability of a road. This durability is related to:
- Stress distribution in the road, for which rheological properties must emphasize "stiffness" of the material.
- Failure criteria related to cracks, for which rheological properties must emphasize "fatigue".
- Failure criteria related to large deformations for which the rheological properties must emphasize creep under repeated shears.

A brief description of the equipment used in Mont Saint Aignan is given.

The stiffness is expressed in terms of complex moduli and is related not only to frequency of stress application and temperature but also to mix characteristics such as filler and bitumen content and also grain size distribution. General laws are checked for fatigue and the expression of fatigue versus stiffness is very attractive ; also, new laws are given, involving the energy consumption during a fatigue test.

Finally, a vibrating creep test is described and criteria are issued from this test to select the materials which will not develop rutting in the roads. The laboratory results are then processed in terms of road performance by the use of strain distribution calculated from a computer. The modulus is an essential parameter: therefore all the results are presented versus the modulus of the layer examined.

Both fatigue and vibrating creep tests are processed this way; the fatigue test by means of the conventional tensile strain at the lower part of the layer considered and the vibrating creep test by means of the maximum shear strains calculated in the layer.

Finally, an important discussion is given on the limitations of this method : examples (rotating stress tensors under the moving load) illustrate the criticism. In conclusion, fundamental mechanical testing can be used for the selection of materials on roads : examples of practical applications are given.

03020

Strength of Bases and Subbases
Charles R. Foster

The results of in-place CBR tests made at various heights above the subgrade are reviewed to determine if the CBR at a given level in an untreated material is a function of the CBR of the underlying material and the height of the test above the underlying layer.

The data presented show conclusively that the above postulation is correct; however, material characteristics affect the

CBR and a general relationship could not be developed.

The data do show that the thin layers of base do not develop significant strength. The author believes the water these thin layers collect and hold weakens the subgrade with the result that a pavement made with a treated base course may be structurally weaker if a thin cushion course is used than if the treated base course had been placed directly on the subgrade.

The data also show that the modulus of an untreated base course will increase with thickness. Thus, thickness equivalencies of treated materials which have fairly constant moduli with thickness, will decrease with an increase in thickness of base. This pattern has been reported for the data developed at the AASHO Road Test.

03021

The Behaviour of Bituminous Mixtures in Laboratory Tests and Under Road Conditions
R. Guericke, F. Weinert

The fatigue behaviour, the expansibility and the stiffness of bituminous mixtures are important parameters for the dimensioning of road structures. After work of about five years informative values for the various bituminous mixtures can be given. The determination of flexibility in the fatigue test has remained problematic. Not sufficiently known are the effects of the frequency of load cycles and the influence of the intervals between the load cycles. As long as these influences are not exactly studied it is recommended to test the fatigue of bituminous mixtures with frequencies of at most 10 c.p.s. (Hz). Moreover, it was found that the results of fatigue tests with constant deformation amplitude are in better agreement with the field conditions than the results of fatigue tests with constant power amplitude.

The determination of flexibility in the fatigue test generally requires much time and work. It was for this reason that in parallel with the fatigue tests the stress and strain were determined in axial tensile tests. As can be concluded from the results obtained so far there exists a close connection between the flexibility in the fatigue test (i.e. number of load cycles until rupture at a given deformation) and of the expansibility in the axial tensile test. The axial expansibility at low temperatures is, moreover, an important parameter with a view to the danger of the formation of cracks due to cooling in bituminous road surfacings.

In parallel with the laboratory tests the behaviour of road pavements under standing and rolling loads has been investigated. In this connection the determination of the radius of curvature of the deformation trough has proved particularly effective and informative. The curvature meters developed by Franz Muller gives exact and excellently reproducible measured values, it is smaller and easier to handle than the Benkelman beam. One measurement takes only one or few minutes.

03022

Relations between Mix Design and Fatigue Properties of Asphaltic Concrete
J. M. Kirk

A great deal is known about the fatigue properties of bituminous materials, but this knowledge is based on tests carried out under various conditions. Consequently, it is difficult to obtain a general picture of how the fatigue properties are influenced by the most important parameters such as binder content, void contents, grading, temperature etc. Therefore, in this paper an attempt is made to generalize as far as possible and to isolate the influence of the most important parameters. The first step is to show that the influence of the three parameters, the penetration grade of the binder, the temperature and the loading time can be combined by use of one single parameter, the stiffness of the binder. Then is shown how the fatigue properties of a mix is influenced by this parameter. Next is shown that the fatigue properties improve with increasing the maximum size of the aggregate and how to isolate this factor. The next step is to show the effect of the binder content and how it is influenced by the content of voids, and a correction curve for this effect is shown. Furthermore, it is shown that a mix must contain a certain minimum of filler in order to obtain good fatigue properties. This leaves only one parameter, the shape of the gradation curve, which is of importance in so far as it determines the number of large voids in the mix, and a large number may lead to poor fatigue properties,

While the fatigue properties are important in thickness design, when a bituminous base is used, they are only part of the problem in mix design, where other important points as the stiffness of the mix, which determines the load spreading capacity, the stability, the workability and the economy must be considered. This will often fix a limit to how good fatigue properties it is possible to obtain, but it is hoped that this paper will enable the mix designer to get close to that limit, which will allow the thickness designer to calculate with a high permissible strain in the material.

03023

Relationship Between Pavement Structural Integrity and Hardness of the Asphalt Cement
Norman W. McLeod

In colder climates, it is of questionable value to concentrate a great expenditure of effort on the design of a conventional, deep strength, or full depth asphalt pavement structure, if the integrity of the structure is to be impaired or destroyed by low temperature transverse pavement cracking. Several years of research on the problem of low temperature transverse pavement cracking in Canada, where this is currently the most serious pavement performance problem, have indicated that it can be most easily and inexpensively remedied by using softer grades of asphalt cement. Field and theoretical evidence are presented to support this conclusion. Finally, to bridge the gap between research and practice, a chart is provided to enable an engineer to select a grade of asphalt cement that will preserve the integrity of an asphalt pavement structure by avoiding low temperature transverse pavement cracking throughout the pavement's service life, provided the asphalt pavement has been properly designed and constructed.

03024

Tensile Behavior of Asphalt-Treated Materials Under Repetitive Loading
Raymond K. Moore, Thomas W. Kennedy

This paper summarizes the findings of an experimental program designed to evaluate the tensile and behavioral characteristics of high quality asphalt-treated materials subjected to repeated tensile stresses by means of the indirect tensile test. The objectives of the study were:
(1) to determine whether the indirect tensile test can be used for the study of the behavior of asphalt-treated materials subjected to repeated tensile stresses,
(2) to define the general nature of the relationship between applied tensile stress and fatigue life and to evaluate the effect on fatigue life of certain mixture and compaction variables, and
(3) to investigate the possibility of estimating the fatigue life of asphalt-treated materials subjected to repeated

applications of a tensile stress either by developing a predictive equation or establishing a correlation with other material characteristics.

Results of the study indicated that the indirect tensile test can be used satisfactorily to evaluate the fatigue characteristics of high quality asphalt-treated materials under repeated tensile loadings. In addition, the general nature of the relationship between applied tensile stress and the fatigue life was determined along with the inherent variation associated with fatigue life. The tensile stress-log fatigue life relationships were essentially linear with failures occurring at tensile stresses ranging from 8 to 40 psi, which were approximately 6 to 30 percent of the static indirect tensile strength. Significant variation in fatigue life occurred, and it was found that the standard deviation varied linearly with the mean of fatigue life, with the coefficient of variation ranging from 30 percent to in excess of 75 percent.

The tensile fatigue characteristics were found to be affected by asphalt content, type of asphalt cement, compaction temperature, and mixing temperature. Within the range tested, it was found that fatigue life was increased by using a more viscous asphalt cement, higher compaction temperature, and higher mixing temperature. It was also concluded that there is an optimum asphalt content for maximum fatigue life. In addition, a simple predictive equation was developed which adequately described the fatigue life of the specimens tested.

Fatigue life was found to correlate with initial stiffness, initial tensile strain, and tensile stress-strength ratio, but these correlations were associated with a large amount of variation. No correlation was found to exist between fatigue life and percent air voids.

03025

Applicability of a Linear Viscoelastic Characterization for Asphalt Concrete
Keshavan Nair, Wayne S. Smith, Chin-Yung Chang

The objective of this investigation was to determine the validity of using a linear viscoelastic constitutive equation to characterize asphalt concrete in the design of pavement systems. The investigation was conducted in two phases. In the first phase, creep tests in compression, tension and torsion, and repeated loading tests were performed on cylindrical specimens of asphalt concrete for various axial loads at different confining pressures and different temperatures to determine the response functions, and establish the degree of linearity and evaluate the time-temperature equivalence of the response. On the basis of these tests creep functions and complex modulus values for the asphalt concrete were determined. The second phase of the investigation was conducted to check if the characterization of the asphalt concrete obtained in the first phase of the program could be used to predict the behaviour of asphalt concrete under stress states which are similar to those that might exist in actual pavements by testing beams and slabs and a Winkler foundation. In this paper only the results of the first phase of the investigation are presented and discussed.

It was found that the type of test (e.g. uniaxial, triaxial, torsion) influences the magnitude and nature of the viscoelastic functions. For one type of test, the results obtained are consistent. Based on the results of tests under hydrostatic stress states it was observed that the samples exhibited a substantial degree of anisotropy. It is hypothesized that this is due to the method of compaction utilized in preparation of the samples. It was also observed that the volumetric response of asphalt concrete was tine dependent and that the usual assumption of incompressibility was questionable. Thermorheological simplicity was found to be a satisfactory assumption for uniaxial compression tests.

In order to reduce the influence of stress level, stress state, anisotropy and other effects to a level that will make linear isotropic viscoelasticity an acceptable characterization of asphalt concrete, it has been suggested that a limit be placed on the strain level that can occur in the asphalt concrete. This was done using the experimental data on the basis of a subjective evaluation. It is strongly recommended that sensitivity studies on the basis of pavement performance be conducted to determine the acceptable variations for ideal material characteristics and hence establish the degree of refinement required in the characterization of naterials for the design of pavement systems.

03026

Dynamic Structural Properties of Asphalt Pavement Mixtures
Charles A. Pagen

An approach to the structural design of pavements is advanced, based on the utilization of the in-service mechanical properties of road materials in the computerized viscoelastic and elastic multi-layered theories. Design and performance of roadways are discussed in light of the fundamental structural properties of the component materials. The primary goal of this program was to evaluate the significant changes in the dynamic mechanical properties of asphaltic concrete mixes used in highway pavement systems.

This study has quantitatively evaluated the effect of laboratory and roadway compaction on: the rheological creep and dynamic moduli, the elastic properties and the ultimate unconfined compressive strength of asphaltic concrete mixtures. The influence of compaction on the loading time and temperature-dependent strength and deformation properties of asphaltic mixtures was investigated in laboratory experiments on the phenomenological level. Such laboratory and roadway correlations are essential in order to evaluate the influence of construction techniques on pavement performance, asphalt mixture design procedures, thickness equivalencies and the structural design of road and airport pavements. The data indicate that highway test studies are required to supplement laboratory and theoretical research work.

The experimental phases of the study involved the testing of three dense asphaltic concrete mixes prepared in the laboratory by gyratory compaction and comparable field core test specimens obtained from a test section in U.S. Route 42 near Delaware, Ohio. Laboratory experiments were performed to validate the application of material science concepts to roadway asphalt mixtures and to determine the limitations of such approaches to highway design and strength evaluation programs. Experiments have quantitatively evaluated the influence of method of compaction, loading time or frequency, age of test specimen and temperature on the failure, and rheological complex and elastic moduli of the materials investigated. The field and laboratory compacted test specimen data have indicated that the application of the linear viscoelastic theory and mechanistic models to asphaltic concrete is valid, as well as that the time-temperature superposition concept is applicable for the research data obtained. Long-term creep experiments and dynamic tests have provided additional and independent checks of the concepts employed. Significant differences in the mechanical properties of the essentially identical laboratory and field compacted test sample were noted for the complex moduli and other strength parameters investigated.

Discussions on the utilization of the research procedures for evaluation of pavement thickness equivalencies, and suggestions for potential highway engineering utilization of the results in the structural design of flexible pavement

systems, future studies of asphaltic concrete mixture properties, and acceptance of construction work are presented.

03027

Deformations in Asphalt Concrete Wearing Courses Caused by Traffic
W. D. O. Paterson

The transient and permanent deformations caused in dense-graded asphalt concrete wearing courses by traffic loads have been measured and are discussed in this paper. The study is concerned mainly with wearing courses ranging in thickness from 2 cm to 10 cm and tested on a concrete-based testing track with controlled conditions of load and temperature. A comparative study made on a local motorway provides some correlation to real conditions.

The deformations were measured using pairs of induction coils 25mm diameter with a high speed chart recorder for readout. Deformations were measured vertically, longitudinally and transversely to give comprehensive results. A technique of coil placement is described.

The asphalt concrete materials used were of high stability and had a fixed dense grading of crushed aggregate and two maximum aggregate sizes of 16mm and 9.5mm. The results of trafficking showed the quantitative effects of load, temperature and pavement thickness on the densification of the asphalt concrete. As the density increased the apparent dynamic modulus and the stability of the mix increased. The apparent dynamic modulus also increased markedly as the pavement thickness decreased towards twice the maximum aggregate size, leading to a quantitative assessment of the role of pavement thickness. Vertical and horizontal strains decreased as the density increased and at lower temperatures vertical strains can be less than middepth horizontal strains. Vertical strains are greatly increased by a rise in temperature while horizontal strains increase only slightly.

03028

The Characteristics of Materials for the Design of Flexible Pavement Structures
P. S. Pell, S. F. Brown

An important part of the development of a structural design approach to the design of flexible pavements is adequate characterisation of the constituent materials in the context of the part they play in the pavement structure.

This characterisation should take the form of the determination of elastic constants and failure criteria so that linear elastic theory may be used to compute critical stresses and strains and the acceptability of these may be assessed in terms of the anticipated life of the pavement.

The characteristics of bitumen bound, cement bound, unbound materials and also cohesive soils are discussed against the background of current knowledge. Some results from recent research projects on bituminous materials and soils are briefly presented.

The importance of reproducing in situ stress conditions in laboratory tests is emphasised and present test methods are critically reviewed.

Some of the more important areas for future research are outlined as a result of this review of the current state of the art. The most important of these is considered to be correlation of laboratory determined results and performance in the road, so that the results of laboratory materials testing can be used with confidence in design.

03029

Mechanical Response of Bituminous Mixture Under Various Loading Conditions
Teruo Sugawara

This paper describes the test results concerning the mechanical response of bituminous mixtures which are required in rational designing and performance studies of pavement structure.

A stress-strain relationship of bituminous mixture was investigated under various loading conditions at various temperatures. A relaxation modulus under the constant rate of strain was computed from the stress-strain curve as a function of loading time.

In the flexure test, mode of fracture, relation between flexural strength vs. temperature, strain at rupture vs. temperature were obtained. As a result of beam flexure test, the movement of the transition point at which the mode of fracture shows a change in mode from brittle to ductile, was measured.

A convergence of the strain at rupture in the ductile fracture zone (2 to 5 x 0.01), in the brittle fracture zone (1 to 2 x 0.001) and at the transition point (4 to 6 x 0.001) was obtained respectively, throughout this investigation. The effect of the rate of strain, binder content, type of mixture and type of binder on the rheological properties of the mixture was also investigated.

At higher road temperatures, the resistance to deformation is one of the primary factors in the pavement performance. In this study, simulated wheel tracking test was carried out. The systematic relationships between the resistance to deformation and moving speed. tire contact pressure, temperature and binder property were obtained: And also the relationship between: the Marshall Stability and the resistance to deformation by the Wheel-tracking test was found. This result may shows a difference between-static and dynamic test on the flow properties of the mixture. A kneading action caused from the wheel passage was briefly discussed.

An electro-hydraulic apparatus was developed to investigate the dynamic response and the fatigue properties of the bituminous mixture, and the dynamic response under the programmed strain wave was discussed.

03030

The Fatigue of Bitumen and Bituminous Mixes
W. van Dijk, H. Moreaud, A. Quedeville, P. Uge

We have carried out laboratory investigations into the phenomenon of fatigue both in bitumen ('asphalt cement') itself and in mixes of mineral aggregate bound with bitumen as used in asphalt pavements. The objectives are to determine the role of the binder and to attempt to establish a method of predicting road performance from laboratory fatigue tests.

Our research into the fatigue of bitumen has been carried out on thin film specimens that have been subjected to

sinusoidal shearing over a range of temperatures and frequencies. In tests with a constant stress amplitude, the initial strain for a given fatigue life has been found to depend strongly on the complex modulus of the bitumen, and the slope of the fatigue curve (log life against log initial strain) to be related to the phase angle between the stress and the strain. When plotting the slope of the fatigue curve against the phase angle there is a maximum which is more pronounced for bitumens of low temperature susceptibility. The fatigue life of bitumen can be interpreted in terms of energy: the energy dissipated per cycle of stress being related to the fatigue damage per cycle, and the fatigue resistance may be regarded as the capacity to dissipate this energy into heat.

Films of filler/bitumen mixtures have also been tested in the same apparatus and it appears that a filler bitumen behaves like an unfilled one of harder grade.

Tests have also been carried out on various asphalt mixes, including a dense wearing course type and an economical base course type with a low binder content. The object has been to correlate the fatigue behaviour of the mixes in bending with that of the bitumen films on the one hand, and with the development of cracking in a slab of mix loaded by a rolling wheel on the other. This last test simulates the tri-axial loading that occurs in practice in an asphalt pavement. Two types of loading have been used in the bending tests: sinusoidal to provide a link with the usual mode of laboratory testing, and intermittent to give strains whose wave-shapes are similar to those that have been recorded under moving traffic in asphalt layers of pavements. It has been found that the rest periods between successive groups of waves, corresponding to the spacing between vehicles, give fatigue lives that are longer than those with continuous sinusoidal loading. In this way, realistic data are being developed for incorporation into asphalt pavement design procedures.

03031

A Fundamental Structural Design Procedure for Flexible Pavements
S. F. Brown, P. S. Pell

The main aim of the conference is to work towards improved methods of structural design for flexible pavements wherein the empirical content of particular methods will be reduced and replaced by analytical methods backed by a knowledge of relevant material properties, details of traffic loading and pavement performance. Such approaches have come to be known as 'rational design methods', though an empirical procedure may in fact be no less 'rational'. 'Improved design methods' or the 'structural design approach' are better descriptions of the aim of this work.

At the 1967 conference, the question was asked: how much more research must we do before such a method of design emerges?

This paper is an attempt to bring together various research efforts and incorporate them in a structural design approach to flexible pavement design. The approach is based on treating the layered pavement system as a structure in the traditional civil engineering manner and designing it accordingly. A framework for the design procedure is presented and is outlined in a simple flow diagram.

The design process involves the consideration of traffic loading, material characteristics under repeated dynamic loads, the computation of load induced stresses and strains and their comparison with the maximum allowable values for the various materials in the structure. An iterative procedure which modifies an initial estimate of layer thicknesses and materials is used in order to produce a pavement which is satisfactory both structurally and economically.

The difficulty of applying this method lies in the complexity of the structure, materials, loading, environment and criteria of performance. However, certain simplifications can be made and the procedure presented is based on a simple fundamental approach to the problem. The basis of the method is the availability of computer solutions for the linear elastic stress analysis of the structure. More sophisticated programmes are being developed to deal more realistically with the complexities both of the structure and the materials but as yet sufficient information is not available on the material characteristics and performance criteria to warrant their use. It is the Authors' opinion that linear elastic theory may be used in the manner presented with some confidence and a design example of the procedure is given.

One of the aims of the paper is to highlight those areas where more research effort is needed, such as the important aspect of pavement performance and its correlation with allowable stresses, strains and deformations in the constituent materials of the pavement.

03032

Calculation of the Deformations Caused by Vehicles to Flexible Pavements
Paolo Ferrari

The repeated flexural deformations that vehicles produce in flexible pavements are the most frequent cause of failure of these pavements. This type of rupture is due to a fatigue phenomenon that no asphalt pavement can escape, because of the nature of the materials of which it is constructed, so that even correctly executed pavements crack after a more or less long period.

It is therefore important to design flexible pavements in such a way that they can withstand the flexural deformations caused by vehicles for a certain time without cracking.

Recent experimental research has made it possible to know the relations existing between the flexural deformations caused to an asphaltic concrete and the number of repetitions of this deformation necessary to bring it to rupture. Starting from this relation, it is possible to forecast the life of a pavement subjected to a certain type of traffic, if the deformations caused by the vehicles are known.

The calculation of the deformations is the subject of this paper. For this purpose, the pavement-subgrade system is schematised as a semi-infinite visco-elastic body, whose mechanical parameters can be determined by a special plate bearing test, described in the paper.

The results of the calculations made in this paper clearly indicate the effects on the deformations in the surface courses of a bituminous pavement produced by weight, number and arrangement of vehicle axles and the speed of such vehicles. These results therefore make it possible, among other things, to more rationally assess the influence of the type of traffic and properties of materials in designing flexible pavements. They also make It possible to obtain the knowledge of maximum strains in the surface course, which is necessary for an essentially rational design of flexible pavements, considering the fatigue processes as a determinant cause of failures.

However in the paper it is pointed that, before this design approach can be fully developed, much more theoretical and experimental work needs to be done, essentially in order to investigate the fatigue behavior of the bituminous concrete under the actual road conditions, where at any point of the surface course a series of strains take place, all different from each other and at irregular time intervals.

03033

Applications of Theory in the Design of Asphalt Pavements
F. N. Finn, Keshavan Nair, C. L. Monismith

Pavement design, like other aspects of engineering design, requires that engineers have the ability to analyze pavement structures in terms of significant system parameters. Moreover, it is necessary that such analyses incorporate essential features of observed pavement performance and appropriately measured values of the parameters to make the necessary quantitative evaluations required for design. It is generally recognized, however, that the parameters involved together with their interrelationships are complex.

In recent years a number of attempts have been made to formulate, in a systematic manner, pavement design systems which bring these factors together as a part of the development of improved methods of pavement design, methods which will have the capabilities to:
(1) accommodate the continually changing loading requirements;
(2) better utilize available materials;
(3) accommodate new materials which might be developed;
(4) better define the role of construction; and
(5) improve the reliability for performance prediction (or of the design estimate).

While it is difficult to develop one pavement design system which, at this stage in time, will incorporate all desirable factors, it is possible to develop a series of subsystems the goal of each of which is to minimize a particular form of distress.
To minimize the effects of various distress mechanisms, design frameworks (subsystems) have been established and specific formats are developed. These subsystems parallel the design approach widely used in Civil Engineering practice in which a structure is selected (designed), its behavior under anticipated service conditions analyzed, and its adequacy with respect to a specific distress criterion determined.

A discussion of the most recent methods available to examine each of these subsystems is included. Considering this information, the authors recommend a specific technique to solve for each distress mode recognizing present limitations in materials characterization techniques and availability of solutions for boundary value problems representative of pavement structures as well as present limitations in knowledge of traffic, environmental, and construction effects.

The concluding section is concerned with a discussion of factors not now included in the subsystems described in the report. Consideration is given to optimization and the applicability of dynamic programming techniques to optimizing the solution of the pavement design problem is discussed. Included in the discussion is the ability of dynamic programming to consider the following factors:
(a) Adaptive System - the incorporation of new information gained through observations of performance to predict future performance,
(b) Sensitivity - the influence of individual parameters on the total system, and
(c) Stochastic Processes - the ability to evaluate the degree of uncertainty in the information that forms the basis for design.

03034

Prediction of the Resilient Response of Pavements Containing Granular Layers Using Non-Linear Elastic Theory
R. G Hicks, C. L. Monismith

A laboratory-field study to better define those properties of granular base materials which significantly contribute to the resilient response of pavement structures under repetitive loadings has been conducted.

Results of the laboratory study, previously reported by the authors, indicated that the stress deformation properties of granular materials when measured in repeated load triaxial compression are non-linear with their modulus values and Poisson's ratios dependent on stress state to a considerable degree.

Field studies included measurements of the response of a prototype pavement, 20 ft. by 20 ft. in plan, to repeated-load plate tests and of an in-service pavement in San Diego County, California to an actual truck load. Both pavements consisted of an asphalt concrete surface, a granular base course, and a clay subgrade. Instruments were placed at various positions in the pavement structures to measure deflections, stresses and strains.

For the prototype pavement, the plate load tests were conducted at the pavement surface with the base course in both a partially saturated and saturated state. Loads were applied through rigid plates at durations representative of moving traffic and in sufficient numbers to assure that a reasonable measure of the resilient behavior could be obtained. These responses were then compared with computed values which were obtained from three different non-linear elastic analyses and laboratory determined stress-strain properties. The results indicated that the predicted stresses, strains and displacements compared reasonably well with field measurements; the responses yielded by the different numerical methods were similar; and the resilient responses of the system were only slightly affected by degree of saturation of the base course.

The approach developed to predict pavement responses for the prototype pavement was extended to a full-scale test road in San Diego County, California, to verify its application to conditions representative of moving traffic on highways. Measurements of strains and displacements were obtained under a slow moving truck and compared with predicted values. As with the prototype pavement, results of the analyses indicated that the predicted and measured responses were in good agreement.

03035

The Modulus of Asphalt Layers at High Temperatures: Comparison of Laboratory Measurements Under Simulated Traffic Conditions with Theory
A. Hofstra, C. P. Valkering

In order to investigate whether elastic theory can be applied to the behaviour of flexible pavements under moving

wheels, particularly at high temperatures, we have measured in our Laboratory Test Track the stresses and strains imposed by a rolling wheel. The test pavements consisted of an asphalt layer on top of a sand subgrade; the temperature of the asphalt layer has been varied between 20 and 60°C. The results have been compared with the theory. Apart from a certain degree of asymmetry of mainly the strain signals, the shapes of the experimental signals correspond well with those predicted by theory. The asymmetry has been found to be little dependent on temperature.

The maximum values of the stresses and strains are also compared with those predicted by theory. In this comparison, for the asphalt layer a Young modulus is used which is dependent on the temperature of the asphalt layer and on the width of the signal (or the loading time). In this way the influence of wheel speed and penetration grade of the binder on the maximum strains as well as the difference in magnitude between the longitudinal and transverse strains in the wheeltrack could be explained.

The comparison of the experimental results with theory indicates a condition of the interface between the asphalt layer and sand subgrade which is intermediate between slip end complete friction.

It is concluded that elastic theory can be used to describe the behaviour of flexible pavements subjected to moving wheels even at the highest temperatures that are likely to be experienced in pavements.

03036 **A Comparison of Plate Load Testing with the Wave Propagation Technique**
D. A. Kasianchuk, G. H. Argue

The repetitive static plate load test method has been used by the Canadian Department of Transport since its development in 1947 for the design and evaluation of the airport pavements within its jurisdiction. The vibratory loading wave propagation technique, of more recent development, offers some advantage over the plate load test in several aspects of the testing procedures. In order to determine the degree of correlation that could be expected between these two methods in the evaluation of the load carrying capacity of pavements at Canadian airports, a pilot test program was conducted during the summer of 1970.

Thirty-five vibratory tests were performed using the Shell Canada Limited equipment and technique at six Canadian airports. The test sites were selected from among those included in the annual plate load test program to represent a wide variety of the asphalt pavement types found in Canadian airports. The wave propagation measurements were analysed to provide values of elastic modulus to be used in the prediction of pavement response by layered system elastic theory. These predicted values were compared to those measured at each site in the actual plate load test.

Although the comparison obtained indicates some relationship between these approaches, further work is required to more accurately assess the predictability of plate load tests from vibratory test results.

03037 **Design of Flexible Pavements for Major Highways**
A. M. Krivissky

On the basis of comprehensive theoretic and experimental research carried out in the Soviet Union a method has been developed for the design of flexible pavements with asphalt concrete or similar surfacing. Structural design of this type of pavements should provide for their performance to be only in the phase of recovery (elastic strain).

Special investigations have shown that evaluation of stress-strain condition of such pavements can be obtained by applying solutions of elasticity theory for lmred semi-infinite space. The following physically real conditions are used in design as limiting criteria:
- Shear limit equilibrium in subgrade soil or in moderately cohesive materials of structural layers;
- Maximum allowable bending-tensile stress in monolithic layers (asphalt concrete, cement-bound materials) for given loading conditions.

The design procedure involves both strain (E,mu) and strength characteristics of materials and soils the latter being shear resistance of soils and moderately cohesive materials (Y, C) and also bending-tensile strength of monolithic materials (R). Design characteristics are normal and can be obtained by means of testing samples, their state simulating the condition of materials or soils in pavement structure.

Although the design procedure includes application of relationships which are rather complex for calculation it has been found possible to draw nomograms that bring complicated calculations to simple graphical solutions. The suggested method makes it possible to design not only a total pavement thickness, but also a required thickness of each structural layer, with detail consideration of properties of the materials used.

The new structural method is well founded by the evidence of good performance of pavements under various climatic and service conditions.

03038 **The In Situ Determination of the Elastic Moduli of Layered Pavements Using SH-Wave Propagation**
M. Kurzeme

A method is presented of determining the in situ elastic properties of layered pavement materials through the excitation and observation of horizontally polarized shear waves (SH-waves). The method consists of generating continuous SH-waves at the frequency and the location desired, detecting and observing the wave motion over some distance from the wave generator, measuring the surface velocity of phase propagation at each imposed frequency, and interpreting the observed variation in surface phase velocity with change in imposed frequency of vibration to deduce the in situ elastic properties of the pavement materials.

Theoretical dispersion relationships have been developed that describe the variation in surface phase velocity with change in imposed frequency of SH-wave motion in idealized layered pavement structures.

The existence of modes of propagation predicted by the theoretical dispersion relationships were investigated on laboratory models of layered pavement structures. These tests confirmed the presence of the predicted modes.

The propagation of SH-waves was then investigated on real pavement structures. A torsional vibrator, capable of

generating predominantly SH-waves, was constructed and a phase velocity measuring system and a field procedure were developed. The relationships between the surface phase velocity of SH-waves and the imposed frequency as observed on a number of two- and three-layer pavements are presented.

To deduce the shear wave velocities within the individual layer materials, the observed relationships have been interpreted by matching with the theoretical dispersion relationships of comparable idealized structures. A knowledge of the material densities allows the calculation of dynamic shear modulus of the materials.

Using the theoretical relationships presented, it is concluded that in favourable cases observations on real pavements can be interpreted, to deduce the in situ dynamic shear moduli of the layer materials. The relevance of the material properties so obtained is dependent on how closely the theoretical model used approximates to the real structure.

03039

A Study of Stress and Strain in the Asphalt Pavement of Tomei Highway
Yuji Miura

The Tomei Highway of 346 km. was constructed in 1969, between Tokyo and Nagoya, serving for the heavy traffic of more than 25,000 vehicles per day, Having been designed by the CBR method adopting the Structural Number and Layer Equivalency that were the results of AASHO Road Test, the whole distance was paved with asphalt concrete of 10 to 15 cm. thickness, that included surface and binder courses, over asphalt stabilized base course of 15 to 22 cm. thickness laid on the various type and thickness of subbase.

On the highway, 17 observation spots were settled, and a lot of electric resistance strain gauge, pressure cells, electrical deformation devices and thermocouples were laid into the pavement. The stress and strain of the pavement, including those in certain depth of the subgrade, were observed in the field under the controlled wheel loads. The purpose of this investigation is to know the behavior of the pavement and to obtain the data for rational design of asphalt pavement structure,

In this paper, three out of 17 observation spots are taken for the study, and not only the details of the paving and measuring techniques but also the properties of the materials, that have been determined both in the field and in the laboratory, are elucidated.

On the other hand, the measured values of stress and strain under the wheel loads are analyzed minutely, the measured data being compared with computed values according to the multi-layered elastic theory. The comparisons are made by the following two methods:
1) Assuming that each pavement is composed of three elastic layers and loaded with single circular load, the elastic modulus of each layers is arranged and determined so as to be equal approximately to the computed and measured values of stress and strain of the pavement, and then compared with the measured modulus taken in the field or in the laboratory.
2) Assuming that each pavement is composed of four or five elastic layers and loaded with dual circular load, the stress and strain of the pavement are calculated by using the elastic modulus obtained from the field measurement or the past data, and compared with the measured values, especially with the lateral strain of the asphalt treated layers. In addition, the results of the investigations and theoretical analysis are discussed concerning the center, longitudinal and traverse position of the loads.

From the comparisons, made by the said two methods, some conclusions are drawn as for the propriety of analysis of the pavement structure by using the multi-layered elastic theory, and that the theory is able to predict not only the distribution of vertical stress and displacement of the pavement but also the distribution of horizontal strain in the asphalt treated layers under the traffic loads.

03040

A Stochastic Approach to Analysis and Design of Highway Pavements
F. Moavenzadeh, J. F. Elliott

A stochastic approach is proposed for the development of a rational method of analysis and design for flexible pavement structures. The approach utilizes a three-layer viscoelastic model, a cumulative damage theory, and systems simulation techniques. In this approach the environmental variables, properties of layered materials, geometry of the pavement structure, and loading variables are described in a stochastic manner utilizing the Monte Carlo simulation techniques.

Through the use of these three interrelated models, the pavement structure and its structural integrity is simulated continuously throughout its design life. The results of the study is used to demonstrate (for a given pavement structure), the nature of damage, the manner in which damage accumulated, and the probable time that damage accumulation exceeds the allowable limits and the pavement requires reconstruction. For the design, several possible alternatives can be simulated, and the one which has the most desirable characteristics can be chosen.

03041

Applications of Computer Codes to the Analysis of Flexible Pavements
Raman Pichumani

The capabilities and limitations of three computer codes suitable for static analysis of flexible pavement structures are presented in this paper. One of these codes, WIL67, is used for the analysis of single-wheel loading; the other two, BISTRO and AFPAV, can analyze the pavement response due to the multiple wheels of very heavy landing gears of modern jumbo jets such as the U.S. Air Force transport aircraft C-5A and the Boeing 747 commercial aircraft. The WIL67 and AFPAV codes are based on finite element structural analysis technique; the BISTRO code makes use of Burmister's layered-system concept.

The BISTRO code, developed by the Shell Oil Company, has made it easy to apply Burmister's general theory for calculating stresses, strains, and displacements at any point in a linear elastic multilayered pavement system due to normal surface loads. This computer program predicts the pavement response due to one load at a time at a designated point in any layer and then uses the principle of superposition to determine the multiple load response. The WIL67 code, developed at the University of California at Berkeley, is a two-dimensional finite element program which solves the layered-pavement problem by treating the pavement as an axisymmetric solid subjected to an axisymmetric load. Although there is a version of this code which can analyze the effects of multiple loads using the superposition principle, the program studied in this research effort is restricted to the analysis of a single wheel load. The AFPAV code is an

extended two-dimensional finite element program capable of analyzing prismatic solids. This program idealizes the layered pavement system as a layered prismatic structure and expresses the applied loading as well as the resulting displacements in terms of Fourier series. Therefore, the accuracy of the solution and the computer time required by this code is governed by the number of Fourier terms used. However, unlike the BISTRO code, the linear elastic response of the pavement system due to multiple wheels can be determined by this code in one step without recourse to the superposition principle. Therefore, the AFPAV code is far more efficient and economical than the BISTRO code for analyzing layered pavements loaded by multiple wheels, particularly with increasing number of layers, and increasing number of points where stresses and displacements are required.

Theoretical pavement response predicted by the AFPAV code is compared with field data from a full-scale flexible pavement test section which was constructed by the U.S. Army Engineers Waterways Experiment Station (WES) at Vicksburg, Mississippi and statically loaded by a 12-wheel assembly of a C-5A landing gear. The dependence of the pavement response on the elastic constants of various layers is demonstrated by a parametric study, thus emphasizing the importance of accurately determining these parameters. In conclusion, it is shown that it is necessary to continually update the capabilities of the AFFAV code to consider the more realistic characterizations of the pavement layers as they become available.

03042 **Experimental and Theoretical Studies of Pavement Behaviour Under Vehicular Loading in Relation to Elastic Theory**
E. N. Thrower, N. W. Lister, J. F. Potter

The paper describes a series of experiments to determine the degree to which multi-layer elastic theory can be used to predict stresses, strains and deflections of pavements under moving vehicles.

Measurements of stress and deflection in flexible pavements of realistic design have been made under pilot-scale conditions over a wide range of wheel loads, speeds and temperatures, and similar tests have also been carried out on a simple concrete slab. Results are presented showing the effects of temperature and wheel load on the measured behaviour and this is compared with that predicted from multi-layer elastic theory using data derived from both laboratory and in-situ testing. The results show that elastic theory can be used to predict the dynamic behaviour of relatively stiff pavements, but that deviations occur under high temperature conditions, where it is difficult to establish an effective modulus for bituminous materials because of the rapid change in dynamic modulus with the timescale of the loading, and for pavements which derive a large part of their-structural stiffness from granular materials.

03043 **Some Considerations on the Theoretical Estimation for Deflection of Pavement Structures**
K. Ueshita, T. Arakawa, Y. Watanabe

Empirical relations between surface deflection and thickness factor of pavement structures show that the effect of thickness of pavement to reduce deflection is more than the one estimated from the theory of elasticity. Extreme case is shown by the soil-cement/subgrade two-layer system which can never been explained by the theory of elasticity. The authors tried to explain these phenomena by using the finite element analyses assuming non-linear elastic properties for subgrade materials. By these computations, experimental relations of the soil-cement pavement could be almost explained. Besides, a useful equation was introduced to formulate the relationship of deflection versus thickness of non-linear elastic pavements.

03044 **Effects of Multiple Wheel Systems and Horizontal Surface Loads on Pavement Structures**
C. P. Valkering

The theory of elasticity has been applied to layered systems representing flexible pavements. The distributions and the maximum values of the tensile strain in the asphalt layer as the compressive strain in the subgrade under multiple-wheel systems have been calculated. The concerted action of the wheels depends, not only on the wheel spacing, but also to a significant degree on the structure which renders weighting traffic for design purposes difficult.

A thickness design method based on these strains as criteria is equivalent to one that is based on shear or deformation energy criteria, provided that the permissible values are obtained at the same stress condition as prevails in the pavement.

Under normal end tangential surface forces the influence of asphalt layer thickness on the normal and shear stresses at the asphalt/base interface has been investigated: the stresses decrease with increasing thickness. At high asphalt temperatures the shear stresses might be critical for the adhesion between, particularly, a thin asphalt layer and a stiff base.

03045 **Design of Full-Depth Asphalt Airfield Pavements**
M. W. Witczak

A theoretical design procedure for Full-Depth asphalt concrete airfield pavements is presented. The design is based upon the use of multilayered elastic theory and utilizes the concept of limiting strains to prevent repetitive permanent deformation and/or shear failure within the subgrade layer and repetitive load cracking within the asphalt bound layer. Development of the allowable strain levels for both failure modes are presented.

The method utilized to obtain limiting strains associated with the subgrade was to theoretically analyze flexible (granular base) pavement thickness requirements as defined by the newly revised U.S.A.C.E. thickness design method. These revisions are related to changes in thickness requirements as well as load repetition effect upon thickness from the previous method. Results indicate that a limiting vartical strain of 1460 microinches per inch, evaluated at a limiting asphalt concrete modulus of 100,000 psi is capable of withstanding 1,000,000 strain repetitions.

Limiting strains associated with the asphalt bound layer have been established from results developed by Kingham from Full-Depth asphalt concrete pavements of the AASHO Road Test study. An allowable tensile strain of 76 microinches per inch will allow 1,000,000 repetitions when evaluated at a critical asphalt concrete modulus of 1,450,000 psi.

Because of the extreme dependency of the stress and strain distributive characteristics of thick Full-Depth asphalt pavements to temperature, monthly cumulative damage techniques were used to develop thickness adjustment factors (TsubF) to adjust thickness requirements for both failure modes due to differing environments. The limiting or critical

modulus utilized in the vertical subgrade strain analysis is related to an average annual air temperature of 75°F. For cooler environments, a thickness reduction may be used. The maximum suggested reduction proposed is 10% (TsubP = 0.90) for environments having a 50°F average annual air temperature. Maximum percentage thickness reductions of 13% are suggested for the tensile asphalt concrete strain analysis. This is equivalent to a maximum TsubF value of 1.00 at 40°F (average annual air temperature) and a minimum TsubF value of 0.87 for 60°F environments.

03046

Sensitivity Analysis of Various Cost Elements in Flexible Pavement Design
Eldon J. Yoder, Farideh Ramjerdi, William L. Grecco

This paper presents a method for predicting the optimum initial service life and optimum periods of resurfacing for flexible pavements. The method is based on consideration of total pavement costs including the cost of initial construction, routine maintenance and major maintenance and increased road user costs resulting from the maintenance operations.

Standard economic analyses techniques were used for determining the average annual cost of alternate designs. A modification of the Radzikowski model was used for estimating routine maintenance cost of flexible highway pavements. The pavement design method developed by the Corps of Engineers was utilized in estimating initial design as well as required major maintenance (resurfacing). A method was developed which presented an estimation of road user costs due to maintenance and resurfacing operations.

Variables evaluated in this paper included:
(1) subgrade type;
(2) initial traffic volume;
(3) rate of traffic growth; and
(4) rate of interest on the investment.
Solutions were made for both 2-lane and divided 4-lane highways.

The results of the study are presented in the form of graphs which indicate the initial design period which results in least cost for combinations of the variables given.

03047

Low-Temperature Pavement Cracking Studies in Canada
Roads & Transportation Association of Canada, Soils & Materials Committee, and Pavement Design & Evaluation Committee

Cracking of pavements at low temperatures has become a serious and extensive problem in Canada. During the past decade, various highway departments, producers and others have devoted considerable effort towards finding a solution. This paper summarizes their progress in finding the causes of the problem and their development of some practical, engineering solutions.

Field inventories were initially conducted to determine the nature and extent of the cracking. From these, and other observations, the bituminous component seemed in most cases to be the major variable. Subsequent field sampling, plus full-scale experiments such as the Ste. Anne Test Road in Manitoba, the Alberta Test Road, the Saskatchewan Test Road and the Arkona Test Road in Ontario, and laboratory investigations confirmed that certain asphalt cements were primarily involved.

Several design approaches were formulated from these findings, the earliest being that of modified specifications. Later, asphalt and mix stiffness or strain limits, fracture temperature calculation procedures, and most recently a cracking frequency estimation technique, were developed as design guides.

The paper demonstrates that while this progress has been significant, some key aspects of the problem remain. One of these concerns the treatment of the many miles of existing, cracked pavements.

03048

The Fatigue of Flexible Pavements
Bonner S. Coffman. George J. Ilves, William F. Edwards

Five asphaltic concrete pavements, each of which measured 20x30 ft. and contained two test areas, were constructed on a 48" compacted clay subgrade. Certain of these pavement areas were fatigue loaded through concentric rings composed of truck tire rubber by superimposing one dynamic 10 Hz haversine pulse on a small static load every second to simulate a continuous line of wheel loads traveling in identical wheel paths 50' apart at 40 MPH. Surface tangential strain, surface deflection and temperature sensors were placed at a number of radii from the load plate centerline and recorded periodically throughout each test. The fatigue of four test areas, as evidenced by visible cracking, was observed closely and noted in a log book. Asphalt and compacted subgrade samples were returned to the laboratory for the determination of structural strength and physical properties. The results of these tests were entered into the Chevron n-layer program along with a number of hypothetical moduli for the natural subgrade underlying these layers. Theoretical strain and deflection profiles obtained from these calculations were compared to measured profiles to determine the best average apparent modulus for this semi-infinite layer. Trapezoidal specimens were sawed from asphalt pavement blocks and fatigue loaded with one 10 Hz haversine pulse per second over a wide range of temperatures and strain levels. An equation relating these quantities to fatigue life was developed and coupled with a theoretical pavement fatigue model to predict the time of initial surface cracking on the four test areas where visible cracks were observed.

03049

Failure Criteria for Flexible Pavements
D. Croney

The term 'design life' when applied to a road pavement implies a terminal or 'failure' condition beyond which the performance of the pavement will be regarded as unacceptable. For design procedures based on past experience a relatively loose definition of failure has been acceptable, but with the growing interest in structural design procedures, failure criteria expressed in more exact physical terms are essential.

This paper discusses the definition of the 'failure' condition which has been accepted for flexible pavements in Britain. The 'critical' condition at which overlaying to extend the life of the pavement should be carried out, is also considered.

Both these performance criteria have, for flexible pavements, been expressed in terms of permanent deformation either expressed as a rut-depth or as total deformation from the original pavement level. Observations made on normal in-

service roads and on closely observed experimental roads have shown that the criteria ore not markedly different for pavements using lean concrete, bituminous macadam or unbound stone bases.

The Present Serviceability Index concept is not regarded in Britain as very applicable to the structural design problem because of its heavy dependence on riding quality factors, not necessarily associated with traffic stresses. However an approximate correlation between the British approach and P.S.I. values is given.

03050 **Permanent Deformation of Flexible Pavements Under Simulated Road Traffic Conditions**
A. Hofstra, A. J. G. Klomp

In a circular laboratory test track the rutting of flexible pavements has been studied at various temperatures under well-controlled conditions.

It has been found that temperature has a great influence on the depth of rutting, the increase in rutting over a temperature range of 20°C-60°C being much larger than the increase in calculated elastic deformation. The permanent deformation per wheel passage correlates with the stiffness of the asphalt binder used and decreases with increasing number of wheel passages.

An increase in thickness of the asphalt layer leads to a distinct reduction in subgrade deformation. The change in thickness through rutting is not larger for a 20 cm than for a 10 cm asphalt layer. Proper mix design proves to be an important factor in relation with permanent deformation.

03051 **Strain and Curvature as Factors for Predicting Pavement Fatigue**
Y. H. Huang

The fatigue cracking of asphalt pavements is caused by the repeated applications of excessive tensile strains in the asphalt-bound layer. To predict fatigue, it is necessary to determine the maximum tensile strain at the bottom of the asphalt-bound layers. Two methods are suggested for determining the maximum tensile strain, based on the two-layer elastic theory. The use of two-layer theory, instead of the conventional three- or multiple-layer theory, is based on the fact that the tensile strains at the bottom of the asphalt-bound layer depend on the property of the asphalt-bound layer relative to that of the underlying layers. Any multi-layer systems can thus be reduced to a two-layer system, if an average modulus of elasticity is used to represent the combined effect of all the underlying layers, Fortunately, the moduli of untreated granular materials and soils generally fall within narrow ranges, and typical values can usually be assumed.

To facilitate the application of the two methods, simple charts are presented for determining the maximum tensile strain under a set of dual tires. The first method, which can be used for pavement design, requires a knowledge of the elastic moduli of both layers and the thickness of the asphalt-bound layer. By entering these variables into the chart, the maximum tensile strain can be easily determined. The second method, which can be used for pavement evaluation, requires the measurement of curvature on the pavement surface. Knowing the curvature, the modulus ratio, and the thickness of the asphalt-bound layer, the maximum tensile strain can be determined from the charts. It was found that for asphalt- bound layers of 4 in. thick or more the curvature-tensile strain ratio is practically independent of the modulus ratio. By simply measuring the curvature on the surface, the maximum tensile strain can be estimated, and the adequacy of the pavement to withstand fatigue evaluated.

Examples are given to illustrate the use of these charts for pavement design and evaluation.

03052 **A Design System for Minimizing Fatigue, Permanent Deformation and Shrinkage Fracture Distress of Asphalt Pavements**
D. A. Kasianchuk, R. L. Terrel, R. C. G. Haas

The design of asphalt pavements includes three major structural subsystems: load-associated fracture, load-associated permanent deformation, and shrinkage fracture. In order to accelerate progress towards a rational design system it is desirable to accelerate improvements in the technology of these three subsystem areas.

This paper suggests a series of needed research and development tasks for each design subsystem. In addition, some discussion is devoted to briefly justifying the recommendations and to summarizing the current state of design knowledge for the three areas.

The paper includes in flow chart form the interrelationships between subsystems and attempts to place the subsystems within an overall pavement design and management framework.

03053 **Failure Criteria Developed from AASHO Road Test Data**
R. Ian Kingham

Theoretical models of pavement deformation behavior such as elastic-layered theory can only be used for design purposes when failure criteria are specified. Although such models can be used to predict stress and strain states, they in no way indicate whether the material in the pavement can withstand the predicted deformations. For elastic-layered theory, limiting values of strain or stress need to be defined before the theory can be used to assist practicing engineers in the design of asphalt pavements.

There is general agreement in the literature that horizontal tensile stress or strain at the bottom of a thick asphalt layer is the controlling criterion for design to prevent repetitive load cracking. Although such strains were not measured at the bottom of the asphalt layer at the AASHO Road Test, they can be inferred from a knowledge of the material characteristics and the measured deflections. Repetitive load cracking was observed to be the predominant mechanism of initial failure at the Road Test. Since the bituminous base sections provided a complete range of performance, from failures to survivors of over 1 million load repetitions it was possible to describe the strain history of these test sections in terms of performance.

The bituminous base sections fell into three performance classifications, depending upon whether they failed the first spring of testing, survived the testing period with a low serviceability rating or survived the testing without any change in serviceability. The horizontal tensile strain, horizontal tensile stress and vertical strain on top of the subgrade data were

computed for each test section in each performance classification. Asphalt moduli for a wide spectrum of deflection measurements were input into the stress and strain computations. Moduli values were determined from dynamic loading in compression. Subgrade moduli were inferred from the deflection measurements.

The results of the elastic-layered computations showed that there were indeed large differences in horizontal tensile strain, horizontal tensile stress and vertical strain in the subgrade, depending upon the performance classification. Secondly, the level of strain or stress for each performance classification was a function of the asphalt base stiffness at the asphalt layer bottom. From the horizontal strain results it was apparent that asphalt pavements can tolerate higher strains at lower stiffnesses.

The horizontal tensile strain and stress relationships with asphalt stiffness were converted into "load repetition to failure" relationships by relating two performance classifications to the number of load repetitions to failure. A log-log relationship was assumed. The resulting family of "fatigue-like" curves for a range of asphalt stiffnesses has been used by Witczak and is the subject of another paper to this conference.

03054

Deflection Criteria for Asphalt Pavements
Sadao Nagumo, Minoru Tsukinari, Seiichi Tanimoto

The structural design of asphalt pavements in Japan is based on the CBR method, but recently attempts have been made to utilize surface deflection in the design of pavements for lightly trafficked roads and those on weak subgrades as well as in the determination of overlay thicknesses.

The Ministry of Construction carried out performance surveys of pavements on about 750 sites of national highways and about 3,600 sites of lightly trafficked roads during the period 1963 - 1965, and 1964 - 1967 respectively.

Full-scale experimental pavements have been constructed successively since 1967. The results of observations of those experiments have indicated that the stabilization or treatment of base, or subase materials with binders is quite effective in reducing the surface deflection and that the surface deflection is much influencing on pavement failures.

From the results of performance surveys on existing roads and experimental pavements, the authors obtained the following formula which expresses the relationship between the critical deflection for asphalt pavements and the accumulated traffic volume:

$\log 10N = 0.179\ d2 - 1.117\ d + C$

where N: Accumulated traffic volume of heavy commercial vehicles, when the pavement becomes to require heavy repairs . . . (vehicle/in one direction)
d: Critical deflection expressed by Benkelman Beam rebound deflection using a wheel load of 4.1 tons . . . (mm)
C: Constant, 6.772 for general national highways and 6.385 for lightly trafficked roads, might be a little varied depending upon the layer thickness of asphalt mixtures and the types of bases and subbases.

When this relationship is applied to the surface deflection of the newly constructed pavements of national highways, it is predicted that no large-scaled repair works will be necessary for at least five years after construction for medium trafficked roads (traffic volume of heavy commercial vehicles: 1,000 vehicles /day, in one direction).

In the design of pavements of lightly trafficked roads which consists of a comparatively thin bituminous surfacing and a base on the top of the existing gravel roads, the authors obtained a design curve which makes it possible to determine the additional layers thickness to give a target deflection on the surfaces.

03055

The Analysis and Design of the Flexibility of Pavements
D. V. Ramsamooj, K. Majidzadeh, E. M. Kauffmann

This paper deals with the application of fracture mechanics to the problem of fatigue cracking and failure of flexible pavements. It describes experiments conducted on four-foot diameter bituminous slabs supported on an elastic foundation in order to verify Paris' crack propagation law. The crack pattern and the actual crack lengths were obtained by X-ray photography and the techniques for analyzing the rate of crack propagation for multiple cracks are presented.

Excellent agreement has been found with Paris' law $dc/dN = AK4$, where dc/dN is the rate of crack propagation, K is the stress-intensity-factor, which measures the general load transmission to the vicinity of the crack tips, in accordance with the load, geometrical and boundary conditions, and A is shown to be a materials constant. On the other hand comparisons made on the basis of the bending stress at the interface of the slab or beam and foundation showed discrepancies. This is not surprising since the stress-intensity-factor is a much more powerful parameter than the bending stress, being able to take into account much more fully the boundary and geo- metrical conditions in accordance with the load and the amount of cracking in the pavement.

The criteria for fatigue failure of pavements is defined as the time for the stress-intensity-factor at the tip of the largest crack to reach its critical value, since rapid crack propagation would then occur, or the time for the total area of cracking to exceed ten per cent of the area of the pavement surface, whichever occurs first.

Finally, assuming knowledge of the load-time history of random loading, and the variation of the material constants (such as the Young's modulus of each layer, the crack propagation constant, A, and the critical-stress-intensity factor, KIC, of the bituminous material) with temperature, rate of loading, age and moisture content, etc., a method of analysis and design is proposed to guard against flexibility failures in pavements. Further simplifications are then introduced to illustrate the effect of using thicker bituminous layers to replace granular material that contribute the same strength according to the AASHO method of design, and to obtain the load equivalency factors for various magnitudes and configurations of wheel loads.

03056

Rut Depth Prediction in Asphalt Pavements
J. E. Romain

A computational procedure and a computer program are presented that enable the highway designer to predict the rut

depth, after a given number of vehicle passages, of a road structure considered for design. The ingredients to be fed in are: the stress distribution throughout the layered road structure under a wheel load; the characterization of the vehicle axles; the statistical distributions of the magnitudes of the wheel loads and of their locations across the road surface; the number of vehicle passages to be withstood; the deformation law of an element of each material under repeated stressing.

03057

Evenness and Serviceability of Roads
W. Schwaderer

Evenness and serviceability are terms about which, in colloquial language, everybody, can make himself an idea, but which can hardly be defined scientifically. Highway engineers always knew that there is a relation between evenness and the degree of serviceability. At the beginning of the thirties a geometrically -abstractly formulated evenness criterion was introduced in Germany for acceptation purposes, which is still valid today. In default of profound knowledge, people tacitly thought that this criterion guarantees a maximum serviceability. Investigations by Carey and Irick brought a serviceability standard and showed that there can only be a relation between evenness and serviceability if evenness is appropriately defined. While evenness can be defined in an entirely mathematical-geometric way and thus stays independent of epochal influences, serviceability is submitted to temporal ideas. Extensive investigations in Germany confirm the American results. Other investigations pointed out the existence of serviceability index limits which for traffic reasons should be strictly kept at the moment of pavement construction (acceptance) as well as at the end of life of a road.

03058

Control of Design of Pavements through Elastic Layers Method Using Real Dynamic Modulus Values
Jorge Tosticarelli, Luis M. Zalazar

The paper describes the first experiences made in Argentina to measure elastic dynamic properties of road materials and the use of actual modulus values so determined to the control of flexible pavements through Elastic Layers Method.

The first part of the paper describes the technique and instrumentation developed to make in situ measurements of elastic properties of the different layers by the Surface Wave Method and laboratory test on cores by non-destructive Resonance and Pulse methods.

The second part of the paper refers to the control of several flexible pavement designs by Elastic Layers Method using real dynamic modulus values obtained by the Surface Wave Method.

The flat terrain of Santa Fe, the unfavourable soil profile and the lack of coarse granular materials in the zone, makes a difficult situation for an economical pavement design.

The used procedure has permitted to clarify the properties of very peculiar structures of pavements as "Sand-Soil Asphalt Emulsion Stabilization" which was quite a pioneer process to make stable subbase and base layers with fine local materials.

03059

Moduli and Critical Strains in Repeated Bending of Bituminous Mixes. Application to Pavement Design
J. Verstraeten

The purpose of this paper is to present results concerning moduli and fatigue strength of bituminous mixes tested in sinusoidal bending (controlled stress tests) with a view to their use in pavement design.

The domains of variation for temperature (T), frequency (f) and number of cycles (N) are respectively: -2O°C <equal to/ less than> T <equal to/ less than> +30°C; 3 Hz <equal to/ less than> f <equal to/ less than> 100 Hz; 10super3 < N < equal to/ less than> 10super6.

The 27 mixes differ by their composition and by the type of bitumen.

The data indicate that the apparent activation energy relation (Arrhenius equation) may be used to evaluate the frequency and temperature dependent response of bituminous mixes. It is also important to note that the apparent activation energy is approximately the same for all the mixes investigated (46 kcal/mole) It is also established that, within the limits of the mixes investigated, there exists a general relation between the ratio |E*| /V sub A (ratio between the modulus of the mix and the percentage volume of aggregate in the mix, voids included) and the product |E*|sub b x gamma (product of the corresponding modulus of the bitumen and a factor which depends on the penetration of the bitumen). The interest of such a relation is to permit, for practical purposes, to estimate the values of the modulus |E*| of a mix knowing its composition, the corresponding modulus |E*| sub b and the penetration of the bitumen.

For the fatigue strength in bending it is established that the critical strain, epsilon sub r (N), for a given number N of cycles depends principally on the percentage volume of bitumen in the mix (voids included) and also on the asphaltene content of the bitumen and the kind of stones. As found previously epsilon sub r (N) is practically independent of temperature and frequency.

On the basis of these results and therefore within the limits of the mixes investigated a general formulation of the fatigue law of bituminous mixes is given and the statistical aspect of the phenomena is taken into consideration for the application of this law.

It is also concluded that in practice the choice of a composition must be made in the general frame of the road conception and not only on the basis of a single property.

03060

Pavement Serviceability Measurements for Pavement Evaluations
Roger S. Walker, W. Ronald Hudson, Freddy L. Roberts

The primary operating characteristic of a pavement at any particular time is the level of service that it provides to the users. One of the important factors influencing levels of serviceability is roadway roughness and one of the generally accepted methods for characterizing roadway roughness is the serviceability index concept. This paper is concerned with methods of achieving this measure for Texas highways through the use of the serviceability-performance concept. This concept requires a correlation between objective, physical measurements of pavement characteristics, and

subjective measures of pavement quality by highway users.

To obtain these correlations, physical measurements were performed with the SD Profilometer while subjective measurements were provided by a 15-member rating panel. Regression models, relating these measurements, are presented and field evaluations and subsequent modifications of these models are included. Correlations of these models with an inexpensive roughness measuring device (the Mays Road Meter) are also discussed. This device provides an economical means for rapidly obtaining routine performance information. The SD Profilometer is used as a measurement standard, thus maintaining compatibility in performance measurements.

The use of spectral analysis as another means of providing a more comprehensive method of identifying pavement characteristics and characterizing pavement performance is presented. An example of pavement identification in construction control and a brief discussion of current research using spectral analysis for providing a more comprehensive serviceability model are discussed.

03061

Spanish Full-Scale Road Test on the Madrid-Barcelona Road
E. Balaguer Camphuis, J. A. Fernandez del Campo

On the Madrid-Barcelona road and in the period 1962-1964, a full scale test road with flexible and concrete pavements was constructed. The length of this test road is about seven kilometers. The flexible pavements were intended for the determination of the behaviour of different types of pavements in real conditions on a very heavy traffic road. 48 different sections of flexible pavements were constructed with three types of bases (macadam base, continuous graded granular base and asphalt base), two types of binders, and eight types of surface courses. In this road, traffic is especially heavy and carefully controlled in that concerning composition and number of vehicles. An electronic dynamic scale was installed.

Hitherto, the evolution of pavements has been followed pointing out their damage on account of the accumulation of traffic effects, and studying the evolution of enough series of parameters to define, in a moment, the conditions of road pavements.

For this purpose studies have been established on:
- Evolution and seasonal variations of elastic deflections measured with the Benkelman beam on the different pavement structures. Also were established correlations between the deflections and pavements temperatures, and also between the deflections obtained by different systems of measure.

- Variations of bearing capacity of the pavements under static and dynamic loads and its changes with factors such as, temperature, moisture content, etc. For this purpose, special instruments for measuring stresses were installed in the pavements.

- Variations of geometric surface by the periodic leveling of studs included in the surface of pavements and by the use of a longitudinal profilometer - (viagrafo) and a transversal profilometer.

- Settlements at different depths in the pavement structures.

- Influence lines of strains under the circulation of heavy axles at different speeds. Consequently, some idea of "response" of the pavements to dynamic loads.

- Evolution of surface texture of the wearing course.

The results obtained have served to establish some laws of behaviour of tested pavements in terms of traffic, some judgments on the road conditions and some laws on the influence of ambience factors in the test results.

The behaviour of the pavement structures with the two types of granular bases is relatively as different under slow loads a s quick loads. For slow loads the structures with continuous graded granular bases give moduli of rigidity greater than the structures with macadam base. For quick loads the moduli are very much more similar, but those of the macadam base are slightly greater. The behaviour of the structures with an asphaltic base are very dependent on the season of the year for its correlation with the pavement temperature. For each speed of load linear logarithmic laws are established between the bearing capacity and the temperature of the pavement.

For all structures also logarithmic laws are established between elastic Benkelman deflexions and pavement temperatures. The parameters for the different structures are included. Conclusions about critical Benkelman deflexions of different structures show the differences in the behaviour of the structures with granular bases and those of asphaltic bases.

Laws are established for the evolution of the transversal profiles (surface deformation) of the different structures and the number of vehicles N passing the road.

03062

Main Findings from the Experimental Research in Mexico
Santiago Corro-Caballero

Since 1962 the Secretaria de Obras Publicas sponsors a research program on flexible pavement design, which is conducted through the Institute of Engineering of the Universidad Nacional Autonoma de Mexico (UNAM). Main purpose of the program is to obtain better methods of design for roads with low traffic volume, taking into account regional conditions of the country in such aspects as materials, traffic characteristics, climate, environment, specifications, construction procedures, safety factors and investment policy.

The experimental studies include three closely interrelated aspects:

1) Research on the performance of three test roads located on two Federal Highways. Project 1 is in a tropical zone; projects 2 and 3 are in a cold steppe region and they were constructed on the same road with only a short transition in between. There are 80 structural sections in the three projects, with pavements ranging from 10 to 50 cm in total thickness. After seven years of testing under actual traffic 72 of the original sections are still in good condition, with present serviceability ratings of 2.5 or more. Each section is one-lane wide and it is 30 m long.

2) Study of the actual performance of existing pavements located in three climatic zones representative of the conditions of the country. Total length under study is of the order of 6000 km, from which 96 field sections will be studied in detail in a factorial experiment. Main variables of the study are climate, traffic, subgrade strength, composite strength and years in service. Length of each section will be 500 m.

3) Research on full-scale pavements tested in a 13 m diameter circular track, under the action of 10 Ton single axle loads applied through conventional 10.00-20 dual tires. The facility was especially designed as part of the program and it has been in operation since December 1970. Each test ring has three structural sections and it is possible to study four rings per year.

After nine years of research, the following conclusions can be stated:

a) There is an urgent need for developing fundamental parameters which can be used for pavement design. In the meantime, it would be convenient to standardize the methods of test to interchange information on an international basis; for the same reason a uniform climatic classification is suggested, in combination with other environmental studies such as water table level and moisture equilibrium.

b) AASHO system of present serviceability rating has been found useful. Acceptance and rejection levels (2.5 and 2.0) have been found adequate for the conditions of the country.

c) Deflection basins determined by use of Benkelman beam are close to Boussinesq's prediction, and maximum rebound deflections did not correlate clearly with pavement design but with the composite strength; this fact should be considered to predict performance or to design overlays.

A tentative design chart is presented based on the experimentation conducted to date. AASHO load equivalence factors were applied; the track will be used in further stages to establish coefficients for other soil types

03063

A Fresh Look at the Interpretation of Pavement Serviceability and an Experiment to Measure the Riding Quality of Roads in South Africa
P. C. Curtayne, R. N. Walker

The need has arisen in South Africa for evaluating the condition of pavements in a systematic manner in order that maintenance can be more effectively managed and financed, In order to make effective decisions on maintenance it is necessary not only to evaluate those aspects of pavement condition which are functional and relate to the comfort and safety requirements of road users, but also those mechanistic aspects which relate to the structural condition of the pavement.

This paper approaches the evaluation of pavement condition from a functional point of view and describes the features and contributing factors that influence the present pavement serviceability; it also suggests methods for their assessment. The term 'present serviceability' as used in the AASHO Road Test related only to the aspects of the general definition concerned with riding quality. The paper concentrates on the assessment of riding quality - a function which is important to the comfort of road users and also to their safety if the road is in a very poor condition. The formulation of the equation for the measurement of the present serviceability index (PSI) is examined by means of a step-wise regression analysis of the original data and it is shown that the inclusion of the term for cracking and patching is not significant. Where the rut depth is less than 10 mm (0,4 in) it need not be considered when evaluating the PSI. It is concluded that the effect of rutting on safety by causing pending of water in the wheel paths should be considered separately from the effect of rutting on the PSI. Limits for rut depth from safety considerations should be set objectively for different climatic conditions.

The paper also describes the results of an experiment for evaluating methods of determining the riding quality of a pavement. A large number of sections of roads were rated subjectively by a large panel of assessors in order to determine the riding quality of each section as accurately as possible. Although the mean ratings for the roads were considered sufficiently reliable, the results of the individual raters were biased to reduce the errors that usually occur in subjective judgements; it was found, however, that this made very little difference to the mean ratings or to their reliability. The results of correlations of the mean ratings with roughness measurements, obtained by means of the BPR Roughometer and the PCA Road Meter, and with the slope variance of the simulated CHLOE profilometer, indicated that each of these instruments can give satisfactory results. The PCA Road Meter results, however, were found to depend on the type of vehicle in which it was used, This implies that the PCA Road Meter should be calibrated against a subjective rating when it is used in different vehicles, Although this is impractical, it is shown that the PCA Road Meter can be satisfactorily calibrated against slope variance provided enough measurements are used.

03064

Comparison between Measured and Calculated Stresses and Strains in Flexible Road Structures
R. Dempwolff, P. Sommer

At two full-scale flexible road structures of a test track extensive measuring programmes were carried out to determine stresses and strains in structures under controlled dynamic load conditions. A rail guided load vehicle, driven automatically, enabled the application of defined rolling loads of a single lorry wheel in the range between 0.5 and 2.0 tons. For testing the influences of loading time (speed) and environmental conditions, the load device was run on each test structure in the speed range between 5 and 50 km/h, and during all seasons of the year at asphalt temperatures between 0°C and 30°C.

Radial strains (longitudinal and transverse) and vertical strains in the asphalt layer, and vertical stresses in the unbound base and the soil were measured at different levels of depth in the structures. The applied transmitters (strain gauges, pressure cells) had been tested successfully in situ for years.

The two investigated rood structures with a total thickness of the asphalt of 22 cm differed only in the stability properties of the asphalt base materials. Therefore direct comparisons could be made between the two structures under the same conditions. As a general result, the differences between radial strains in the asphalt were bigger than the differences between the vertical stresses in the u&ound base and in the soil.

For the comparisons between measured and calculated values a so-called effective dynamic stiffness modulus of the

asphalt materials was introduced which accounts for the material properties, the temperature and the "effective" loading time. The numerical data were calculated by the computer programme BISTRO, which is based on the theory of elasticity for multilayer systems. The dynamic moduli of the materials were determined in the laboratory by a known vibration method, and in situ by the wave propagation method.

The best correlations between measured and calculated values were found for strains in the lower part of the asphalt layer and for the stresses in the unbound base and the soil, even when the stiffness conditions for the asphalt layer were low at asphalt temperatures of 30°C. When asphalt temperatures exceeded 25°C, maximum tensile strains were observed in the middle part of the asphalt pavements at the interface of two layed asphalt courses.

03065 **Load-Deformation Characteristics of a Pavement with Cement-Stabilized Base and Asphalt Concrete Surfacing**
Per E. Fossberg, J. K Mitchell, C. L. Monismith

This paper describes studies concerned with the evaluation of the usefulness of elastic theory for predicting the behavior of soil-cement pavements under loading, and with determination of the influence of various thicknesses of asphalt concrete on the response of such pavements to load, For these studies, two square soil-cement test pavements, each 20 ft. by 20 ft. in plan and 8.5 in. thick, were constructed on a soft clay subgrade. One of the two pavements was loaded to a level resulting in cracking of the soil-cement layer. Both were tested under repeated loading with 0, 1, 3 and 5 in. of asphalt concrete surfacing. Stresses, strains, and deflections measured in the test pavements were compared with values predicted by both elastic layer and finite element solutions using material parameters determined in the laboratory.

For all the repeated load tests, the deflections of the base increased nearly linearly with the plate load, were primarily dependent on the total load applied, and tended to decrease with increasing plate size. A similar dependency existed between applied load and vertical stresses recorded in the subgrade. Vertical stresses in the surfacing and in the base directly under the loaded area were, however, primarily governed by the plate pressure, regardless of plate size. Generally, horizontal strains in the base and surfacing increased with increasing plate size for any one plate pressure, and increased with decreasing plate size for any one plate load.

For both the cracked and the untracked pavement, providing 5 in. of asphalt concrete surfacing reduced the deflections of the base by approximately 20 percent; the same reduction was obtained in subgrade stresses. This relatively small reduction resulted because the asphalt concrete course had a stiffness of only about 1/8 that of the soil-cement for the conditions of test. The asphalt concrete had a large effect, however, in reducing the vertical stresses in the base, and also in reducing the horizontal strains, particularly in the upper part of the base.

The study showed that both elastic layer theory and finite element analyses can be used to predict pavement performance under loading. In this study, both methods tended to underestimate vertical deflections, suggesting a potential shortcoming of deflection as a criterion for pavement performance. While both methods were satisfactory for predicting vertical stresses, the finite element solution proved superior in predicting horizontal strains in the surfacing and base, since it permitted the reinforcing effect of the loading plate to be taken into account. Using the finite element analyses with an incremental loading procedure it has also been shown that for a pavement structure with a relatively stiff base or surfacing, assumption of linear stress-strain characteristics of the subgrade is perfectly adequate for analytical purposes.

03066 **The Structural Behaviour of Bituminous Surfacings in an Experimental Asphalt Pavement**
Charles R. Freeme, Claude P. Marais

In many of the advanced theoretical methods of pavement design - a subject which is currently being studied throughout the world - attempts are being made to include the effects of the fatigue of the bituminous layers of a pavement structure. The consensus of opinion is that this will result in improved design procedures which will reduce the occurrence of this type of distress. In order to engender confidence in these procedures, it is first necessary to make a comparison of theoretical prediction techniques with in situ field measurements taken under actual loading and environmental conditions.

A detailed study of one section of a heavily trafficked experimental asphalt pavement with a granular crushed-rock base and a 100 mm thick qap-graded surfacing was undertaken in which both linear-elastic and non-linear elastic finite-element computer techniques were applied to predict elastic deflection at various depths within the pavement structure, and maximum tensile strain at the surfacing/base interface. These results were examined mainly on the basis of a comparison between the measured and predicted behaviour of the pavement layers. In addition, a less extensive investigation was made on other sections where both gap-graded and asphaltic concrete surfacings of various thicknesses had been constructed on the same experimental pavement structure. In situ pavement tests, such as CBR and wave propagation measurements, were combined with information acquired from a laboratory investigation to establish the most realistic modulus for each pavement component.

The modulus of the granular crushed-rock base was shown to be stress dependent and had a major effect on the variation of elastic deflection with depth below the surface of the pavement structure. This characteristic of the base material must also be taken into account when strains at the surfacing/base interface are computed using theory, for loadings (wheel load and tyre pressure) over a wide spectrum.

It is further shown that the AASHO load equivalency factors, normally used in pavement design to convert mixed traffic (wheel loads) to an equivalent number of standard wheel loads, do not apply to the design of bituminous surfacings less than 100 mm in thickness. In this regard recommendations are made to take into account mixed traffic in a more realistic manner.

03067 **The Structural Analysis of Asphalt Pavements from Field Loading Tests**
William S. Housel, James H. Ito

The analysis of structural behavior of asphalt pavement presented in this paper started some years ago with the detailed study by Ingimarsson of the results of Hybla Valley tests reported by Benkelman and Williams. That study is continued by including all of the test sections and translating the results into terms of the stress reaction or strength developed by each of the pavement components. It was also found desirable to supplement the Hybla Valley tests by another notable

program of field testing conducted by the U.S. Army Engineers Waterways Experiment Station at Vicksburg, Mississippi. This investigation featured direct measurement of pressure transmitted to the supporting soil from loads applied at the surface with deflections measured at various depths and lateral offsets. The results reflect the characteristics of pressure distribution and the geometric limits within which a soil of given strength can sustain the stresses imposed by surface loads.

Thus these two outstanding investigations provide basic data on stresses in the soil mass or pressure distribution as it is generally known. The Vicksburg tests provide the basis for isolating the lateral distribution of applied load by shear transfer on the perimeter surface through the pavement structure from the load transmitted directly to the subgrade by the central column. These two stress reactions designated as perimeter shear and developed pressure are expressed by the linear equation for bearing capacity used successfully for many years in the design of soil supported structures.

The magnitude, sequence of development, and variation in these stress reactions with the size of the bearing area are determined in the analysis of the Hybla Valley field loading tests. The limiting values of these stress reactions and the settlement at which they occur are controlling factors in the structural design of flexible pavements. Results from those test sections at Hybla Valley which were loaded to capacity have been worked out by the solution of sets of linear equations and are reported in the paper. With the quantitative value of these stress limits established, the linear equation can be translated directly into terms of the pavement thickness required to reduce the contact pressure on the pavement surface to the permissible pressure transmitted to the supporting subgrade.

The primary objective of this paper was to present observed stress limits in flexible pavements from full-scale field loading tests as the background for design. However, space limitations do not permit more than a brief discussion of the obvious application to flexible pavement design. An example is given of a balanced design in which the full strength of all pavement components are combined assuming flexibility of the pavement structure sufficient to mobilize perimeter shear in unison with the full supporting capacity of the subgrade. Analysis shows that the Hybla Valley test sections were not so designed and the rigidity or high resistance to punching shear of the thick well-constructed bases prevented the most economical combination of subgrade bearing capacity with pressure distribution through the pavement structure. Comparative analysis of this approach with other methods of design and field experience is available but must be presented later.

03068

Nondestructive Vibratory Pavement Evaluation Techniques
A. H. Joseph, J. W. Hall jr.

The U.S. Army Engineer Waterways Experiment Station (WES) has performed several studies since the Second International Conference on the Structural Design of Asphalt Pavements in an effort to develop techniques and criteria for use in the nondestructive evaluation of flexible pavements and the prediction of performance of the pavements under various aircraft loads. This paper covers the results of three studies:
(a) development of criteria relating elastic deflection beneath prototype loads to performance of pavements subjected to trafficking with those loads,
(b) development of techniques of extrapolation of deflections under steady-state vibratory loads to predict elastic deflections beneath static prototype loads, and
(c) development of an automated nondestructive testing system and utilization of this system in accumulation of data from airfield pavements throughout the United States that confirm the nondestructive evaluation procedures by comparison with conventional Corps of Engineers (CE) criteria.

Relationships between the elastic deflection of a pavement beneath a static wheel load to the number of repetitions of that load to cause failure of the pavement have been developed for flexible pavements. These relationships were made from data accumulated over a period of years from full-scale airfield and highway test pavements. These relationships are not only important in the nondestructive evaluation procedures, but may also provide the link for theoretical treatments of layered systems to predicted performance of these systems.

The multiple-wheel heavy gear load (MWHGL) test sections at WES consisted of instrumented pavements that were tested with various single- and multiple-wheel loads. Pavement deflections measured beneath the steady-state vibratory loadings were extrapolated with a fair degree of accuracy to predict deflections under static loading with the test load carts. Load-deflection ratios obtained with a large mechanical vibrator were related to performance of the test sections under traffic and to conventional pavement strength parameters.

Airfield pavements throughout the United States, which provided a range of pavement types and environmental conditions, were evaluated by both nondestructive techniques and conventional test pit methods, and comparisons of these results are presented,

03069

Laboratory Fatigue and Its Relationship to Pavement Performance
R. Ian Kingham, B. F. Kallas

The traffic testing of asphalt pavements in a Washington State University test track provided an opportunity to explore the fatigue mode of failure in asphalt pavements. Observations of 8-foot wide pavements surviving 247,000 applications of a dual-wheel load weighing 10,600 lbs. showed that alligator crack patterns were confined to the bottom of the asphalt bases. The experiment was designed to compare the performance of an asphalt concrete base, a sand asphalt base and a crushed stone base.

The principal objective of this complimentary study was to determine if test track failures could be predicted from the results of a laboratory, flexural beam, fatigue test. Secondly, the performance results allowed a check to be made on field failure criteria derived from the AASHO Road Test. The cumulative damage hypothesis of Miner was used to predict the time to failure for each test section using either the laboratory or the field criteria.

The analysis procedure required the computation of horizontal tensile strains associated with each application of load. Complex modulus tests on asphalt bases and surfacing, and modulus of deformation tests on undisturbed samples of subgrade soil provided input into the Chevron elastic-layered program. For the laboratory fatigue tests, controlled stress and controlled strain tests were completed at three temperature levels to bracket most of the testing temperatures at the test track. Equations were derived to express load repetitions to failure as a function of strain and temperature for each asphalt mixture. Similarly, the field failure criteria developed previously from AASHO Road Test data related load repetitions to failure strain and the stiffness of the asphalt mixture.

The extensive program of laboratory fatigue testing has added considerable knowledge to the behavior of asphalt mixtures in the flexural beam test. For both constant stress and constant strain tests, the effect of temperature was particularly significant. The laboratory fabricated test specimens provided the same results as those specimens cored from untraveled portions of the test pavements. This finding suggested that lab fabrication can produce a specimen representative of the field.

Both stress controlled and strain controlled flexural beam test results tended to over-predict the actual number of repetitions to failure. Predictions for the stress controlled test were closer than those for controlled strain and very close to those observed for three of the six Full-Depth asphalt test sections. The field failure criteria gave slightly closer predictions than laboratory results. This finding offers some promise for the application of the field criteria to asphalt mixtures that have different dynamic modulus - temperature relationships than that for the AASHO Road Test bituminous bases. Neither the field failure criteria nor the laboratory fatigue criteria predicted satisfactorily the lives of the crushed stone base test sections. For this base type, the use of elastic layered theory, combined with Miner's hypothesis is suspect.

03070

Practical Design Applications Based on Washington State University Test Track Results
Milan Krukar, John C. Cook

The Washington State University Test Track is a practical apparatus for the evaluation of the strengths of different pavements and materials. Tests run on different base materials, untreated and treated, during a six-year span reveal that many ideas about the value of the use of some materials need revision.

The description and results from the four test rings are briefly presented. Design equivalencies for the different materials are developed. The results from the test track seem to cast some doubt on the benefits of the use of untreated rock bases. Results indicate that increasing the thickness of untreated base does not necessarily increase the pavement life. Under certain economic conditions and surface condition criteria, cracked pavements with untreated bases may be preferable to pavements with treated bases.

Studies on asphalt bases show that treated bases are no substitute for a good subgrade. It does very little good to construct thick asphalt pavements on weak non-uniform subgrades. The practicability of laying thin asphalt concrete surfacing on a good subgrade without a base has been demonstrated and can be applied in the construction of low-volume, low-cost roads.

Comparison of results from field data with elastic n-layer theory reveals that results are, in general, comparable. Differences may not be due to faulty instruments, but to the nature of the theory itself, which requires assumptions based on laboratory results which may not duplicate actual conditions.

The value of the use of inferior aggregates treated with asphalt cement has been demonstrated. The superiority of deep strength asphalt pavements has been shown.

Environmental conditions during construction and testing have played a more important role in the life of a pavement than either the type or thickness of base and/or pavement.

03071

Traffic Tests of Airfield Pavements for the Jumbo Jets
R. H. Ledbetter, H. H. Ulery jr., R. G. Ahlvin

A flexible pavement test section was constructed and tested to failure under full prototype aircraft loadings. These tests were designed to gain information pertaining to the behavior of flexible pavement structures and subgrades under multiple-wheel heavy gear loads (MWHGL), such as the C-5A and the Boeing 747. The test section was constructed to carefully controlled strengths to a full 12-ft depth, and five items of various thicknesses were incorporated above the 4-CBR subgrade.

Gradations, plasticity restrictions, minimum thicknesses, and similar specification controls were consistent with design requirements for a U.S. Air Force "medium-load" airfield. This is an airfield capable of supporting KB-50, KC-135, and similar aircraft. The test pavements would thus be generally considered to be of very good quality. The C-5A was designed for operation on medium-load airfields.

The loadings and multiple-wheel configurations indicated the need for determining wheel interaction effects both in the pavement structure and to the same depth within the subgrade soil. Therefore, two of the items were instrumented with stress, strain, deflection, pore pressure gages, and temperature probes. The stress and deflection instrumentation was placed at various depths throughout the full 12-ft depths of the items; stress and deflection were the primary measurements made.

The instrumentation was loaded both statically and dynamically (slowly moving vehicle) with one main 12-wheel landing gear of the C-5A, a 6-wheel component of the C-5A gear, a twin-tandem component of the Boeing 747 landing gear, and a single wheel, which was one wheel of the C-5A gear. Various test loadings were conducted on each of these gears with the test loads per wheel ranging from 6000 to 60,000 lb.

An analysis of the soil behavior patterns investigated to date has resulted in the following:
a. Both stress and deflection distributions showed differences in pattern between the two instrumented items.
b. Assuming elastic behavior, theoretical predictions of deflection versus depth or of offset versus deflection are not good except for a single-wheel load.
c. Stress and deflection distribution patterns under a single-wheel load are different from those under a multiple-wheel assembly.

Behavior of the test items was determined in terms of the traffic applications to produce failure under each of the loads applied. In all, over 20 combinations of load and test item structure were studied, permitting comparisons of behavior related to thickness, type of structure, and single versus 4- and 12-wheel loadings.

In general, behavior of the test pavements under multiple-wheel heavy gear loads was better than simple extensions of prior pavement design criteria would indicate for higher repetition levels. The 12-wheel C-5A aircraft loading seemed to

yield elements of pavement behavior somewhat different from behavior recognized previously under one-, two-, and four-wheel loads.

03072

Evaluation of Flexible Pavements by Nondestructive Tests
H. A. Balakrishna Rao

A vertical oscillator operating on the surface of a layered medium generates dispersive waves. The elastic properties of the various layers are determined from the characteristics of the surface waves (dispersion curves).

This paper deals with two asphaltic concrete test sections on which vibration tests were performed. The elastic properties of the various layers are used to theoretically predict the deflection basin under a loaded plate. A comparison between the computed and measured displacement fields shows that the computed deflection basin is considerably shallower than the measured deflection basin. This discrepancy is attributed to the low strain level input generated during the determination of layer properties by the vibration method.

A technique to modify the elastic properties of the layers based on the actual strain level inputs generated by field loading conditions is introduced. This technique was recently developed at the University of Kentucky and, at the present time (1971), is primarily used to modify the elastic properties of the subgrade only. However, the principle of this modified procedure greatly strengthens the concept of nondestructive testing as a practical tool for evaluating the performance of airfield pavements.

The average modified elastic property of the subgrade and the elastic properties of surface and base courses as determined by the vibration method are used to compute the new displacement field which is compared with the measured displacement field.

Further modifications of the proposed method to account for the actual distribution of strain within the pavement system would upgrade the nondestructive testing procedure to provide a meaningful and practical evaluation of the load-carrying capacity of a pavement.

03073

Pavement Performance Using Residuals in the Deflection Test
A. J. Scala

The paper describes investigations into permanent deformations arising in a pavement during the Benkelman Beam Test. The study is particularly concerned with pavements giving low deflections - subgrade deformation is only a minor part - and hence any permanent movement is probably due to a lack of strength in one or more of the pavement layers.

Although the elastic deflection or curvature values may be satisfactory on a road for the particular traffic, in the absence of an indication of permanent movement it may not be presumed that the structure or any layer is behaving elastically. When the front legs and probe of the beam are within the deflection bowl at the start of a test using the original W.A.S.H.O. procedure and no other factor is influencing the residual deflection, a positive residual reading should be observed. On the other hand, if a negative reading (equivalent to a permanent rise in the pavement) is recorded it can be symptomatic of adverse behaviour and should be significant in an evaluation of a pavement by elastic deflection.

The study shows with a number of examples that the residual deflection can provide an indication of permanent movement. A performance study undertaken on a number of sections indicates that a measure of permanent deformation is equally as important as rebound deflection in the evaluation.

03074

The Alconbury Hill Experiment and Its Relation to Flexible Pavement Design
P. D. Thompson. D. Croney, F. W. H. Currer

In a paper given to the First Conference on the Structural Design of Asphalt Pavements results obtained from the major full-scale pavement design experiment at Alconbury Hill during the first four years were given. The present paper summaries the conclusions after 13 years.

Although the major trends - such as the superior performance of dense bituminous base material and of rolled asphalt surfacings - have continued to be apparent, certain of the earlier tentative conclusions, and particularly those relating to the role of the subbase, have needed revision.

The traffic using the experimental road has been weighed by an electronic weighbridge and the number of cumulative 8200 kg (18,000 lb) axles has been calculated using the A.A.S.H.O. equivalence factors. This will allow a direct comparison to be made with the results of the A.A.S.H.O. Road Test for the forms of construction common to both experiments.

A simple structural analysis based on elastic theory has been made for certain of the sections using lean concrete, wet-mix slag and rolled asphalt road bases. Although the broad conclusions are in agreement with the experimental findings the analysis illustrates some of the practical problems entailed in applying structural analysis techniques to the design of road pavements.

03075

Pavement Performance in the S12 Road Experiment, An AASHO Satellite Test Road in South Africa
D. J. van Vuuren

Experimental sections of asphalt pavement totalling 2 km in length were incorporated during the construction of a heavily trafficked route between Johannesburg and Witbank with the object of assessing the suitability of various pavement materials and structures for carrying heavy traffic in the local environment. The experiment was planned as an AASHO Road Test satellite project to be used in an attempt to adapt the AASHO Road Test findings to South African conditions.

After two years of traffic, certain performance trends have become apparent. In particular, the early failure of a section with a cement-treated base, following the development of severe shrinkage cracking and pumping, has been closely followed. It is likely that at least 10 years will elapse before firm conclusions can be drawn on the performance of the remaining sections.

In order to obtain earlier results from road experiments of this type, a completely automatic heavy-vehicle simulator has been designed and constructed which is capable of applying 300 000 equivalent 80 kN axle load passes per day. The maximum wheel load is 80 kN, and the machine simulates the weaving action of normal traffic across the road. Initial results obtained with the simulator on the experimental sections are reported.

03076

Flexible Pavement Performance in New York
John M. Vyce

New York State recently completed an extensive investigation of flexible pavement performance. This study involved serviceability measurements on 175 pavements located throughout the state and subsequent comparisons with a number of design, operating, and environmental variables. The results are summarized here with emphasis on two areas:

1. The data are compared with AASHO Road Test results, and differences are discussed along with apparent causes.

2. Performance data are related to design criteria. The most important factor in determining proper asphalt thickness is rate of traffic loading, with climate a secondary influence. Soil support values had little influence on pavement performance and were excluded as a design factor. Graphs relating traffic to performance are presented, along with a design procedure developed using data from this study.

03077

On Structural Characteristics and Performance of the Calcareous-Soil-Sand-Asphalt Base Courses Used in Argentina
Laboratorio de Investigaciones Viales Facultad de Ingenieria-Universidad de Buenos Aries - Departamento de Tecnologia-Direccion Nacional de Vialidad-Buenos Aries, Argentina

The jobs of enlargement and strengthening of the highway network in the littoral region of Argentina, have always come across the problem of the high price and scarcity of conventional aggregates. This is due to the scanty production centres and to the need of carrying the material over distances sometimes over 250 miles. The above mentioned circumstances have brought about the need to use local aggregates which do not meet the quality requirements corresponding to the aggregates for conventional asphalt mixes particularly to asphalt concrete. On the basis of these non-conventional aggregates it has been necessary to develop asphalt mixes for the base courses for new pavements, especially for strengthening of roads which must be adapted to stand the extraordinary increase in load and frequency of vehicles registered in last decade. moreover, it has been necessary to estimate, based on experience, a criterion of the equivalences between these non-conventional mixes and the conventional ones, allowing the structural design of the new roads and of the strengthenings.

Among materials available, we have natural siliceous sands of fine and uniform gradation, which do not permit the obtention of asphalt mixes of adequate stability. We also have boring-pits of soils A-4 (AASHO) of the 3rd horizon. Their peculiarity is having undergone a not altogether developed process of calcification which determines the presence of varying percentages of soft and porous calcareous noduli. The mixture of calcareous soil, coarsely pulverized, with approximately equal amounts of sand, processed in the plants, shows 20% retain on sieve #4, dry way, whilst in wet sievage, the lumps of soil disintegrate and a percentage of passing #200 of about 30% is reached. The incorporation in hot of 8-9 per cent asphalt of penetration 70-100 originates the mixes called "calcareous-soil-sand-asphalt" widely used in Argentina as the base course in new pavements and strengthenings. Conventional aggregates are only used for the wearing course. The amount of the former mixture used in the last 15 years is estimated in 2.5 million tons.

We have studied the behaviour of the calcareous-soil-sand-asphalt mixes during the compaction process, both under laboratory (Marshall method) and field conditions. The job compaction initiated with pneumatic tyred equipment and completed with steel wheeled roller, determines densities corresponding to a laboratory compaction with approximately 20 Marshall blows on each face, yet, no consolidation under service is observed later. Simultaneously we have studied the mechanical characteristics in relation to compaction, especially the stiffness modulus calculated on the basis of stability and Marshall flow by the Nijboer formula.

Bearing in mind the composition of the mixture, we have studied its resistance to water, based on the swell test, as a function of the asphalt content and of the degree of compaction. Laboratory results confirm the performance and show that the fraction of calcareous soil has been adequately stabilized by the joint action of heat during the process of partial drying and that of the asphalt absorbed in the porosity inherent to the particles calcareous soil.

The triaxial test shows that the behaviour of the calcareous soil-sand-asphalt mix, under load, greatly depends on its high non-viscous cohesion, or Nijboer initial resistance (independent from the deformation rate, but depending on the temperature).

The work hypothesis that has uphold these studies and is confirmed by the experimental results, is that the structure of the calcareous-soil-sand-asphalt mixes is different from that of conventional mixes. In these, the finest fractions of the total aggregate are dispersed in the asphalt, constituting the binder medium covering the coarser fractions in the loose condition, and are displaced towards the voids between the particles of the granular structure formed b) the compaction process. In this way, the finest fractions do not reach a high densification condition, since the stresses determining compaction are mainly borne by the granular structure. In the calcareous soil-sand-asphalt mixes, the effective asphalt content is only sufficient to cover with thin coats the lerge surface area existing, and to partially occupy the void between the fine particles in the high degree of densification that these reach, because of directly bearing the compaction stresses, since there is no granular structure acting as a matrix. It is therefore understood that the coarser fractions (calcareous noduli and soil lumps) not hard enough, remain dispersed in the compacted asphalt mortar, in which there is a granular microstructure answering for the frictional resistance and especially for the non-viscous cohesion. The properties of this asphaltic mortar are the ones that govern the characteristics and behaviour of the calcareous soil-sand-asphalt mixes placed as base course.

The set of results snows that the quality criteria and demands adopted for the conventional asphalt mixes for base courses cannot be extrapolated to the calcareous soil-sand- asphalt mixes. The optimum job compaction corresponds to a mean density in the Marshall test with a number of blows between 15 and 20. The control of the increase in density as a function of time under traffic will be continued until the final density is reached. The variation of the stiffness modulus as a function of time under traffic shows, in every case, first a decrease of the modulus after 30 days and then an increase in the modulus at an age of 300 days under traffic.

This evolution may ue explained by the production of fines though granulometric degradation and their later incorporation to the asphalt binder. The coefficient of equivalence of the thicknesses of calcareous soil-sand-asphalt relative to a conventional material such as asphalt concrete, has been determined by the ratio of the R values of both materials proposed by Ruiz. The values found tend to a maximum. We intend to continue with periodical measurements in order to reach a long range comparative value of the behaviour of the calcareous soil-sand-asphalt, as compared with asphalt concrete, which will objectively back up the estimation of thickness as which should be used in the future.

03078

Sensitivity Analysis of Three Flexible Pavement Design Techniques
T. R. Buick, J. C. Oppenlander

To better understand the art and science of pavement design, three highway design techniques were studied to determine the relative effects of various design parameters on pavement thickness. The analysis phase of this investigation consists of formulating each technique into a comprehensive mathematical or graphical thickness model. An evaluation of the influences on thickness of the major design factors was accomplished by a sensitivity analysis with a theoretical and two practical measures of parameter importance.

The theoretical measure of parameter importance reveals considerable differences among techniques as to the process of resolving design thicknesses and to the relative theoretical influence of various parameters that estimate the same major design factors. However, the practical parameter importance measures, which account for variations in parameter values as well as the formulated parameter-thickness relationship, demonstrate a greater similarity in the importance of generic factors among the design methods. For flexible pavement design, traffic load and subgrade support are the more influential factors in the determination of pavement thickness.

03079

Output Measurements for Pavement Management Studies in Canada
Roads & Transportation Association of Canada, Pavement Design & Evaluation Committee

The Pavement Design and Evaluation of the Roads and Transportation Association of Canada has conducted extensive, nationwide studies of pavement performance for several years. The results have been widely applied to design purposes. In recent years, a pavement management system has been defined to provide a logical framework for the activities of the Committee.

A significant portion of these activities has been in the area of pavement output measurements. The paper summarizes this work. It is concluded that the present serviceability measure of Riding Comfort Index is one of the primary outputs that should be known on a mass inventory basis.

Procedures for acquiring such mass inventory data on Riding Comfort Index, using a Car Road Meter for estimating purposes, are outlined in the paper. The important considerations and limitations of the approach are discussed, and the extension of the approach through a photo inventory technique is briefly considered.

03080

The Catalogue of Structures of the Direction des Routes et de la Circulation Routiere Francaise (French Highways Authority)
M. Chantereau, Ph. Leger

Present methods of structural design, based on a combination of theoretical and empirical considerations, do not seem to be entirely satisfactory for several reasons:

- They very rarely take account of certain elements of "good practice" which are essential for the proper behaviour of pavements.

- They do not easily allow of extrapolation to pavements of a new type or to a different environment.

- They give the designer a fallacious impression of accuracy whereas in fact they are very imprecise and depend to the highest degree on the quality of the materials and their application.

Consequently we have turned in France to the idea of a catalogue of structures, giving possible structures for a certain number of categories of soil and traffic, and giving for these different solutions the advantages and drawbacks liable to be encountered either at the time of carrying out the work or during the life of the pavement. The catalogue also indicates the required composition of materials and the necessary conditions of performing the work, together with the characteristics of predictable non-destructive testing (deflexion, speed of wave propagation, etc...). Structures for overlaying of existing pavements are also included in the catalogue.

Where traffic is concerned, account has been taken only of heavy vehicles (without bringing in the notion of equivalent traffic), and 4 classes are proposed, each corresponding to an order of magnitude of the total heavy traffic which the pavement must be able to bear before being totally remade.

Subgrades have also been placed in 4 categories, on the basis of the U.S.C.S. classification and in certain cases additional geotechnical characteristics (index of plasticity, C.B.R. index) of hydraulic conditions (depth of the water table, drainage) and of depth of freezing.

In the case of overlaying, the subgrades categories are replaced by 4 other categories, defined in the light of deflexion (overall properties of the existing pavement), where necessary corrected in the case of particularly frost-susceptible soils, and in the light of the properties of the pavement courses (radius of curvature of the deflected pavement, pollution of courses, etc...).

The structures proposed are then designed taking account of:
- Existing theoretical elements (stress on the subgrade bending stress in bounded courses)
- Specific characteristics of the materials used (e.g. rigidity under relaxation or adaptation to minor settlement, the effects of temperature, etc...)
- Problems of construction (number of courses, compacting, roughness)
- Data available on existing pavements.

03081 **The Increase of Asphalt Topping Stability**
0. K. Dobozy, B. Bartha

We give account of a rather less regarded impairment of asphalt roads, of a decomposition of bitumen taking place at the building of casted or prefabricated asphalt toppings by the hot method which is a primary damage. We report on a process which enables to protect the toppings against this and another method against the secondary corrosion of asphalt caused by the chemical removal of snow and ice. We show the deterioration of asphalt toppings, to what extent it may be reduced and the stability of toppings increased by these processes.

03082 **Properties of Materials Used for Surfacing and Stabilized Base Structures of Pavements for Heavy Trafficked Roads**
N. V. Gorelyshev, V. N. Kononov

The large part of the USSR territory is notable for its continental and sharp continental climate. Even in the moderate climatic zone the year round temperature changes ere equal to 60 to 70 deg. C and in the eastern and northern regions they are as high as 80 to 90 deg. C. In some regions the transition of temperature over a zero point takes place up to 80 times. Such severe climatic conditions influence a pavement not less than traffic loads and imply the necessity of not only designing the depth of surface and base courses but also regarding their thermo-physical properties.

Till the end of 50's a two-layered bituminous concrete surfacing on a crushed stone base was prevailing as a pavement structure. The depth of the crushed stone base varied from 20 to 40 cm due to design loads. An additional (underlying) course was made of sand or gravel with the purpose of draining end protecting the subgrade against excessive freezing.

In 60's such structures had ceased complying with demands of ever- growing traffic due to gradual wear of crushed stone during deflections of bases and rapid loss of surface evenness. For heavy trafficked roads the pavement structures on bases only from stone materials stabilized with different binders were proposed. Whatever the type of a binder, all the above mixes are claimed to comply with one general demand: the mix grading must provide maximum density and shear resistance of the material in the base course.

The requirements of grading, strength and wear resistance of rock materials stabilized have been specified. Another general and obligatory requirement to all mixes is their frost resistance specified according to a climatic zone.

Depending on the type of a binder, the base course is of different deformability, crack resistance, elastic modulus, thermal conductivity, bearing and distributing capacities.

As far as deformability and crack resistance are concerned, the bases of bituminous mixes are the more preferable the more severe and continental the climate is. But even in the warm climate their advantages over other bases are beyond doubt.
The least deformability and crack resistance are inherent in the mixes in which the crushed stone materials are treated with small portions of cement. Even in cases of minor temperature changes the cement-bound bases show cracks.

The intermediate deformability, strength and distributing capacity are inherent in stone materials treated with granulated blast-furnace slag or a mixture of slag and fly-ash. The various bases for heavy trafficked roads are constructed of the above stabilized materials.

In this case the most typical structures of pavements are as follows:

A. - The two-layered bituminous concrete surfacing with the 9-10 cm overall thickness or single-layered bituminous concrete one 7-8 cm thick.
- The base of bituminous mix (with crushed stone of gravel) to be compacted in one lift 15-18 cm thick.
- The subbase of crushed limestone to be watered in course of rolling in 15-16 cm thick layer or ash-slag mixtures 15-16 cm thick.
- The draining layer made of sand, as a rule. The design-depth is due to the required water-thermal regime of the subgrade.

B.- The same surfacing as for the structure type A.
- The base of bitumen-coated crushed stone 8 cm thick (this structural layer is omitted in the regions of moderate and soft climates).
- The base (or the subbase) out of crushed stone or crushed gravel with the addition of 15 to 20% of granulated blast-furnace slag or of 4 to 6% of Portland cement. The depth of the layer is 20 to 25 cm.
- The draining course.

Such structures have proved to be unsettleable and crack-resistant. At the same time the procedure of compacting bituminous mixes in one layer up to 20 cm deep was developed.

The compositions and properties of bituminous concrete represent a particular problem. In the case of large loads end sharp changes of temperature and humidity bituminous concrete should meet high requirements of its strength, deformability and skid-resistance. With due regard for these requirements a new standard has been worked out.

03083 **Design of Flexible Pavements in Czechoslovakia; Recent Research Works**
I. Gschwendt, I. Poliacek

In 1961 a recommendation for the design of flexible pavements was presented for approval of the Central Road Administration in Slovakia. The design method is the result of the work on a research project performed by a team of research workers.

The method contains design principles used for selection of the structure and the total thickness of the pavement as well as the material and the thickness of the different layers. The total thickness is determined taking into consideration the protection of the pavement and subgrade against frost effects. In the design of the structure of the pavement the following factors are considered:
- the influence of traffic during the whole service life of the pavement
- the bearing capacity of the subgrade
- the characteristics of materials used in the pavement structure

- the mechanics of the behaviour of the pavement under a load and
- the method of construction.

The designed pavement is assessed with regard to the required performance characteristics (the service life) and the stresses to which the various layers will be subjected. The design criterion for serviceability is the deflection of the pavement. The stresses in the pavement are assessed according to the tensile (bending) stress arising from the action of a design load at the bottom of the surfacing or at the bottom of one of the base courses. In this case the criterion is the permissible tensile (bending) stress of the material.

When calculating the deflection and the stresses, the real pavement is simulated by an ideal three-layer system consisting of perfectly bonded layers of flexible materials. The elastic properties of the various materials are considered in design (table) values; the elastic modulus of the subgrade is derived from a CBR value established in the laboratory.

The correctness of the design can be checked by load bearing tests performed on the finished pavement. In view of the fact that the structural design uses design values instead of real (instantaneous) values of the deformation properties of the materials in the pavement and the subgrade, the deformations measured in the bearing test will be lower than the calculated ones and similarly, the real stresses in the pavement will differ from those established by a calculation.

03084 **Current Design and Construction Procedures in Switzerland**
U. Kunz, M. Blumer

Various peculiarities such as great frost depth, heterogeneous soil, unsatisfactory topographical conditions and the large variety of available materials, excludes the unlimited application of foreign results and procedures. The tendency in Switzerland is towards empirical design methods which are suited to the specific conditions of the site and which take own experience into consideration. Standards for routine designing, described in this report, were published in 1971.

Systematic observation on the performance of roads during the periods of frost and thaw have shown that:
1. Large deformations through frost-heave can be avoided if the depth of the pavement structure amounts to at least 50% of the frost depth.
2. Decrease in stability during the thaw period is only considerable if frost has clearly penetrated the roadbed.

On sufficiently designed roads, influence of frost may be neglected as long as the design is based on the most unfavourable stability strength during the thaw period. Exceptions are highly frost-sensitive soils with equally unsatisfactory environmental conditions. In such cases measures must be taken to avoid frost damage, e.g. replacement of material, stabilisation of the soil foundation layer or the inclusion of a heat insulation layer on the subgrade.

In order to lay down thickness equivalency values for currently used materials in Switzerland, the strength of various asphaltic concretes was compared with gravel on a test road. The results showed that the relative strength not only depended on the characteristics of the material but also on the strength of the layers underneath and the thickness. With the aid of thickness equivalency values which only take consideration of the characteristics of the materials but not of the other facts it is barely possible to compare the strength of various materials. Diagrams, however, are suitable for this purpose (e.g. fig. 3 of this report).

Designing is undertaken step by step according to the suggested method:

1. Determination of the soil (frost sensitiveness) and environmental conditions (depth of frost and hydrological conditions). Decision on whether construction can be carried out on the natural soil or whether constructional measures must first be undertaken to avoid frost damage (fig. 2).

2. Determination of the type and thickness of the base course in function of soil stability (CBR value) and the daily equivalent 18-kip axle loads (TF). The base is to form a permanent stable support for the bituminous surface; it may be made up of gravel or stabilised material (fig. 4).

3. Determination of the minimum thickness of asphaltic concrete with crushed aggregates as a function of the daily equivalent 18-kip axle loads (TF). It must be assured that the strength is sufficient even following a great number of axle load passings to avoid cracking through frost or fatigue (fig. 4).

At the conclusion of the report, a method for strengthening of existing roads is described. It starts by determining the Spring deflection permitted (d sub crit) in function of the number of axle load passings (N) during the design period. This is followed by measuring the existing Spring deflections (d sub 0) on the road and extracting from a diagram the required thickness of the bituminous cover (fig. 6).

03085 **The Current Design Procedure for Flexible Pavements in Britain**
J. V. Leigh, D. Croney

The paper first reviews briefly the development of design standards for flexible road pavements prior to 1960.

Since 1960 recommended standards of design for such pavements have been given in the Road Research Laboratory's Road Note No. 29 (A guide to the structural design of flexible and rigid pavements for new roads). The designs, which cater for all classes of road from motorways to those associated with housing estate developments, have been widely accepted throughout the country. They are based almost entirely on the performance of a large number of experimental roads constructed in England, Scotland and Wales.

Early editions of the Road Note classified traffic in terms of the number of commercial vehicles per day likely to be using the road 20 years after construction. Six traffic categories only were considered, leading to discontinuities of design between the various categories. As more information has become available from the road experiments some refinements of design have become possible.

In the 1970 edition of the Road Note traffic is expressed in terms of the number of 18,000 lb (8200 kg) axles to be carried by the pavement during the chosen design life. Axle-load spectra studied on typical roads using permanently installed weighbridges have been converted to equivalent 18,000 lb (8200 kg) axles using published AASHO equivalence factors.

An intensive analysis of the results from the road experiment has enabled continuous curves to be developed relating the cumulative number of standard 18,000 lb axles to be carried with the thicknesses of subbase, base and surfacing. The design charts are reproduced in the paper.

03086 **Structural Design of Full-Depth-Asphalt-Pavements and Field Tests in Comparison with German Standardized Asphalt Pavements**

G. Leykauf, W. J. Kawohl

The "Institut fur Bau von Landverkehrswegen" of the Technical University Munich has carried out upon order of "Mobil Oil AG" investigations to determine the necessary thickness and the fatigue life of "Full-Depth" asphalt pavements.

In the scope of a theoretical investigation "Full-Depth" constructions have been designed in analogy to the German Standardization of asphalt pavements for five traffic classifications from a very slight traffic to a very heavy one, applying elastic theory to multi-layer systems. The thickness of Full-Depth constructions was determined in a way that the vertical stressing on subgrade is the same as for the corresponding standardized pavements with an asphalt base course of round aggregate. The stressing was computed by the equations of Odemark and Boussinesq, whereby asphalt pavements of all constructions have been divided into several layers with different dynamic moduli of elasticity corresponding to the average temperature in these layers. To allow an economical use of the "Full-Depth" constructions the necessary thickness was computed for three different bearing capacities of subgrade.

Also for these determined "Full-Depth" constructions the radial stressing at the bottom of the asphalt pavements were calculated according to seasonal influences by aid of the tables of Jones; in connection with the hypothesis of Miner it is possible to predict the cumulative stressing and the expected fatigue life. By a comparison with the corresponding standardized constructions it is evident that "Full-Depth" constructions are expected to have a longer fatigue life.

Field tests were carried out on two test sections, one with an asphalt pavement using normal design standards for slight traffic and a bituminous round aggregate base (Field 8) and the other with a Full-Depth asphalt pavement on a poor subgrade and for slight traffic as designed by the institute (Field 9) .

In both test fields the clear dependence of temperature could be observed by measurements of strains and deflections. The increased stiffness or load-carrying capability of the Full-Depth asphalt pavement at rising temperatures was proved. The Full-Depth asphalt pavement design can therefore be expected to have a longer fatigue life. The temperatures measured during the 1970/71 winter revealed that the Full-Depth asphalt pavement had a greater thermal insulating effect than granular base.

The field tests showed that the Full-Depth method is superior to the standardized asphalt pavement construction in load-carrying capacity. In spite of the extreme susceptibility of the subgrade to frost damage, frost heave occurred to almost the same extent in both sections, also the heave which occurred in Field 9 was much more uniform and there was less surface irregularity or distortion.

03087 **Developing an Operational Pavement Design and Management System and Updating it with Elastic Theory**

B. Frank McCullough, W. Ronald Hudson, Ramesh K. Kher

Pavement design is a complex soil structure interaction problem involving variables in the broad categories of load, environment, construction, maintenance, materials, economics, geometric configuration, and performance. A great deal of effort has been expended in the study of pavement behavior and performance, including full-scale testing such as the AASHO Road Test. Unfortunately, no long-term coordinated effort has been made to develop comprehensive methods of pavement design and management. Governmental agencies involved with highways are usually divided administratively into design, construction, and maintenance sections. This typically results in dissection of the physical problem with little or no attention paid to the interrelationship between design, construction, maintenance, and management.

The general format of most existing procedures for pavement design revolves around the determination of layer thicknesses. Other design details are subsequently adjusted in accordance with these thicknesses. Details such as pavement type, thicknesses and schedules of overlays, maintenance and seal coat requirements, traffic handling during maintenance operations, and selection of the optimum design strategy are usually never considered in present design methods.

This paper concerns a systems method of pavement design and management which uses a computer to analyze many phases of the pavement design problem. Two major parts essential to pavement system development are included:
(1) an initial system which actually works and which can be used for initial design and further study, and
(2) a concept and functional method for continuous study and updating of the system as required.

The program presented herein used over 50 input variables and analyzes a great number of possible solutions, generated within the boundary constraints. The output is an ordered set of pavement design strategies which can be used by the administrator in making a rational design decision.

An important part of any pavement design system involves upgrading it to include the best possible technology. The feasibility of upgrading the working systems model is demonstrated through an example whereby the structural subsystem of the design method is improved using elastic layer theory, fatigue concepts, and stochastic variations of material properties. A new mechanistic model is developed, based on the primary distress manifestation of cracking. This model will replace the empirical relationship used at present to simulate a gross transformation between the input variables and the performance of a pavement.

03088 **Structural and Mixture Design of Low Volume Roads Using the Elastic Theory**

R. E. Root, E. L. Skok jr., D. L. Jones

The purpose of this paper is to establish mixture and thickness designs for materials to be stabilized in place on several low volume U.S. Forest Service Roads. The results of a repeated load triaxial compression test in terms of resistance to permanent deformation are used to establish appropriate mixture designs.

Thickness designs are established by the elastic theory using the stress-strain properties of the materials determined

from the repeated load triaxial compression test and an appropriate failure criteria. The stress-strain properties were defined for one temperature (75F) and one loading time (1 sec) in order to reduce the amount of testing required. The failure criteria used, consists of limiting the vertical strain at the top of the embankment and the tensile strain at the bottom of the stabilized layer. These criteria were adopted from the work of others and applied to the pavement system being studied. Several assumptions were made in order to use these criteria with the limited testing schedule used. A thickness design curve is developed using an analysis of the elastic properties of the materials by the Chevron N-Layer Elastic Systems Program and the adopted failure criteria. Designs are established for three low volume roads using the developed design curve.

It is tentatively planned to use one of the designs developed in this study for the construction of a test road. The variables to be studied from the test road include: asphalt type, asphalt content and thickness of the stabilized layer. The test road will be instrumented to provide measurements of the critical parameters defined by this study.

03089 **Evaluation and Revision of the AASHO Interim Design Guide for Asphalt Pavements**
B. A. Vallerga, C. J. Van Til

A major objective of the AASHO Road Test was to provide information for use in developing pavement design criteria and pavement design procedures. Following completion of the Test, AASHO developed the Interim Design Guide for Flexible Pavement Structures. Details of the development of this Guide were presented to the 1962 conference. Since that time some 32 of the 52 state highway departments have reported making direct use of it, either in whole or in part. Of the states not reporting direct use, some have made some indirect use and others plan to attempt to adapt them to their use.

Because of the extensive use which has been made of this design guide, and the fact that no revisions had been made since originally issued, National Cooperative Highway Research Program Project 1-11 was initiated in 1967 to develop information for evaluating and preparing recommendations for revising the Guide. The initial effort in the first phase of this project was submitting to the state highway agencies a comprehensive request for information form consisting of 72 questions prepared to elicit specific pertinent information relative to procedures currently being used for design of flexible, rigid, and overlay pavements. Also included were theoretical analyses of the significance of the variables in the design procedure, and a comparison of the design procedures with theoretical relationships developed through recent research efforts by agencies engaged in the study of theoretical aspects of highway materials and design. The results of the first phase of this project are presented in the form of a summary of the significant findings and conclusions.

Based on the results of the first phase, an implementation phase was instituted with the objective of preparing a revised guide. This revised guide was presented to the AASHO Design Committee for their consideration. Although the revisions made no changes in the basic design equation or in the design procedure, considerable explanatory and background material was added for clarification and for assistance in selection of the appropriate values of the design parameters. A brief description of the most significant additions made in the draft of the revised guide is presented.

03090 **Theoretical and Practical Advantages of Single-Pass Construction of Thick Bituminous Road Courses**
R. N. Varlan

Slab effect of the bituminous road courses over a certain thickness and the good behaviour under the traffic charges of the flexible pavement structures with great thickness of the asphalt layers, have been on the one hand proved experimentally by full-scale teats (e.g. WASHO-Road Test and AASHO-Road Test) and, on the other hand, demonstrated from some theoretical studies (e.g. Jeuffroy-Bachelez's method) already for a long time.

However, the single-pass construction of the thick bituminous courses and, especially, of the road bases which reach today usually thicknesses of 12 - 20 cm, has been applied much later, although the advantages for the practice of the utilization of such technology are not negligible. From theoretical view-point can be also demonstrated the improvement of the stress-strain conditions in the road structure.

This paper describes briefly, in its first part, the manner by which has been build in Romania, as far back as in 1965, a bituminous road base with a great thickness (14 cm) spreaded and compacted in a single-pass with medium capacity finishers (80 to/h) made in Germany. In the paper are enumerated the practical advantages obtained in the construction site and are done comparisons with the knowledges revealed in other studies published in the highway literature referring to some similar realizations (e.g. from Germany and Great Britain).

In the second part of the paper, it tries to show by theoretical way, the improvement of the stress-strain distribution in the road structure and, consequently, the increase of the road life, owing to the utilization of the thick bituminous layers. In this scope, the road structure is considered as a three-layer medium and are utilised the Jeuffroy-Bachelez's, Jones-Peattie's, and Shell's methods, transposed in some original graphics, in order to permit to set off the rates variation of the tensile stress at the base of the upper layer (sigma sub t i), of the vertical stress at the subgrade level (sigma sub z) and of the deflection at the surface course (w), for the analyzed three-layered road structures.

From those presented, result some conclusions in connection with the incontestable advantages of the single-pass construction technology and the general utilization of the thick bituminous road courses.

The elaborated graphics can be also utilized for the structural design of three-layered flexible pavements.

03091 **Design and Dimensions of Standardised Bituminous Pavements in the Federal Republic of Germany - Data, Requirements, Performance, Developments**
Heinrich Vogt, Peter von Becker

The paper presents a survey of current practice in using standardised bituminous road constructions in West Germany. Data, requirements and wearing qualities of bituminous mixtures and road constructions are laid down in Technical Standards and Guidelines. They permit a large number of different base constructions using hot mixed bituminous material.

Methods for classifying traffic and for determining the type and thickness of construction needed for each class are discussed, as are the standardised thickness for surface and base courses. The layer equivalencies of different base

materials are discussed. The five standard construction types using bituminous mixtures are presented together with the requirements concerning subsoil, subgrade and frost protection course for standardised pavements.

The paper further discusses the bearing capacity of road base and surfacing and examines the relation between construction, live-load and road serviceability. Research work carried out on test sections of standardised pavements is reported as well as theoretical considerations. Suggestions are made for amending and improving some of the standards.

03092

Danish Experiments with the French Falling Weight Deflectometer
A. Bohn, P. Ullidtz, R. Stubstad, A. Sorenson

The falling weight deflectometer is a portable apparatus used for measuring the deflection of a road surface under the influence of a load pulse of very short time duration. This pulse simulates a fast moving wheel load, and it can be adjusted to correspond to any desired wheel load of 5 tons (5000 kp) or less. The unit is built into a trailer frame, which is easily pulled by a passenger automobile. To date, about 20 falling weight deflectometers have been produced in Denmark.

The validity of comparing the effect of the falling weight to the effect of a moving wheel load has been investigated by two means, both of which showed good correlation between the two effects. One set of measurements was undertaken in Holland, where photo-electric equipment was used to measure the deflection due to a passing wheel load. Another set of measurements was undertaken in Denmark, using an accelerometer. The acceleration signal was integrated twice with an analog integrator to obtain the deflection in question.

Static and dynamic surface deflection tests have shown poor correlation to each other, especially for roads with thick asphalt concrete layers. Investigations undertaken on a Danish experimental road, on the other hand, showed good correlation between dynamic deflection measurements and the corresponding theoretical elastic deflection values.

The asphalt concrete moduli used in these theoretical calculations were the results of dynamic three-point bending tests. The moduli of the unbound layers were found by low frequency sound wave measurements taken on-site.

Curves are shown which allow conversion of measured deflections from an arbitrary temperature between 5°C and 30°C to the corresponding deflections at 20°C (standard temperature). The 20°C curve can then be used to analyse certain limiting criteria. The limiting criteria are the strain in the bottom of the asphalt concrete layer and the verticle stress on the subgrade. These can be set to whatever values are deemed reasonable at the 20°C standard temperature. Finally, the diagrams can be used to help find the necessary thickness of a possible additional asphalt concrete reinforcement layer.

03093

Study of Some Aspects of Strengthening Thin Concrete Pavements with Flexible Overlays
Mittar P. Dhir

03093

Reported in this paper is a study on the strengthening with flexible overlays of thin concrete highway pavements existing in India. Concrete panels of 10 ft. by 10 ft. by 4 in. were cast indoors with typical ground support conditions. Strain gauges were fixed to their under-faces by mounting the gauges on precast concrete blocks which were made integral with the slab concrete. Granular overlays of 3, 6 and 9 in. W.B.M. were constructed successively on one panel for testing, and similarly bituminous overlays of 2, 4 and 6 in. A.C. were laid on the other. Static load tests were carried out at interior, edge and corner positions using 12-in, diameter steel plates with loads applied up to 9000 lbs. Strains and surface deflections were measured.

The load test data show that flexible overlays do bring about reduction in load stress in concrete slab but that reduction is relatively limited. Broadly speaking, 9-in. W.B.M. overlay or 6-in. A.C. overlay reduces the load stress to about 60 percent for all the three load positions. Analysis of the pavement as an elastic layered system corroborates the test measurements and indicates that even 4-in, concrete slab acts as quite a rigid base. Test data show that the equivalent angle of load dispersion for W.B.M. overlays increases from 33°-34° for interior loading to 37°-38° for edge loading to 45°-47° for corner loading. The corresponding values for A.C. overlays are 45°, 49°-51° and 51°-53°. One inch of A.C. overlay is seen to be equivalent to 1.3-1.7 in. of W.B.M. overlay.

Test data were also developed through measurements on outdoor sections on the effect of flexible overlays on temperature differential in concrete slab. The data show that the differential is reduced to about 50 percent by +4 in. A.C. overlay and to about 40 percent by +6 in. W.B.M. overlay.

The study indicates that 4-in. concrete pavement cannot be saved from distress with reasonable thicknesses of flexible overlays under long term application of 9000-lb wheel load. Where thick subbases already exist, as for most of such roads in India, it would appear desirable to provide the flexible overlay from the point of flexible pavement requirements, keeping reflection cracking, etc. in view. Measures to take the operation of loads away from the inside of the concrete edges would go to enhance the life of concrete slab.

Reported in the paper are also broad indications available from 5-year performance study of about 50 different specifications of flexible overlays laid as an experiment on sections with cracked and uncracked concrete slabs. In the case of uncracked slabs, reflection cracking has developed in overlays of up to 6 in. thickness. There is as yet no reflection cracking in +4.5 in. overlays on cracked slabs. Asphaltic concrete, with a high binder content, has shown good resistance to reflection cracking.

03094

Pavement Overlaying in France - Organization - Set Up
B. Fauveau, M. Siffert

1 - The first part of the communication comprises a general description of the organization of the technical highway services in France, and the original organization set up in France, and which has been in operation since 1964, to cope with the considerable increase in the need for pavement overlaying.

2 - The second part contains a detailed description of the organization of pavement overlay teems (P.A.R.'s) and of the

Coordinating Centre. An organization chart is presented, and the authors define the missions of these bodies as they were originally conceived. The results achieved during the first five years of operation of the P.A.R.'s and the Coordinating Centre are given.

3 - In the light of the missions assigned to P.A.R.'s and the necessity of an evolution, the roles of the different services involved in the implementing of pavement overlay projects are than analysed. The current evolution and the predictable evolution in the near future are presented in the light of the extent of the demands which arise.

4 - A more detailed analysis of an overlay project, from its original conception through its implementation to follow-up observations, gives a clear picture of the interrelations between the various services concerned with overlays. This analysis reviews the resources available to the Administration for planning and following up its project and drawing useful information from it.

Continuous measurement methods (deflexions, roughness and skidding resistance) provide elements for assessing the quality of the work carried out and how it stands up to conditions of use over a period of time. An overlaid pavement must possess characteristics such that it comes up to what the user expects of it; operations of the "half-way" type must be practically done away with, and curative maintenance must be replaced by preventive maintenance.

03095 **The Development of Overlay Design Procedures Based on the Application of Elastic Theory**
M. C. Grant, R. N. Walker

In many cases it is economical and convenient to improve the structural condition of a pavement by means of an asphalt overlay. A number of different methods can be used for the design of the overlay, one of the most popular being based on deflection measurements and limiting deflection criteria. New methods based on a structural design approach have been proposed by various investigators. One of the difficulties of this approach is the measurement of the moduli of the various pavement layers to use in the theoretical calculations.

This paper presents two new charts for designing overlays developed from the results of a theoretical analysis of model pavements using linear elastic theory. The one chart is used to determine the thickness of overlay required to reduce the deflection to the design limit. Since this chart was developed using a dual-load configuration which closely simulates that used in the Benkelman beam deflection test procedure, it is believed that it will give more accurate results than existing charts developed from considerations of a single loaded area. It is proposed that design deflection limits for overlays constructed on asphalt surfaced roads with granular bases be obtained from the deflection-load repetition relationship developed by the Asphalt Institute, and the assumption is made that this will limit distortion to an acceptable degree during the design period. The other chart is designed to eliminate cracking of the overlay and gives the relationship between radius of curvature and tensile strain in the asphalt layer for various thicknesses of asphalt. It is concluded that the use of these charts could be useful for designing overlays in cases where it is necessary to use simple evaluation techniques and simple overlay design procedures. However, it is shown that the stress-dependency of materials in the existing pavement can have a significant effect on the relationships established, and this can only be taken into account if more sophisticated testing and analysis procedures are used.

Two simple methods are described for measuring the in-situ moduli of pavement layers. The first involves measurement of both deflection and radius of curvature, and on roads with thin surfacings enables estimations to be made of the base/subgrade modular ratio and of the base modulus. It is concluded that this information would be of particular value when having to make a decision on whether it would be worthwhile improving a road by means of an asphalt overlay.

The second method uses measurements of the deflection at various depths within the pavement structure using a modified Benkelman beam procedure. This not only enables the vertical strains at any point to be calculated (from the change in deflection within a finite depth), but also enables the moduli of the various materials to be calculated using elastic theory. In this way any weak layers within the structure can be identified or the effect of an overlay or new loading condition on the vertical strains within the structure can be determined. An example of the use of the method is given in the design of an overlay to strengthen an airfield runway for the coming of Boeing 747 aircraft.

03096 **Dynamic Non-Destructive Testing of Pavements in France**
R. Guillemin, J. C. Gramsammer

Nine non-destructive testing equipments are now in use in the French Laboratoires des Ponts et Chaussées. They were first used in the course of the year 1966.

This paper contains two main chapters. The first accounts for the various techniques of exploitation of the experimental results leading to the determination of the elastic and geometric characteristics of pavements. The second consists in a series of concrete examples giving a general survey of the applications of non-destructive testing in the field of pavements.

Chapter II: Dynamic non-destructive testing made with the light vibrator consists mainly in determining the phase curve of a vibration of known frequency in order to obtain the dispersion curve which gives the relation between the propagation velocity and the wavelength. The analysis of the dispersion curve leads to the elastic and geometric parameters of the structure.

It is shown in this paper that very often the experimental phase curves present periodical oscillations; the latter are due to interference between two or more waves of the same frequency. Several techniques are developed either graphic or with spectral analysis, it is then possible to separate the waves and identify them.

The various techniques of interpretation of the dispersion curves are examined. Since the light vibrator is systematically used in France these techniques are conditioned by the fact that they have to be easy to use and quick to get under way. Several graphical methods for interpretation of the results concerning the structures with one or two surface layers are described.

Chapter III: The first examples deal with the study of the setting of materials treated with hydraulic binders. It will be

particularly seen in the first example that it is possible with dynamic non-destructive testing to detect several inadequacies in their young age.

Several examples are described concerning a posteriori controls either on new pavements or on reinforcements. The last two examples concern particular studies in which the light vibrator was appreciated. one of them deals with the study of the behaviour of a pavement submitted to frost. It is obvious with this technique that the pavement is deeply weakened during the thawing period. The other example is a study on the influence of temperature on the viscoelastic properties of an asphaltic concrete, the main result being that on one hand the elasticity assumptions remain valid in the usual frequency and temperature fields and on the other hand a relation is given between the Rayleigh speed of asphaltic concrete in function of temperature.

03097

The Use of Gap Graded Mixes in Asphalt Overlay
K. Knight, P. Groth, F. M. L. Akeroyd

A type of gap graded mix intermediate between continuously graded asphalt concrete and a high sand content gap graded rolled asphalt has been used in the Natal asphalt overlay programme with good results. A full scale overlay experiment at Umbumbulu, trial sections at Tugela and a survey of some 150 miles of overlay already completed are described and their performance evaluated.

The mix used appears to give good performance in layers thinner than called for in terms of current design methods. Explanations are given for its apparently superior flexibility and crack resistance over the more traditional asphalt concrete.

Indirect tensile strength tests have been undertaken, which indicate a high tensile strength for this mix in the temperature ranges experienced in Natal.

Economics of stage construction are possible because of the good performance of thin (less than 4") layers of gap graded mix even over old distressed pavements of high deflection levels.

03098

The Use of Deflection Measurements for the Structural Design and Supervision of Pavements
Ph. Leger, P. Autret

PHYSICAL INTERPRETATION OF DEFLEXION
The value of the deflexion is a convenient though not exhaustive means of judging the quality of a pavement and of summarily evaluating the structure (type of material and thickness) of the overlay which may be necessary.

It is accepted by some engineers that the fatigue of a subgrade, i.e., its settlement under a given number of loadings, depends to a first approximation only on the vertical elastic deformation of the soil when a load passes over it; examination of the results of calculations on two-course pavements has shown that the ratio of the deflexion at the top of the soil mass to the deformation at the interface remains practically independent of the elastic moduli, provided that the thickness of the top course does not vary.

This leads to the assumption that deflexion is a valid criterion of longevity in the case of pavements which deteriorate mainly as a result of inadequacy of bearing capacity of the underlying soil.

Moreover, the application of the theory of elasticity shows that in an elastic two-course pavement the deflexion is roughly proportional to the deformation of maximum tensile stress as the interface of the two courses. Consequently, in the case of a two-course pavement and assuming a failure by excessive deformation of the upper course, the deflexion suffices to reflect the criterion of the limit of admissible tensile stresses within a certain range of thickness of the course.

DIFFICULTY OF MEASUREMENT - IMPERFECTION AND INADEQUACIES
In the case of granular course, deflexion is not an indication of the evolution of deterioration. Certain processes of deterioration have no connection with deflexion. The measurement may vary considerably with the time of year, weather conditions, and conditions of loading (speed, the distribution of stresses under the wheels of vehicles, etc.).

Very often the value of the deflexion does not alone suffice to reflect the mechanical behavior of the pavement, and gives no indication of the condition of the surface.

If deflexion is taken as a criterion of failure, i.e., a limiting value corresponding to a given number of loads, this limit (which varies with the type of structure) remains to be specified.

RELATION WITH OTHER TEST
The paper deals with these other issues:

1/ The concept of radius of curvature.
2/ Contribution to the determination of a limiting threshold of deflexion.
3/ Analysis of structures before overlaying.

03099

Deflection Criteria for Flexible Pavements and the Design of Overlays
N. W. Lister

The long-term performance of flexible pavements can be determined by the magnitude of the transient deflections which occur under traffic. A continuous programme of deflection measurements extending over fifteen years has been carried out on the full-scale road experiments in flexible construction built by the Road Research Laboratory. Over 300 experimental sections and in addition 30 lengths of major road whose construction is of particular interest have been tested annually with the Benkelman Deflection Beam under a wheel-load of 3175 kg (7000 lb). The measured deflections have been corrected for the influence of temperature on the stiffness of the bituminous components, and 'standard' deflections at 20°C have been related (a) to the age of the road expressed in terms of the cumulative total of equivalent standard 8200 kg (18,000 lb) axle loads carried, and (b) to the condition of the pavement in terms of rutting and cracking. The deflection histories thus derived enable the development of critical conditions within the pavement when strengthening of the road would be most appropriate, to be related to deflection behaviour under traffic.

Well-defined relations between standard deflection values measured early in the life of pavements and their lives have been established. For lives exceeding 10^6 standard axles they are of the form:

life = 1 / (deflection)^3

For pavements with crushed stone, rolled asphalt and coated macadam bases under rolled asphalt surfacings the curves are similar, but acceptable deflection levels are lower on pavements with cemented bases.

Charts making due allowance for the slow increase in deflection which takes place during the life of a pavement are being prepared to enable prediction of road performance from deflection values measured at any time to be made. An example is given.

Overlays have been applied to certain full-scale road experiments as they have been retired from service and deflection studies have been continued. The behaviour of overlays laid to strengthen normal roads is being similarly studied. Relations have been derived for the reduction in deflection brought about by overlays of different thicknesses applied to various types of pavement on different subgrades. The results have been compared with those predicted from the application of multi-layer elastic theory. Deflection histories of overlaid pavements have been used to prepare recommendations for overlay thicknesses to achieve any required extension of pavement life. The implementation of recommendations for pavement strengthening is considered.

03100

Test Sections
R. Sauterey, M. Siffert

The growing economic importance of road traffic in modern life places fresh responsibilities on the highway engineer with regard to the structural design and overlaying of pavements. Purely theoretical or purely empirical hypotheses are no longer satisfactory for insuring that the pavement shall have a suitable length of life without entailing excessive costs. Consequently, existing hypotheses have to be permanently checked and corrected, and working methods and material must be adapted to the new demands of road traffic. In short we have to define technically and economically optimal structures.

In the context of the program undertaken by the Laboratoire Central des Ponts et Chaussees (Central laboratory of bridges and highways) for the overlaying and structural design of pavements it was seen to be necessary to organize a program of studies relating to about thirty test sections; these sections are representative of current technology applied in accordance with directives which specify thicknesses, the quality of materials and the conditions of their application.

These sections, which are located in various regions of France are studied by regional laboratories which possess adequate resources for non-destructive testing, and whose engineers are in permanent liaison with the contractors concerned. This article describes the conditions under which this program has been laid down, the different techniques represented and the principal results obtained.

The need to have a thorough knowledge of the pavement before overlaying and especially of the conditions of production of the materials involved, together with the way in which the work itself is performed were all seen immediately to be essential. The principal measurements made after completion of the work may be listed as follows:
- Measurements of deformability: Lacroix deflectograph, Benkelman beam, detectors, measurement of radius of curvature and evaluation of the Rd product; measurements of deformation of the longitudinal profile and the transverse profile.
- Use of the light vibrator: a non-destructive method for assessing the rigidity of materials and detecting doubtful zones.
- Reconnaissance of the structure and its evolution by means of core sampling and exploratory drilling and analysis of samples of materials.
- Assessment of the importance of the effects of heavy traffic on the pavements concerned.

Apart from the assessment of the immediate quality of the overlay and its evolution over a period of time, this test program has made it possible to develop certain procedures and to establish correlations betwen certain measurements; it has also enabled us to study certain deteriorations and to seek their causes; to study the influence of environmental factors (traffic, weather conditions, drainage, shoulders, hard shoulders etc.) on the behavior of the pavement. The initial results obtained enable us to give a fresh orientation to certain hypotheses relating to the conditions of production of materials and to the execution of the work, the thicknesses of materials applied etc.

The lessons drawn from this study should be immediately applicable to the improvement and development of highway techniques.

03101

Applications of a Theoretical Procedure to Airfield Pavement Evaluation and Overlay Design
C. J. Van Til, B. A. Vallerga

The results of research on theoretical aspects of pavement design and performance have been applied successfully to the solution of practical problems of evaluation of load-carrying capacity of existing pavements and the design of strengthening overlays. Procedures used included the determination of a modulus of resilience by cyclic laboratory triaxial tests of undisturbed samples of pavement component materials and underlying layers of soils; the measurement of deflections in the field; the verification of modular values by comparing measured and computed values of deflection; the establishment of evaluation and design criteria in terms of limiting values of stress or strain which are specifically applicable to pavement, traffic, and environmental conditions at the site; and the preparation of overlay design curves based on these limiting values of stress or strain and on a fatigue curve developed from past traffic and pavement performance at the site.

The procedures used are presented in the form of brief descriptions of their applications to investigations conducted at three airports used by jet aircraft: Salt Lake City Municipal Airport, San Francisco International Airport, and Fairbanks International Airport. These examples serve to show the evolution of the procedure from the early applications at Salt Lake City in 1967 to the Fairbanks investigation completed in 1971. Application to a wide range of conditions is demonstrated by the fact that traffic volumes varied from very heavy on the multiple runways at San Francisco, moderate at Salt Lake City, and relatively light at Fairbanks; and that supporting soils and climate varied from soft, compressive "bay muds" and a mild climate at San Francisco, to coarser-grained soils and severe climate at Fairbanks. An investigation procedure is presented which is based on experience to date. Further developments in the procedures are

expected with future usage.

03102 **3rd International Conference on Asphalt Pavements - Volume II - Preliminary pages and Table of Contents**
n/a

03103 **Report of Session I - Factors Influencing the Design of Flexible Pavements**
Chairman: Alfredo Pinilla

A detailed discussion of the papers presented in the session, follows:

Chairman's Opening Address
Alfredo Pinilla
President, Permanent Commission of Asphalt Buenos Aires, Argentina

It is an honor for me to have the opportunity of participating in this First Session of the Third International Conference on the Structural Design of Asphalt Pavements.

First of all I would like to congratulate The University of Michigan, the Transport and Road Research Laboratory, The Asphalt Institute and Eurobitume for the organization and arrangements of this Conference. This represents quite an effort, and is of positive benefit to all of us in the development of new ideas and research related to structural design of asphalt pavements. On this occasion, I would also thank the organizers for having invited me to act as Chairman of this First Session.

At the present Conference, as at the two previous ones, an important number of papers have been presented for discussion by over a hundred specialists from many countries for the purpose of improving basic theoretical and practical field research. The fundamental purpose of this Conference is to bridge the gap between theory and practice in bituminous structure design.

During this week over seven hundred specialists in asphalt technology from all over the world will exchange information and research results pertaining to this scientific area. There will be special emphasis on better scientific and rational design for flexible pavement structures. This is in order to provide engineers with new accurate methods and procedures for the design and construction of new roads, also for strengthening old pavements and generally improving methods for future research.

Et cetera. . .

03104 **Report of Session II - Properties of Materials**
Chairman: J.E. Buchanan

A detailed discussion of the papers presented in the session, follows:

Chairman's Opening Address
J.E. Buchanan
Past President, The Asphalt Institute
College Park, Maryland, U.S.A.

Ladies and gentlemen. I invite your attention to the two pages in the printed program which describe Session II of this Conference. I have the honor and duty to serve as Chairman. My purpose will be to facilitate the meeting for maximum benefit to everyone. All of us at this Conference well know the fundamental and universal value of roads to all people and all countries in the world whether those countries be under-developed or advanced in economic status. Some 40 countries are represented here today. We also know, without belaboring the point, that asphalt is highly useful in the first stages of road improvement, to provide initial access to new areas. Asphalt is equally useful in upgrading roads as development occurs. Then comes the problem of providing asphalt pavements for heavy-duty usage, represented by present and future motor vehicles and airplane traffic.

This International Conference is focused on the structural design of asphalt pavements having in mind principally the design of pavements for heavy traffic duty. This special focus is not to be interpreted as implying any lack of appreciation of the importance of the simpler types of asphalt-surfaced roads. Certainly not. The basic fact is that the lower and intermediate types do not have the analytical and design challenges inherent in the problem of designing heavy-duty asphalt pavements.

We harbor the idea that the design of heavy-duty asphalt pavements should be susceptible to analytical and engineering procedures with a degree of reliability achieved in the design of structures made of steel and concrete.

Et cetera . . .

03105 **Report of Session III - Design Theory**
Chairman: Egil Nakkel

A detailed discussion of the papers presented in the session, follows:

Chairman's Opening Address
Egil Nakkel
General Director, Department of Road Construction Techniques
Federal Road Research Institute
Cologne, Germany

Ladies and Gentlemen. In opening the Third Session of this Conference I would like to thank the organizers for giving me the opportunity of taking the Chair at this Session. It is a privilege to be here, and I am indeed honored to have been invited to come in this capacity to one of the most important international conferences where outstanding experts on asphalt pavements have come to meet from all over the world. Not only I feel privileged by this post. At the same time it

credits and honors the experts from my country and all those who are here from Continental Europe.

I believe that all the participants from Continental European countries and the Moderators, too, will agree with me that the rational design of asphalt pavements is a problem very close to our hearts - -after all, our countries belong to those where pavements are exposed to the heaviest of stresses, either on account of the volumes of traffic or due to the fact that extremely heavy axle loads are permitted.

There is still another reason for taking such pleasure in acting as Chairman of a Session at this Conference. Never before has there been such good cooperation, such uniting of efforts of the organizers of the Ann Arbor Conferences (already a tradition)with the Permanent International Association of Road Congresses and the European Bitumen Association (Eurobitume) in making this Conference possible.

Et cetera . . .

03106

Report of Session IV - Failure Criteria
Chairman: Philip J. Rigden

A detailed discussion of the papers presented in the session, follows:

Chairman's Opening Address
Philip J. Rigden
Vice President, South African Council for Scientific and Industrial Research
Pretoria, Republic of South Africa

Ladies and Gentlemen, it is for me a pleasure, and a privilege, indeed a signal honor, to have this opportunity of chairing a Session at this Third International Conference on the Structural Design of Asphalt Pavements. I would like, if I may, to take this opportunity to thank the Conference Organizing Committee for inviting me again to this "Ann Arbor in London" Conference. I think the organizers are to be congratulated on all they have done to make this Third Meeting possible and to attract so many delegates from so many countries. I can only hope that, at the end of this week, the total effort involved and the exchange of ideas and information that take place will have proved well worth while.

When I spoke as a Session Chairman at Ann Arbor in 1967, I made a plea for the Conference organizers to sit down and try to define for us the questions which we must aim to answer in 1972. I also made a plea for a measure of international cooperative effort in research in preparation for 1972. In regard to this latter point I must confess to some disappointment, as I don't think this has been done, or achieved. Perhaps I was expecting too much; there are indeed considerable difficulties in such an exercise. In Pretoria, I recall, we gave a lot of thought to how this might be done in the field of flexibility and fatigue testing of bituminous surfacings. This was going to require a large program of exchange of samples between different laboratories in different countries. The logistics, and indeed costs, of such an operation looked rather formidable and we didn't follow it up.

Et cetera . . .

03107

Report of Session V - Pavement Performance
Chairman: Desmond F. Glynn

A detailed discussion of the papers presented in the session, follows:

Chairman's Opening Address
Desmond F. Glynn
Director, Australian Road Research Board
Victoria, Australia

The main objective of this Third International Conference on the Structural Design of Asphalt Pavements is to bridge the gap between theory and practice relating to the structural design and construction of asphalt pavements.

The first four sessions have reported the latest research progress in regard to environments and traffic factors, properties of materials, design theory, and failure criteria. The next two will attempt to show how such data should be used in current design and construction procedures, and in strengthening existing pavements.

The present session considers full-scale experiments which will have been planned and designed by research workers but, in most cases, built by practicing engineers. Thus many minor construction details will very often mask, or at least greatly modify, the research expectations. Research workers aim to report their latest progress in their papers and to discuss the general standing of the topic with other research workers. This has been the traditional way in which research has advanced.

Practical engineers hope to be informed about research findings relevant to each aspect of pavement practice and, if possible, for recommendations to be made about the best ways to incorporate such findings into the practice of pavement design and construction. But both have been trained to think as scholars. This session should thus provide a common watershed at which contributions from both could be pooled; thus providing a deeper understanding of the true weight to be given to each of the studies reported.

Et cetera . . .

03108

Reception and Conference Banquet
n/a

Photos of the Reception and Conference Banquet held in The Great Room, Grosvenor House, London.

03109

Report of Session VI - Current Design and Construction Procedures
Chairman: William N. Carey, Jr.

A detailed discussion of the papers presented in the session, follows:

Chairman's Opening Address
William N. Carey, Jr.
Executive Director,
Highway Research Board National Academy of Sciences
Washington, D.C., U.S.A.

This Third Conference is aimed at bridging the gap between theory and practice in the matter of structural design of pavements. This is an end devoutly to be desired and many of the excellent papers that have been accepted for this Conference demonstrate rather clearly that we are coming closer to bridging this gap. However, much remains to be done and there will need to be a Fourth and perhaps a Fifth Conference.

To my mind at this point in time, practice in the design of asphalt pavements is ahead of theory. I say this because we do design flexible pavements and build them. They do perform their function with excellent service. We need not be ashamed that the word "design" should be in quotes since what it is that we really do is to exercise engineering judgment based on a great deal of experience with different traffic, with different soils and with other different materials. On the other hand, theory, while far advanced in recent years, is not yet ready to provide us with a comprehensive and rational asphalt pavement design system. This is clear from the discussions at this Conference. I wish to discuss very briefly some of the reasons that this is so.

The development of such a rational design system has been hampered by the understandable desire of engineers to find a relatively simple formula that will work. There has been a reluctance to face up to the truly stupendous complexity of the problem.

Et cetera. . .

03110

Report of Session VII - Strengthening Existing Pavements
Chairman: Ray Millard

A detailed discussion of the papers presented in the session, follows:

Chairman's Opening Address
Ray Millard
Deputy Director, Transport & Road Research Laboratory
Crowthorne, Berkshire, England

This is the last of the sessions of this Conference at which we shall be considering a particular theme. There has been a logical pattern in the themes of each succeeding session. In the first two sessions the theme was analysis - to define the factors that we have to consider in designing asphalt pavements, first the external factors, the characteristics of the traffic loads that roads are called upon to bear and the influence of the wide range of climatic conditions in different parts of the world on pavement design. The analysis continued in a review of the properties of the wide range of materials available for building and maintaining flexible road pavements.

From analysis we moved to synthesis, reviewing in the next three sessions the knowledge that is available from theory and from practical experience, and attempting to fit this knowledge into a coherent framework. Now in the previous session and in this one we are attempting to review how the accumulated knowledge can be put to good use. In the last session we were developers concerned with the design of new pavements. In this session we are good conservationists seeking how to preserve the value of our existing assets.

To the road engineer new construction is infinitely more exciting than maintenance. Superficially at least there is a great deal more satisfaction to be gained from creating something new, from pushing a project through the stages of planning design and construction, to completion when it will be there for all to see and to use, a demonstrable example of the contribution that engineers can make to the good of mankind. Besides this road maintenance is very pedestrian stuff indeed.

But the wind has begun to change . . .

Et cetera. . .

03111

Report Of Session VIII - Summary Session
Chairman: Sir William H. Glanville

A detailed discussion of the Conference follows:

Chairman's Opening Address
Sir William H. Glanville
Engineering Consultant
Northwood, Middlesex, England

We have now reached the final session of the Third International Conference on the Structural Design of Asphalt Pavements. It is the business of those who speak today to look back over what has been written and said and to try to distil the essence from it. But first of all I should like to say that in my opinion the Conference has been a great success. As you have already heard, instead of the 400 participants first envisaged the number has been 800 or more - twice as many - and some hundreds more than in 1967. The meetings have been well attended and the discussions have been lively and informative.

The atmosphere has been a happy and friendly one, and I feel sure that engineers and others who have taken time off from their normal duties will feel amply rewarded and after they have recovered from the social side of Conference activity, mentally refreshed. Several of those who, like myself, have attended many conferences, have expressed the view to me that this has been one of the most successful conferences that they have attended: the mode of operation, the circulation of reports and papers, the Moderators' reports and the orderly discussions have been most effective. Of the

	alternative ways of organizing conferences, none of which by the nature of things can be perfect, this has been shown to maintain interest and to lead to the development of related thinking and to the fusion of ideas. Et cetera
03112	**Corrections By Authors To Papers Printed In Volume I** *n/a* These corrections have been appended to the appropriate Acrobat files in the ISAP database of papers.
03113	**List of Registrants** *n/a* An alphabetical list of 3rd Conference registrants, their position and their affiliation.
03114	**Index of Contributors and Discussers** *n/a*

code	ISAP 4th Conference -- Titles & Abtracts
04000	**4th International Conference on Design of Asphalt Pavements - Volume I - Preliminary pages and Table of Conents** *n/a*
04001	**The Use of Distress Prediction Subsystems for the Design of Pavement Structures** *F. Finn, C. Saraf, R. Kulkarni, K. Nair, W. Smith, A. Abdullah* This report presents the results of an investigation designed to develop procedures for predicting distress in asphalt pavements using mechanistic parameters of stress, strain, and deformation. The specific forms of distress considered were fatigue cracking, permanent deformation, and low-temperature cracking. Two computer programs were developed, one for fatigue cracking and permanent deformation (PDMAP) and one for low-temperature cracking (COLD). The programs should provide capability in simulating the occurrence of pavement distress and can be used in pavement management systems, diagnostic investigations, formulation of design criteria, and preparation of material and construction specifications. Field verification of such programs is limited, since most of the available field data were used to develop the damage prediction models. The programs are considered implementable and have been successfully executed on state highway department computer equipment. One of the conclusions of the investigation is that field verification is necessary in order to calibrate the basic predictions to local conditions.
04002	**Asphalt Pavement Design - The Shell Method** *A. J. M. Claessen, J. M. Edwards, P. Sommer, P. Uge* The original Shell method for the structural design of asphalt pavements has been up-dated and extended to incorporate all relevant design parameters. The method is based on a model in which the pavement structure is regarded as a linear elastic multi-layered system in which the materials are characterised by their modulus of elasticity and Poisson's ratio. The computer program BISAR is used to compute all stresses, strains and displacements at any point in the system under any number of vertical and/or horizontal surface loads. In this way, the primary design criteria have been established, i.e. the compressive strain at the top of the subgrade and the horizontal tensile strain in the asphalt. Secondary criteria such as permissible stresses in cementitious base layers, permanent deformation of the asphalt, etc., are also included. The permissible value for compressive subgrade strain has been derived from analysis of AASHO Road Test sections and structures conforming to CBR design. The permissible asphalt strain was determined from extensive laboratory measurements for various mix types at different stiffness moduli of the asphalt. In the application of the asphalt fatigue criterion allowance is made for the influence of the transverse distribution of wheel loads and for effects of healing and intermittent loading. The traffic data are converted into an equivalent number of standard design axle load applications. To introduce the influence of the ambient temperature a procedure has been developed to relate the mean annual or monthly air temperature to an effective asphalt temperature, depending on the thickness of the asphalt. The moduli of subgrade and unbound base layers should be determined at appropriate stress levels whereby the latter modulus is a function of the subgrade modulus. The asphalt moduli of a large number of typical asphalt mixes have been determined from extensive laboratory measurements. It is demonstrated that the modulus of a given mix, relevant for the structural design, can also be derived with sufficient accuracy using a nomograph. For practical design purposes it is appropriate to take a loading time of 0.02 seconds and a Poisson's ratio of 0.35 for asphalt and unbound materials and 0.25 for cementitious base layers. To provide a practical system for road engineers, sets of design charts have been prepared from which combinations of thicknesses of the asphalt and unbound base layers can be derived for various mean annual temperatures, for a number of typical mixes and for various subgrade moduli. Examples of these curves are given. Special attention is paid to a method of predicting the permanent deformation (rut depth) of the asphalt layers during the expected service life of the pavement. In this case the traffic data are converted into an equivalent number of standard single wheels. The application of the design method to the design of pavements for aircraft with multiple wheels is also dealt with. Examples of design curves for some types of aircraft are given. The various laboratory tests and full scale road trials carried out to investigate the validity of the design method have been summarised. The practical use of the design method is illustrated by means of some examples.
04003	**Fully Monitored Motorway Trials in the Netherlands Corroborate Linear Elastic Design Theory** *W. G. Bleyenberg, A. J. M. Claessen, F. Van Gorkum, W. Heukelom, A.C. Pronk* In the Netherlands, the Studie Centrum Wegenbouw (Study Centre for Road Construction) set up a Working Party to investigate the applicability of theoretical design models by means of comprehensive experiments on fully monitored motorway trial sections. The road trials were designed to cover a wide variety of conditions. In two types of construction - one with full depth asphalt and one with a sand-cement subbase - strains at different levels in the structures, surface deflections and soil pressures were measured under a variety of conditions of temperature and of load, speed and lateral position of the loading vehicle. Both test sections were constructed in stages. The paper gives representative results of measurements for two stages of construction of the pavements. Material properties of subgrade, sand cement and asphalt and the thicknesses of the layers were measured both in situ and in the laboratory. These data were then introduced into the BISAR computer program, based on linear elastic multi-

layer theory, to calculate values of strains, deflections and soil pressures corresponding to the measured quantities and the results have been compared with one another. In addition, BISAR computations have been made to investigate the influence of a variation in test parameters (moduli, Poisson's ratios, shape and stress distribution of wheel contact area, etc. The widths (durations) of recorded regular strain signals were used to characterize the loading time.

Measured and computed quantities are mostly presented as a function of the stiffness modulus of the asphalt (incorporating the effect of temperature and loading time). All data could be converted into values per unit load, demonstrating that the behaviour of both structures was linear. Generally, the results showed increasing scatter at lower asphalt moduli. Computations showed that variations in test conditions also have their strongest influence at low asphalt stiffness. In some cases a stronger difference between longitudinal and transverse strain was found as compared with the computed values.

On the whole, measured values of strains, deflections and soil pressures showed good agreement with the corresponding computed values, particularly with higher asphalt moduli.

04004 **Predictive Design Procedures - A Design Method for Flexible Pavements Using the VESYS Structural Subsystem**
William J. Kenis

This paper describes a procedure for the analysis and design of flexible pavements. The analytic techniques upon which this procedure is based have been assembled from the application of sound fundamental principles and their evaluations from results of laboratory and field studies. The concepts used have been formulated in State Highway Planning and Research, National Cooperative Highway Research Program, Administrative Contract, and FHWA staff studies, Work on the procedure was initiated by the Pavement Systems Group of the Offices of Research and Development in order to develop a reference document to assist the pavement designer in analyzing the structural integrity of flexible pavements. Work was accomplished under Federally Coordinated Program Project 5C "New Methodology for Flexible Pavement Design."

The design procedure described includes use of the most recent developments for the analysis and design of flexible pavements. Although it may be used to evaluate the distress and performance of in-service pavements, the procedure is written specifically for application to the structural analysis and design of new pavements. In either case a pavement section of known geometry is chosen and its behavior over time is predicted by sets of mechanistic models which have been computer programmed. The computer program package, known as the VESYS Computer System, computes distress and performance in terms of rutting, roughness, and crack damage. These damage indicators are then used in a distress performance relationship to predict the serviceability history of the pavement. Results of the analysis must be compared with sets of design criteria imposed by the user agency. The analysis process is repeated until the computed levels of damage and serviceability meet the acceptable levels established by the design criteria.

04005 **Comparison of VESYS IIM Predictions to Brampton/AASHO Performance Measurements**
J. Brent Rauhut, R. C. G. Haas, Thomas W. Kennedy

VESYS IIM is one of the most advanced models to date for simulation of a flexible pavement structure. However, this does not within itself imply its adequacy for practical use. Thus its ability to predict the performance of inservice pavements is of primary importance to its eventual utilization for analysis and design. The paper provides comparisons of VESYS IIM predictions and measured performance of four sections of the Brampton Test Road and four sections of the AASHO Road Test.

VESYS IIM as currently configured normally requires 47 input variables, twelve of which include multiple values in arrays. For simplicity, these input variables may be classed into four categories having rational engineering significance when considered separately. These classifications include:
1) pavement thickness dimensions,
2) traffic and wheel load data,
3) materials characterizations, and
4) control variables.

The most important departure of VESYS IIM from more conventional analytical methods is in material characterizations. These material characterizations include creep compliance curves for viscoelastic responses, permanent deformation coefficients to describe permanent deformation potential for each layer, and the fatigue coefficient and exponent commonly used for the asphalt concrete characterized with respect to temperature. A very detailed contemporary test program has been conducted for the Brampton Test Road so much useful data was available. For the AASHO Road Test, however, it was necessary to obtain material samples and to conduct specialized testing to obtain the necessary material input.

Comparisons of predicted and measured values show that performance predictions may not as yet be made at a sufficiently high confidence level. This is not surprising, however, considering the state-of-the-art for characterizing materials and inability of theoretical structural models in current use to deal with material changes with time. A significant finding of this study is that the calculated rut depth values approximated the measured rut depth for three of the eight sections when reasonably accurate input values were used. This success, even though limited, suggested that VESYS IIM holds considerable promise and may be expected to offer better predictive capabilities as improvements are made to both the program and to the material characterization procedures.

While no definite conclusions can be made concerning predictions for cracking, present serviceability, and service life, these models do appear to function rationally and should also provide improved predictions as the state-of-the-art for materials characterizations and for the models themselves progress.

04006 **Sensitivity Analysis of FHWA Structural Model VESYS**
J. Brent Rauhut, John C. O'Quin, W. Ronald Hudson

VESYS IIM is one of the most advanced models developed to date for simulation of a flexible pavement structure. As currently configured, it normally requires 47 input variables, 12 of which involve arrays of multiple values. As the development of the input values can be time consuming and some require data not normally available, it is important to understand the relative effects of the individual variables upon practical solutions. For instance, there is no reason to

implement a detailed material testing program or an analytical study to obtain accurate values for an input variable that has little or no effect on the calculated responses. On the other hand, a variable to which the solution is very sensitive may warrant an extra amount of effort for accurate characterization.

This paper describes and reports results of an extensive sensitivity analysis for VESYS IIM conducted by Austin Research Engineers Inc under contract to the FHWA. Preliminary screening reduced the number of independent variables to be considered and allowed division of the analysis into two independent studies, one for the VESYS IIM roughness model and one for the VESYS IIM cracking model. These considerations permitted a reduction of the problem to two factorial experiments, one of 11 variables for the cracking model, and one of 15 variables for the roughness model. Fractional factorial techniques were then employed to effect an enormous reduction in the number of solutions required for the sensitivity analysis. The result was a regression equation for each calculated response representing the VESYS IIM model for that response and leaving little information "unexplained." The independent variables in the equation were coded in an orthogonal scheme, which allowed relative comparisons of the variations for each factor in terms of expected range of values in the field.

The results of this sensitivity analysis are reported and it is clear that a number of the variables have so little effect that little effort is warranted to obtain relative high accuracy for their values. This fortunately includes a number of variables that are difficult to evaluate such as the time-temperature shift function for the asphalt concrete, load duration and distribution, permanent deformation characterization for the base material; the correlation between the fatigue coefficient K sub 1 and the exponent K sub 2, creep compliance for the various layers, and stochastic distributions for several of the variables. Estimates will suffice for a number of these variables and can also be added to the computer program as constants for use when values are not available and are not furnished as input.

In general, the importance of the independent variables to the computed responses is consistent with known physical realities. As might be expected, primary emphasis for the rutting predictions should be placed on reliable values for the permanent deformation characterization for the asphalt concrete surface material. If a prediction of cracking damage is of special interest, a reliable relation for fatigue life potential must also be obtained. The relative importance of all significant variables is described.

04007

Field Verification of the VESYS IIM Structural Subsystem in Utah
D.I. Anderson, J.C. McBride, D.E. Peterson

The need to encorporate elastic and viscoelastic models into a practical flexible pavement design procedure is well founded. A limited verification of the VESYS IIM design procedure, and an investigation of the possibilities of implementing the system in Utah were carried out.

The program is based on a 3-layer model corresponding to the bituminous, base gravel and soil materials. The test samples were formed using the identical asphalts and gravel materials placed in the selected pavements. Air-tight containers were used to store the asphalts from the time of construction, and were found to be relatively unaged. The indirect tensile test was employed to obtain the creep compliance, permanent deformation, and fatigue data needed to generate the projected performance data. The base gravel and soil materials were tested using a cylindrical test specimen under confining pressure to obtain the creep compliance and permanent deformation data for the second and third layers. Actual traffic data measured over the pavement life was used as input.

Estimates of the performance of some pavements were produced, and compared with the measured performance data. These predictions were found to be adequate for the magnitudes and times measured. Future work in the study will evaluate the procedure in a wider range of performance data, pavement materials, traffic loadings, and environmental conditions.

Implementation of the procedure in its present form would require significant changes in the structure of Utah's present overall design scheme. The obligations of various state organizations would require alteration. Also, some form of prediction of transverse, temperature- associated cracking would be necessary in many states to obtain an optimum design based on performance.

Preliminary results show that the VESYS IIM program has great potential, and every effort should be made to fine tune the models and encorporate the procedure into practical application.

04008

Evaluation of Flexible Pavement Design Methodology Based Upon Field Observations at PSU Test Track
M.G. Sharma, W.J. Kenis, T.D. Larson, W.L. Gramling

Field observations as related to distress and performance of test flexible pavements under accelerated traffic loading at the Pennsylvania Test Track Facility have been presented and correlated with the corresponding value as predicted by the FHWA computer program (VESYS IIM). Eight flexible pavement test sections carrying about 1.5 million 18 kip equivalent axle loadings were evaluated. On each section, rut depth, cracking and present serviceability index (PSI) were measured at periodic intervals. An account was made of the environmental and traffic conditions throughout the test period and samples of materials used in the facility were tested in the laboratory to determine the properties necessary for input to the VESYS Computer Code. Using the VESYS IIM program estimates of the extent of fatigue cracking damage, rut depth, and PSI were computed and compared with measured performance data. Results indicate that it is possible to predict the relative magnitudes of these distress and performance indicators. In this paper an attempt is made to point out reasons for deviations between measured and predicted values. Suggestions are made concerning the eventual use of mechanistic structural subsystem for the analysis and design of flexible pavement systems.

04009

Implementation and Verification of Flexible Pavement Design Methodology
Jatinder Sharma, L.L. Smith, B.E. Ruth

Presented in this paper is the evaluation of two computer models(VESYS and PDMAP) for the design of flexible pavements. The Chiefland, Florida test section was chosen to verify the above mentioned models. This section is the first project of a series of ten projects to be studied over a three year period.

Laboratory tests on the Asphaltic Concrete Surface Course consisted of an Incremental Creep Test, a Dynamic Compression Test and a Flexural Fatigue Test; on untreated materials, the tests consisted of Incremental Creep and

Dynamic Compression at ranges of stresses expected at in situ. The Kneading compactor was used to make samples and a MTS electrohydraulic closed loop system was used to run the tests.

Fatigue tests on the fabricated beam specimens showed a higher potential for fatigue life than beam specimens from the undamaged portion of the roadway which is about 10 years old. Aging is a significant factor in the prediction of pavement performance.

It is possible to predict cracking and rut depth with reasonable degree of accuracy, provided that the Modulus of Elasticity for different materials is based on the measurements over the entire length of the sample.

04010 **Selection of Pavement Models in a Rational Pavement System to be Used by the Dutch State Road Laboratory**
R. Frank Carmichael, Jan Eikelboom, Peter M.W. Elsenaar, W.R. Hudson

Simulations of the observed pavement performance parameters (i.e., skid resistance, rutting, structural cracking, and evenness) have been prepared using behavioral models, and data from in-service Dutch pavements. The study was performed to evaluate and compare various available mathematical models for predicting pavement behavior, for possible use as elements in the development of a Rational Pavement Management System (RVBS), by Rijkswegenbouwlaboratorium (RWL) for use in Holland. The predictions of the behavioral models were compared with available field measurements from different test sections in an attempt to verify each model's capabilities. Rutting and structural cracking models were of primary interest because of their effects on structural design, evenness and skid resistance models because of their effects on safety and comfort.

The study included the following work items:

1. The Selection of Pavement Structures - Existing pavement structures in Holland were selected for the simulations and data concerning pavement construction, traffic, and pavement condition survey data were used as input for and verification of the simulations.

2. Model Selection - After review of 15 mathematical prediction models of pavement behavior, a total of eight behavioral models, two in each category of interest, skid, evenness, rutting, and cracking, were selected for structural simulation. Simulations of performance of selected pavement structures were prepared using these eight models, and the results were reviewed to ascertain the validity of the models.

3. Simulation Results - The simulation results from the eight behavioral models, recommendations as to future developments of RVBS, and improvements which are necessary for the use of any of these models in RVBS are presented.

This is the first phase of a three stage development of a Rational Pavement Management System, RVBS, for Holland. The study will help RWL to select behavioral models for use in the first working RVBS, which is to be developed in the second phase of work.

04011 **A General System for the Structural Design of Flexible Pavements**
W.R. Barker, W.N. Brabston, Y.T. Chou

Presented herein is a procedure for design of three types of flexible pavement: conventional, bituminous concrete, and chemically stabilized. These represent nearly all flexible pavements being constructed at this time. Designs are based on analytically determined strain values as computed by a layered elastic model of a pavement structure. The subgrade strain is related to performance through empirically determined criteria whereas the strains in structural layers are related to performance through laboratory determined material fatigue strengths. With the exception of granular materials and cracked stabilized materials, stiffness properties of the pavement material are determined through laboratory testing. For the granular materials and the cracked stabilized materials, empirically based charts are provided for determination of the stiffness. An adaptation of the cumulative damage permits the consideration of cyclic variation in bituminous materials due to variations in temperature, the variations in subgrade strength resulting from freeze-thaw cycles, the mixture of different traffic vehicles, and the distribution of traffic across the width of the pavement. An example problem is provided which illustrates the use of the procedure.

04012 **Esso Road Design Technology**
B. Celard

The pavement design method developed at ESSO embodies a rutting and a fatigue subsystem. The input data encompasses the climate, traffic and subgrade variables on the one hand, and the asphalt mixes dynamic properties on the other. These properties are measured through three tests: dynamic modulus, dynamic creep and uniaxial push-pull fatigue tests. They are performed on realistic specimens prepared with the Esso laboratory compactor. The test results are processed statistically and the damage laws are obtained: these connect the elemental damage undergone by the material to each stress and temperature conditions. The stresses inside the pavement are computed assuming the pavement can be modelized as a three-layer elastic system. The total damage caused to the pavement is obtained by integrating the related elemental damage over the climate and traffic variables:
- the rutting subsystem attempts to provide an actual prediction of the rut depth development for surface courses, asphalt overlays and asphalt layers laid on top of stiff foundations,
- the fatigue subsystem only provides a comparative index which allows arraying the different structures, and can be used as an optimization criterion.

Besides the method itself, a simplified testing equipment for asphalt mixes was developed. Its simplicity and low cost allow performing the dynamic tests on a routine basis and therefore contribute to make the design method available to practising engineers.

04013 **Kentucky Research: A Flexible Pavement Design and Management System**
Herbert F. Southgate, Robert C. Deen, James H. Havens, William B. Drake jr.

Various strategies for designing pavement structures are discussed. Initial full-life design, stage designs and planned extensions of service life, final design, surface renewals for deslicking, no-defect designs for high-type high-volume facilities, and allowable-defect designs are considered. Economics enter in terms of salvage value of existing pavements

and alternate designs using different proportions of materials within the structure.

The elastic model represented in Chevron's n-layered computer program is the basis for theoretical relationships. Ranges of values are given for input variables such as Young's moduli, Poisson's ratio, thicknesses for layers, tire pressure, and load. The Kentucky CBR is related to modulus by E = 1500 x CBR and is correlated with the AASHO Soil Support value and other strength relationships. The modulus of crushed stone base is shown to be a function of the moduli of the asphaltic concrete and subgrade. Appropriate relationships are given.

Graphs show interrelationships between asphaltic concrete thickness and asphaltic tensile strains, subgrade strains, and surface deflections. Structures are interpolated as a function of asphaltic concrete thickness and percent of asphaltic concrete in the total thickness. These graphs are interpolated to illustrate the relationship of Kentucky CBR versus total pavement thickness for structures in which the asphaltic concrete has a specified modulus and accounts for a specified proportion of the total thickness. The CBR-total thickness graphs are combined to make the Kentucky design nomographs. All of the above are theoretical and empirical relationships which are not dependent upon fatigue criteria.

A tensile strain-fatigue criterion is derived and correlated with Kentucky experience. The analysis is based on limiting elastic energies and may be treated thereafter in terms of limiting strains or limiting stresses.

The subgrade strain criterion is also associated with Kentucky field experience and is extended as a function of axleload; load and repetitions are interrelated to provide equivalent axleloads in kips for single axleloads, and EAL's for single axleloads. These values are illustrated as log strain - log repetitions of 18 kip (8OkN) equivalents. A method for determining a design CBR value is discussed.

Methods of determining design periods, or design life, are discussed. Ways of determining appropriate traffic volumes are discussed and include available AADT data, use of classification and weight data from W-4 Tables, and modifications to account for known and unusual traffic variations such as for recreational areas, rural routes, and heavy hauling operations.

The methodology for computing load-damage factors is given, discussed, and compared to damage factors developed by the AASHO Design Committee from Test Road data. The value of subgrade strain correlated to Kentucky experience is that strain developed for an 18 kip (80 kN) axleload applied to typical Kentucky designs. Other axleloads producing other strains in the same structures are expressed as ratios to the 18 kip (80 kN) axleload. Thus, the coupling of repetitions, axleloads, and subgrade strain is accomplished in the load - repetitions equations. Graphs relating repetitions of 18 kip (80 kN) axleloads to subgrade and asphalt strains allow determination of the respective strain values for input to the CBR - thickness graphs or the Kentucky design nomographs to obtain design thicknesses with respect to the asphaltic concrete moduli.

The Kentucky criterion for rutting allows maximum rutting for the least traffic but minimum rutting for the highest traffic. A procedure is developed for adjusting thicknesses to a fmal design thickness for each of the four moduli given in the design nomograph. The appropriate modulus for a given locale is determined from pavement temperature histories. A method is given in this paper. For Kentucky conditions, the recommended modulus is a function of the percentage of asphaltic concrete thickness in terms of the total design thickness.

The choice of percentage of asphaltic concrete of the total design thickness and their respective moduli permit development of design charts showing the thickness versus log repetitions of 18 kip (80 kN) axleloads. Each line on the chart is for a given CBR. All the designer needs to use these charts is the design CBR and number of repetitions. Since the design charts are mathematical solutions coupled with fatigue criteria, changes in the fatigue criteria can be properly made by simply relabeling the CBR lines to appropriate equivalent values. The design charts can be used to design overlays and to determine when overlay construction should be scheduled in terms of accumulated EAL's. Again, AADT charts and yearly W-4 table classification and weight data can be readily used to estimate accumulated EAL's and to modify the design period, or design year, to account for increased weight limits, changes in style of cargo hauling equipment, routing, and distribution of vehicle types in the traffic stream.

Verification of this design system involve several sources, including some 30 to 40 years of design and behavioral experience within Kentucky and including a full-depth asphaltic concrete research pavement. Recent investigations involve re-analysis of AASHO Test Road data -- both single and tandem axleloads. Results indicate the AASHO Test Road data can be analyzed and explained by elastic theory. The design level of terminal serviceability is shown to be a function of design repetitions. This relationship is also expressed in terms of axleloads. Coupling the variable terminal serviceabilities with axleloads and, in turn, with Kentucky equivalent damage factors petit superpositioning of the AASHO Test Road data in terms of 18 kip (80 kN) EAL's for single axleloads. An additional relationship equating equal damage for single and tandem axles using AASHO Road Test data permits superpositioning of the tandem-axleload data over the single-axleload data with virtually no increase in data spread. Superimposed on the AASHO Road Test data are Kentucky moduli solutions showing excellent agreement of field data and theory.

Airport pavement thickness designs obtained from The Asphalt Institute's Full-Depth Asphalt Pavements for Air Carrier Airports is closely duplicated by converting aircraft wheel loads to equivalent 18 kip (80 kN) axleloads. A method is given equating moduli with frequency of loading cycle. It is shown that the Kentucky asphalt tensile strain criteria can be expressed by an equation (given in the paper).

The verification of this design system involves the incorporation of test data from Kentucky, Canada, the AASHO Test Road at Ottawa, Illinois, and test roads in Colorado, San Diego, and Kentucky. In addition, The Asphalt Institute's airport pavement design method uses aircraft strut and wheel loads which can be converted to an equivalent highway 18 kip (80 kN) EAL loading for pavement design by the Kentucky method. In one example, The Asphalt Institute's airport pavement thickness was 17.0 inches (332 mm) full depth asphaltic concrete. The same aircraft loadings resulted in a Kentucky design thickness of 17.2 inches (337 mm).

Pavement management concepts are discussed and a method is presented illustrating the required data and its use to accumulate EAL's annually for comparison with the design EAL. This method can be used to determine overlay priorities, overlay design thicknesses, and scheduled financing. Condition survey analyses coupled with economic analyses may indicate a pavement structure should be reconstructed, or even relieved by constructing a new corridor. A discussion of automatic feedback of field data is presented. Pavement condition reports may be fed into the data bank. However, such data should be analyzed separately to prevent improper adjustments to the design system due to causes of failure other

than pavement fatigue. Construction of overlays for any purpose should be logged into the data bank. The overlay, whether for extending service life or improving skid resistance, provides an additional structural thickness and will modify the design life.

04014

The Belgian Road Research Center's Overall Approach to Asphalt Pavement Structural Design
J. Verstraeten, J.E. Romain, V. Veverka

A structural design system for asphalt pavement, based upon the utilization of measured fundamental properties of materials, is presented, While the experimental methods for the determination of the fundamental properties of the materials are now well defined, they involve sophisticated tests which are not well adapted to everyday practical purposes (long time, high cost). For this reason predictive methods, based on numerous laboratory results obtained for the different kinds of materials, are made use of, mainly for bituminous mixes and granular materials.

The different elements of design, namely, criteria for riding quality, loading conditions, stresses and strains in layered systems, fundamental properties of road materials and climatic factors are reviewed. Models for cracking and for rut depth are supplied. A field verification is reported,

For the pavement design method itself, two approaches are presented. The first is a complete rational one, while the second is more approximative, but simpler than the first and, consequently, more practical.

04015

The Application of Simplified, Fundamental Design Procedures for Flexible Pavements
S.F. Brown, P.S. Pell, A.F. Stock

Prior to acceptance in practice of complete analytically based pavement design procedures, engineers have to be introduced to the basic concepts involved and this can best be achieved by use of a simplified approach. The Simplified Design Method has been successfully used for such educational purposes and is described in detail. It makes use of charts and equations but has also been programmed onto a computer of modest size. The Analytical Design Method is a more versatile, but still somewhat approximate, design tool in the form of a computer program. The immediate use which can be made of a design package of this kind is demonstrated by investigating the effects of mix variables on layer thickness.

04016

Method for the Structural Design of Asphalt Pavements
J. Eisenmann, U. Lempe, C. Leykauf

In the outlined design procedure the flexible pavement structure is considered as a linearly elastic multi layer system in which the road building materials are characterized by Young's modulus and Poisson's ratio. By aid of the computer programs BISTRO and BISAR, developed by Shell, the maximum stresses at the interfaces of the layers were determined. The primary criteria for the behaviour of the asphalt layer has been found to be the main shear stress (tau)max at the bottom of this layer. The stressing of the unbound base courses and of the subgrade can be evaluated by the compressive stress (delta)(sub)z.

As to the dynamic properties of bituminous bound materials extensive laboratory tests have been carried out. The Young's modulus has been determined in shear tests in subjection to temperature and loading time, whereat the parameters -- grain shape, binder hardness, binder content and void content -- have been varied. With the same test equipment also the fatigue under shear stressing has been investigated ; the paper presents the influence of the different parameters.

Using the hypothesis of Miner the consumption of life time of a flexible pavement can be determined by accumulation of the ratios occurring load cycles n(sub)i to permissible load cycles N(sub)i for all stressing conditions. For this the occurring traffic can be substituted by an equivalent number of load cycles with a standard axle load using the equivalence-factors known from the AASHO road test. Due to the strong influence of temperature to the asphalt properties different seasons with ambient temperatures in the pavement have to be taken into consideration. The results of continuous temperature measurements are presented.

By Miner a cumulative failure can be expected if the total of Sigma n(sub)i/N(sub)i is greater than 1. But this fictive life time is not identical with the end of the service life of the pavement. The results of a theoretical investigation are presented, in which the computed fictive life time of two test sections of the AASHO road test is compared with the measured Present Serviceability Index p ; it is evident that the theoretically worked out permissible number of load repetitions gives the time when cracking of CLASS 1 - as defined in the AASHO road test - occurs, that is at an index of p approx = 4,0.

This shows, that the theoretical worked out service life will differ more or less from the reality. Therefore, when designing a new flexible pavement construction first the consumption of service life for a standardized road construction approved in praxis has to be determined in the mentioned manner and then the thickness of the new construction has to be varied so that this critical value is not overpassed. In this paper an example of designing a new pavement construction with an insulation layer out of hard foam is given. It is expected that this design method can be improved by the results of the test track "Hilpoltstein" ; in a theoretical study statements have been given on the service life of this temporary by-pass which shall be compared with real behaviour.

04017

Procedure for the Structural Design of Pavement Used on Italian Motorways
Franco Giannini, Gabriele Camomilla

A description of new methods for the structural design of flexible pavement should dwell mainly on new procedures for determining fatigue resistance and resistance against the accumulation of permanent deformations. It may be of equal importance, however, to set out a complete calculation procedure, based on already known theoretical formulations, but integrated with a series of practical suggestions indispensable for the functional transformation of this "rational" method, into an effective design.

The practical assumptions and specific evaluations set out herein, have been proposed, though in hypothetical form, in a number of sources in existing literature, but are essentially the fruit of repeated application and test results. The latter data have been taken from tests conducted on a modern, highly controlled motorway network operated with particular

concern for travel efficiency and supported by continual and costly maintenance. This report is intended to contribute to the effectiveness of methods long proposed, by suggesting the practical systems for their step-by-step application so as to obtain reliable results. These suggestions are presented in a general fashion so that prescinding from the numerical values offered as examples in the text, they can be applied to situations other than those encountered by the authors.

Another important factor in the application of the method is the confirmation of the validity of Miner's Rule which permits us to isolate the influence of individual design parameters, control their variability so as to determine their specific contribution to fatigue damage, and finally, and above all, to summarize these contributions, which act under widely varying conditions, in a coherent fashion.

The verification of the validity of this rule enables us to transform the current calculation procedure, i.e. the fatigue structural design scheme, which up to now has only had conceptual validity.

No explanation is given in the text of the evaluation of damage due to the accumulation of permanent deformations, but a complete description can be found in the works listed in the bibliography, which provides detailed evaluation of the initial verifications made in Italy. Obviously, given the technical acceptability of the proposed procedure, it provides a valuable tool for optimum economy in both construction and maintenance of highway pavements.

04018

An Optimal Design Procedure for Multilayer Pavements
T.E. Glynn, J.C. Byrne, R.W. Kirwan, M.S. Snaith

This paper describes a procedure for finding the optimum layer thicknesses of conventional flexible pavements. The pavement is modelled as a multilayer system subjected to the pulsed load equivalent of wheel loading on a circular contact area. The optimization scheme is based on a direct search method that compares predicted responses with specified design criteria in a multistage analysis. The direct search produces a finite set of discrete alternatives which takes into account structural stiffness and flexural fatigue. Those trial sections that satisfy the primary design constraints, and are at the same time economically attractive, are reduced to the optimum layer configuration by referring to an objective function. The objective function includes weighted terms for permanent deformation, fatigue life, and cost of construction materials in place.

The set of feasible solutions is determined on the basis of linear elastic theory while the reduced set is evaluated by non-linear analyses. The objective function is not a unique expression as its aim is to find the optimum solution relevant to local or regional requirements. The procedure is illustrated by a design for a four-layer pavement. The design avails of an elaborate set of experimental data for soils and bituminous materials.

04019

Asphalt Pavement Design for Arizona
R.A. Jimenez

There is a general consensus that a procedure for the structural design of asphalt pavements must reflect considerations of the loads imposed, physical characteristics of the pavement layers, effects of the environment on those physical characteristics, definition of a layer failure, and a means for following changes in the load response of the pavement with time in service. The report presented is concerned with some of the details in developing and describing the proposed pavement design method.

The pavement system is to be composed of three linear elastic layers -- an asphaltic concrete surface, a granular base, and a subgrade. The modulus of elasticity and Poisson's ratio are of fixed values for the surface and base courses. These reference values are partially justified on the basis that both layers meet certain minimum requirements specified for their manufacture. The value for Poisson's ratio is also fixed for the subgrade ; however, the modulus of elasticity is presently determined from correlation with test values such as CBR , R-value, and others.

The procedure's objective is to determine the thicknesses of the surface (H1) and the base (H2) to satisfy two design criteria. These are based on limiting radial tensile stresses at the bottom of the surface course to preclude cracking of the surface and on limiting vertical compressive strains on the top of the subgrade to minimize settlement or rutting of the surface. These criteria for failure were selected since the primary state highways do not show distress originating with shear failure in either the surface or the base. Values fo r the critical stresses and strains are obtained by calculation (using the Chevron program) at three specified points in the system. The maximum radial tensile stress occurs at a point directly under a wheel and at the first interface; the maximum vertical strain on top of the subgrade may be located either directly under a wheel or midway between two dual wheels for single and tandem axled trucks.

Satisfactory values for H1 and H2 are those that yield "fatigue life" greater than the design life of the pavement. As a consequence, the limiting stresses and strains are related to the number of applications of these expected over the design period. The general "fatigue " equations for asphaltic concrete and the subgrade are assumed to be in the form (sigma)(sub)T or epsilon(sub)C = aN(super)- b where the a's and b's are material constants. A procedure has been developed to evaluate the constants a and b for asphaltic concrete. However, to date we have not satisfactorily established the values for these constants in the strain equation and so are accepting the Shell characterization for strain fatigue as epsilon(sub)C = 0.0105 N(super)-0.200.

The calculations for stress and strain in the system require that the loading system be identified with the magnitude of the wheel load and the tire inflation pressure. Through the examination of loadometer studies and questionnaires the traffic loads on the highways can be characterized for the design purpose. Traffic loads are grouped into five categories which are passenger, pick-up (2P), front axle (FA), single axle (SA), and tandem axle (TA). The design values of wheel load, tire inflation pressure, and percentage of each axle category are obtained for each type of highway from loadometer data collected in previous years. Environmental effects on the physical characteristics of the layers are considered to affect separately each of the two criterion. The effect of lower temperature is accounted by increasing K1 (E1/E2) and thus the tensile radial stress. The effect of higher moisture is achieved by decreasing E3. Temperature and rainfall variations have a linear relationship with elevation in Arizona and these have been assumed to also have a linear variation with a regional factor which is comparable to AASHTO's regional factor. It is assumed that the effect of AASHTO's regional factor on its Structural Number is the same as our correction factor (C.F.) is to our K1.

At the present, no definite procedure has been proposed to follow or detect structural changes in a pavement ; however, the Dynaflect is being used to obtain deflection data. Recent analyses of Dynaflect deflections show lack of time-of-year

effects on K1 values and suggest a need for modifying the measuring technique. A complete example of a pavement design is presented to illustrate the procedure.

04020

New Method for Asphalt Pavement Design Adopted in the USSR
M.B. Korsunsky, P.I. Telyaev

The report deals with the method for flexible pavement design recently accepted in the USSR.

This method allows to design a structure resistant, to both multiple applications of loads and of natural factors which is at the same time the most effective economically. The ability of asphalt pavement structure to resist well the load action is estimated by means of three criteria considering both the work of each layer and of the whole structure. The design is made for each layer and the criterion for evaluation of a layer is chosen depending on a degree of layer discreteness. The design of asphalt concrete pavements and other monolithic layers is performed on the basis of the criterion of "bending tensile strength" in order to keep them from fatigue crack formation. The design of subgrade soil and discrete layers is made according to the criterion of "shear resistance" to prevent them from permanent deformations. The whole structure is designed on the basis of elastic deflection in order to avoid its degradation under multiple moving loads. A method based on the above mentioned criteria is developed for designing the road pavements, which should have practically reversible (elastic) deformations under service loads. To determine stresses and strains in the road pavement layers and subgrade, the use is made of the solutions of the elasticity theory problem for layered semispace.

The ability of road pavement structure to withstand the frost and water deleterious effects is evaluated by using the criteria of "frost-resistance" and "drainage capability" of a structure. This value is of special importance for a subgrade of silty and clayey soils in the regions of excessive moistening and seasonal frost penetration. The road pavement structure is considered to be frost-resistant if actual expected heave of a subgrade soil is less or equal to the allowable value of pavement frost heaving.

An assessment of the expected heave is based on the regularities of the migration of water from water-table to the frost boundary of a soil. The main regularities are those characterizing the rate of frost penetration through pavement structure and the intensity of water inflow to the frost boundary. The drainage properties of a structure are considered to be satisfactory if the thickness of filtration layers is sufficient to provide:
- temporary absorption of the arriving water without decrease in strength of subgrade soil before the drainage facilities begin to work during the first stage of thawing when the pavement structure beneath the middle of a carriageway has thawed and the edges of a drainage course are yet frozen and the drainage facilities have not operated;
- appropriate drainage of the water from the base courses during the second stage.

Relationships for designing such drainage are based on the regularities of a steady regime of movement of free and capillary water flows in a draining layer of a pavement. To make the results of calculations closer to the data obtained the theoretical relationships are corrected for experiments.

The new method permits the following main factors determining the behavior of pavement structure in service to be considered: parameters of the equivalent vehicle, traffic density, soil types, climatic and hydrological conditions, subgrade construction, properties of the materials used, and the requirements for pavement performance. This method takes into account both deformative and strength characteristics of soils and materials. Design parameters are specified. But if necessary they may be obtained by direct sample testing under design moisture and temperature.

The report contains formulae for determination of stresses and strains arising in different layers as well as for establishing their admissible values. The experimental data which show the acceptability level of the formulae are given. The relationships for determination of actual and required frost-resistance as well as those for determination of drainage capability are presented, along with description of the basic principles of design automation and search for an optimum decision. Reliability of structures designed by the new method is demonstrated. An example of flexible pavement design under adverse soil and hydrological conditions is given.

04021

Development and Field Verification of a Mechanistic Structural Design System in Ohio
Kamran Majidzadeh, Leon 0. Talbert, Moses Karakouzian

This paper describes the development and field verification of a generalized mechanistic design system presently under implementation in Ohio. This Ohio pavement structural design system has been developed through the merger of various mechanistic subsystems developed in recent years.

Since the basis of any rational design approach is the stress distribution theory, an elastic stress distribution theory has been utilized in this system. The stress distribution theory, however, is presented in a generalized form incorporating geometrical and material non-linearities. The geometrical non-linearities include the effects of cracks, joints and discontinuities in the pavement system. As a result, this design system is capable of solving various boundary value problems associated with overlay design, joint stress analysis and fatigue crack propagation. The stress distribution in the vicinity of joints, cracks and other discontinuities can easily be calculated and their effects on other functional relationships of other subsystems can be determined.

The Ohio pavement structural design system is composed of two basic, independent subsystems, permanent deformation (rutting model) and fatigue models, as well as a subsystem describing the effect of environment (such as thermal fracture and thermally-induced failure) on the pavement structure. The environment subsystem considers the effects of environment on pavement material input variables and its expected performance due to thermally-induced stresses.

Due to the mechanistic nature of the Ohio pavement structural design system, it is applicable to design and analysis of new pavements, as well as determination of asphalt overlay thickness requirements for rigid and CRC pavements.

04022

A Thickness Design Procedure for Pavements with Cement Stabilized Bases and Thin Asphalt Surfacings
J.K. Mitchell, C.L. Monismith

A thickness design procedure applicable to a pavement system consisting of a cement-stabilized layer resting on a subgrade and protected by a thin asphalt surface layer is described. Stresses and deformations are estimated using

layered elastic theory. The first step is to select a thickness adequate to prevent fatigue in the cement-stabilized layer. The second step is to insure that the combination of load and thermal stresses will not crack the stabilized layer.

The procedure accounts for the fact that cement-stabilized bases will crack shortly after construction due to shrinkage stresses. Base and subgrade stiffnesses can be determined either by laboratory tests or estimated by approximate procedures. Comparisons of thicknesses obtained by this procedure for highway type loading conditions with those by existing procedures show that the new method gives comparable values. Generally, the thicknesses are great enough to minimize initial pavement cracking, and may, therefore, be conservative for low numbers of repetitions of heavy loads.

04023

Trends in the Development of Flexible Pavement Design in Hungary
Ervin Nemesdy, Imre Keleti, Tibor Boromisza, Laszlo Gaspar

The authors describe the Hungarian practice of flexible pavement structure design and pavement strengthening. The catalogue of typical pavement structures is currently being compiled. Two main deficiencies are attributed to the semi-empirical design method used:
- The cheracterisation of the soil load bearing capacity by the CBR value is uncertain, and
- the equivalent number characterising the quality of asphalt materials is independent of temperature.

Hungarian research is in progress to simplify the computer calculation of these multi-layer systems. Work is also being done on a computer interpolation of the Jones-tables of a three-layer system. A simplified program has been written in order to reduce computer time and capacity, which calculates four pavement structure layers by the finite elements method. The soil layer is assumed to be en elastic semi-infinite continuum characterised by the Young's modulus and the Poisson value. This computer program may also be run on smaller computers. The authors investigated the sensitivity of the design method to changes in the soil load bearing capacity in the cases of pavement structures designed for low, medium end heavy traffic. The elastic moduli of the asphalt courses have been determined at the Central European annual average air temperature (+15C) and the typical temperature (+5C) of the thaw period. On the grounds of the results obtained it can be stated that the role of the soil load bearing capacity in the design of pavement structures is smaller than hitherto assumed.

The splitting strength of asphalt materials is tested and the elastic modulus is determined at the same time. The magnitude of the splitting strength is considerably influenced by the loading speed and the temperature, so these are specified at 50 mm/min and +5C, respectively. The calculated modulus values may be used for approximate calculations of the pavement structure, they may furthermore be correlated with the characteristic values of the complex deformation moduli obtained by the fatigue tests.

04024

Thickness Design Procedure for Asphalt and Emulsified Asphalt Mixes
L.E. Santucci

A simplified thickness design procedure for pavement structures constructed with asphalt mixes, dense-graded emulsified asphalt mixes, or cement- modified emulsified asphalt mixes is described. Elastic layer principles are used in the development of the procedure. Two critical strains--the horizontal tensile strain at the bottom of the treated layer and the vertical compressive strain at the surface of the subgrade-- are examined in determining the proper pavement thickness. Allowable values for tensile strain are based on laboratory fatigue tests, with consideration given to the slower crack propagation time encountered in the field. Vertical subgrade strain criteria developed from field observations of pavement behavior have been selected to minimize surface rutting caused by overstressing the subgrade.

Environmental considerations, in particular, the effect of temperature, the curing effect of emulsified asphalt mixes, and the effect of frost on subgrade strength, are considered in the design. The diametral resilient modulus device is used to define the stiffness characteristics of the treated mixes over the expected range of in-service temperature and curing conditions.

A relationship is proposed showing the important effect of the volume of air voids and asphalt in a treated mix on its fatigue behavior and, hence, the thickness requirements for the pavement structure. In the case of emulsified asphalt mixes, this effect can have a much greater influence on the design thickness than the lower strength condition of the mix during its early cure.

The paper contains a step-by-step outline of the design procedure for the practicing engineer to follow in determining pavement thickness requirements. A design example is included with the necessary work sheets to show the proper use of design charts, graphs, and equations. The procedure does not require the use of computers. However, simple computer programs written in BASIC have been developed to eliminate the tedious hand calculations described in the paper. These programs cover the design of pavements made with asphalt, emulsified asphalt, or cement-modified emulsified asphalt mixes.

The tensile strain or fatigue criteria used in this procedure predicted well the 10-20% cracking observed on the San Diego County Experimental Base Project after seven years' traffic. Support for the vertical subgrade strain or rutting criteria is shown by an analysis of performance of mixes examined in a circular test track at our laboratory.

04025

Moving Loads on a Viscoelestic Double Layer: Prediction of Recoverable and Permanent Deformations
G. Battiato, G. Ronca, C. Verga

In this paper a two layered viscoelastic incompressible system subjected to a sequence of moving loads is considered. Materials characteristics are described by a simple analytical expression for the Creep Compliance function, as verified by laboratory creep experiments carried out on a large class of asphalt concretes. The calculation of the viscoelastic deformations (vertical, transverse and longitudinal strains) and vertical surface displacements is performed with reference to three orders of effects:
1) the passage of a single load
2) the accumulation of the recoverable viscoelastic deformation due to a sequence of moving loads; this effect arises from the viscoelastic delay in deformation recovery
3) the calculation of the permanent deformations due to each single load passage when the existence of a Maxwell model in series is assumed in the rheological model defining the characteristics of the first layer.

Interface conditions can be varied choosing rigidly bounded layers or frictionless slip.

With reference to point 1) our viscoelastic calculations show that the prediction of the deformations can be obtained with sufficient accuracy by means of elastic methods in general for the first layer only. If the response of the second (subgrade) layer is not completely elastic, the elastic methods underestimate the deformability of the lower layer by a factor that increases with the depth and is more relevant for soft subgrade materials.

At a distance from the surface of the road, that corresponds to 4-5 times the radius amplitude, this factor may be of the order of 2. If one is interested in calculating the vertical displacements under the load, the predictions of the elastic methods are inaccurate even for the points belonging to the surface of the road.

The lack of symmetry of the deformations with respect to time reversal is observed. The slow viscoelastic recovery of the vertical and transverse deformation for times which follow the load passage makes it possible the accumulation of the deformations with repeated moving loads.

With reference to point 2) we show that the contribution of the residual viscoelastic deformations can be of the same order of magnitude as the contribution of the single load passage in some critical but realistic traffic conditions. Furthermore, when the subgrade behavior is nearly elastic, the residual viscoelastic deformation accumulated in the first layer is independent of the subgrade stiffness.

A considerable accumulation of the deformation is observed for the vertical and transverse deformation, not for the longitudinal deformation. With reference to point 3) our results show that if the subgrade material has an ultimate elastic behavior, the passage of each single lead produces a small permanent deformation which concerns the asphalt concrete layer only and is independent of the subgrade stiffness.

04026

The Validity of Design Procedures for the Permanent Deformation of Asphalt Pavements
S.F. Brown, C.A. Bell

The approach to predicting permanent deformation in asphalt pavements suggested by Romain and Barksdale is examined in detail with particular reference to its validity under controlled laboratory conditions as a preamble to applying the ideas in practice. Attention is given to the correct representation of stress by use of invariants and the careful planning of laboratory materials tests following a review of the relevant literature. Non-linear elastic analysis is required to estimate stresses under the high temperature conditions relevant to the permanent deformation problem. The results from pavement experiments including suitable instrumentation are compared with the predictions of permanent deformation carried out by various authors. A firm conclusion about the validity of the Romain/Barksdale approach is not considered possible on the evidence presented but the need for further work is indicated.

04027

Permanent Deformation Law of Bituminous Road Mixes in Repeated Triaxial Compression
L. Francken

The experimental work carried out at the Belgian Road Research Center in the field of permanent deformations of bituminous road mixes has for primary goal the determination of a phenomenological deformation law which is to be fed into a structural design method directed towards the limitation of rutting.

The experiments were carried out by means of an electro-hydraulic testing machine. Cylindrical samples of 5 bituminous mixes were submitted to dynamic triaxial tests at different temperatures, frequencies and stress conditions ; in these tests the vertical stress is a sinusoidal function of time and the lateral stress is a static one. The results obtained have been interpreted by considering two important mechanical characteristics : the dynamic stiffness modulus |E*| and the creep curve.

1) The stiffness modulus |E*| is a decreasing function of time (or number of cycles); its value measured after 10^3 seconds obeys the frequency-temperature interchangeability principle. The master curves obtained are similar to those determined in bending, and they may be predicted in many cases from the mix composition. The dynamic stiffness modulus is strongly dependent on the amplitude (sigma sub 1) of the dynamic component of the vertical stress; this nonlinear behavior may not be overlooked for vertical stresses exceeding .3 MN/m2.

2) The creep curves observed may be described by means of a time dependent function of the form

epsilon sub P (t) = At^B + C (exp Dt-1)

in which A, B, C, D are parameters to be fitted (by computer) to the experimental points.

In order to establish a general law of permanent deformation the influence of the physical conditions characterizing the test on the value of these 4 parameters has been investigated.

This leads so far to the following conclusions:

- A purely parabolic behavior (C = 0) may be observed if the highest value of the shear stress corresponds to an experimental point which is below a typical intrinsic curve. This condition may be used as a design criterion against plastic failure.

- The parameter B seems to be less dependent on the physical conditions and ranges from .1 to .3. A mean value close to .25 is a realistic value. A method allowing the evaluation of the creep curve of bituminous mixes is presented for two cases :

1/ When the vertical stress oscillates between zero and a maximum value, and provided that C = 0 (plastic failure criterion) the creep curve takes the form

epsilon sub P (t) = K [(sigma sub 1 – sigma sub 3) / |E*|] t^B

where sigma sub 3 is the confining pressure, K an empirical constant and t the time (corresponding to the quotient of the number of cycles by the frequency of the vertical stress).

2/ An expression based on the energy dissipation concept is proposed in order to predict the permanent deformation under more general stress conditions, This more general formulation reduces to the former one when taking into account the dependence of the dynamic stiffness modulus on the amplitude sigma sub 1.

04028

Evaluation of Rutting Due to Viscous Flow in Asphalt Pavements
S. Huschek

This paper is to be considered as an attempt to develop a generally applicable method for calculating the permanent deformation of bituminous layers due to viscous flow. Using a computer program based on linear, elastic multi-layer theory, the stress/strain distribution in a road under a wheel load can be calculated. The static stress/strain distribution is transformed into a "moving distribution" with respect to speed v = x/t. So as a result, stress and strain at every given point becomes a function of time.

This permanent deformation in one layer caused by the passage of one wheel is calculated assuming viscoelastic properties characterized by a Maxwell element. The total rut depth is obtained by summing up the irreversible deformations of all viscoelastic layers. It is important to consider the viscosity eta of the dashpot as a time dependent value increasing with the number of loadings. Thus, the phenomenon of "consolidation" taking place in asphaltic layers under traffic can be described. The material characteristics are derived from an unconfined compression creep-test which is described in this paper.

The following conditions which influence rutting are taken into account: temperature distribution, number and amount of wheel loadings, transverse distribution of wheel passages, and speed of vehicles. The proposed method can be used to evaluate the mechanical properties of bituminous mixtures required to resist traffic forces under different climatic conditions. Though the presented method is to be considered as a practical engineering approach, it is useful to evaluate the relative performance of different bituminous mixtures and different structural configurations. The validity of this method is shown by comparing the results with measurements made on a Swiss test-road since 1972. The effect of consolidation is shown by comparing the mechanical properties of field core specimens from bituminous layers from the normal lane and from the passing lane.

04029

A Computer Based Subsystem for the Prediction of Pavement Deformation
R.W. Kirwan, M.N. Snaith, T.E. Glynn

This paper describes a subsystem capable of predicting the lateral profile of pavements after any number of axle loadings. The method employs a sophisticated computer program, together with a high level of materials characterisation. The paper is divided into three parts.

(a) A description of the research program DEFPAV is given. This program is capable of computing the load induced stresses and elastic strains beneath a moving wheel load. Furthermore it produces at the same time an estimate of the surface profile due to permanent deformation in each of the constituent layers of the pavement structure. A modification of the program which is suitable for use by road engineers is discussed.

(b) A description of the methods used to obtain both the elastic and creep properties of pavement materials is given. The methods discussed are designed to be usable by the average well equipped materials laboratory rather than a research laboratory.

(c) A description is given of the verification procedures undertaken by this research group to demonstrate that DEFPAV may be used with some confidence in multilayer pavement problems. Furthermore a computation is presented which demonstrates that a program such as DEFPAV may be used to estimate load equivalence factors for different environments and loading conditions.

04030

A Working Design Subsystem for Permanent Deformation in Asphalt Pavements
Frank R.P. Meyer, Ralph C.G. Haas

Rutting represents one of the most common forms of distress in flexible pavements throughout the world. In order to rationally design pavements, in terms of economics, safety, serviceability to the user, and structural damage, it is necessary to be able to predict the actual magnitude of rutting under any given set of conditions.

This paper describes a method of predicting rut depths in flexible pavements. It is based on the evaluation of permanent deformation characteristics of asphalt concrete and unbound base course materials. Statistically designed laboratory experiments provided information about the behaviour of these materials under simulated field conditions. From these laboratory results, mathematical models were developed to predict rutting. Verification was conducted through correlations with actual field test measurements of rut depths.

Asphalt concrete was initially investigated and predictive models were developed in terms of load applications, stress state, temperature, air voids and asphalt penetration as variables. These models were verified using actual measured rut depths from full depth sections at The Brampton Test Road in Ontario. A high degree of correlation was achieved.

The next phase of the study examined unbound base materials. Similar predictive models were developed, in terms of density, stress state and load application as variables. These laboratory based models were applied to the conventional flexible pavement sections at Brampton, again with a good degree of reliability.

Finally, after a sensitivity analysis of variables expected to be significant in affecting rutting, a simplified regression equation incorporating only the important variables was developed. Granular and asphalt equivalencies were used and good agreement between predicted and measured values were found for sections at The Brampton Test Road, Ste. Anne Test Road and San Diego Test Road.

04031

A Subsystem to Predict Rutting in Asphalt Concrete Pavement Structures
C.L. Monismith, K. Inkabi, C.R. Freeme, D.B. McLean

A design subsystem is presented to estimate the amount of permanent deformation (rutting) resulting from repeated

traffic loading. Relationships between applied stress and permanent strain defined by repeated load triaxial compression tests are presented for fine-grained soils, granular materials, and asphalt concrete. Stresses resulting from wheel loads are estimated assuming pavements to be represented as layered elastic structures. The stresses, in turn, permit estimation of permanent deformation in each layer of a specific pavement by

(1) Computing the permanent strain at a number of points within the layer, the number being sufficient to define the strain variations with depth.

(2) Estimating the deformation by summing the products of the average permanent strains and the corresponding differences in depths between the locations at which the strains were determined.

Total rut depth is estimated by summing the contributions from each layer.

To illustrate the potential applicability of the procedure, comparison of the amount of rutting with that observed in an in-service pavement is presented. In addition, to illustrate how the method can be used in practice, a number of examples are included, representative of both unsurfaced (low volume) and surfaced roads.

04032

Methods of Predicting Deformation in Road Pavements
E.N. Thrower

Rigorous computations of the permanent deformation in pavements by methods which satisfy all the necessary equations of equilibrium, compatibility and material behaviour are difficult and extremely time-consuming, so that-simpler approximate methods are normally used. The implications of one such approach, which is in common use, are discussed. The method is based on deriving the permanent deformation from experimentally-determined material deformation properties, in association with a stress distribution determined separately ignoring the permanent deformation.

The further simplification is often made that in the computations, a moving load can be replaced by a pulse load, but the results of computations made by this separative method for pulse and moving loads, using both linear and various non-linear deformation laws, lead to the conclusions that this approximation can result in serious distortions of the assessment of the relative contribution to the total surface displacement from the individual layers.

Because of several doubts and difficulties associated with the use of separative approximations, the permanent deformation in a linear visco-elastic model of a pavement is discussed; this is a rigorous analogue of the linear cases treated by the separative approximation. It is shown that the permanent deformation in such a structure depends only on the deformational properties of the layers, and not at all on their elastic properties; this is in total conflict with the separative approach. Further, the permanent deformation due to a pulse load depends on the deformational properties of the layers in precisely the same way as the deflection of an elastic structure depends on the elastic properties of the layers, and can be computed using the same programmes. Comparison of the results obtained for pulse loads by this method and by the separative approach shows considerable discrepancies, both in the total displacement and in the relative contributions from the respective layers. and it is concluded that some care is needed in the use of the separative approximation.

The behaviour under a moving load can be obtained from that under a pulse load by superposition, but it is shown that the integrals involved do not converge in the linear case. It is concluded that to obtain physically reasonable results by either the separative approximation or a visco-elastic approach requires a knowledge of the deformation properties at low as well as at high stresses.

04033

Design of Asphalt Overlays for Pavements
J. Bonnot, P. Autret, A. De Boissoudy

An important program of systematic overlay of the national primary road network has begun in France in 1969. A pavement overlay design method has been established, and is described in this paper. The most important - and most difficult - phase of overlay design is the characterization of the old pavement: the principles of the method used are summarized.

The paper first describes the method used to confirm the design of a pavement structure incorporating an old pavement and an overlay. A multilayer elastic model is used; an equivalent traffic and an equivalent temperature are used to take into account the variations of axle loads and pavement temperature. The method attempts to take into consideration the probabilistic nature of pavement distress, resulting from the scattering of pavement thickness, overlay material composition, fatigue life, and bearing capacity of old pavement. Distress risk has been chosen as a function of traffic. The method attempts also to take into account in someway the effect of future maintenance on the overlaid pavement.

The overlay design method has the form of a Catalogue of overlay structures in which overlays are calculated once for all. For the overlay of old flexible pavements, the various old pavements have been classified in 36 cases, according to deflection and thickness of old pavement. The overlay thickness has been calculated for each of these cases and for several traffic classes. It has been found that for overlays with cement or slag treated base, the overlay thickness depends only on traffic and deflection of the old pavement; and that for overlays with bituminous base, the overlay thickness depends on traffic, deflection on the old pavement, and on thickness of asphaltic concrete in the old pavement.

The design method has been confirmed using data on the in situ behavior of thirty actual pavement overlays, which has been observed for 4 to 9 years; these data allow a comparison between theoretical and observed relations between strain (or stresses) in overlays and overlays life.

A method is also given for the design of asphalt overlay of old pavement with cement treated (or slag treated) base. Two cases must be considered : the cement treated base shows fatigue cracks but has kept its cohesion, or has lost its cohesion. For old pavements of that type, overlay thickness are always high.

04034

Design of Asphalt Concrete Overlays Using Layer Theory
Harvey J. Treybig, B.F. McCullough, Fred N. Finn, Richard McComb, W. Ronald Hudson

This report is a user's manual for thickness design of flexible overlays for flexible pavements. The design procedure is limited primarily to fatigue cracking and rutting criteria. Three cases of existing pavement condition are recognized by the procedure. These subsystems are:
1) existing pavement with remaining life,
2) existing pavement mildly cracked, and
3) existing pavement severely cracked.

Each requires input from the following areas:
1) deflection testing,
2) condition surveys,
3) traffic data, and
4) materials characterization.

The deflection testing serves as an aid in establishing "design sections" and in characterizing the subgrade. The condition surveys are used to select the proper design subsystem. Traffic data must be in the form of 18-kip equivalent axle loads. The materials characterization consists of laboratory testing to determine modulus values for each material.

The overlay thickness design involves the use of inputs from the above four areas along with an elastic layered theory computer program, a fatigue equation and a rutting equation to determine a thickness that satisfies both the fatigue and rutting criteria. A complete example problem solution for the remaining life subsystem is presented.

04035 **A System for the Prediction of Pavement Life and Design of Pavement Strengthening**
N.W. Lister, C.K. Kennedy

Consideration about twenty years ago of possible approaches to forecasting the life of existing pavements and to designing overlays using, as far as possible, simple in-situ measurements of pavement strength led to the development of a systematic programme of deflection-testing on the full scale road experiments already in service, or being built by the Road Research Laboratory. Lack of knowledge about the real stress-strain behaviour of roads dictated the investigation of possible direct correlation between deflection and the deterioration of roads, deterioration characterized primarily by the development of rutting in the wheel paths.

The experimental programme designed to relate deflection measured by the Benkelman Deflection Beam to pavement condition and traffic is briefly described. The preliminary information presented at the last Conference has been greatly extended and confirm strongly defined relationships between deflection measured early in the life of the road and the onset of critical conditions defining the need to strengthen. When combined with further similar relations shown to exist between critical deflections and the traffic carried, design charts for predicting unexpired pavement life can be drawn up: these are presented for the main types of pavement.

The reduction of deflection brought about by overlaying has been quantified and pavements already overlaid have been studied in order to establish deflection performance relations for strengthened pavements. From the information design charts have been developed defining overlay thicknesses required to extend the life of a road to carry any given traffic. Considerable experience in overlay design has led to great emphasis being placed on the need to define, by closely spaced measurement, the considerable variability of strength which normally exists on a road in need of overlaying. A system for predicting pavement life and designing overlays from this type of information obtained on the road by surveys using the Deflectograph and the Benkelman Deflection Beam is briefly described, with reference to other published work.

The latest development in the design procedure is a computer programme capable of treating the variability of deflection in a consistent manner in such a way as to eliminate the risks of localised early failure or over design in the strengthened pavement. Assessment of successive 100 m lengths of road on a moving average principle is used to define minimum cost solutions which are then used by the engineer as the basis for designs which take into account engineering constraints.

Deflection surveys carried out on a number of normal roads having a range of base types are compared with the predictions of the design charts presented. Examples are given of both new construction and strengthened pavements; one example where the design life of an overlay has now expired is considered in more detail.

04036 **Pavement Evaluation and Overlay Design - The Shell Method**
A.I.M. Claessen, R. Ditmarsch

A method is presented for evaluating pavements by deriving the structural properties from the shape of the deflection bowl under a test load. The structural properties of the existing pavement are expressed in terms of effective layer thicknesses and Young's moduli of the materials. The shape of the deflection bowl is characterised by the ratio of the deflection at a given distance from the load to that measured under the centre of the test load. Charts prepared from computations with the BISAR computer program for multi-layer elastic systems are used for the interpretation of the deflection measurements.

The method can be used, in principle, in conjunction with any type of test load, provided that the appropriate loading conditions are taken into account. Preferably, the measurements are conducted with the Falling Weight Deflectometer (FWD) since its characteristics of force level and loading time are more representative of heavy traffic than most other systems, which are affected adversely by the configuration of the loading and recording systems and/or by indirect measurement of deflections.

Preliminary studies demonstrated that satisfactory results were obtained with a prototype FWD. The data in this paper were obtained with a new FWD modified to allow quick operation with remote control for routine pavement evaluation. Special attention is given to routine operation, including data processing, and to the interpretation of measurements on more complicated structures such as those with cementitious base layers. From the structural properties of the pavement, derived from the deflection bowl measurements and the number of axle loadings carried during service, the residual life of the pavement, expressed in terms of the number of standard axle load applications, can be determined. This information is used to estimate the overlay thickness required for future estimated traffic, using the newly developed design method, in which influences of climate and asphalt mix type can be taken into account. Practical examples of the evaluation and overlay design method are given.

04037

A Practical Approach to Flexible Pavement Evaluation and Rehabilitation
A.C. Bhajandas, G. Cumberledge, G.L. Hoffman, J.G. Hopkins III

A practical scheme for evaluating and rehabilitating flexible pavements is presented. It considers safety, riding quality, and strength as primary factors for evaluating the condition of a roadway. Criteria for safety are not discussed.

Riding quality standards are expressed through the Present Serviceability Index, PSI. Terminal Serviceability Indices, TSI's are established for Interstate, Principal, Minor Arterial, Collector and Local Access Highways from PSI distributions obtained on 5,492 miles of flexible pavement. These TSI's are shown to be flexible and dependent upon funding and construction capability. Thus flexible failure criteria for each type of highway are established.

Spring deflections measured through the dynamic deflection measuring device Road Rater are used to assess pavement strength. Correction curve for surface temperature and adjustment factors for season are established to facilitate comparison under standard conditions.

Permissible deflections on crushed stone bases for various failure criteria are drawn from the AASHO Road Test data. Permissible deflections on bituminous concrete bases are established from a study of ten sections of a test track facility located at State College, PA.

The deflection-overlay relationship drawn from data of ten sections in south central Pennsylvania serves as the basis for overlay design. These overlays show no significant distress upon five years of service. The simplicity of the proposed scheme with a small additional cost for testing, evaluation and design make it feasible for implementation by State Highway Agencies.

The proposed scheme ensures that all type's of highway are given equal consideration and that the worst mileage of each highway type is resurfaced or rehabilitated.

04038

Evaluation and Overlay Design for Flexible Pavements on Low Volume Roads
Pieter De Kiewit, Peter C. Koning, R. Frank Carmichael, W.R. Hudson

The evaluation and overlay design of low volume pavements is a major expense for many governing bodies such as small cities and counties. All over the world such governmental agencies have many miles of flexible pavements to maintain; usually with only small staffs to handle the job. The problem is often complicated further because the agency does not have adequate funding. It is also becoming clear that in the future the maintenance of road pavements will claim a greater part of the funds that are available for highway and road development. Because of these and other factors a rational pavement evaluation and overlay methodology is needed to assist the engineer and preserve the existing investment.

To fulfill these needs, an evaluation and overlay design procedure has been developed based on dynamic deflection measurement, elastic layered theory, and behavioral models for fatigue and rutting (Ref 1). The most important aspects of this procedure are that it is 1) currently operational, 2) based on the best theory available, and 3) developed for easy use. This paper describes the procedure and illustrates it with an example problem applied to conditions in Holland. The criteria according to which maintenance operations are carried out are divided into three main groups:
1. Traffic criteria (geometry),
2. Structural characteristics, and
3. Safety and comfort criteria.

A total evaluation procedure must consider all of these elements. For practical application we have chosen a method which emphasizes these aspects, and recognizes the more relevant items for the type of road which is to be evaluated. In the case of the low volume roads, the structural element and the consequences of different maintenance strategies is important and this will be a main part of the paper presentation. Consultation with the road owner and his needs will establish the requirements for the consideration of the traffic, safety, and comfort aspects.

04039

Optimal Design of Asphalt Overlays
M.D. Rafroiu

It is often economical and convenient to improve the structural condition of a pavement by means of asphalt overlays. Many different methods can be used for the design of these overlays. Only part of them are fitted for an optimal design. New methods based on a structural design approach have been proposed in the last ten years. Generally, the present design methods are based upon deflection measurements and limiting deflection criteria. The difficulties of this approach are: the measurements of the equivalent modulus of the existing pavement, the evaluation of the elastic modulus of the overlay, the correlation between constructive requirements and theoretical accuracy (which may not agree perfectly), the maintenance and overlay policy and other factors as well.

This paper presents a new method for designing asphalt overlays when optimization is required at least from an economic standpoint. Two main situations are taken into account : the existing pavement needs only to be strengthened as no important distortions are reported, the existing pavement is heavily rutted, cracked or disintegrated and it is supposed to undergo particularly deep investigation and, if necessary, a new and complete structural design would be done. Only the first situation is studied in this paper.

The new method is based upon an energy approach which requires that the energy absorbed by the highway body, when deflection under exterior loading occurs, should not exceed a limited amount which is related to the composition and the value of the traffic the pavement is supposed to bear through the design period.

The design criteria are based upon limiting tensile stresses at the bottom of the layers, shear stresses in the center plane of the layers and, most of all, requiring a given bearing capacity of the "rejuvenated" pavement. Since only one layer (as overlay) may not fulfill all requirements derived from the design criteria, it has been assumed that in certain situations two layers would be necessary, such a solution being supposed to offer both economic and constructive advantages.

The method also permits an iterative procedure in order to get an economic optimum.

Since new developments have been made, both theoretical and experimental accuracy checks have been done.

The method has been accepted for current overlay design and is now in use in parallel with the existing standardized method.

04040

A Pavement Analysis and Structural Design Procedure Based on Deflection
P.G. Rufford

Recognition of flexure cracking as a primary mode of distress of asphalt pavements in New South Wales, Australia, highlighted the need for a structural design procedure based on deflection. As the Benkelman beam was considered the most suitable equipment for measuring deflection for general design purposes, it was felt necessary in the first instance, to develop a pavement analysis technique to interpret the Benkelman beam measurement of deflection. This pavement analysis technique involved analysing the Benkelman beam deflection bowl using elastic theory to assess the flexibility of the subgrade and the overall flexural strength of the pavement. The elastic theory analysis was tested both theoretically and empirically to define the limits of its application and to provide the confidence required to use it in practice. In-situ non-destructive testing has particular application to reconstruction and overlay design and therefore the analysis was developed into a design procedure for this purpose. As the overall flexural strength of the pavement was expressed in terms of an equivalent thickness of a standard base material, the design procedure used the basic AASHTO pavement model. It involved designing the pavement to a design Benkelman beam deflection which was determined from the performance of the existing pavement in relation to the TRRL design deflection levels. This paper presents the pavement analysis technique and the structural procedure for reconstruction and overlay design. It also includes an example of an overlay design to demonstrate this procedure.

04041

Overlay and Stage-by-Stage Design
P. Ullidtz

A structural design procedure based on elastic theory is presented. The main aspects of the procedure are discussed, i.e. failure conditions, loading and climatical conditions, determination of elastic parameters and of allowable stresses and strains and finally calculation of the critical stresses and strains.

The main emphasis of the paper is on the determination of the elastic moduli of the different materials in a pavement structure, because a correct determination of the moduli is a prerequisite for the application of the theory of elasticity. A non-destructive method of determining the moduli of two- and three-layer systems is presented. The method is based on the use of dynamic plate loading tests (e.g. falling weight deflectometer tests) and the calculations may be carried out with the use of some diagrams and a programmable pocket calculator. For more complex structures, i.e. structures containing four or more layers, use of at least a programmable desktop calculator is required.

The moduli are calculated from the deflection basin, and information on the subgrade modulus may be obtained to an equivalent depth of 10 -12 meters. The method is therefore especially well suited for determining the modulus of the subgrade before construction of the road. The moduli may be determined both for structures containing linear elastic materials only and for structures having a non-linear elastic subgrade, for which the stress dependent modulus may be approximated by the following simplified relationship:

E = C x (sigma sub 1 / sigma prime)^n

where E is the modulus, sigma sub 1 the major principal stress, sigma prime a reference stress and C and n are constants.

With this relationship a modified version of the method of equivalent thicknesses may be used and some simple equations for calculating the critical stresses and strains in the centerline of the load are presented.

The validity of this model for determining the stresses and strains under actual traffic loadings has been verified through full scale experiments and the determination of the allowable stresses and strains is based on laboratory tests and the results of the WASHO and AASHO Road Tests, modified in accordance with the experience gained from Danish road design during the last decade.

04042

Structural Design of Asphalt Pavements and Control of Environmental Influence on Performance
William S. Housel

This paper reviews the development of field loading tests to measure the bearing capacity of soil masses and pavements supported by soil masses. Time, load, settlement or deflection, and the size of the bearing area are the four basic quantities which must be measured to determine load bearing capacity. The relationship between these variables has been clearly and accurately established by more than forty years of research and practice by various agencies.

The time, expense, and inherent difficulty of running full scale field loading tests over a wide area of variable soils involved in the design and construction of highway pavements places them beyond the resources of the majority of practicing engineers. Consequently it has been a major objective of the International Conferences on the Structural Design of Asphalt Pavements to develop laboratory tests to measure the fundamental properties of the materials used in the pavement structure and formulate design procedures based on these tests.

This primary objective and the corollary requirement of field verification have been achieved by an exhaustive study of data from the Hybla Valley project where both field loading tests on the pavement structure and laboratory tests of the materials in each component of the pavement were available. In every case including subgrade, base course, and the bituminous surface, the stress reactions and soil resistance coefficients measured by the field loading tests could be computed from the laboratory tests within an acceptable range of accuracy for the materials involved and the normal experimental error which would be expected in comparing field and laboratory tests.

The results of this correlation using the design procedures proposed in this paper are summarized in a tabulation. These design procedures are within the capabilities of any well informed and competent practicing engineer in the field of highway engineering and do not require the background of a research specialist.

Aside from routine laboratory tests for classifying the materials, the controlling laboratory tests to measure the fundamental properties required in the design are the triaxial compression and direct shear tests. These were the tests used in the early investigation of granular materials by Berry which are summarized in Table 3. These data demonstrated that internal stability of dense granular soils and highly consolidated granular materials was sufficient to control the design of flexible asphalt pavements. Internal stability was defined as that mechanical property of granular masses which produces resistance to displacement by mutual support of adjacent particles too large to be measurably affected by molecular forces.

Computations based on these data showed that the mechanical advantage of aggregate interlock produces resistance to displacement which in Berry's tests, ranges from 1 to 17 times that obtained from theoretical equations. The key to the surprisingly high internal stability is measured by the "Aggregate Interlock Factor K," defined as an exclusively peculiar structural property of granular material unaffected by the theoretical capacity computed from traditional concepts of elastic behavior.

The test results under discussion, available since 1936, provide a body of experimental evidence to be evaluated which cannot be passed over without careful study. For many years internal stability based on these data has been successfully applied in design of caissons and high capacity bearing piles supported on highly consolidated granular soils and granular cohesive mixtures. These practical applications have demonstrated that these materials will develop internal stability up to the crushing strength of the grains without lateral displacement. It should be recognized that the vital role of such granular materials and mixtures becomes a controlling factor in design of flexible asphalt pavements.

04043 **Pavement Management Design Considerations for Canadian Airports**
G.H. Argue, B.B. Denyes, G.Y. Sebastyan

A synopsis is given of Transport Canada structural design practices for the provision of airfield asphalt pavements at Canadian airports. Pavement management design considerations in the related areas of construction, evaluation, operations, maintenance and rehabilitation programming are also discussed in a general manner. A short summary of Transport Canada research and development objectives as related to asphalt pavement structural design are outlined. A detailed treatment of standards and practices may be found in the Transport Canada manuals listed in the references.

04044 **Pavement Management Guide: A Summary**
Pavement Management Committee, Roads & Transportation Association of Canada

The Pavement Management Guide summarized in this paper is concerned with the practices and procedures illustrated within.

The Guide suggests that the basic purpose of a pavement management system is to achieve the best value possible for available public funds and to provide safe, comfortable and economic transportation. This is accomplished by comparing investment alternatives at both the network and project levels, coordinating design, construction and maintenance activities, and making efficient use of existing practices and knowledge. This paper provides a very brief summary of the Guide. It discusses benefits and implementation guidelines associated with pavement management, network investment programming, optimization of project investment, pavement evaluation, structural design of flexible and rigid pavements, construction, maintenance, data banks, and guidelines for research management.

04045 **The Consideration of Frost in the Design of Asphalt Pavements**
L. Caniard, C. Peyronne

The purpose of the article is to describe a new method for the consideration of frost in the design of asphalt pavements. The originality of the method developed by the Administration Francaise des Ponts et Chaussees resides in the fact that the harmfullness of frost is to be characterized by a frost index transmitted to the soil, and not by a depth of frost. Finally, a numerical model which is more precise than other models currently in use is used, which makes it possible to treat the case of structure containing several courses. The initial parameters involved in the method are:
- the thermal characteristics of the winter, and the manner of synthesizing them through the choice of a standard frost index,
- the thermal characteristics of the asphaltic materials making up the pavement. This article indicates how they have been determined,
- the mechanical properties of the asphaltic materials, and the influence of temperature,
- the heaving of the soil by frost, and its bearing capacity at thaw.

A numerical model, whose equations are elucidated, allows the calculation of temperature changes in the pavement, and forecasts the final position of the frost front, as well as the frost index transmitted to the foundation soil. The article presents some computation diagrams.

According to the result of the temperature calculation, three cases are possible:

- The thermic protection ensured by the asphalt pavement is sufficient, so that there might be no fear of any loss of bearing capacity of the underlying soil; the structure is to be retained.

- The thermal protection is inadequate, and there is a loss of soil bearing capacity. The consequences to the useful life of the asphalt pavement are examined. If the mechanical resistance is suitable, the structure is retained.

- In the case to the contrary, the method indicates how it is possible to either increase the thickness of the pavement (which improves thermal protection and mechanical resistance), or to make the soil less susceptible to frost. The article gives some examples of the practical application of the method, and describes verifications carried out in an experimental test station.

04046 **Determination of Pavement Layer Moduli from Surface Deflection Data for Pavement Performance Evaluation**
Lynne H. Irwin

In order to utilize mechanistically based methods for pavement design and evaluation, there is a need to know the moduli of elasticity of each layer in the pavement system. For pavement evaluation and overlay design it is preferable to know

the in situ moduli, rather than resorting to elaborate and costly laboratory approaches to materials characterization.

Techniques for measuring moduli in situ have primarily been based on two techniques: surface vibratory testing and surface deflection testing. This paper reports on a method whereby surface deflection data may be evaluated using layered elastic theory to estimate the elastic moduli of each pavement layer. Moduli determined by this method are known within an accuracy of ten percent or better. Accuracies of this degree compare favorably with the point to point variability of in situ moduli due to construction and materials variation, and thus may be considered satisfactory.

The method of obtaining the layer moduli reported in this paper relies on the use of layered elastic theory computer programs. It is necessary that the thickness and Poisson's ratio be known for each layer, although the results are not highly sensitive to the value assumed for Poisson's ratio.

In the method, points on a two-dimensional surface deflection basin are fitted to the field data. Iteration is required to align the measured and computed points by adjusting the assumed values for the layer moduli. Presently the method relies on trial-and-error iteration using the BISTRO computer program. It is suggested that a new program be developed which would enable a more direct determination of the moduli.

A case study is presented to demonstrate the application of the method to the evaluation of a test pavement for a heavy duty haul road to support 400,000-pound gross vehicle weight lignite coal trucks. Deflections of the test pavements were obtained using the Dynaflect apparatus and a fully loaded haul vehicle. The major difference in the magnitude of surface loading served to illustrate that the assumption of linear elasticity is not valid over such a range.

The evaluation of one of the eight test pavements is illustrated by example, and it is predicted that the pavement will not be satisfactory for the anticipated loading and traffic. The prediction was borne out after several years of use.

04047

OPAC Design System
Ramesh Kher, W.A. Phang

OPAC (Ontario Pavement Analysis of Costs) is a computerized system that compares the performance and cost of hundreds of design alternatives for flexible pavements within just a few hours. Using the system, pavement design engineers can select the most effective pavement design that has the least cost.

OPAC predicts the life of a pavement. The deterioration in Riding Comfort Index (RCI) has been made a function of repeated traffic loading and annual cyclic environmental changes. The deteriorations caused by the two factors have been respectively modelled using data from the AASHTO (Illinois) Road Test and Brampton (Ontario) Road Test. Subqrade surface deflection under a standard wheel load has been used as a predictor of future behavior of a pavement. Successful thickness designs in the province were analysed using Elastic Laver Theory and several iterations of such analyses resulted in a set of modulus values which were thereafter assigned to various paving materials and six different categories of subgrades in the province. Through AASHTO Road Test data, an excellent correlation between subgrade surface deflection, traffic, and pavement performance has been developed to allow calculation of that component of pavement deterioration which is caused by traffic. The other component, caused by environment, has been modelled from the Brampton Road Test data. It is based on the difference in deterioration predicted due to traffic, as previously indicated, and actual measured deterioration of Brampton Road Test sections over a period of eight years. The two submodels for pavement deterioration are combined to predict the performance of any pavement section,

OPAC predicts pavement costs throughout the life of a pavement. Various cost components are: initial capital expenditure, subsequent resurfacing and maintenance expenditures and salvage return. OPAC is so comprehensive that it also includes road user delay cost in its economic analysis of design alternatives. OPAC provides an evaluation of the various cost components of a pavement on the one hand and various possible consequent costs to the users on the other and makes it possible to examine design trade-offs, The final decision regarding the selection of a design remains with the pavement design engineer who must also consider such location information as construction problems, aggregate depletion and traffic safety.

OPAC is very accessible, simple to use. Communication between the pavement design engineer and OPAC is achieved through a terminal which is linked by telephone to an IBM 360 computer. A question and answer dialogue is established between the computer and the engineer using the keyboard of the terminal. In response to questions posed by the computer, the pavement design engineer enters basic design specifications such as subgrade condition traffic projections,
, performance requirements,
available material and their costs. Within seconds the computer returns its analysis to the terminal , printing out various design alternatives to meet the engineer's specifications.

In operation since March 1974, OPAC's ability to analyze and predict cost and performance provides the basis for effective pavement management, and for assisting planners in providing, within the available budget, an economically designed road system that considers the needs of the province's travelling public.

04048

Prediction of Sulphur-Asphalt Pavement Performance with VESYS IIM
Robert L. Lytton, Donald Saylak, Daniel E. Pickett

The utilization of sulphur in sulphur-asphalt pavements is receiving considerable attention for a variety of reasons. One reason is that sulphur is one material which is expected to be in ample supply in the foreseeable future. Because of its ability to function both as the aggregate as well as an integral part of the binder, sulphur has been used to upgrade locally available, poorly graded sands in sulphur-asphalt sand mixes and as a partial replacement for asphalt cement in conventional bituminous concrete pavement mixtures. Because of limited field experience with these pavements, the viscoelastic layered pavement analysis program VESYS IIM was used to predict their performance in a variety of climates and to compare this performance with that of conventional asphaltic concrete pavements placed in identical conditions. Material properties of the mix designs used in the analyses were all measured in the laboratory. The resulting predictions showed that sulphur asphalt pavements may be expected to have less rutting and maintain a higher serviceability index but to have a comparatively greater susceptibility to fatigue cracking than conventional asphaltic concrete pavements.

04049 **Evaluation of Existing Pavement Based on Deflection and Radius of Curvature and Overlay Design**
Y. Miura, T. Tobe

To perform maintenance and repair of an asphalt pavement having reached its service limit, it is necessary to make a mechanical evaluation of the existing pavement and subgrade. On a road being in service, however, it is difficult to perform destructive examination. It is therefore needed to establish an evaluation procedure by non-destructive method. In view of this, the author et al. have dealt with a procedure for evaluating existing pavements by determining the stiffness moduli of the subgrade and pavement from data obtainable from the surface of pavement, i.e. deflection and radius of curvature induced in the neighborhood of the center of loading, and with the aid of the two-layer system. Further, concerning the method to determine the radius of curvature, an examination was made of the deflection curve taken as the basis for this.

There are two methods of dividing the existing pavement into two layers: one into the subgrade and pavement and the other into the asphalt treated layer and bearing layer. The former is suitable for evaluation by compressive strain of the subgrade and deflection and the latter, by tensile strain at the bottom of asphalt treated layer and radius of curvature,

Field verification was made on local roads being in service about 10 years and by comparing the stiffness moduli of the subgrade and pavement, which were estimated from material testing of the existing pavement with due consideration for environmental and traffic conditions, to those estimated by nondestructive method. For the subgrade, the resilient modulus from a repeated compression test performed with the field suction condition reproduced in laboratory was compared to that obtained by nondestructive method. As a result, it was confirmed that the nondestructive method permits to estimate the stiffness modulus with good accuracy.

As for the asphalt treated layer, the values determined by the Shell procedure were compared with those obtained by nondestructive method, and it was confirmed that there existed good correspondence. It should be noted that this comparison was done at a reference temperature (20C) and that temperature correction was therefore made for all of the field data.

Since it was ascertained that not only deflection but also the stiffness moduli of the pavement and subgrade follow a logarithmic normal distribution, field measurements of deflection and radius of curvature were statistically treated to present an adequate procedure for determining a typical structure of existing pavements.

As the existing pavement was evaluated by the two-layer system, overlay design was made by the three layer system. That is, examinations were made assuming the pavement structure as being divided into the subgrade, pavement and overlay when a limit is placed upon strain on the subgrade or deflection and as being divided into the bearing layer, asphalt treated layer and overlay when a limit is placed upon tensile strain at the bottom of asphalt treated layer or radius of curvature.

The values of deflection and radius of curvature estimated by computation for two types of overlay used on the site were compared to the values measured after the overlaying. As the result, the computed values were found close to the average of the measurements, proving adequacy of the design.

04050 **A Stochastic Model for Pavement Performance and Management**
F. Moavenzadeh, B. Brademeyer

A methodology for the analysis and selection of pavement systems, given a set of goals and constraints is presented. A set of models at three different levels of analysis is discussed.
1) analysis of the physical behavior of the pavement system,
2) analysis of the distress and performance of the pavement system, and
3) analysis of the selection and optimization of maintenance activity given the initial pavement design configuration.

The first involves a mechanical model of the pavement system, which is taken as a stochastic linearly elastic or viscoelastic layered halfspace subject to a static circular normal loading, which predicts the primary responses of the pavement system. These are the stress, strain, or deflection at any point in the halfspace.

The second model uses the Boltzmann Superposition Principle to convert the primary responses into limiting responses under a realistic operating environment, with mechanical and phenomonological models to convert these limiting responses into cracking and permanent deformation. These distress parameters are then introduced into a probabilistic version of the AASHO serviceability equation, and the serviceability and reliability of the system are predicted. Changes in the state of the serviceability are modeled as a homogenous Markov process.

The third level of analysis utilizes transfer functions to convert maintenance activities into improvement in system performance. Decision analysis, with traffic and maintenance levels being the independent variables, is then used to rank and optimize various maintenance alternatives with or without budget constraints. In all of the levels of analysis, the system responses and performance are random variables, as is traffic, with environment and maintenance level being deterministic variables. Sensitivity analyses performed at M.I.T. have shown that the trends predicted by the model are in reasonable agreement with the anticipated behavior of real world systems.

04051 **The Analyses of Asphalt Pavement Research Results on the Tomei and Chuo Expressways**
Nihon Doro Kodan

This progressive report summarizes two topics obtained from the pavement research program carried out on the heavily travelled expressways.

1. Relationship between Thickness Index, TI and 10 t EAL Applications. To examine the relationship between thickness index, TI and 10 t EAL applications, the following three basic variables were evaluated.
a. Evaluation of pavement performance by means of pair-wise comparison.
b. Evaluation of traffic condition in terms of 10 t EAL applications.
c. Evaluation of pavement structure in terms of the equivalent asphalt thickness, TI, as placed incorporating subgrade and underlying materials into the calculation.

Relationship between TI vs. 10 t EAL applications to the terminal level revealed that there were two types of pavement

lives, the structural one represented by cracking and the functional one represented by rutting. The former showed the curve linear relationship between TI and 10 t EAL applications. However, the latter did not correlate with axle load applications but is limited to around 10 x 10^6 axles.

2. Development of a Mathematical Model for Rut Depth Prediction. In the foregoing analysis, rutting resistance of the bituminous mixture was recognized to be very important to extend the overall pavement life. Therefore, significant factors affecting the occurrence of rut depth were investigated by a statistical method and then mathematical models to predict rut depth were developed.

The most significant factor selected was 10 t EAL applications followed by PI of recovered asphalt, air void, type of aggregate, annual sunshine duration, TI and slope index. Rut depth prediction model could predict rut depth at the accuracy of +/- 3.2 mm with 95% confidence level.

Modification of the structural design curve is now in consideration and mixture design criteria were modified based on these test results.

04052

Failure Models and Pavement Design and Rehabilitation Systems Developed and Adapted for Conditions Prevailing in the Nordic Countries
The Nordic Cooperative Research Project for the Application of the AASHO Road Test Results (STINA)

Application of the road test results in other areas than the test site faces three main problems
- pavement failure mechanisms
- subgrade characteristics and their seasonal variation
- the relation between failure and axle load spectrum.

These problems have been dealt with in a joint research effort in the Nordic countries (Denmark, Finland, Iceland, Norway and Sweden), which has been in operation since the beginning of 1974.

Three failure models (AASHO modified, Texas and Ontario) have been fitted to serviceability data from test roads and found applicable when using the same parameter values as those giving the best fit in their original application.

In an analytical examination of pavements complying with Nordic standard specifications, assuming current asphaltic pavement fatigue criteria, a range of subgrade criteria was reached, which contained within its limits the Shell subgrade formula. Examination of the power law for load equivalence factors gave an exponent range around four.

From a previous quite extensive axle load study at some 200 test points in the Swedish road network vehicle equivalent factors have been calculated, using different exponent values in the "fourth power formula". It was found that variation in the exponent had much greater influence upon the vehicle equivalent factors than variation in the traffic load spectrum.

Application of the analytical design and rehabilitation models (SAMP) to Nordic conditions have been examined and an extension of such systems applicable to decision processes for rehabilitation is suggested.

04053

Design System for Minimizing Asphalt Concrete Thermal Cracking
Mohamed Y. Shahin

A design system for minimizing asphalt concrete thermal cracking has been developed. Asphalt concrete "thermal cracking" occurs in the form of transverse, longitudinal, and/or block cracking. Major factors causing these cracks include (1) very-low temperatures resulting in tensile stress that exceeds mixture tensile strength, and (2) daily temperature cycling resulting in repeated tensile stresses and strains that cause asphalt-concrete thermal fatigue. Therefore, thermal cracking occurs not only in cold climates, but also in climates where there is a large daily temperature range and high solar radiation. The author has found several pavements in Phoenix, Arizona having severe block cracking, even though the minimum air temperature is 30°F. However, the average daily temperature range is about 30°F and the solar radiation is quite high causing a large pavement daily temperature range. Similar cases were found in Texas, Alabama, Florida, and So. California. Although the initial occurrence of the cracks has little effect on pavement performance, routing and filling the cracks becomes a maintenance problem. If cracks are not maintained they may rapidly deteriorate. As water infiltrates the cracks, swelling or consolidation of pavement or subgrade layers may occur causing considerable roughness. Spalling of the cracks in airfields can cause foreign object damage (F.O.D.) to aircraft engines. As severe as the problem may seem, thermal cracking can be minimized or completely eliminated for new asphalt pavements through the use of a rational mixture design system. Such a system has been developed and verified and is presented in this paper.

The verification showed that the system is a reliable tool for selecting the most suitable asphalt grade, asphalt supplier, and mixture design for minimizing thermal cracking. The inputs to the system are the environmental conditions where the pavement is to be constructed, asphalt grade, asphalt concrete mixture characteristics, and variability associated with the inputs. The output of the system is the amount of thermal cracking as function of age, expressed in ft^2/100 ft2 or ft/100 ft ^2. A procedure is also described to assess the effect of different amounts of thermal cracking on pavement structural integrity and surface operational condition.

04054

Volume II of Proceedings - preliminary pages
n/a

04055

Session I -- Design Methods (discussion)

Moderators: W. R. Hudson, R. C. G. Haas

Moderators' Opening Remarks . . . W. R. Hudson
Presentation by Author . . . A. I. M. Claessen
Discussion of Paper by . . . A. I. M. Claessen et al
Discussion Form Questions/Comments
Presentation by Author . . . F. N. Finn
Discussion of Paper by . . . F. N. Finn et al
Discussion Form Questions/Comments
Summarization of Paper . . . R. C. G. Haas
Discussion Form Questions/Comments
Miscellaneous Written Remarks

04056 **Session II -- Design Methods (discussion)**
Moderators: J. F. Shook, L. E. Santucci

Moderators' Opening Remarks . . . L. E. Santucci
Presentation by Author . . . W. J. Kenis
Presentation by Author . . . J. B. Rauhut
Summarization of Papers . . . J. E. Shook
Summarization of Papers . . . L. E. Santucci
Discussion Form Questions/Comments
Miscellaneous Written Remarks

04057 **Session III -- Structural Design Systems (discussion)**
Moderators: R. G. Aalvin, T. F. Mcmahon

Moderators' Opening Remarks . . . R. G. Ahlvin
Presentation by Author . . . J. Verstraeten
Presentation by Author . . . W. R. Barker
Presentation by Author . . . B. Celard
Discussion Form/Questions Comments
Moderators' Summary . . . T. F. McMahon

04058 **Informal Session A -- a New Pavement Design (discussion)**
Chairman: G. Y. Sebastyan

Opening Remarks . . . G. Y. Sebastyan
Discussion Form Questions/Comments
Miscellaneous Written Remarks

04059 **Session IV -- Design Methods (discussion)**
Moderators: P. S. Pell, S. F. Brown

Moderators' Opening Remarks . . . P. S. Pell
Summarization of Papers . . . S. F. Brown
Presentation by Author . . . W. D. 0. Paterson
Review of Design Papers . . . P. S. Pell
Discussion Form Questions/Comments
Miscellaneous Written Remarks

04060 **Session V -- Permanent Deformation (discussion)**
Moderators: R. D. Barksdale, R. G. Hicks

Summarization of Papers . . . R. G. Hicks
Summarization of Papers . . . R. D. Barksdale
Discussion by Authors
Discussion Form Questions/Comments
Miscellaneous Written Remarks

04061 **Conference Banquet**
n/a

CONFERENCE BANQUET . . . photo

04062 **Session VI -- Overlay Design (discussion)**
Moderators: B. F. McCullough, R. A. McComb

Moderators' Opening Remarks . . . R. A. McComb
Presentation by Author . . . J. Bonnot
Presentation by Author . . . H. J. Treybig
Presentation by Author . . . N. W. Lister
Presentation by Author . . . C. K. Kennedy
Presentation by Author . . . A. I. M. Claessen
Moderators' Summary . . . B. F. McCullough
Discussion Form Questions/Comments

04063 **Session VII -- Overlay Design Methods (discussion)**
Moderators: K. Wester, W. Visser

Moderators' Opening Remarks . . . K. Wester
Moderators' Summary . . . N. Visser and K. Wester
Discussion of Summarized Papers
Discussion Form Questions/Comments
Miscellaneous Written Remarks

04064 **Informal Session B -- Overlay Design Papers (discussion)**
Chairman: G. B. Sherman

Opening Remarks . . . G. B. Sherman
Discussion Form Questions/Comments
Miscellaneous Remarks

04065 **Session VIII -- Summary Session (discussion)**
Moderator C. L. Monismith

Conference Summary . . . C. L. Monismith and F. N. Finn
Appendix A - Paper Categories
Appendix B - Pavement Maintenance and Rehabilitation Considerations
Remarks . . . J. F. Shook
Remarks . . . N. W. Lister
Remarks . . . C. F. Scheffey
Discussion Form Questions/Comments
Concluding Remarks . . . C. L. Monismith and F. N. Finn
Conference Closing Remarks . . . E. Tons

04066 **Corrections to Papers Printed in Volume I**
various

Corrections to Papers Printed in Volume I.

These corrections have been placed at the end of each relevant file.

04067 **List of Registrants**
n/a

List of Registrants

04068 **Composite Bituminous Pavement Design to Prevent Transverse Cracking**
I. Deme, F. D. Young, R. W. Culley

Previous research projects have demonstrated that asphalt type and grade are the major factors influencing transverse cracking of asphalt pavements at low temperatures. Paving mixes made with asphalts of low temperature susceptibility (high penetration index) and/or soft grades have been found to be resistant to transverse cracking.

Composite asphalt pavements, comprised of an upper non-cracking and a lower transverse crack susceptible layer of asphalt mix were constructed over sand and clay subgrades in Manitoba and Saskatchewan. The composite pavements did not crack providing evidence that the asphalt in the top layer was the prime factor responsible for the initiation of transverse cracking at low temperatures. The project also demonstrated that transverse cracking of mixes, normally susceptible to cracking, can be prevented or reduced when such mixes are restricted to use as binder courses or pavement bases in conjunction with a non-cracking asphalt surface course. Pavement temperature studies indicated that the insulation provided by the surface course(s) was sufficient to shield the temperature susceptible underlayers from their critical cracking temperatures.

A procedure has been developed for selecting composite asphalt pavement lift thickness in areas with low winter temperatures. It is based on preventing cooling of the layers of various asphalts to their critical cracking temperature. The design approach takes into consideration the critical cracking temperature of the asphalts used, the pavement temperature distribution with depth, and the intensity and recurrence intervals of low temperature extremes in the area. The use of composite asphalt pavements in accordance with these design principles optimizes both the low temperature performance of the pavements and the use of asphalt resources.

04069 **Urban Pavement Management on a Coordinated Network-Project Basis**
M. A. Karan, R. C. G. Haas

This paper describes the basic components of an urban area pavement management system, and the development of some of the key technology. The approach is primarily concerned with determining investment priorities on a network basis, rather than with sophisticated within- project design.

A user-related "Urban Serviceability Index", USI, measure has been developed. It is a combination of subjectively established Riding Index and Appearance Index, which can be correlated with objective, mechanical measurements of roughness and damaged area of the pavement, respectively.

A performance prediction model, incorporating the USI measure and various pavement classes, has been described. It can be applied to alternative improvement "strategies" and the priorities to be applied to these strategies can be determined through an optimization model. A key feature of the optimization model is the ability to evaluate trade-offs associated with project timing or scheduling.

Finally, the basic components of a pavement inventory system, based on periodic acquisition of performance and other data, have been described. This data is used as "feedback" and the inventory system becomes an inherent component of the overall pavement management system.

04070

Materials Characterization for Asphalt Pavement Structural Design Systems
T. W. Kennedy, A. S. Adedimila , R. C. G. Haas

Elastic and viscoelastic analyses of pavement structures must rely on proper characterization of the pavement layer materials. Variations in materials properties through testing error, lack of uniformity, or differences between tests can significantly affect the design thicknesses selected. This paper suggests that inadequate or improper materials characterization can invalidate the results of structural analyses.

The paper first relates the structural responses of major interest in design to the appropriate structural subsystems and the basic materials properties required. Criteria for selection of methods to determine these properties are then described and a classification of available tests, matched to properties, is presented. Both elastic and viscoelastic characterization is considered.

A simple example of the potentially significant effect of variations in materials properties on the number of traffic applications carried by a given pavement structure is presented.

04071

Evaluation of Subgrade and Its Overlying Flexible Pavement Layers
S. K. Khanna, D. Raja Rao

In a rational design approach for flexible pavements, stresses and strains at critical points in the pavement structure are to be limited to acceptable values. But, the difficulty arises in determining the strains at critical points and their acceptable values. Again, to evaluate the performance of flexible pavements, the maximum surface deflection alone under standard wheel load condition is not sufficient. Some investigators have shown that the product of deflection and the curvature of the deflected basin under the standard wheel load reasonably is constant for a given type of pavement. In terms of critical points of the pavement structure, the maximum deflection controls the limit vertical strain over the subgrade and the curvature of the deflected basin controls the limit horizontal tensile strains in the stiffened layer.

In this study theoretical design charts have been developed for evaluating the structural performance of flexible pavements under the standard wheel loads by deflection criteria which takes into account the maximum deflection and the curvature of the deflection basin in terms of spreadability. A method to determine the elastic moduli of the subgrade and its overlying flexible pavement layers using plate load tests under standard wheel load conditions has also been suggested.

To verify the above evaluation chart, an experimental investigation was conducted through full scale laboratory tests under static wheel loads using rigid plate as well as dual wheels. These tests were carried out over the subgrade, three layers of water bound macadam and bituminous carpet. During these load tests, the surface deflections as well as deflections over the subgrade and other layers were measured.

From this test data, the effect of deflection ratios, plastic deformations and the subgrade deflections with variation in plate types and pavement thicknesses are studied. The suggested method also includes the determination of elastic moduli and equivalent elastic moduli of pavements.

In India, the base course construction generally consists of water bound macadam layers. Such layers do reduce enormously the deflections under the standard wheel loads up to an optimum thickness, but due to lack of cohesion, it does not always improve spreadability with increase in its thickness. This drawback of water bound macadam as base course for heavy traffic conditions is clearly brought out in this study.

04072

South African Mechanistic Pavement Design Procedure
R. N. Walker, W. D. 0. Paterson, C. R. Freeme and C. P. Marais

The mechanistic procedure for pavement design described in this paper is total in its concept and largely complete in its content and verification. The design philosophy, which is based on mechanistic rather than empirical models distinguishes between maintenance which strengthens the pavement structure and that which merely improves the surfacing condition. By using for structural design purposes a life with a high confidence value, and average lives for the estimation of the nature and timing of maintenance, a realistic economic analysis is made using a discount rate that includes the effect of inflation. The uncertainties involved in relating models of material behaviour to models of pavement behaviour, and especially performance, are identified as areas for future work. The errors involved in traffic prediction are quantified and these show that strong preference should be given to dynamic weighting techniques when a mechanistic design is considered. Controlled trafficking tests are used to show that load equivalency factors vary enormously depending on pavement composition and the criterion of distress.

Bituminous materials are fully characterized with respect to fatigue, crack propagation and deformation, and some new original work is included. It is recommended that stiffness and repeated load tests be used in measuring these properties, and that it is essential to use a viscoelastic response in the case of deformation analysis.

Much new work on cementitious materials is presented. These materials are characterized by linear elastic behaviour in flexure, and by fatigue behaviour as a function of maximum tensile strain. The effects of shrinkage cracking and thermal stresses are quantified in the design. The characterization of granular and cohesive materials draws on published data together with initial results from recent work.

A highlight of the paper is the strong verification obtained for the traffic-associated behaviour of bituminous and cementitious materials in full-scale pavements under controlled accelerated trafficking tests using a Heavy Vehicle Simulator. Mechanistic evaluation of the test data yielded a fund of unique information, especially in permitting a precise identification of the timing and location of cracking in cementitious layers. A number of full-scale experimental pavements under normal traffic were also used to verify the behaviour of bituminous materials.

Finally, a two-level approach is proposed for implementing mechanistic design techniques. The comprehensive procedure which can handle any combination of loading, environment and material properties is normally only warranted in special cases, and en application of this to the design of container terminal pavements for wheel loads in the range 70-450 kN is used as an example. A second and much simpler procedure, which utilizes a catalogue of designs, is used as a preliminary analysis to the comprehensive one, and is also recommended for routine pavement design use for design traffic not exceeding 20.10^6 equivalent 80 kN axle loads.

04073	**Simple Elastic Models for Pavement Evaluation Using Measured Surface Deflection Bowls** *G. Wiseman, J. Uzan, M. S. Hoffman, I. Ishai and M. Livneh* A simple procedure for pavement evaluation is presented, and its applicability verified. This procedure is based on the interpretation of measured surface deflection bowls, using the Hogg and Burmister two-layer elastic models, with a rigid bottom at a finite depth below the subgrade. The real multi-layered pavement structure is replaced either by a plate or by a single elastic layer. Therefore, influence charts and evaluation nomograms can be easily prepared for any specific case of pavement thickness and loading configurations, and are presented in the paper. Of the two models presented, the Hogg model is simpler to use at the present time, as separate evaluation charts are not required for each pavement thickness. Since both models result in approximately equal values of the subgrade modulus (E sub 2), there is little justification for using the more complicated Burmister model for this purpose. The Burmister model, however, shows more promise for quantitative evaluation of the pavement structure. Examples of the interpretation of measured surface deflection bowls, using these simple models, are given in this paper. They have proven to be a valuable aid in flexible pavement evaluation. Their very simplicity should make them attractive to pavement engineers.
04074	**Index of Contributers and Discussers** *n/a* Index of Contributers and Discussers

code	ISAP 5th Conference - Titles & Abstracts
05000	**5th International Conference on the Design of Asphalt Pavements - Volume I, preliminary pages and Table of Contents** *n/a*
05001	**The Development and Implementation of Analytical Pavement Design for British Conditions** *S.F. Brown, J.M. Brunton, P.S. Pell* A description is given of the computer program ANPAD which provides three basic facilities for using analytical procedures in pavement design calculations. These include the ability to compute the required layer thickness, the design life or asphalt mix proportions for a balanced design, the particular option being selected on the basis of the available data and design constraints. Examples are given to illustrate some applications of the program. Prediction methods for dynamic stiffness and fatigue characteristics of asphalt mixes are used in ANPAD. However, the resistance of a particular mix to permanent deformation requires realistic laboratory testing and the techniques available are reviewed in the light of recent experiments. The implementation of analytical design methods in Great Britain is illustrated by some examples of full-scale trials in which unconventional asphalt mixes have been used. The paper also provides a description of the computer program CUDAM which includes the consideration of cumulative damage in fatigue when determining the required layer thickness of an asphalt base.
05002	**Thickness Design of Asphalt Pavements - The Asphalt Institute Methods** *J.F. Shook, F.N. Finn, M.W. Witczak, C.L. Monismith* Unlike previous editions, the ninth (1981) edition of The Asphalt Institute Thickness Design Manual (MS-1) is based on mechanistic design methodology. Elastic theory and concepts of limiting subgrade strain, to control permanent deformation, and limiting tensile strain in the asphalt layers, to control fatigue cracking, were adopted. Typical material Properties, modulus of elasticity and Poisson's ratio, were selected from available test data. A comprehensive computer program was developed to produce design charts for use in the manual. Design charts were prepared for structural sections consisting of asphalt concrete surface and base placed directly on subgrade, asphalt concrete with emulsified asphalt base and asphalt concrete with untreated granular base. Three environmental conditions, each consisting of a separate 12-month temperature distribution, were used to represent temperature effects on asphalt mixture properties. Untreated aggregate bases were considered to have stress-dependent properties. In addition, subgrade and untreated base properties were made to vary on a monthly basis to account for freezing and thawing effects. Loads were represented by a dual tire, equivalent to the load produced by a standard 80 kN single axle load. An extensive verification study was made using the design charts prepared for the manual. Comparisons were made to several existing design methods, including previous editions of The Asphalt Institute manual. In general, the comparisons produced similar design thicknesses, except at very high traffic and high subgrade strength levels, particularly, when untreated bases are used. Comparisons also were made to performance data collected on full-scale test road projects and existing highways. Six separate sources of data, representing 402 individual design comparisons, were used in the study. Results indicated that the ninth edition of The Asphalt Institute Thickness Design Manual (MS-1) produced design thicknesses that on the average were 41 mm (1.6 in) greater than the observed thicknesses, but also produced unconservative designs 12.7 percent of the time.
05003	**Rational and Practical Designs of Asphalt Pavements to Avoid Cracking and Rutting** *J. Verstraeten, V. Veverka, L. Francken* The structural design approaches to asphalt pavements, presented at the 4th International Conference (Ann Arbor 1977) are improved. For the rational approach. the improvements concern the design against cracking by fatigue of the bituminous layers and are based on a new resistance criterion taking into consideration the beneficial influence of the rest periods between the loads. They also concern the design against permanent deformation (limitation of the rut depth) and this on the basis of new results obtained in the field of the mechanical properties which precise, for bituminous mixes, the law of permanent deformation to be considered in the practical applications. For the engineering approach, and with a view to including the above improvements. new design charts are set up. Moreover,a simplified method to determine the resistance to rutting is presented; its application complements the information that can be obtained from the design charts. Finally, experimental verifications are presented.
05004	**The AGIP Viscoelastic Method for Asphalt Pavement Design** *G. Battiato, C. Verga* In this paper a simplified viscoelastic method for pavement design based on the analysis of a three-layer system subject to moving loads is considered. The first layer is representative of all the asphalt layers, whose mechanical characteristics are described by a very simple analytical expression which can be obtained by uniaxial creep laboratory tests. The second and the third (semi-infinite) layers are considered elastic. All the layers are supposed to be rigidly bounded and incompressible (Poisson's ratio = 0.5). A computer program called PAVIS 3 (Pavement Viscoelasticity - Three Layers) has been developed to calculate strains at all points of the three-layer system, caused by the passage of moving loads. The load is supposed to be uniformly distributed on a round track. The following notable viscoelastic effects have been foreseen:

- the lack of symmetry between strains calculated for positive and negative distances along the direction of load motion;
- the influence of speed;
- the difference between the maximum amount of longitudinal and transverse strains calculated at the base of the asphalt layers.

An experimental validation of the above theoretical results has been performed by measurements carried out on a large test track in southern Italy. The new viscoelastic design method allows the determination of the critical tensile strains in the bituminous layers, under different temperature situations and speeds of commercial vehicles, thus furnishing the necessary parameters for the calculation of the fatigue life of flexible and semi-rigid structures.

A complete subsystem for the prediction of permanent deformations in the asphalt layers is included.

A computer program (MOREL) has been developed for the calculation of permanent deformations. Temperature and traffic conditions are taken into account by means of a nomograph.

05005 **Mechanistic Design for Timber Haul Pavement**
F.T. Hsia, H.H. Richter, J.W. Padgett

This study was undertaken to establish a thickness design procedure for the design of timber haul pavements using the mechanistic approach. The procedure is based on a model in which the pavement structure is considered as a linear elastic multi-layered system, and the layered materials are characterized by their dynamic mechanical properties. The primary design criteria are fatigue life of the asphalt concrete and permanent deformation of the subgrade. A method of conversion was introduced to convert the timber sale volume to the form of 18-Kip equivalent axle axles. Possible alternative seasonal variations in timber traffic patterns were incorporated into the design system to ensure the optimum use of the pavement and to assess seasonal haul limitations during the spring thaw period. Alternative pavement design strategies were also included to cope with the involuntary underthickness situation. The evaluation of both mechanical properties and economic feasibility of locally-available construction materials from different sources is included in the material characterization subsystem of the design process to dictate the selection of the asphalt and the aggregate base. The material characterization subsystem is made possible through an environmental rectification procedure derived from an in-depth analysis of field measurements, meteorologic data and general trends of environmental patterns. The design was programmed onto a computer of modest size, but an example problem is provided to illustrate the use of the procedure.

05006 **A Design for Pavement to Carry Very Heavy Traffic**
N.W. Lister, W.D. Powell, R.T.N. Goddard

In the United Kingdom standards for the structural design of road pavements are based largely on results obtained from full-scale experiments. Over the 30 years that many of these experiments have been in existence, comprehensive date have been obtained on their performance. However, there remain serious shortcomings in their use to develop a comprehensive set of design standards. In particular, it is difficult to design roads to carry traffic much greater than the traffic levels accumulated by the full-scale experiments themselves and, because of the recent marked increase in the damaging effect of traffic on the most heavily trafficked roads, there is now an urgent requirement for designs well beyond the proven range of present design recommendations. This paper describes how this need has been met by the development of an interim design in fully flexible construction from the best current information from mechanistic models combined with that from full-scale road experiments and performance testing.

Fatigue cracking, although not usually the first cause of deterioration of fully flexible pavements in the U.K., is important, particularly on the more heavily trafficked roads, because of the consequent need to reconstruct both surfacing and roadbase of a cracked pavement. A computer model of the pavement structure has been developed to predict fatigue performance taking into account variations in pavement temperature and wheel-load spectra. The model has been calibrated by testing a pavement under controlled conditions in a pilot scale test facility and then validated by comparison with the fatigue behaviour of full-scale pavements of known performance.

To ensure adequate resistance to deformation, the deformation behaviour of pavements to carry heavy traffic has been examined in relation to that determined from full-scale and laboratory experiments. Linear elastic analysis was used to demonstrate that vertical stresses in the soil under traffic were not excessive.

This approach has been used to formulate novel designs for roads carrying very heavy traffic, cumulative traffic in excess of 80 million equivalent standard 80 kN axles over a 20 year design life. The design consists of a thick course of well compacted coated macadam placed between layers of rolled asphalt wearing course and lower roadbase. This construction combines the deformation resistance of dense coated macadam with the good fatigue properties of rolled asphalt. Such a design was first adopted for the reconstruction in 1979 of a section of the M6 motorway, where the new 20 year design life was 160 msa. Structural properties of pavement components and of the subgrade were checked during reconstruction and the performance of the pavement has shown the design to be soundly based.

05007 **Design Procedure for Premium Flexible Pavements**
F.L. Roberts, N. von Quintus, W.R. Hudson

In certain situations, particularly major urban freeways, it is practically impossible to close highways for maintenance due to extremely heavy traffic conditions. In order to overcome this problem, a comprehensive study for the Federal Highway Administration has been carried out to identify flexible and composite pavement structures which will perform as premium pavements with an absolute minimum of maintenance for a period of 20 years. This paper reports the results of a detailed study of the characteristics and requirements for such pavement structures. To accomplish this goal, the study identifies the major distress types which have seriously limited the maintenance-free life of flexible pavements, selects analytical models for use in a structural analysis for the pavement, and develops a design criteria for each distress type. A complete review of material properties was completed to identify those materials capable of satisfying the premium pavement criteria. As a result of this project, a detailed design procedure was developed in which fatigue and transverse cracking, rutting, roughness, and environmental factors such as temperature and moisture, were used to develop design charts for thickness and material selection to meet the requirements for the design and construction of premium pavements. This paper presents a portion of the basic design charts that were developed in that study and includes an example problem to illustrate the procedure.

05008 **Pavement Design Optimization by an Analytical Method**

I. Gschwendt, I. Poliacek

The paper deals with the description of an analytical design method's application for flexible pavement at the optimization of pavement structures. Whereby the permissible stresses in the pavement layers, the compression stress on the subgrade as well as the protection of the pavement against subgrade frost penetration effects are taken into account. In assessing the pavement one works with the fatigue strength of materials and the use efficiency of this strength is evaluated by the aid of the "utilization coefficient''. In assessing the temperature regime of the pavement - the temperature change of bituminous layers and hereby the change of their strength and deformation characteristics - are considered also. The changes are expressed by the duration of certain periods and in the case of necessity the changes in traffic load in the course of the year are considered too.

With regard to the significance of several assumptions in the analytical method, a laboratory research of the materials and soils fatigue strength was carried out, further the temperature regime of pavements was measured, as well as the subgrade's moisture regime. The interface friction of the pavement layers was investigated theoretically, by measurements on pavement models and during the construction of experimental sections. Several results of the research pointed to the necessity to make corrections in the hitherto considered assumptions.

05009 **The Texas Flexible Pavement Design System**
R.*L. Lytton, C.H. Michalak, T. Scullion*

The Texas Flexible Pavement Design System incorporates all seven components of a complete pavement design system: (1) the "Russian deflection equation method" which uses elastic moduli and thickness of pavement layers to calculate pavement deflections; (2) a non-linear search technique to compute elastic moduli for multiple layers (2 or more) using surface deflection measurements made by non-destructive testing devices; (3) performance equations for all significant types of pavement; (4) distress prediction equations for all significant types of distress on each pavement type; (5) a computerized system for selecting the optimum pavement design for a specific project; (6) a computerized system for optimally selecting projects within a pavement network (the subject of another paper in the proceedings of this conference); and (7) a consistent method of observing and rating pavement distress and performance.

The development of this system has encompassed a period of years requiring the construction of a flexible pavement data base which incorporates pavement construction histories, material properties, and layer thicknesses on approximately 400 sections of pavement along with climatic , deflection, ride, and distress data from several annual surveys.

This paper summarizes the developments in items (1) through (4) mentioned above, notes how they are used in item (5) and discusses the development of survivor curves which are used in item (6). Item (7) was developed several years ago, has been reported previously, and is not covered in this paper.

The entire system is now in a position to be of substantial assistance to the Texas State Department of Highways and Public Transport.ation in its continuing efforts to maximize cost-effectiveness in planning, designing, construction, and rehabilitating its entire state pavement network.

05010 **Design Criteria of Asphalt Pavement Structures at High Service Temperatures**
A.F. Bissada, S.K. Hamdanl, H.R. Guirguis

This paper includes a study of the behavior of two asphalt pavement structures under traffic and environmental conditions in Kuwait. The objective being to indicate those criteria that should be incorporated in the pavement design procedure with due consideration being given to the performance under the prevailing excessive pavement temperatures, which range between +10C and +75C.

The approach is based on monitoring the performance of each pavement during seven years of service at four different locations. This included an analysis of the major traffic, environmental, and material parameters affecting the performance of the pavement sections. The measured permanent deformation at each section was compared with the calculated reduction in the asphalt layer thickness based on the recent Shell procedure, and a correlation has been found in this respect.

The stress-strain values in these two pavement structures were determined for a wide range of moduli appropriate to the temperatures and time of loading at different hours of the day and for three given air temperatures: 35C, 27C. and 18C, representing the average daily temperature of the hottest, moderate, and coldest season of the year in this area, respectively. Weighted values of repetitions to failure were derived from three design criteria: subgrade strain, tensile strain in the asphalt layer and shear stress within the asphalt layer controlling its shear failure.

Using Miner's hypothesis of damage accumulation, the relative damage due to each of these criteria was calculated during the day hours as well as for the whole seasons of the year. The results of this analysis show that the introduction of a criterion for limiting shear stresses within the asphalt pavement layers, in addition to the other two primary design criteria, is necessary for the design and control of permanent deformation failures at elevated service temperatures.

05011 **Mechanistic Design of Asphalt Pavements and Verification Using the Heavy Vehicle Simulator**
C.R. Freeme, J.H. Maree, A.W. Viljoen

The first approach to the mechanistic design of asphalt pavements in South Africa was presented at the Fourth International Conference on the structural Design of Asphalt Pavements (1) in 1977. This approach was discussed in some detail and a number of examples were given as verification. Several improvements have since been made, mainly as a result of differences found in practice and from extensive testing carried out with the Heavy Vehicle Simulator (HVS) on pavements throughout South Africa. These tests covered a wide variety of designs, materials, traffic and environmental conditions.

The current mechanistic design method is described in the paper. The method takes account of fatigue and deformation in bituminous materials (different approaches being used for thin asphalt surfacings and thick bituminous bases), crushed-stone materials, cementitious materials of various strengths, natural gravels and soil subgrades. The degree of sophistication in the characterization of these materials may range from the selection of data from tables, up to repeated load triaxial and beam bending tests.

The models used are based on simple linear elastic computer programs such as CHEVRON, and a purpose-modified

program MECDE, up to the multi-loading program ELSYM.

The criteria for distress used for different materials were developed and improved over a period of time from both laboratory and field tests. Rut deformation limits are based on laboratory repeated-load measurements and the results of tests with the HVS. The limits for cementitious materials are treated in two phases - the pre-cracked and past-cracked phases.

A wide variety of different base types have been tested, using the fleet of four HVSs. These include pavements with crushed-stone bases, bituminous bases, cementitious bases and natural gravel bases, and concrete pavements.

The HVS test consists of applying a variety of wheel loads and measuring the elastic deflection and permanent deformation of the individual pavement layers. A large number of repetitions are then applied at a selected wheel load. During the test numerous indicators are used: these include deflection and deformation with depth; surface deflection and curvature. and rutting; state of cracking; surface profile; temperature; and density and moisture conditions in the pavement.

The large volume of data on the behavior of different pavement types has led to a high degree of confidence in the use of mechanistic design in South Africa. It has also been possible to modify designs in practice and to reduce pavement costs without a loss of confidence that the pavement will carry the expected traffic. In this way many millions of rands have been saved in South Africa, thus justifying many years of research into mechanistic design.

05012 **ALIZE III Practice**

P. Autret, A.B DeBoissoudy, J.P Marchand

The French method of the structural design of overlays and new pavements is based on several themes many of which have already formed the subject of L.C.P.C. communications presented at Ann Arbor over the last few years : the catalogue of new pavements by Mr Chantereau and Mr Leger (1977), non-destructive testing of pavements by Mr Leger and Mr Autret (1972) and Mr Guillemin and Mr Gramsammer (1972). diagnosis of existing pavement by Mr Bonnot, Mr Autret and Mr De Boissoudy (1977), test sections by Mr Sauterey and Mr Siffert (1972), laboratory tests by Mr, Bonnot (1972).

Today, now that the L.C.P.C. ALIZE III computation program is used extensively in laboratories and companies or in design offices requesting this program, it appears to be worthwhile completing the presentation of the method underscoring, in particular, the numerical values used in France, taking into account the experience gained over fifteen years of laboratory testing, in situ checks, site observations analyses, test section follow-up reports etc....

This article includes V chapters :
- theory of ALIZE program use;
- traffic : Traffic is represented by a typical unit load and application intensity. The French numerical values are indicated together with a key allowing a change of reference axle loads;
- materials : The main standard French materials are presented in the form of sheets summing up their mechanical and physical properties as well as the experimental numerical dues relating to them:
- practical application : This chapter details the process of calculation and indicates how to take account of the dispersion of thicknesses in place, the variation of the mechanical properties of a material and the offset coefficient to be applied to laboratory tests to take account of in situ behaviour in order to result in the design of the structure with some probability of meeting requirements;
- application example : To illustrate each of the three chapters, and also to demonstrate how to transpose the method to suit other conditions than the French environment, the application of a concrete example is given.

05013 **Design of Pavements in Tropical Regions with the Finite-Element Method**

F. Wolff

Bituminous pavements in tropical regions have - apart from the lacking anti-frost layer - an essentially thinner pavement construction than e.g. German roads with a respectively comparable traffic volume.

On introducing constant modules of elasticity in the layers into the calculation of these pavements with non-bound subbase (e.g. gravel) - only those are investigated here - tensile stress values occur at the bottom of the subbase which cannot be sustained by such materials as experience shows. The conclusion from this is that the stress-strain behavior of road construction materials can only be described with reservation with constant modules of elasticity. In the following stress-strain relationships, taken from latest literature, of asphalts (temperature-dependent modules of elasticity) and of subbase and subgrade (stress-dependent modules of elasticity) are presented.

As the calculation method used so far in road construction engineering - the multi-layer-theory - allows a variation of the stiffness of the materials only in the depth, the finite-element-method is applied here. The usability of this method is investigated by means of examples for which analytical solutions are at hand; based on this an appropriate FE-grid and a limitation of the axially symmetric continuum is developed for the later non-linear calculations. The non-linear stress-strain behavior is taken into account by the incremental method in the FE-program. The material-specific stress-strain behavior of road construction materials is shown by means of the developed FE-program with simple impressive examples.

Furthermore the differential stress-strain behavior due to the differential stress-strain relationships is presented for a given three-layer pavement. Completely different stress distributions in the pavement result from this compared with the calculation with constant modules of elasticity.

Furthermore characteristic values for the estimation of the bearing capacity of a pavement are developed, and the sensitiveness of the values to alteration of the system parameters is investigated. Then pavements which are given by a design curve developed empirically (Road Note 29, 31) are compared with the calculation method and the characteristic values developed herein.

It proves that the calculation method and the characteristic values are suitable to make statements on the stresses and strains of pavements.

05014 **Use of Pavement Test Facility for the Validation of Analytical Design Methods**

S.F. Brown, J.W. Pappin

The results from an experimental study of asphalt pavements with granular bases are used to illustrate the value of a pavement test facility for validating analytical design methods. The particular aim of the project was to continue development of analytical procedures for the prediction of permanent deformation in pavements but this also involved the measurement and computation of transient stresses and strains. Seven pavements were tested of which three are studied in detail . Each structure had about 40 mm of asphalt, about 140 mm of crushed limestone base and a silty clay subgrade of about 6% CBR. A new finite element computer program called SENOL was used to calculate stresses, strains and permanent deformations. The latter involved a novel two-stage procedure using a plane strain configuration for the final calculation of permanent deformation. The computations of stress and resilient strain were adjusted in the light of the observed behaviour and this exercise illustrated the importance of having adequate non-linear stress-strain relationships for all materials. Although reasonably accurate values of both resilient and permanent strain were calculated, the stresses were low.

05015 **Behavior of Flexible Road Pavements Under Tropical Climate**
F.J. Gichaga

Most road pavement designs in tropical Africa are empirical and are derivatives of design methods developed in Europe. Experience on some recently constructed roads shows that road pavements have tended to fail sooner than expected thereby leading to unplanned expenditure in the exercise of reinstating them. This paper describes field studies carried out to establish long-term structural behaviour of typical high standard roads in Kenya. The studies involved measurements of elastic deflections using Benkleman Beams, traffic loading patterns, cracking and rut depths for selected test pavement sections along six typical high standard bitumenized trunk roads of varying design procedures. Results of the studies show that pavements are weakened by repetitions of traffic loads but tend to develop strength with age. For a pavement approaching failure cracking is accompanied with high deflections. The older designs, which required mainly surface dressing as a form of surfacing, gave pavements which performed exceptionally well with service lives exceeding fifteen years. The pavement models which were based on newer design procedures, which specified thick asphaltic concrete surfacings, showed cracks and rutting in less than five years of service. Results also indicate that higher pavement deflections are obtained during the months of high rainfall and high temperatures.

05016 **Development of an Asphalt Concrete Distress Criteria Using In-Service Planning**
R.F. Carmichael III, W.R. Hudson

Data are presented from 63 hot mix asphalt concrete pavements which were selected to fill an experimental factorial of three levels of traffic, three levels of existing pavement surface conditions, and the different environmental regions of the Republic of Argentina. While laboratory fatigue testing and permanent deformation testing of hot mix asphalt concrete specimens offers valuable insight concerning the fatigue and permanent deformation resistance of various mixes, the in-service fatigue cracking and rutting performance of pavements is somewhat different. The objective of the reported study was to develop hot mix asphalt concrete fatigue cracking and rutting relationships using data gathered from in-service experimental test sections. The criteria were specifically developed for the Direction Nacional de Vialidad (DRV), National Highway Department, of Argentina as part of a project to develop a new pavement overlay design procedure. Recognizing the need for a criteria based on Argentine materials, mix designs, environmental loads, and considering that hot mix asphalt concrete reacts differently to in situ loads as compared with laboratory fatigue and deformation tests, the experimental study was designed and performed.

The experiment design and the types of data required are discussed. The primary data are Benkelman Beam deflections, thicknesses, common material's strength tests, such as the California Bearing Ratio test, historical traffic records, and detailed condition survey information. In addition, the procedure used to establish final materials properties is out lined. Elastic layered theory was the analytical tool used with the field data to predict asphalt tensile strains and subgrade vertical strains. The developed fatigue and permanent deformation models for hot mix asphalt concrete pavements are presented. The final models show excellent agreement with other models in the literature and are being incorporated into a new overlay design procedure for Argentina.

The major steps required for the development and verification of distress criteria using data from operating field sections are presented. The 63 sections used for this development were selected from all parts of Argentina to include the effects of different climates, typical soil types, and construction materials used.

05017 **Verification of the Design Method for Asphalt Pavements in Switzerland**
I. Scazziga

A structural design method for asphalt pavements based on the results of the AASHO-Road-Test is currently used in Switzerland since now 10 years and a discussion about a possible revision is actually taking place. Informations from three different sources are analyzed in the phase of preparation of this revision. The study of the performance of different pavements under traffic, which have been subjected to a special observation program since their construction and now have up to more than 15 years of age shows, compared to the results of theoretical performance values, that with few exceptions under special conditions the pavements are behaving far more better than could be expected. The size and the degree of precision of some elements contributing to the study is not sufficient to give exact figures of the amount of over-designed thickness. However it can be said that pavements designed for 7 to 15 millions standard axles on a subgrade with a CBR of 10% could easily afford a thickness reduction of the equivalent of 50 mm asphalt concrete when their structure has unbound or to a certain extent cement stabilized materials in the subbase. These findings are already confirmed in the case of semi-rigid pavements by the intermediate results of full scale tests in a circular test track under moving wheel loads. In the comparison of different major design methods pavements designed by the Swiss or AASHTO method are distinctly the most conservative ones, those determined with the Shell pavement design method are the thinner ones at the opposite end. The truth, as in many cases, may well be in the middle of both extremes and this would also be confirmed by the observation program.

05018 **Four Asphalt Pavement Case Studies Using a Mechanistic Approach**
F. Hugo, P.J. Strauss, G.P. Marais, T.W. Kennedy

Several sections of road pavement in Southern Africa were overlayed in 1973 for different reasons. Three typical sites were selected from these for this study, one which had very little deformation but with some ageing, another section of similar design to the first but with greater deformation and cracking in places and a third section in good structural condition but with a serious problem as far as skid resistance was concerned. All overlays were designed using standard deflection reduction techniques and checked against the latest available information on mechanistic design methodology

(1972). The three sections have performed well within the predicted distress criteria as suggested by mechanistic methods and showed no classical fatigue cracking and little deformation. Two of the three sections, however, displayed surface cracking within six years. Analysis of the materials indicated acceptable fatigue performance as well as relatively low stiffnesses as is generally required for thin asphalt. A detailed investigation of the deflection bowl using a modified Benkelman beam to monitor movement under a passing wheel showed a reverse curve right in front of the wheel which indicated considerable visco-elastic behaviour. This lead to the conclusion that in addition to the accepted modes of distress namely tensile strain at the bottom of the asphalt layer and vertical strain at the top of the subgrade, tensile strain at the top of the asphalt due to secondary and horizontal shear stress in the layers as a result of moving loads had also to be considered. This was especially important where the pavement material was susceptible to shear stresses or exhibited visco elastic behaviour. Finally the methodology developed was utilized for the design and construction of a relatively thin sand/calcrete asphalt layer directly on top of an in situ sand to obtain an economical solution using the available sub-standard material.

05019 **The Performance of Highway Pavements in the Netherlands and the Application of Linear Elasticity Theory to Pavement Design**

J. Ros, A.C. Pronk, J. Eikelboom

In 1971 the Rijkswaterstaat (National Public Works Department) constructed 9 trial sections, each 200 metres in length, on Highway A15 in the Netherlands. Each section was of a different structure and the range included structures in current use, variants on these and even experimental structures. The strains and pressures were measured at different levels in the structures when subject to the load of a standard lorry at varying speeds and temperatures. This paper presents results of these measurements.

The stiffness properties of the subgrade, sand cement, slag and the various types of asphalt were determined as far as possible both in situ and in the laboratory. The results were then used in the BISAR computer program and the computed strains and soil pressures were compared with the measured values. In general, the correlation was reasonable, particularly at the higher asphalt stiffnesses. Fatigue properties were also determined in the laboratory.

The results were also used to compare the computed relative life and the 'actual' life based on a 90% cut-off value for the measured strains; the former proved to be higher than the latter.

The performance of the trial sections under normal traffic conditions was monitored for an 8-year period.

Periodic measurements of skid resistance, evenness, rut depth and deflection as well as visual inspections have been carried out. The evenness of all sections was still good after 8 years. There were differences in the degree of rutting and cracking but these were still acceptable.

An overall assessment revealed some of the design methods to be conservative. The results and findings have been partly responsible for thinner structures being used on highways.

05020 **Prediction of Rutting in Asphalt Pavements on the Basis of the Creep Test**

H.J.N.A. Bolk

In this paper the results are given of further investigations into the practical applicability and accuracy of some existing methods for the prediction of rutting, based on the static creep test. Furthermore, a first step is taken in the development of a new prediction method (behavioural model) based on static as wellas semi-dynamic creep tests.

The measured rut depths on eight test sections were analysed in order to determine the rutting behaviour of asphalt pavements in practice. Using core samples from these sections, creep tests have been carried out which allowed the input material parameters for the various rutting behavioural models to be determined. This was followed by a comparison of the computed values with the measured rut depths.

It appears that of the existing prediction methods considered here, the Shell method produces the relatively best results. By using corrected temperatures an improvement can be achieved. The principal problem, however, remains the fact that the gradient of the calculated deformation curve is too small.

The main differences between the new method and the Shell method concern the determination of the air and asphalt temperature, the correction for the missing lateral confinement in the creep test and the correction for the dynamic effect. For the determination of the absolute magnitude of the rut depth the new method generally produces (apart from one test section) an equivalent or an even distinctly better result. It is especially important that the gradient of the calculated deformation curve agrees better with the behaviour in practice after the initial stage. It appears that a (slight) improvement in the ranking is obtained with respect to the Shell method, this especially applies to the overall picture.

This investigation is based on a retrospective prediction. Consequently, it appears possible to make a simple correction for the influence of an extremely hot summer period. In a final behavioural model such effects have to be taken into account in an analogous way.

05021 **Verification and Calibration of PDMAP and COLD Computer Programs**

C. Saraf

This paper presents the results of a study which was conducted to verify and calibrate the distress prediction models included in the two computer programs PDMAP and COLD. The specific forms of distress considered were fatigue cracking and permanent deformation, which were covered by PDMAP and low-temperature cracking covered by COLD.

The required data for this study were obtained from the Florida Department of Transportation and were used in the verification and calibration of PDMAP models. Utah Department of Transportation supplied the data for the verification and calibration of the model used in COLD program.

A brief description of the steps involved in this study is included in this paper. The method of verification and calibration of all the three models is also briefly described and the calibrated models along with their outputs are presented for comparison with the field observations.

The results of this limited study indicated that pavements built with two different surface thicknesses (2" and 3") will

require two fatigue distress prediction models. However, only one rate of rutting prediction model was needed to predict rut depths in most of the test sections (88% of total) within +/-50% of the observed rut depths.

The COLD program was calibrated and used in comparing the predicted probability of cracking with the observed frequency of cracks in the field. The results of this comparison indicated that the model can predict the frequency of cracking qualitatively in pavements using the same grade of asphalt binder. Pavements using different grades of asphalts would probably need their own calibration of the prediction model.

05022 **Verification and Application of the VESYS Structural Subsystem**
W.J. Kenis, J.A. Sherwood, T.F. McMahon

At the Fourth International Conference, the general modular framework of the VESYS structural subsystem was presented. Since then, major improvements to the models were made. These improvements allow for the input of variation in material properties with seasonal environmental changes, discrete axle load groups, up to eight layers, prediction of fatigue in any layer, low temperature cracking damage and the permanent deformation occurring in each layer. One of three optional modes of the Primary Response Model uses the principle of quasi elasticity to compute time step solutions to the Chevron N-layer elastic theory BVP, resulting in the time varying response at any point in the pavement due to a stationary load applied to the pavement's surface. This response is treated in a similar manner as in VESYS-IIM through Boltzman's superposition principle to calculate the pavement's viscoelastic response when the load is moving across the pavement's surface at any speed. A second option allows for input of a single modulus for each layer and season, and the elastic layer theory BVP calculates a single time-independent response. A third optional mode computes the layer moduli indirectly from the layer creep curves. The terms "viscoelastic-plastic" and direct and indirect "elastic-plastic" are used to distinguish between the three different options available.

A comprehensive study of the predicted versus measured behaviors of selected AASHO Road Test sections is made using the new VESYS subsystem. In addition. the results of two in-house research studies conducted at FHWA are summarized as examples of the use of VESYS in a research capacity. One of these is an effort to evaluate the potential of "Sulphlex" paving mixtures in light of the recent energy crisis. Another is that dealing with the development of load equivalencies which realistically represent load induced distress in various environments. The use of these functions are a critical component in studies dealing with life cycle costing analyses such as cost allocation and selection of optimum maintenance strategies.

05023 **Evaluation of In-Situ Moduli and Pavement Life from Deflection Basins**
W.P. Kilareski, B.A. Anani

The determination of the in-situ pavement material moduli is an essential step in the non-destructive structural evaluation of flexible pavements. If the modulus values of the various layers can be determined, then the remaining pavement service life can also be predicted. This mechanistic evaluation can then serve as a rational basis for pavement management systems. This paper describes the results of a research project designed to determine the in-situ modulus values and remaining pavement life based upon the deflection basin obtained from a Road Rater device.

Elastic layer theory and the Gaussian method of elimination were used to formulate surface deflections in terms of elastic modulus, load intensity, and layer thickness. The resulting equations were used to analyze the effect of changing layer modulus on the surface deflection. On the basis of this analysis, a computer program for calculating in-situ modulus values from Road Rater deflection basins was developed.

The calculated in-situ modulus values were then used to calculate the maximum tensile strain in the bituminous concrete base laver of a four laver pavement system. The Road Rater deflection basin was used to calculate the surface curvature index, SCI; the base curvature index, BCI, and the base damage index, BDI. These criteria were correlated with the maximum tensile strain, the fatigue cracking of the pavement sections and the traffic loading. A relationship was established between the SCI and the traffic loading resulting in the prediction of remaining pavement life. Results are presented graphically in terms of the structural number (SN) of the pavement section.

05024 **Distress/Performance Relationships and Overall Performance Concepts for Flexible Pavements**
R.D. Pedigo, F.L. Roberts, W.R. Hudson, F.N. Finn

As traffic loads, environment, and other forces act upon the pavement system, the pavement responds with stress, strain, deformation, fracture, or wear. These responses are termed "behavior". Most of the analysis models currently used to design flexible pavement structures are predictors of behavior. When the predicted behavior reaches a limiting value, distress is initiated. With time, various types of distress develop and interact, and the resulting accumulation of distress acts to counter the ability of the pavement to serve traffic. It has long been recognized that the ability to predict such serviceability losses before they occur could be of great value to agencies that are charged with providing and maintaining roadways. In this paper flexible pavement distress/performance relationships are examined, the development of performance production models is discussed, and the combination of various pavement condition and performance variables into an overall performance measure is illustrated.

Pavement condition and serviceability data from several sources were examined, and distress/ performance relationships were investigated. It was found that rut depths less than 0.2 inches (0.5 cm.) have no effect on serviceability. The variable which was most highly correlated with serviceability was (root)C+P where C+P = cracking plus patching in sq. ft. per 1,000 sq. ft. Relatively, low values of R^2 were obtained from regression analyses, and the addition of other distress variables did not significantly improve the fits obtained with C+P alone.

Some significant problems encountered with the data examined in this research effort are discussed. The authors suggest that in the light of these problems, indirect or interactive performance modeling techniques are more suitable than standard approaches to performance modeling.

The greatest current demand for pavement performance models comes from agencies that have begun to develop pavement management systems. Systematic pavement management requires that comparison be made among alternative plans of action in order to determine the most appropriate strategy for designing, maintaining and rehabilitating a pavement section or a pavement network. If several factors are to be involved in the comparison of alternative strategies, then a method of combining these factors into a single overall performance indicator is required in order to carry out such comparisons efficiently and economically. Three methodologies for achieving such a combined index are discussed: (1) deduct values, (2) utility theory and (3) unique sums. Some advantages and disadvantages of each technique are noted,

and examples of the use of these techniques are provided. These methodologies provide highway agencies with a means to efficiently construct a more relevant measure of pavement performance for improved pavement management.

05025 **Development of a Road Profile Statistic for Compatible Pavement Evaluation**
D.W. McKenzie, W.R. Hudson

One of the most important applications of the Surface Dynamic Profilometer is to provide a stable calibration reference for Response-Type Road Roughness Measuring instruments (RTRRM). The latter devices, of which the Maysmeter is typical, are relatively inexpensive and are used by many agencies for routine pavement monitoring.

Two approaches are possible for developing profile statistics suitable for both roughness measuring device calibration and for general roughness evaluation. The first is dynamic modelling of a hypothetical device, with certain physical constants pre-defined and with a sequence of profile elevations taken as system input. The alternative statistical approach which is described in this paper is to obtain data from RTRRM instruments on representative road sections whose profiles have been measured and then use regression techniques to select a profile statistic which the instruments are capable of measuring precisely.

A special class of profile statistics, termed Root-Mean-Square Vertical Acceleration (RMSVA), has been shown to reveal many of the road surface properties normally associated with roughness. An RMSVA-based roughness index, which was tailored to describe the behavior of eight Maysmeters run on 29 pavement test sections, is now the basis of a large-scale calibration program in Texas.

Although the Maysmeter calibration problem motivated the development of RMSVA roughness indices, careful monitoring of a set of calibration test sections and other pavements have revealed interesting surface properties that could never be detected by Maysmeters or by other RTRRM devices which reduce roughness evaluations to a single number. The RMSVA indices computed from a road profile can provide a "signature" that reflects roughness over a broad range of profile Wavelengths. Already, distinctive signatures corresponding to certain pavement classes, or types of deterioration, have been tentatively identified and are presented herein. Their interpretation remains a promising subject for future research.

05026 **A Method for the Evaluation of the Structural Condition of Pavements with Thick Bituminous Road Bases**
M. Dauzats, R. Linder

The first disorders found in the bituminous pavements built in France since 1979 have led to accelerated development of a method for the analysis and follow-up of this type of pavement.

After a summary statement of the behavior of bituminous pavements, based on 1400 km, this document describes a method based in part on the general principles of organization common to all stabilized structures and in part on specific tests; the originality of the method lies in the interpretation of these tests. Following a short description of the means of investigation, a large share of this document is devoted to analysis of the mechanical performance of the pavement based on such standard tests as deflection, the product R x d, and recent tests like the ovalization test, the value of which is that it measures elastic strains in the pavement. Tests of materials taken in situ, in particular the direct tensile test whose foundations are given, serve to determine the moduli of the materials and the characteristics at failure, and, via correlations, the allowable fatigue strain at 10^6 cycles.

The method makes use of calculation of the probability of failure of the pavement based on the probabilistic hypothesis of the appearance of structural deterioration according to the dispersion of thicknesses, the nature of the material, and the fatigue law of the material.

This method, used in the follow-up and maintenance of pavements, helps to judge the structural quality of the pavement and provides the information needed in deciding what maintenance work should be done, or in some cases for overlay design.

05027 **Lacroix Overlay Design by Three Layer Analysis**
W.Th. Hoyinck, R. van den Ban, W. Gerritsen

A practical method is presented for evaluating existing pavements by three layer analysis of Lacroix deflection bowls. To this and the two upper layers are first considered to act as one compound layer, behaving like a plate, resting on an elastic foundation of infinite depth, according to Hogg's model.

By inserting a Young's modulus for the top layer applicable to the Lacroix test conditions, the compound upper layer can be split up in two layers, having the same flexural rigidity. Testing of both uncracked and cracked sections of the same road is sufficient to express the structural properties in terms of affective layer thickness of the first layer and Young's moduli of the second and third layer. These data can then be entered into the Shell 1978 Design Manual to establish the required overlay thickness. Taking fully into account the settlements of the supports of the reference T-frame of the Lacroix Deflectograph as well as the supports of the Benkelman Beam resulted in a relationship between Lacroix and Benkelman deflections. This enables one to use Lacroix data for evaluation of pavements by methods requiring the input of Benkelman Beam deflections. Verification of the adopted model is demonstrated for different types of construction and temperature conditions by comparing computed deflection bowls with recorded ones. A practical example of the evaluation and overlay design method is given.

05028 **Structural Capacity of In-Place Asphaltic Concrete Pavements from Dynamic Deflection**
H.F. Southgate, G.W. Sharpe, R.C. Deen, J.H. Havens

The proper design of asphaltic overlay thicknesses involves four major factors: the in-place modulus of the subgrade, an estimate of the structural capacity of the existing pavement, estimates of the future traffic expressed as equivalent axle loads and required or desired design levels, and a thickness design procedure. This paper deals with estimating the in-place subgrade modulus and the remaining load-carrying capacity of the existing pavement. The method presented herein is valid for any Road Rater or other dynamic tester such as the Dynaflect. This procedure was based upon a 600-pound (272.4-kg) peak- to-peak dynamic load applied at a rate of 25 Hz. The steady state deflections have to be adjusted for load, dynamic frequency, and location of sensors. This method should be applied only to those testers that use a constant vibratory load.

05029 **Pavement Survey as a Mean to Define a Road Network - Preventive Maintenance Policy**

M. Poulet, J.C. Gramsammer

In 1965, France initiated a vast program for the strengthening of its national roads (about 30,000 km) and the development of its motorway network (over 5,000 km in 1981). In order to preserve the capital thus invested and to avoid the reoccurrence of the situation which, in the winter of 1962-1963, led to the serious deterioration of part of its highway facilities, a maintenance policy, as preventive as possible, was set up as of 1972.

This maintenance policy is based in particular on systematic and periodic surveying of the condition of pavements. To accomplish this, the French Road Research Laboratories (Laboratoires des Ponts et Chaussees) were required to adapt and to develop nondestructive surveying systems, initially designed to study the behaviour of traditional flexible pavements, to enable the evaluation of pavements having thick layers of treated materials, the investigation of surface properties (skid resistance, evenness) of pavements, and the surveying of road alignment characteristics and installations.

After having described these new investigation facilities and illustrated briefly their applications within the area of continuous pavement surveying and more detailed nondestructive testing, the article describes the methods used for processing the measurement data, and in particular the creation of a highway data bank.

05030 **Aspects of the Interpretation and Evaluation of Falling Weight Deflection (FWD) Measurements**
A.C. Pronk, R. Buiter

In the Netherlands the Falling Weight Deflectometer (FWD) is used more and more for routine evaluation of existing pavements, design of new pavements and investigation of mechanical properties of (new) pavement materials (recycled asphalt, crushed concrete, cement bound crushed asphalt etc.).

The paper deals with some aspects and problems that may arise with the interpretation of FWD measurements. Subjects like the apparent velocity of the deflection disturbance, the effective layer thickness of the asphalt, the determination of the subsoil modulus, non-linearity and the effect of loose asphalt layers are involved.

For this purpose in 1978 a test program on a number of full-depth flexible pavement structures was started. Afterwards pavements with a bound road base (sand cement, slag) and a few with unbound bases (crushed concrete, crushed asphaltic concrete) were included in the test program.

The result obtained on the basis of a linear-elastic multi-layer model were compared with results from surface wave propagation methods and laboratory tests on in situ taken cores. Although further investigations into inertia effects are desirable it can be concluded that falling weight deflection measurements using a (non) linear-elastic multi-layer model provide reliable results for the structural evaluation of pavements.

05031 **Simplified Methods for Evaluation of Asphalt Pavements**
J.M.M. van der Loo

In this report a procedure is described to evaluate flexible pavements in a quick and simple way by means of deflection measurements with the falling weight deflectometer. Full depth asphalt pavements and pavements having an unbound base layer are considered as a linear elastic multi layered system. With aid of a computer program developed by Chevron deflections and strains at the interfaces of the layers are calculated. At a standard asphalt temperature of 18C the design life of a pavement, expressed in a number of standard axle loads, is derived from a permissible strain level in the asphalt layer and the subgrade. Due to a test load of 50 kN the characteristics of a deflection bowl are related to the design life of the pavement. Within a range of operating temperatures of 5 to 30C the results of the deflection measurements can be related to the standard temperature. Related to the deflection characteristics the residual life of a pavement can be estimated from available data about passed and expected number of axle loads. The simplified evaluation method has to be an aid for determining road sections having a high priority for maintenance planning. Measuring a large number of roads of a road system in a more general way these sections can be selected. The method is not dealt with determining overlay thickness. Detailed investigations of selected road section together with economical considerations will give the answer how the pavement has to be improved.

05032 **A Pavement Management System for Provincial Roads in the Netherlands**
A.A.A. Molenaar, Ch.A.P.M. van Gurp

This paper describes a pavement management system developed by the Laboratory for Road and Railroad Research of the Delft University of Technology. Since the described models and techniques are developed, using data gathered on provincial roads, the system is intended for this type of secondary roads. For reasons of efficiency and simplicity distinction is made between evaluation techniques on two levels, i.e. on a network level and on a project level. Special attention has been paid to the development of performance models to predict the deterioration of the pavement condition in terms of strength, ride quality and skid resistance. Overlay design graphs are given for the rehabilitation of the pavement strength and ride quality of the pavement surface. At the same time it will be shown how the evaluation techniques are used to estimate the budget required to maintain a pavement network. Finally a method for the optimization of the overlay design on project level will be described.

05033 **Improved Pavement Performance Relationships in Brazil**
C.A.V. Queiroz, W.R. Hudson

A considerable amount of public money is spent on pavement maintenance every year, as pavements continuously deteriorate over time due to traffic loadings and climatic factors. For efficient use of maintenance resources, it is necessary to estimate the future condition or deterioration level of the different pavement sections in a specific network. This estimate is only possible if the pavement engineer or planner has available reliable predictive models.

Predictive models of this type can be used to identify those road projects most in need of preventive and corrective maintenance or rehabilitation. Pavement predictive models also find their application in Pavement Management Systems, in which all the activities involved in providing pavements are considered in an integrated, coordinated manner.

A major highway research project has been conducted in Brazil since 1975, and has the objective of yielding parameters, methods, and models to permit the optimization of investments in highway construction and maintenance so as to minimize the total road transportation cost. To accomplish this, considerable data has been collected in Brazil on

pavement behavior and performance. Pavement attributes have been monitored for up to three years and include measurements of roughness, cracking and patching, rutting, and Benkelman Beam deflections. Test pits were dug to measure in-situ density, CBR, and moisture while laboratory testing produced material gradings, Atterberg limits, laboratory CBR and density of the road materials, as well as asphalt surfacings resilient moduli. These data, predictive models, and test results are analyzed in this paper.

05034 **An Integrated Maintenance System for the Assessment, Diagnosis and Treatment of Flexible Pavements**
M.S. Snaith, H.J.H. Bailie, E.T. Stewart, D.M. Orr

The Department of the Environment for Northern Ireland, Roads Service and the Department of Civil Engineering of the Queen's University of Belfast established a Joint Project to effect improvements in the planning of road maintenance in Northern Ireland. The problem has been tackled by considering maintenance under three headings: relatively rapid road condition surveys, priority assessment for remedial treatment, and objective quantitative testing of the road pavements with various selected road machines.

The MARCH program suite was available from the City Engineers' Group in England and was adopted to give an initial framework for maintenance management. The screening and priority assessment are carried out by the program following data collection by relatively unskilled staff, for discrete maintenance lengths of road. In parallel with this, considerable work has been carried out in the development and proving of various road machines to ensure an accurate assessment of serviceability and to assist in the determination of the cause of any decline where this is observed.

To obtain the maximum benefit from the above, a data bank has been established to act as an interface between the MARCH suite and the information gathered by the road machines. Furthermore it is suggested that within this data bank a "diagnostic" subroutine may be used to determine both rapidly and accurately the state of a road pavement.

The paper demonstrates the manner in which the various individual developments forma coherent maintenance planning system, which in turn seeks to standardise pavement assessment, enhance remedial treatment selection and maintain a reasonable level of pavement serviceability in a time of financial restraint.

05035 **Rational Pavement Management in the City of Amsterdam**
Ir. G.H. Kellersmann, Ir. J.v.d. Klooster

Within the scope of increasing interest for rational pavement management the Road Department started to build up an automated Road Databank (comprising about 6,300 'street-sections') in 1975 and started to build up a new Pavement Management System in 1978. This new system can be fitted in a model (see figure 1) and comprises a procedure which will be executed continuously with a cycle time of 2 years.
1. Execution of a broad Periodical Visual inspection (P.V.I.) and Overall Measurements on all street-sections to separate a group of 'good' and 'suspect' street-sections.
2. Execution of an Extensive Visual Inspection (E.V.I.) and Supplementary Investigation only for the suspect street-sections to separate a (second) group of 'good' street-sections and 'bad' street-sections.
3. Determination of road technical structural maintenance measures only for the bad street- sections.
4. Determination of final structural measures also defined by other boundary conditions like renewal or installation of pipes and cables, tramrails, modifications of road profiles, only for the bad street-sections.
5. Preparation of structural maintenance programs on long and on short terms.
6. Updating these programs by means of results of the latest E.V.I. and Supplementary Investigation.
7. Relating budget shares to maintenance levels by means of data in Road Databank (using Road Databank as a management instrument).

- All data of street-sections are stored in the automated Road Databank, so that ranges, tests and selections of groups of good, suspect and bad street-sections can be executed by computer.
- The Overall Measurements concern evenness, road friction and deflection.
- The P.V.I. and E.V.I. are based on the well known visual inspection system developed by the Texas Transportation Institute, whereby the E.V.I. registrates the location of the damages on maps.
- The Supplementary Investigation concerns measurements of evenness, road friction and deflection; estimations of axle loads; plate bearing tests, creep tests, etc.

05036 **Washington's State's Pavement Management System**
R.V. LeClerc, T.L. Nelson

This paper reviews the problem facing transportation agencies with their present method of financing pavement upkeep and rehabilitation, and describes a solution based on pavement management practices. The goals of the pavement management system developed for the Washington State Department of Transportation are presented, together with a description of the four broad areas of data processing which combine to constitute the foundation of the system.

Basic information file data on pavements which were available or generated to form the background for the system are listed, and the incorporation of these data into a master file is described. Also shown are the methods used to analyze and convert the master file data from pavement condition ratings to pavement performance curves for each project. The performance curves are then used, together with appropriate cost data, to optimize rehabilitation at the project level, producing the most cost-effective type and time of pavement fix. How the network level programming follows from project level optimizing to give a six-year (or other) rehabilitation schedule is set forth. Included is the monitoring feature which provides a summary of pavement condition throughout the pavement system before and after the rehabilitation action.

Means for adjusting the program to fit budget or manpower constraints are reviewed. The use of the PMS to determine what the rehabilitation dollars will give in terms of pavement serviceability over the six-year period is discussed, with illustrations to show how the program can be adjusted to achieve a particular level of serviceability. Also shown are the means for utilizing the program to demonstrate the consequences of delayed rehabilitation.

Other possible applications and uses of the WSDOT/PMS data analysis procedures in areas of pavement design, construction, and maintenance are outlined.

It is concluded that the system, operating on biennial pavement condition ratings, provides a good solid framework for orderly analyses to estimate the economic benefits of the type, timing, and sequence of rehabilitation activities applied to a pavement. As such it is expected to be a great aid to WSDOT in providing the citizens of the state with the best

pavements for their tax dollars. The system features procedures for easy updating and simple modification which should make it particularly suitable and attractive for adoption by other transportation agencies utilizing their own pavement data information files.

05037 **Development of an Improved Pavement Management System**
D.R. Luhr, B.R. McCullough, A. Pelzner

The computer program, Pavement Design and Management, System (PDMS), was developed at The University of Texas at Austin through a cooperative effort with the U.S. Forest Service. This pavement management system calculates and optimizes pavement design and rehabilitation strategies on a project level after being given information about available construction materials, material characteristics, expected traffic volume and loads, various costs, and required pavement performance. An improved version of PDMS was developed that greatly increases the capabilities of the system, while at the same time improves the rational basis for predicting pavement performance.

A structural analysis of AASHO Road Test pavement sections was conducted using a non-linear elastic layer procedure. The materials were characterized for four seasonal periods in this analysis, and the results compared favorably with deflection measurements made at the road test.

A regression analysis was performed to develop a performance prediction equation. The dependent variable used was the change in Present Serviceability Index (PSI), divided by the change in vehicle applications, for each seasonal period. The use of this performance variable allowed the consideration of seasonal characteristics of pavement materials and seasonal traffic volumes. Pavement deterioration is calculated by adding the change in PSI due to each vehicle type, instead of using Miner's rule to estimate cumulative damage. Since each vehicle type is considered separately, there is no need to consider equivalency factors. This is an important advantage since AASHTO equivalency factors are found to have serious limitations.

The performance variable is used to predict the PSI-Traffic curve for the pavement structure, thereby allowing the evaluation of the performance area under this curve. This performance area can be used to calculate the cost/area ratio, which assists in evaluating the pavement performance, especially when vehicle user costs are not known.

It is concluded that the additional capabilities provided through these developments are important to a pavement management system. The mechanistic approach used in developing the performance model provides a good foundation for the inevitable extrapolation that occurs in design practice. However, it is no substitute for a comprehensive data base.

05038 **The Development and Use of a Pavement Management System in the United Kingdom**
P.D. Thompson, L.W. Hatherly

In 1970, the Committee on Highway Maintenance, set up by the UK Ministry of Transport reported on all aspects of highway maintenance including standards, engineering, management, training and many others. For the management of maintenance it recommended the development of a maintenance assessment system which led to the system produced by the Transport and Road Research Laboratory (TRRL), Computerised Highway Assessment of Ratings and Treatments (CHART).

The CHART system embraces inspection, rating, computer processing and the output of information which can be in several different forms. In addition to the collection of CHART visual information, the overall management system encompasses mechanical measurements for the assessment of structural condition (deflection), of skidding resistance (SCRIM) and texture measurement and of road profile. The use of the Bump Integrator and of the high-speed profilometer (HSP) for profile measurement is described.

The paper deals with the development of the CHART system and its various components as well as illustrating the way in which the rating is carried out by the computer. The various items of mechanical equipment are also described and illustrated.

The rating system is complicated and varies depending on the defect being rated. For interpretation of the priorities for structural treatment, a number of ratings are combined. Although it is not possible to comment on the range of ratings computed, an illustration is given to show how the results are interpreted and the priorities assessed.

A variation of the assessment system output is used by the Greater London Council in the management of the Capital's major road network. For the mechanical measurements and accident records, transparent overlays are produced which can be placed on a map of the network. In this way, the engineer can quickly assess those sites in need of his attention.

Finally. some innovations are referred to which are being developed in the course of the continual enhancement of the system.

05039 **Development of a Pavement Management System for the Arizona Department of Transportation**
R. Kulkarni, K. Golabi, F. Finn, E. Alviti, L. Nazareth, G. Way

A comprehensive Pavement Management System (PMS) was developed to assist the highway engineers and managers of the Arizona Department of Transportation in making consistent and the most cost-effective decisions related to maintenance, design, and rehabilitation of pavements. The major elements of the PMS are: a Data Base Management System, a Network Optimization System (NOS), and a Project Optimization System (POS). In this paper, the development, testing, verification, and implementation of the NOS are described.

The NOS can be used to determine which rehabilitation policies will achieve prescribed performance standards at a minimum cost. This information can be used to prepare 1-year, 5-year, and 10-year pavement rehabilitation budgets to maintain prescribed performance standards. With an iterative procedure, the NOS can also be used to determine the highest performance standards that can be maintained with a fixed budget. These results can be used to allocate a given budget among different roads in the state, in a manner that provides the best possible value for the public dollar.

The NOS is fully operational on the Arizona DOT'S computer facilities. The system is currently being used in assisting the management to formulate budgetary and engineering policies related to maintenance and rehabilitation of pavements. Because of its modular nature, it has been possible to make several improvements in the NOS with only input data restructuring, but no programming changes.

05040 **Implementation and Verification Examples of Successful Pavement Management**
M.A. Karan, R. Haas, D.A. Kobi, A. Cheetham

The development of pavement management technology has undergone considerable progress during the past decade. Techniques now exist for all components of the pavement management process, although they are still far from perfect.

An important development in pavement management has been at the network level. However, this has been relatively recent in that pavement management started at the project level. As a consequence, most pavement management implementation and verification to date has been at the project level and has been fairly widely reported in the literature. In the late 1970s, however, the first successful cases of implementation and verification of network level pavement management began to appear. These have involved a comprehensive set of procedures and techniques that can be applied in a common framework and are applicable to a range of jurisdictions from small cities to large State or Provincial Highway Departments.

The foundation of pavement management is good data and its evaluation. In order to be used effectively, however, the data and evaluation should itself be "manageable". A means for achieving such manageability, not only in evaluation but also in using the information in pavement management, lies in automation. Savings in time and costs, through increased efficiency, can be realized. Such automation can range from the initial data acquisition, and its processing to the priority programming for networks through the actual design and economic calculations for individual projects to the use of computer graphics and tabulations for communicating the results.

This paper describes a comprehensive set of pavement management procedures which have been developed and successfully applied to a variety of rural and urban networks. It outlines a general framework for these procedures, involving both the network and project levels of pavement management, and then provides examples of the implementation at both levels. These examples begin with the acquisition, analysis and presentation of inventory data. Use of the data in network level implementation is then described as well as the development of a priority program of work and the evaluation of alternative budget levels. Automation in data acquisition and processing, data analyses, priority analyses and optimization including the economic evaluation, and computer graphics presentation of results is illustrated in the examples.

Brief examples of project level implementation are also provided. These similarly illustrate the use of automation from initial data acquisition to design analysis to final presentation of results,

05041 **Optimization of Highway Maintenance and Structural Rehabilitation**
D.W. Potter, W.R. Hudson

Funds allocated for maintenance and rehabilitation of road pavements are becoming an increasingly important component of highway authority budgets. This paper describes an investigation into the effect of the maintenance/rehabilitation policy on the cost to the highway authority and the cost to the road user over a specified analysis period. Two-lane rural roads with a range of pavement structures, pavement conditions and traffic volumes are considered. The Highway Design Model is used to estimate both authority and user costs under a range of maintenance/rehabilitation policies. Policies which minimize overall cost (authority cost plus user cost) are determined, together with the sensitivity of overall cost to maintenance/ rehabilitation policies. Policies which minimize overall cost (authority cost plus user cost) are determined, together with the sensitivity of overall cost to maintenance/rehabilitation policy. A methodology for incorporating future uncertainties (traffic growth, monetary inflation and available funds) is included.

The results of the study show that maintenance activities can significantly affect overall costs. It is realized that this study is very restrictive in terms of the road traffic situations considered. However, coupled with studies of a similar nature (Refs 18 and 19) a reasonable basis is established for this conclusion. Detailed conclusions concerning recommended maintenance practice for specific cases and the associated cost saving are presented. The point is made that the recommended maintenance practice can vary considerably depending on the aspects of the case being considered. Also, while cost increases associated with departures from the recommended strategy may be small when expressed on a percentage basis, the monetary value is by no means insignificant.

The study indicates'that quantities which depend on future events can be incorporated into a present-time evaluation in a realistic manner. Although decision analysis methods have been used in the areas of business management for several years, their adoption by road construction and maintenance authorities has been somewhat slower.

Because discount rate has a major influence on costs when the analysis period is-medium to long term, the need for a careful interpretation of the effect of inflation in evaluating future costs is emphasized. Further, considerable effort is warranted in order to obtain a satisfactory estimate valid for the duration of the analysis period.

05042 **The Texas Rehabilitation and Maintenance System**
R.L. Lytton, D.T. Phillips, C.Y. Shanmugham

The Texas Rehabilitation and Maintenance System (RAMS) is a series of computer programs which have been written to assist in the management of pavement networks. In the management process, specific projects and maintenance strategies must be selected and the best sequence of rehabilitation and maintenance activities over a planning horizon must be planned so as to remain within the available resources of budget, men, materials, and equipment. The selected projects should maximize the expected benefit from the use of these resources in terms of reliability and traffic served.

This paper describes the computer programs in some detail, gives the mathematical formulation of two of them, discusses how all of them are used in sequence in achieving an optimal set of project selections, and gives some simple examples of the use of the programs. Reference is made to more detailed reports which document the programs and describe the algorithms used in solving the optimization problems that are involved. The algorithms are described as state-of-the-art developments in operations research.

The example problems demonstrate that computer-assisted decision making in pavement rehabilitation and maintenance management can be expected to realize between 2 and 27 percent more beneficial project selections.

05043 **A Method of Integrated Priority Programming and Budget Level Analysis for Pavement Maintenance and Rehabilitation**
R. Haas, A. Cheetham, M.A. Karan

Total expenditures for maintenance and rehabilitation of a pavement network should represent an optimum combination of the two types of activities. Under the usual situation of budget constraints, this requires priorities to be established.

This paper describes an integrated method for programming maintenance and rehabilitation for paved road networks for any chosen program period. It begins with a common inventory of condition, serviceability, structural adequacy, traffic, unit costs and other information. The maintenance programming subsystem evaluates alternative treatments for different types, density and severity of distresses and produces a demand-based budget using a maximization of cost effectiveness. The rehabilitation programming subsystem similarly evaluates alternatives and a priority list of year-by year projects, over the program period, based on benefit maximization, is produced. The total of maintenance and rehabilitation costs for any given year does not exceed the total budget limit.

A case application is provided to illustrate the method. It uses the arterial street network of a small city, subdivided into 100 sections. The outputs include section-by-section, year-by-year, recommended programs of maintenance and rehabilitation work.

An additional feature of the method is a capability for evaluating the long-term effect of various budget options of average network serviceability. The rehabilitation budget levels, one representing the expected funding and one being zero budget, have been tested for the case application. As expected, average network serviceability was estimated to decrease significantly over the 10-year programming period for the zero budget case.

Finally, it is recommended that year-by-year updates be carried out on the inventory and the maintenance and rehabilitation programs.

05044 **Airfield Pavement Performance Prediction and Determination of Rehabilitation Needs**
M.Y. Shahin, S.D. Kohn

Since many in-service airfield pavements are approaching their design lives, there is a need for a comprehensive pavement management system. Such a system has been developed for the U.S. Air Force by the U.S. Army Construction Engineering Research Laboratory (CERL). The system provides the user with a pavement condition rating procedure and methodologies to select a timely maintenance strategy. This rational and systematic approval should result in decreased maintenance costs.

05045 **Development of a System for Efficient Pavement Management for Municipalities**
P.C. Koning

A Working Group set up by the Studie Centrum Wegenbouw (Study Centre for Road Construction) is developing a system for the application of efficient road management by municipal road managers in the Netherlands. Starting from a provisional system, a suitably adapted system has been developed by testing and verification in actual practice. This has more particularly been done in a "modal" municipality chosen for the purpose in this country. To this end, a comprehensive data acquisition survey of the whole road network was carried out, and visual inspections and measurements were performed over a period of some years. Also, standards for maintenance criteria were established, prediction methods for the behaviour with the passage of time were investigated, and planning techniques were developed.

The result of this testing and verification procedure comprises recommendations for setting up a scheme of data acquisition and visual inspection and for the exemtion of various measurements and their value assessment. Standards and behaviour predictions should be used with the necessary caution.

The amount of detail, and the number of factors, determining the execution of maintenance measures increase according as the planning period is shorter. The content of the data acquisition survey, and the measuring and inspection methods employed, are more particularly adapted to these circumstances. It is explained how the collected data are used in planning the maintenance for the various terms envisaged.

In the first phase of the Working Group's activities which have yielded the results reported here the emphasis has been on the development of a systematic procedure which is clearcut and suitable for practical application.

This paper therefore has a descriptive character. The results of visual inspections and of measurements are dealt with only in so far as they play a part in connection with the development of the above-mentioned systematic procedure.

05046 **Programmable Calculators in the Assessment of Overlays and Maintenance Strategies**
P. Ullidtz, K.R. Peattie

A technique for assessing the serviceability of an existing pavement and predicting its future life under specified traffic loading and seasonal conditions has been developed. It is based on a simplified form of multi-layer elastic theory which can be incorporated in programs for the larger programmable pocket calculators. This program will handle structures having up to four layers consisting of one bituminous layer, two unbound granular layers and a subgrade.

The properties of the material in the existing pavement are determined from non-destructive measurements of surface deflection using a Falling Weight Deflectometer or some similar instrument which measures deflection at the centre of the loaded area and at various distances from it. A method is given for converting the moduli of bituminous materials determined at one temperature and time of loading to values appropriate to other temperatures and times of loading.

The overlay program gives the residual life, in years, of each of the granular layers in a pavement and of the subgrade. It will also provide the residual life of each of these layers after the application of a bituminous overlay of stated thickness and modulus to the pavement structure. Different values of moduli can be assigned to the various layers according to the seasons of the year being considered.

A pavement management program has been developed to determine the effect of applying an overlay on the total life of the pavement or to compare the benefits of applying one of a number of alternative maintenance procedures such as overlaying and surface dressing. The extension of life resulting from the application of each maintenance procedure considered is determined and, if the costs of each are known, the ratio of functional benefit to cost is evaluated. The most effective maintenance strategy for a given road network within a stated cost budget can be found by applying the pavement management program to the individual road sections making up the complete network.

05047 **ESSO Overlay Design System**
S. de la Taille, P. Schneck, F. Boudeweel

The method of new pavement design developed at Esso has been adapted to provide an overlay design system. The basic idea is to modelize the old pavement in order to be able to calculate stresses and strains, considering the traffic and climate conditions. It is then possible to define design criteria, corresponding to the requirements of an overlay:
- the old pavement must be relieved.
- the overlay itself must work under acceptable conditions.

The modelization is achieved through the old pavement analysis, while the mechanical properties of the mixes considered are assessed : dynamic modulus, resistances to permanent deformations and to fatigue. The minimum thickness of the overlay is computed for each mix considered in order to match the design criteria. A selection between the various solutions is made from technical and economical considerations, to find out the most suitable one for the work.

An example of application of the system is presented. The problem was to find out a suitable mix and to compute the required thickness for an overlay of a ring road in Northern Ireland. Ruts and cracks in the temporary wearing surface made it compulsory to overlay the structure. The analysis of the old pavement (visual inspection, borings and deflection measurements) showed that it was very weak. Analysis of deflection values permitted a modelization, and the obtention of design criteria: reduction of horizontal tensile strain at the bottom of the old pavement to 1.2 x 10^-5, overlay fatigue index of 120 x 10^-3, and acceptable resistance to permanent deformations of the overlay mix.

Six mixes altogether were envisioned for the study: 2 Hot Rolled Asphalts, 2 Asphalt Concretes and 2 Dense Bitumen Macadams for Wearing Courses. In a first step, a single course overlay was considered, and the minimum thickness for each mix computed. Because of the high values obtained, a two-course overlay was then envisaged: a wearing course made of 40 mn of Hot Rolled Asphalt, and a base course to be determined. The minimum thickness of the base course for each mix was computed to match the design criteria, which led, together with considerations on the resistance to permanent deformations of the mixes, to selecting the Asphalt Concrete with the lower binder content in a 100 mn layer. This solution was retained and the pavement overlaid without any particular problem. A deflection follow-up was carried out: the overlay considerably reduced the deflection values, down to the level computed with the Esso Overlay Design System, pointing out the validity of the procedure.

05048 **Pavement Evaluation and Overlay Design - Practical Method of Belgian Road Research Center**
V. Veverka, J. Romain

This paper presents a practical method of pavement evaluation and overlay design. The proposed method results from field observations and assessments of a large number of flexible roads, from a study of statistical distributions of the parameters influencing the life expectancy of a bituminous pavement (deflection, load characteristics, temperature and thickness of the pavement, composition and mechanical properties of bituminous materials) and from an application of layered elastic theory. The paper presents the description of empirical and theoretical predictive models developed in the context of this study and aiming at the evaluation of the life expectancy and the distress evolution of the existing pavement. The proposed method includes:
a) pavement evaluation procedure
b) overlay design.

The pavement evaluation using empirical or theoretical predictive models is based on four parameters: cumulative number of heavy commercial vehicles (during the past service period), deflection, degree of cracking and repairs and rut depth.

The fatigue condition of the pavement is evaluated from deflection and cumulative number of heavy commercial vehicles. To evaluate the structural condition, the observed and predicted values of degree of cracking and rut depth are compared. The diagnosis is formulated and the remedies (further maintenance, strengthening, reconstruction) are chosen according to structural and fatigue conditions.

The overlay design uses:
a) design charts (current design method)
b) computer programs (full design method).
The overlay design charts have been developed by application of layered elastic theory. Several examples illustrate the practical implementation of the proposed method.

05049 **The TRRL Method for Planning and Design of Structural Maintenance**
N.W. Lister, C.K. Kennedy, B.W. Ferne

Effective use of the large sums of money now being spent world wide on strengthening roads requires a design system capable of matching spending to needs; it should establish priorities for work and also the nature and extent of strengthening on the roads selected for treatment. Economical solutions can generally be obtained if a relatively thick overlay is applied before the structural integrity of the road pavement is seriously impaired, when the road is in a critical and not a failed condition. The Transport and Road Research Laboratory has therefore developed a method for the planning of structural strengthening that can predict the remaining life of the pavement so that the strengthening can be timed to coincide with the onset of critical conditions; the method can also design the necessary thickness of overlay required to extend the life of a road to carry the predicted future traffic.

Papers to previous Conferences have described earlier stages in the development of the method from a systematic study of the relation between the deflection under a loaded wheel and the performance of pavements in the Laboratory's many full-scale road experiments; the work has been supported by detailed observations of the deflection behaviour of pilot-scale pavements and by analytical techniques. This paper outlines the method concentrating on the latest work to complete its development, evidence of its validity and examples of its use.

Extensive experimental data is presented that has been used to develop charts relating deflection to pavement temperature so that deflections measured over a range of temperatures on different pavements can be corrected to equivalent design deflections at a standard temperature of 20°C. The development of pavement deterioration and its relation to deflection levels is illustrated, in particular the increasing uncertainty as pavement failure approaches, uncertainty that may be avoided by suitable definition of critical conditions and timely maintenance intervention. Typical evidence is presented defining experimental relations between deflection and critical life. The information has been

consolidated into design charts for the prediction of remaining pavement life to the onset of critical conditions; separate design charts have been produced for the four main types of road base used in the United Kingdom. Measurements on a number of in-service pavements demonstrate the validity of the charts over a wide range of traffic. Observations of the reduction in deflection achieved by different types of overlay material are presented. These results have been combined with information on the performance of overlaid pavements to produce overlay design charts. Levels of probability of achieving a particular residual life or, in the case of an overlay, an extension of life are defined on the design charts.

Maintenance decisions based primarily on deflection but supported by other information have been made on many roads in the United Kingdom over a 20 year period. Comparisons are made of the cost-effectiveness of the deflection approach with decisions based on engineering judgement alone. Four major maintenance schemes on Motorways and Trunk Roads, and also 9 smaller projects under the control of one maintenance unit are considered. The use of deflection to determine the depth of deterioration in a Motorway pavement and the design of its reconstruction is also briefly described. Finally the paper indicates the present use of the deflection method in the United Kingdom for planning of maintenance priorities and for detailed design of strengthening measures.

05050 **A Study of Resiliency for Pavement Design in Brazil**
J. Medina, E.S. Preussler, S. Pinto, L. Motta

Resiliency of pavement materials and subgrade soils as determined through repeated load tests is studied for pavement design of Brazilian Highways. A research work conducted by the pavement mechanics group at the Federal University of Rio de Janeiro with the support of the Brazil Federal Department of Highways is underway since 1978. Satisfactory comparison has been obtained between deflections measured and those computed using the FEPAVE program and data from repeated load tests. The large deflections producing premature cracking and rapid deterioration of asphaltic surface layers are due usually to the low resilient modulus of granular layers submitted to low confining pressures and not to resiliency of subgrade soils. Moisture contents of subgrade soils in the tropical region analyzed are quite low: at optimum of standard Proctor test or below it. Also, many soils of lateritic nature exhibit good behavior as subgrade and pavement materials with respect to resiliency.

Fatigue characteristics of asphaltic mixtures determined at different temperatures are used to establish an approach to overlay design.

05051 **Cracking in Wearing Courses**
J.P. Marchand, H. Goacolou

The use of fracture mechanics in the study of pavements is a further step towards a better knowledge of the mechanisms, and thus of the influences of the parameters, governing the behaviour of a pavement.

The model presented in this article forms a part of this approach, since it takes into account the vertical discontinuities created by the transverse shrinkage cracks of courses treated with hydraulic binders. Its two-dimensional character is well suited to the study of pavements and the finite element method provides a good approximation to the modelling of the crack. The examples given show that it is possible to determine the directions of propagation of an existing crack for each type of loading encountered in pavement mechanics. It may be matched to a multi-layer two-dimensional model for use in interpreting the results of testing, to detect the presence of a vertical crack in the treated road base before it has begun its propagation into the coated material.

The presence of such a crack is reflected by a substantial increase in deflection and a decrease in the radius of curvature by comparison with measurements made on a crack-free pavement.

The wearing course design method proposed takes into account the influence of cracks ; it is presented in a branching form that schematically represents the various stages of propagation of the crack. The model may be used to give an approximate determination of the time taken by cracks to spread upward into the wearing courses.

This design method yields a better qualitative understanding of cracking phenomena in coated materials.

05052 **Probabilistic Fatigue Design for Flexible Pavements**
K.R. George, S.K. Nair

A general framework for the probabilistic prediction of load associated fatigue distress mode is presented. Using this framework, a prediction model is developed for fatigue life treating-traffic, material properties, and environmental effects as stochastic variables. The main steps in developing the model are:
(1) solution for structural response (using CHEV5L program) in terms of tensile strain at the-bottom fibers of base,
(2) prediction of fatigue life from structural response using an empirical relationship proposed by Hwang and Witczak [1979],
(3) development of regression model relating fatigue life to such field variables as load, ambient air temperature, subgrade support value, and pavement geometry,
(4) prediction of cumulative fatigue damage employing Miner's rule, and
(5) development of design equation specifying reliability.

By virtue of the fact that the parameters affecting fatigue distress mode are random variables, cumulative distress, delta, is a random variable. The critical damage at failure, denoted as D, is not always close to one, as implied in Miner's law, but in fact assumes a wide distribution: therefore, D is a random variable also. As both delta and D are random variables, fatigue life can be estimated with only a certain reliability (confidence level). Reliability, R, is the probability that serviceability will be maintained at adequate levels, from a user's point of view, throughout the design life of the facility. An expression relating mean value and coefficient of variation of delta and R is proposed, which, by virtue of its deterministic format, can be used in design.

Pavement design using the above expression will require distribution functions (or frequency distributions) for wheel load, ambient air temperature and subgrade support value of the region under consideration; typical distributions of these random variables are presented. Respectively, load, air temperature, and subgrade support value conform to shifted exponential, Weibull, and lognormal distributions.

To assess the reasonableness of the proposed procedure, structural number selected for a specific traffic loading, environmental, and subgrade conditions has been compared with that of the conventional AASHTO Interim Guide design

procedure and also with that of the zero-maintenance design procedure.

05053 **The Interpretation of Repeared Load Parameters for a Glacial Subgrade from Soil Properties**
R.W. Kirwan, E.R. Farrell, D.N.D. Hartford, T.L.L. Orr

This paper presents the results of an investigation to establish simple methods for estimating the resilient and permanent deformation parameters of a till subgrade from standard laboratory tests.

The subgrade deformation parameters necessary for the satisfactory design of a flexible pavement depend on the water content and dry density of the subgrade soil and on the applied stresses and other factors. A programme of repeated load triaxial tests has been carried out to investigate the influence of these variables on the required parameters such as resilient modulus, Poisson's ratio and creep compliance. The experimental data from the repeated loading tests has been used to prepare charts relating the resilient modulus and creep compliance to the dry density and water content. These charts show that the creep compliance is very sensitive to change in water content and, except for samples with high dry densities, the resilient modulus is more sensitive to changes in water content than dry density and decreases as the water content increases.

Repeated load tests were also carried out in a laboratory pavement simulator. The deformation parameters interpreted from the pavement deflections measured in these tests are in close agreement with the values predicted by the charts from the repeated load triaxial testing programme for the in-situ dry density and water content.

The effect of variations in the modulus of resilience and creep compliance of the subgrade on the performance and design life of a pavement was investigated. This was carried out by examining the experimental results and the results of a parametric analysis using a finite element program. The results of the parametric analysis show that changes in the subgrade properties have a greater effect on rutting of the pavement than on the fatigue life of the asphalt layer.

05054 **Field Validation of an Overlay Design Procedure to Prevent Reflection Cracking**
B.F. McCullough, S.B. Seeds

A computer model was developed in 1977 under the sponsorship of the FHWA for analysis of reflection cracking in overlays on rigid pavements. This paper provides a description of the program (RFLCR) and a brief discussion on the theory behind its development. More importantly, the paper discusses the sensitivity of the program to certain input parameters and provides some basis (in the performance of overlays in Texas) for verification and acceptance of the procedure. The model will, however, continue to be examined, improved and calibrated for use in Arkansas as part of a joint project with the University of Arkansas, the Arkansas State Highway and Transportation Department.

05055 **Structural Finite Element Design of Unbound Material Pavements from Cyclic Loading Triaxial Tests**
J.L. Paute, J. Martinez

In this paper we intend to expose the application of a structural design method for unbound granular layered pavements founded on the direct determination of materials and soils behaviour parameters by cyclic triaxial loading, and on the utilization of obtained experimental results in structural design by means of a finite element computer code.

Materials experimental study is achieved in triaxial cells, with a completely pneumatic loading system, allowing the cyclic application of axial stress and cell pressure, as well as sample axial and radial strains measurement. In this way, it is possible to characterize the behaviour of unbound materials and soils under traffic, as well in terms of resilient response as permanent deformation at large number of cycles. Sample dimensions (160 mm diameter by 320 mm height) authorizes the study of materials with 0/20 mm particle size distribution.

Experimental results, obtained on unbound crushed stone and soils, have been analysed in terns of resilient and permanent deformations moduli. The influence of applied stresses on the elastic moduli values shows a great dependence between shear modulus and spheric pressure and between bulk modulus and deviatoric ratio. Presented in terms of permanent deformation at a given number of cycles versus applied stresses results allow drawing stress-strain equivalent diagrams. They give permanent deformation moduli values directly utilizable in structural irreversible deformations calculus at a given cumulated traffic.

Taking account of different obtained experimental results, structural design is carried out with a finite element computer code. In this way, it is possible to integrate non-linear elastic behaviour and applied stress versus cumulated strain parameters. Calculations have been achieved for various structures types with different geometrical and mechanical properties.

In conclusion to our work and as shown by other researchers, cyclic triaxial testing appears to be an efficient way to characterize unbound granular materials and soils for pavement design. The resulting experimental data can be directly used in calculus for determinating structural resilient response and permanent deformation. Design based on such methods should lead to a better structural optimization and it's of interest to develop and generalize it.

05056 **Characterization of Freeze/Thaw Affected Granular Soils for Pavement Evaluation**
T.C. Johnson, D.M. Cole, L.H. Irwin

As part of a continuing investigation of techniques for predicting the effects of frost action on pavements, we have conducted field and laboratory tests to determine the nonlinear resilient modulus of granular soils affected by freezing and thawing. Three sands with varying amounts of silt were subjected to repeated-load triaxial compression tests in the frozen state, immediately after thawing, and at various stages of recovery as moisture tension increased during desaturation. By means of regression analyses the resilient moduli were expressed as functions of the significant parameters. In the frozen state these included temperature or ice content, total moisture content, and either the second stress invariant divided by the octahedral shear stress, J sub 2 / tau sub oct, or the octahedral shear stress alone. In the thawed and recovering states the significant variables were the moisture tension, the dry density and either of two stress parameters, J sub 2 / tau sub oct or the first stress invariant J sub 1.

To verify the laboratory characterizations, in-situ dynamic plate bearing tests were conducted on three field test sections, each consisting of about 50 mm of asphalt concrete and 1500 mm of one of the three soils tested in the laboratory, underlain by a gravelly sand subgrade soil. Repeated plate-bearing (RPB) tests were conducted 13 times between October 1978 and September 1979, and falling weight deflectometer (FWD) tests were performed 9 times from February through

April 1980. Both types of tests were conducted at two load levels, in the range from 200 to 600 kPa plate pressure, and the testing dates encompassed changes in seasons and in conditions in the test soils ranging from frozen to thawing, recovering and completely recovered. The surface deflection basins were measured in each test, and prevailing subsurface temperatures and moisture tensions were monitored.

The sequence and thickness of the layers prevailing within the test soil during each test were defined by temperatures, frozen or thawed state, and moisture tension level. The layer thicknesses, plate loads, and nonlinear materials characterizations for each layer as determined from the laboratory tests, were entered into an elastic layered system program termed NELAPAV, to calculate stresses, strains and deflections. By an iterative process the program calculates moduli and stresses that are mutually consistent.

The calculated deflections agree reasonably well with the deflections measured during in situ load testing. The calculated resilient moduli show the expected seasonal variation, with extremely high values in the frozen condition, decreasing dramatically upon thawing, and increasing somewhat during late spring, summer and fall. From these results it was concluded that laboratory repeated-load triaxial tests performed at successive stages of the freeze/ thaw/recovery cycle can accurately characterize the nonlinear, stress-dependent moduli representative of each stage. Soil moisture tension measured in situ through cycles of thawing and recovery can provide the basis for assessment of the timing of the thawing/ recovery cycle and of the laboratory determined modulus representative of each stage.

It was also found that NELAPAV could be used to calculate moduli from a measured deflection basin, by a process of successive trials. This method is considered less accurate than the method employing both laboratory and field tests, but its use is appropriate for pavement evaluations in cases where non-destructive testing is to be used exclusively, rather than combined with sampling and laboratory testing.

05057 **Analysis and Design of Pavement to Resist Thermal Cracking Using Fracture Mechanics**
R.L. Lytton, U. Shanmugham

A fracture mechanics based model has been developed that predicts the occurrence of transverse cracking in asphalt concrete pavements. Cracks are assumed to begin at the surface of the pavement and propagate downward as temperature cycling occurs. The rate of crack growth is based upon the Paris and Erdogan equation from which the number of temperature cycles required to crack a pavement can be calculated. The summation of the reciprocals of the cycles to failure was used to define a cumulative damage function, which is used to calculate observed crack frequency with acceptably small standard errors.

The mechanistic model calculates the change in stress intensity factor during each day due to the temperature cycle. Stress intensity factors are calculated from regression equations generated from a multi-factorial experiment using a finite element model of a multi-layered pavement structure. Fracture parameters are derived from readily available rheological properties of the bitumen.

Data used to validate the model were collected in Michigan. An empirical equation with very strong statistics was developed from the Michigan data and may be used to predict crack spacing. The empirical equation is limited in application to subgrade conditions and mix properties typical of Michigan pavements. The mechanistic model is sensitive to both subgrade and mix variables and thus was used to develop an empirical equation useful in the design of pavements to resist temperature cracking.

The mechanistic model is capable of providing more insight into the causes of low temperature cracking, and suggests other areas where the model can be improved profitably including the healing of asphalt concrete pavements due to residual stress, combining several modes of crack propagation, and determining fracture properties of aged mixes.

05058 **Laboratory and Field Fatigue Characterization for Sulphur Extended Asphalt Paving Mixtures**
J.P. Mahoney, R.L. Terrel

Data from experimental pavements recently constructed and tested at the Washington State University Test Track are analyzed to determine the fatigue relationships for conventional asphalt mixtures. The laboratory mix designs, test track construction and instrumentation are discussed. Additionally, laboratory fatigue parameters are derived for the same three mixtures by using sawed beams from the experimental pavements and tested in a rolling wheel fatigue apparatus. The fatigue analysis reveals that the conventional dense graded asphalt concrete has a flatter fatigue curve when compared to the two mixtures which contained added sulphur (30/70 and 40/60). This can be a desirable characteristic at high levels of repetitions to failure (low bending strains). The sulphur extended asphalt mixtures are able to accommodate higher bending strains at lower levels of repetitions to failure. The differences in the fatigue relationships for both the conventional asphalt concrete and the sulphur extended asphalt mixtures as determined by the fatigue parameters (K sub 1 and K sub 2) are small. The need for durability evaluation of SEA paving mixtures is discussed.

05059 **Recycling Asphalt Concrete: Guidelines and Performance Potential**
D.N. Little, J.A. Epps, R.J. Holmgreen

Recycling asphalt concrete pavement materials presents a very attractive alternative to pavement rehabilitation which must be considered. Recycling may conserve not only appreciable quantities of asphalt cement but also aggregates, providing not only economic but also environmental advantages.

The Guidelines for Recycling Pavement Materials (NCHRP Report 224) is summarized in this paper. These guidelines provide the tools to the pavement engineer for equitable consideration of recycling alternatives.

Recycled materials have proved comparable and, at times, even superior to conventional asphalt concrete based on both laboratory and in situ testing. Results of in situ pavement studies using the Dynaflect on twenty-five recycled pavements in eleven states are presented.

Laboratory characterization of recycled mixture properties of creep compliance, time-temperature shift, permanent deformation, thermal cracking and fatigue are presented. These properties were input into the VESYS IIM structural subsystem to predict performance of the recycled materials used in pavement systems in a variety of climates. Predicted performance of the recycled materials compared favorably with that of a dense graded, high quality asphalt concrete used as a control or comparison mixture.

Recycled asphalt concrete mixtures can be designed to provide acceptable structural properties and acceptable resistance to low temperature induced stresses.

05060 **A Summary of Sulphur-Asphalt Design Technology**
G.J. Kennepohl, D.C. Bean, L.J. Miller, R.C.G. Haas

Sulphur-asphalt pavement design technology has undergone extensive development in North America and abroad since the early 1970's. These pavements represent a viable alternative to conventional asphalt pavements and they offer potential economic and performance advantages. Extensive laboratory, field and analytical investigations have been conducted to verify the design technology.

This paper reports on the design technology for sulphur-asphalt pavements as developed by Gulf Canada Limited and cooperating organizations and individuals. Several major aspects of the technology are addressed, including materials production, properties and quality assurance, structural design and economic considerations. Examples of each aspect are presented.

Sulphur-asphalt mixes have been found to have a lower temperature susceptibility than conventional mixes and they therefore offer the designer increased flexibility with respect to low-temperature and permanent deformation requirements. In addition, increased fatigue life and/or thickness reductions can be achieved under certain conditions. Production, transport, placement and compaction of sulphur-asphalt mixes is done with conventional methods and equipment. It is essential to produce the sulphur-asphalt binder by preblending the components, rather than by separately introducing the components and "pugmill blending" them, for reasons of improved engineering properties plus quality assurance.

The paper provides a summary list of some of the field trials conducted in North America, Europe and the Mid East. Observations to date have verified the laboratory and theoretically based design results related to permanent deformation and low-temperature cracking, as well as the upgrading possible with low-quality aggregates. Thickness reduction and/or fatigue resistance advantages remain to be verified.

Finally, the paper briefly reviews the potential economic advantages of using sulphur-asphalt. These relate to materials cost savings, conservation of materials and potential performance advantages.

05061 **Characterization and Design Analysis of Bituminous Pavements**
S.K. Khanna, M.G. Arora, K.R.N.S. Setty

With rapid motorisation and industrialization in India, bituminous pavement surfacings are becoming more and more common in the country. However, the design of bituminous pavement layers is still based on ad hoc experience and empirical strength tests. This paper aims to develop analytical method of design for bituminous pavements based on more realistic strength characterisation tests simulating the stress environment in the pavement layer under actual traffic loads. Three types of bituminous pavement specifications commonly used in India viz. bituminous concrete, bitumen bound macadam and sheet asphalt as recommended by the Indian Roads Congress (IRC) have been included in the study. Water bound macadam comprising crushed stone aggregate/overburnt brick aggregate was employed as a base course. Local Boorkee-soil (I.S. classification –SM) represented the subgrade soil.

Stiffness moduli of pavement component materials were determined by the conventional triaxial tests. In certain cases where horizontal stresses developed at the bottom of the bituminous layers under traffic loads are tensile in nature, the stiffness modulus may be different from the case where the horizontal radial stresses are in compression. In order to simulate the radial stresses in tension, thick hollow cylindrical triaxial specimens were cast and tested under axial compression. Radial tension was simulated by inducing water pressure inside the central hole. Analysis of results of all pavement materials tested indicates nonlinear relationship between strength modulus and applied stress. Since stiffness is also dependant on duration of loading, creep tests in tension as well as compression have been carried out. The creep compliance is also dependant on stress level as well as duration of loading.

Semi-full scale pavement sections were installed in the pavement testing laboratory employing the local soil as subgrade and the WBM and various bituminous specifications as the base and surface courses. Over each combination of base course/subgrade, three different thicknesses of bituminous pavement layers of each specification were installed and the load-deformation and pressure transmission characteristics of the pavement system were observed under static plate loads simulating the traffic loads. The results of semi-full scale testing exhibit supremacy of bituminous concrete layer over bitumen bound macadam and sheet asphalt in terms of its greater resistance to surface deformation and better pressure transmission characteristics.

Axisymmetric finite element model has been developed for a multi-layer pavement system which is based on the non-linear elastic stress-strain behaviour of the pavement component materials under simulated traffic loads. The stiffness of pavement materials as determined from laboratory characterization tests are used as design input into the analytical model to predict the load response characteristics of the semi-full scale pavement sections. The developed analytical model exhibits closer agreement with the experimental data than the conventional linear elastic model. It is proposed to apply this model for structural evaluation of existing weak flexible pavements in India and evolve design charts for Benkelman Beam Deflection method of design of bituminous overlays under the Research Scheme R-6 sponsored by the Ministry of Shipping and Transport (Roads Wing), Government of India.

05062 **Volume II of 5th Conference Proceedings - preliminary pages and Table of Contents**
n/a

05063 **Moderator's report and discussion of Session I papers**
C. L. Monismith, M. W. Witczak

Moderators: C. L. Monismith, Professor of Civil Engineering, University of California, Berkeley, USA

M. W. Witczak, Professor of Civil Engineering, University of Maryland. College Park, USA

In this report, the moderators will attempt to use the papers which have been presented to the conference (and included in this session) to develop some general recommendations about the design process within the framework of Figure 1. We believe that the information contained in the papers provides a basis for any organization to develop its own design procedures for asphalt-type pavements. Moreover, as long as good construction procedures are followed in building the resultant designs, we believe that this methodology should provide a high level of confidence in the performance of the pavements. Should proper construction procedures not be followed, it permits a reasonable estimate to be made of the shortfall in performance, e.g., as measured by traffic transported, and to take appropriate action.

05064 **Moderator's report and discussion of Session II papers**
J. Bonnot, J. Remain, J. Verstraeten

Moderators: J. Bonnot, Technical Director, Laboratoire Central Des Ponts et Chaussees, France
J. Remain, Scientific Advisor, Belgian Road Research Center
J. Verstraeten, Deputy Director, Belgian Road Research Center

In this session, the emphasis is placed on the "Verification" of design methods and models; that is, the comparison of predicted and observed performances. Nine papers have been assigned to this Session, coming from six countries: 3 papers from the United States, 2 papers from the Netherlands, and one paper each from Kenya, South Africa, Switzerland and the United Kingdom. Papers have been offered that deal with such comparisons in the case of overall empirical methods and in the case of the elements involved in theoretical or semi-theoretical methods, namely:
- stresses and strains
- deflections
- rutting or permanent deformation
- cracking
- PSI as an overall performance index

Further, comparisons between predictions from different design methods have been made. These items will be reviewed in succession. We shall then attempt to place the different contributions in perspective and to synthesize the state-of-the-art in the matter of verification.

05065 **Moderator's report and discussion of Session III papers**
A.A.A. Molenar, R.C. Koole

Moderators:
A.A.A. Molenar, Delft University of Technology,
R.C. Koole, Shell Research, Amsterdam, The Netherlands

This section on pavement evaluation is scheduled between the session on pavement design and the verification of design sessions we had yesterday and this morning, and the sessions on pavement management and pavement rehabilitation tomorrow.

Your moderators feel that indeed this is the right time to discuss pavement evaluation aspects, because after we have built our pavements in Session I and II and before we will discuss how we can get the most out of our maintenance and rehabilitation budget, we should discuss techniques and methodologies by which we are able to determine where, when and which maintenance activities should be applied in order to restore or to keep the condition of the pavement system at a desired level of service. Your moderators like to describe evaluation of pavements as: the process of measuring the structural and functional condition of the pavement, followed by verifying whether the condition is above or below predefined minimum acceptance levels and warning levels.

Furthermore, one should estimate the length of the time period that will elapse between exceeding the warning level and reaching the threshold (i.e. the minimum acceptance level), since this enables scheduling in time of maintenance activities (Figure 1). Also, a first estimate should be made of the nature of the required maintenance activity in order to be able to plan the maintenance budget over a certain time period. In order to be able to make such projections, regular check-ups of the pavement condition are necessary (1, 2, 3). This definition of pavement evaluation given by your moderators is wider than what is meant by evaluation in the opinion of others. They define evaluation as measuring properties of pavement layers, like for instance elastic moduli.

For the time being your moderators like to stick with their cinemascopic definition since we feel these limited definitions do incorporate the danger that taking measurements or calculating elastic moduli are becoming a goal themselves. This of course may never be the case. We will come back to this in detail in the second part of this session. Also, the wide definition of evaluation given by your moderators stresses the axiom that the strength of the chain is determined by its weakest link. By this we mea" that measuring, data processing and overlay design techniques should be equally well developed. For instance, it makes no sense to spend a lot of money to obtain deflection equipment which is capable of characterizing very accurately the deflection bowl if an overlay design technique is used which utilizes only the maximum deflection as input. However since we know different opinions exist on the meaning of the word evaluation, we would encourage the authors to comment on the definition given here by your moderators, and to give their views on what the evaluation process should be.

Having some well known definition makers in our session like Dr. Hudson and Dr. Finn
we are sure we will succeed in this.

05066 **Moderator's report and discussion of Session IV papers**
R. Haas, W.R. Hudson

Moderators:
Ralph Haas, Professor of Civil Engineering, University of Waterloo, Canada
W. R. Hudson, Professor of Transportation Engineering, The University of Texas at Austin, U.S.A.

This Session deals with Pavement Management and Pavement Management Systems. It is our honor and our responsibility to summarize the papers selected for this session. But to simply summarize the papers is not enough; rather, it seems necessary to provide a background and an organized framework for comparing and putting into perspective

the contributions made by the work described in these papers

05067 **Moderator's report and discussion of Session V papers**

Jon A. Epps, R. G. Hicks

Moderators:
Jon A. Epps, Professor of Civil Engineering, Texas A&M University, U.S.A.
R. G. Hicks, Professor of Civil Engineering, Oregon State University, U.S.A.

INTRODUCTION

Expenditures for streets and highways are a large part of today's transportation budgets. A sizeable portion of these budgets is disbursed for pavements with an increasing proportion of this amount devoted to preserving the existing pavement network. In spite of the increases in expenditures for maintaining the existing systems, estimates indicate that funds will not be sufficient to keep streets and highways at an acceptable level of serviceability. This, together with current inflationary trends and the necessity for energy conservation, requires the efficient management of our local street and highway systems.

Purpose

The purpose of this report is to summarize the recent developments pertaining to the maintenance and rehabilitation of highways. Included will be a general discussion of maintenance and rehabilitation strategies available to engineers, methods available to optimize the selection of the best strategy for a given situation (pavement condition, traffic volume, etc.), and finally, methods for determining overlay thicknesses and/or predicting remaining life of existing pavements. The discussion is based not only on the review of the ten papers accepted for this session, but also the critical review of other recent publications.

In this report pavement maintenance is defined as those processes, both preventative and corrective, which do not involve major alterations in the existing pavement structure. Rehabilitation includes reconstruction, overlays and recycling, and their combinations to restore or improve the serviceability and/or structural capabilities of the pavement. A general framework for such activities is shown in Figure 1. The sections which follow include: (1) discussion of these alternatives and methods used to optimize their selection, and (2) where overlays are required, descriptions of methods for computing the thickness to ensure adequate service.

Organization of Session

In carrying out their task, your moderators have tried to strike a balance between the information presented in the ten papers and information presented elsewhere. The intention of this approach is to stimulate discussion and to allow the authors to add finishing touches to work completed over one year ago. Professor Epps will summarize the papers dealing with maintenance and rehabilitation strategies. Professor Hicks will summarise those papers which consider overlay design. Authors will then have an opportunity to rebut our remarks. This will be followed by discussion (both prepared and from the floor). Dr. Epps will conclude with the summary of the significant findings and recommendations resulting from this session.

05068 **Moderator's report and discussion of Evening Session**

F.N. Finn

Moderator: F.N. Finn, Consulting Engineer, U.S.A.

This session is the evening meeting; it is not quite as well organized as the formal sessions are; it is an informal session in that regard and I want to ask you to bear with US a bit. We have an opportunity for some very lively discussions and we have some questions. We also will have some discussion this evening for all of you to participate in and I want you to feel free to get up and make remarks, ask questions, put people on the spot.

I wanted to make just a few opening remarks to lay a bit of ground work on Pave- ment Management Systems. I know you are being inundated with an awful lot of information and at times that can be and will be confusing to US. Sometimes when we talk to each other about pavement management systems we are very sincere and we try to be as factual about it as possible, convinced that what we have to say is in fact the latest word in technology. But sometimes when we begin to talk to administrators, policy-makers and decision-makers and sometimes when we talk to, what I call, the traditional highway engineers, it looks to them as though it is all fantasy. So then the question that is posed to those who are here this evening: is it fact or fantasy?

05069 **Moderator's report and discussion of Session VI papers**

P. S. Pell, S. P. Brown, C. K. Kennedy

Moderators:
P. S. Pell, Professor of Civil Engineering, University of Nottingham, United Kingdom
S. P. Brown, Reader in Civil Engineering, University of Nottingham, United Kingdom
C. K. Kennedy, Head of Department of Civil Engineering, Plymouth Polytechnic, United Kingdom

The properties and characterization of materials relevant to performance is an essential and inherent part of the structural design process for asphalt pavements. This topic, therefore, has been dealt with generally in many of the papers presented in other sessions and this particularly applies to asphaltic materials which, of course, constitute the main structural layers in asphalt pavements. However, the purpose of this session Is to present papers whose primary concern is with certain types of material and their behavior under specific conditions rather than overall pavement design methods. In all cases the material response and performance has to be considered in the context of the role they play in the structure of the complete pavement.

The eleven papers assigned to this session and critically summarized below by the Moderators, cover seven topics. Tne characterization of soils and granular sub-base material, both for analysis and performance, is required input data for all structural pavement design methods and is often treated with considerable simplification. In the view of the Moderators, this is an area which warrants considerably more attention and becomes increasingly more important as the asphalt layers become thinner and a number of papers are relevant to these unbound materials. Improvement in the properties of asphalt mixes by the use of various additives is an ongoing development of growing interest for reasons of economy and the improved performance required under present-day heavy traffic loadings. This is reflected by two papers on sulphur-asphalt. The current concern over the best and most economic use of natural resources has led to the development and

use of recycled asphaltic material and this is the subject of one paper.

Four papers are concerned with the mechanisms and design sub-systems related to various types of cracking of asphalt layers, namely, reflection cracking, thermal cracking and a probabilistic approach to fatigue cracking. Each of these deals with a difficult aspect of performance criteria which are still in an early stage of development and not yet incorporated in complete pavement design methods. Tne final paper reports the development of a design procedure for Indian conditions based on characterization testing of materials commonly used in that country.

05070 **Moderator's report and discussion of Session VII papers**
J. F. Shook, W. Visser

Moderators:
J. F. Shook, Principal Engineer, The Asphalt Institute, USA
W. Visser, General Manager of Pavement Consultancy Service, The Netherlands

The two moderators of Session VII were asked by the conference Technical Advisory Committee and the International Executive Committee to summarize the results of the proceeding six sessions, and to report, from their respective points of view, the outlook for the near future, particularly with reference to the outlook for implementation and to research needs. As explained earlier by Mr. Visser, we have separated our report into two parts. I will review and report on Session I, Pavement Design Methods, Session II, Verification of Design Methods and Session VI, Material Properties. Mr. Visser will report on the remaining three sessions. We hope this procedure will not be too confusing and that we will not contradict one another to any great extent.

I am pleased, particularly to be able to include verification of design procedures in my portion of this report. Much effort has been put into the development of design procedures, both empirical procedures and procedures based on theoretical or semi-theoretical models, in the past twenty years. Somewhat less attention has been given to material testing I believe, and considerably less to field verification. Field verification is very difficult, and I am pleased to note that 24 of the 33 papers in Session I, II and VI make some reference to field verification, as do, also, many of the papers in Session III and V.

Now, for the rest of my presentation; first, I will summarize the more important points raised by the moderators in their respective reports, and then discuss the issues of implementation and research.

05071 **Comments on the Next Conference (the 6th)**
n/a

The moderators of Session VII asked the audience to make comments about the next (sixth) conference:
1. Should there be a sixth conference?
2. Dn we need a change in format of the conference?
3. Should the scope be changed to include other topics?
4. How can the conference help to encourage Implementation?

The participants contributed to the Discussion with written comments:

05072 **Corrections to papers printed in Volume I**
n/a:

This file contains all the errata for the published papers. These corrections have been appended to the papers to which they are relevant.

05073 **List of Registrants**
n/a

The names, affiliations, and addresses of all 5th Conference participants.

05074 **Rehabilitation Design Incorporating Past Experience of Pavement Behaviour**
M. C. Grant, P. C. Curtayne

It is often found in practice that too narrow an approach is taken in the design of pavement rehabilitation. Selected rehabilitation procedures are used in which only a few of the important factors that should affect the design are considered. Furthermore, much of the information that could be obtained by evaluating the condition of the pavement and its past behaviour is not fully exploited. Although these deficiencies may be recognized it is often difficult to combine qualitative judgements with sophisticated numerical analysis.

This paper presents a broad framework for the evaluation of pavements. Emphasis is laid on the cause of distress in the choice of the type of rehabilitation and the use of various types of information that can be used in the design process. Because obtaining information is expensive, a selective and iterative procedure is used starting from simple observations and progressing to more sophisticated testing, if justified. Irrespective of the amount of testing, uncertainties regarding the best form of rehabilitation will remain and the final choice can be made with the help of Bayesian decision diagrams. Some simple tests are described that can provide information about the cause of distress and the structural capacity that can be used in this approach.

05075 **Index of Contributors and Discussers**
n/a

An alphabetical listing of contributors and discussors.

code	ISAP 6th Conference -- Titles & Abstracts
06000	**6th International Conference on the Design of Asphalt Pavements - Volume contents and preliminary pages** *n/a*
06001	**Structural Design of Asphalt Pavements for Heavy Loads** *J.F. Shook, J.A. Burton* A thickness design method for Full-Depth asphalt pavements, based on the use of multi- layered elastic theory and subgrade vertical strain criteria, is described. Design charts and tables are provided in the manual for two climatic conditions, a cold climate with frost conditions, and a warm climate with relatively constant subgrade conditions. Guidelines are given for selecting design wheel loads for a variety of vehicles, such as fork-lift loaders, off-road haulers, log-handlers and straddle carriers. The procedure is applicable to single load, dual load and multiple wheel load problems. Ten years experience with an earlier version guided the authors in selection criteria and typical material properties used to produce the design procedure.
06002	**ILLI-PAVE Based Full-Depth Asphalt Concrete Pavement Design Procedure** *Marshall R. Thompson* The basic concepts and the development of a FULL-DEPTH ASPHALT CONCRETE THICKNESS DESIGN PROCEDURE are presented. The proposed procedure is based on resilient soil and material testing procedures, the ILLI-PAVE structural model, and design algorithms developed from an extensive ILLI-PAVE data base. Traffic (18k equivalent single axle loads), subgrade modulus, location (pavement temperature effects), asphalt cement grade (AC-10, AC-20) and design reliability factors (AVERAGE-INTERMEDIATE-HIGH) are considered. Comparisons of ILLI-PAVE, SHELL, and The Asphalt Institute thickness requirements indicate ILLI-PAVE thickness requirements are quite reasonable. In general, ILLI-PAVE thicknesses are 'intermediate'. The ILLI-PAVE based procedure is 'modular', easy to use, and can be easily modified to accommodate a range of AC mixtures (gradation, asphalt cements, fatigue characteristics, etc.), subgrade conditions, and local climatic effects
06003	**An Integrated Approach for Determining Additive Requirements in Hot Mix Recycling** *V.P. Sepvas, A.C. Edler, M.A. Ferreira, E.J. van Assen* Additives are needed in hot mix recycling in order to rejuvenate aged binders when this cannot be accomplished by using only new penetration grade bitumens. However, the use of additives can have significant adverse effects on the behaviour of asphalt mixes. Despite much progress in this area, questions relating to aspects such as time-dependency and chemical compatibility remain largely unanswered. The paper examines some of the earlier work undertaken in the development of additives and evolution of specifications, and the subsequent research aimed at developing a comprehensive method for the effective determination of the need, correct type and amount of additive for particular recycling situations.
06004	**Development of a Structural Design Procedure for Asphalt Pavements With Crushed Rubble Base Courses** *G.T.H. Sweere, A. Penning, E. Vos* This paper describes the first phases of a major research project carried out in the Netherlands into the possibility of recycling demolition waste as a base course material for asphalt pavements. Since no long term experience regarding the structural contribution of base courses built with recycling materials was available, a fundamental research into the behaviour of base courses in general was initiated. The following phases in the research project can be distinguished: - Material characterization, with emphasis on cyclic loading triaxial testing of unbound base course materials. - Development of a finite element computer program for calculation of stresses and strains in pavements. - Construction of a series of full scale test pavements, equipped with transducers for measurement of stresses and strains. - Verification of the finite element model, using the data from the test pavements. The first two phases of the project are described in detail, followed by a description of the first test pavement. In the material characterization phase of the project, a number of recycling base coarse materials such as crushed concrete, crushed bricks and mixtures of these materials were tested, together with Eifellith lava as a reference material. Cyclic loading triaxial tests were carried out to determine the resilient modulus M sub r as a function of the stress level. Also, static loading triaxial tests were carried out in a search for a simpler test for determination of M sub r. A Large number of standard tests was carried out on all the materials investigated in order to check the possibility of a quick assessment of material quality. The general purpose finite element program DIANA was modified in such a way that it can take into account the stress dependent resilient behaviour of granular materials. A secant approach to the contour model developed by the University of Nottingham is used to model the data from the cyclic Loading triaxial tests for input to the DIANA program. Details of the calculation procedure are given, together with the results of a first series of calculations. Finally, the layout of the first of a series of test pavements is described. The test pavements are equipped with transducers for measurement of stresses and strains to provide the data needed for validation of the design procedure being developed in the final phase of the project.
06005	**Rational Model for the Flexible Pavements Deformations** *P. Jove, J. Martinez, J.L. Paute, E. Ragneau* The improvement of flexible pavements design methods required for the "Laboratoires des Ponts et Chausses" in France the development of researches and experimentations in three ranges:

1. The unbound granular materials and soils behaviour study.

2. The creation of a numerical analysis model.

3. The pavements behaviour observation.

The first part of the paper presents the experimental results on the materials. The studies we achieved with the repetitive loadings triaxial on the unbound granular materials allowed the modelization of the nonlinear elastic behaviour of these materials and the drawing of relationships between a "permanent deformations modulus", the loadings number and the stresses which are applied. We demonstrate also that, for a family of UGM completely crushed, the elastic performances are above all dependent on the chippings shape and that the permanent deformations are very related to the moisture content. For the subgrades we show that the elastic deformations are related to the effective pressure due to the weight of the soil and the pavement structure. The relationships, determining the permanent deformations modulus, take also into account this parameter, the value of which is dependent on the hydrologial environment of the pavement. The second part of this paper is composed of the presentation of a design method allowing the determination of the internal forces and the rutting about a pavement. In a first time, we determine the stresses obtained in reversible deformations. For this, we use a nonlinear finite elements method, which allows to take into account the behaviour laws obtained experimentally. The advantage of this method is at first explained on an example, in comparing the results we obtained with those corresponding to a linear elastic behaviour of the materials. Then, we demonstrate how the systematic utilization of a such method allows the determination of charts for the pavements design. We show after how, from the stresses obtained in reversible behaviour, we can use the permanent deformations laws to determine the rutting of a pavement. An example illustrates this design method and we give the evolution of rutting depth in function of the cycles number.

The reader can refer to the paper by Messrs. AUTRET, de BOISSOUDY and GRAMSAMER (ref. 91, which shows the means used to align the theoretical models from experimentations in true scale.

06006 **Influence of Bitumen Hardness on the Fatigue Behaviour of Asphalt Pavements of Different Thickness Due to Bearing Capacity of Subbase, Traffic Loading and Temperature**
W. Arand

The most well known and worldwide used fatigue laws are based on the results of bending tests on specimens of bituminous materials. Using one of these fatigue laws it can be demonstrated that the number of applicable load alternations increases with decreasing temperatures. Asphalt pavements however show increasing tensile stresses with drop of temperature because of the restrained thermal contraction within a range of adequate low temperatures. Superposition of these thermal induced tensile stresses to the bending stresses will result in a smaller number of applicable load alternations until a first cumulative damage will occur, if the pavement is kept below a certain temperature limit. The use of a harder bitumen type - par example a bitumen pen 20 instead of a bitumen pen 80 - entails a shifting of the critical temperature of about 15C in the direction of higher temperature. Therefore we can draw the conclusion that the use of harder bitumen types at lower temperatures involves a significant smaller number of applicable load alternations until fatigue occurs.

Because of the higher life expectancy of asphalt pavements with harder bitumen types within the range of higher temperatures, however, it will be difficult to take a decision on the application of harder or softer bitumen types with regard to the fatigue behaviour, if we don't have sufficient information about structural, traffic and especially climatic requirements.

In order to solve the above mentioned problem the following topics should be investigated:

- determination of hourly variation in temperature spread as well as in traffic with regard to traffic volume and traffic structure spread for one representative year and definition of classification schedule for both;

- determination of bending stresses and thermal induced tensile stresses in asphalt pavements of different thickness due to traffic loading and temperature as well as to hardness and sensitiveness of bitumen to temperature and superposition of both kinds of stresses:

- evaluation of the number of applicable load alternations until the occurrence of cumulative fatigue damage on the base of known fatigue laws and interpretation of the results with the aid of MINER's hypothesis;

- development of selection principals for the application of proper bitumen types with regard to structural, traffic and climatic requirements.

06007 **The Influence of Stiffness-Progress of the Different Pavement Layers on the Size and Shape of Rut Depth in the Pavement Surface**
A. Gerlach, A. Loizos, H. Lucke

Various institutions in the F.R. of Germany and abroad are presently considering the problem of ruts as a criterium of damage. Observations in practice have shown that rut formation is one of the main reasons for repair work on roads and is an important characteristic relating to traffic safety.

In the most widely developed road dimensioning concept up to date, the VESYS-system, only the permanent deformations formed at the centre of the applied load are considered in the theoretical determination of rut depth. Furthermore, only central traffic loading along a line is taken into account. In addition to the rut depth considered here, the shape of the rut normal to the direction of traffic movement is also a governing factor in relation to the present serviceability. This follows from the assessment of the rut depth in terms of the present serviceability index PSI, which refers to a base width of 1,22 m. The importance of the rut shape in relation to traffic and travelling comfort is also evident by further literature research.

With the aid of the VESYS rut model and based upon the multi-layer theory, a method has been developed for theoretical determination of the size and shape of ruts. By this method, the contributions of individual layers to rut formation in the pavement surface may also be determined.

06008 **Effects of Load Distributions and Axle and Tire Configurations on Pavement Fatigue**
Herbert F. Southgate, Robert C. Deen

Damage factor relationships for axle and tire configurations are presented. Adjustment factors are provided to account for variations in load distributions within axle groups, distances between axles of a tandem, and variations in tire pressure for both dual and flotation tires.

Properly accounting for accumulated fatigue of a pavement requires a reasonable measure of traffic volume, proportions of vehicle styles (classifications) within the traffic stream, dates of service, estimate of the average damage factor for each classification, and estimates of tire contact pressures.

All adjustment factors presented are based on analyses of a limited number of structures and should be used with caution. The accuracy of these analyses is not in question, but the range of structures investigated was limited. They are intended to indicate the trend, shape, and sensitivity of various inter-relationships and their relative magnitudes. Modifications may have to be made upon the analyses of additional pavement structures. Kentucky traffic may differ from that in other areas, both in types of vehicles in the traffic stream and the type and direction that cargo is being transported.

06009 **Seven Years' Experience With the Structural Aspects of the Shell Pavement Design Manual**
A.H. Gerritsen, R.C. Koole

The experience gained with the Shell Pavement Design Manual (SPDM) since its publication in 1978 has been evaluated in 1984/85, which resulted in two essential conclusions. First, its use in practice has not revealed any systematic deviation in the structural design procedure and second, the users of the manual generally express a desire for more explicit information with respect to various aspects of the design procedure, especially with respect to the incorporation of safety margins.

This paper discusses some of the aspects of the structural design procedure in more detail and gives practical guidelines to raise the level of confidence of the design result from 50% to 85% or even 95%. With proper safety margins incorporated, the SPDM design results are found to be very similar to those of other design procedures. Unlike many other design procedures, however, the SPDM makes it possible to select the level of confidence suited for a specific design situation.

Two case studies serve to confirm that (i) the actual service life of a pavement is close to the designed value provided the actual material properties are used for the design, and (ii) the estimation of the material properties generally includes some uncertainties, which require the use of proper safety margins.

06010 **Influence of Mix Design on Reflection Cracking Growth Rates Through Asphalt Surfacing**
T. Brooker, M.D. Foulkes, C.K. Kennedy

The mix design of asphalt surfacings rarely recognises the different functions these layers perform when laid over granular, bituminous and cement bound roadbases and the consequent need for different stiffness and fracture toughness properties. This paper defines the conditions under which reflection cracking due to thermal stresses will occur and enables estimates of the combined influence of thermal and traffic stresses to be made. The influence of mix variables and fabric interlayers are also discussed in relation to test results.

A Temperature model has been developed to determine roadbase daily temperature range and mean surfacing temperature for each month of the year, within a composite pavement; these determine the magnitude of crack opening movements and the brittleness of the surfacing. Thermal reflection cracking is considered to result from a daily cyclic fatigue mechanism rather than an extreme low temperature mechanism.

Test rigs have been developed to simulate both thermal and traffic movements but only a limited number of tests have been performed with traffic simulation; results are still being evaluated. Finite element analyses of the pavement structure indicate that stress intensity factors decrease as the crack develops under thermal stresses but increase under traffic stresses. Thus initial crack development is controlled by thermal stresses and final cracking to the surface is assisted by traffic stresses. The finite element model shows that thermal stress intensity factors are related to cyclic crack opening, crack length, mix stiffness and surfacing thickness. It also enables crack growth rates during testing to be determined from cyclic displacements at the surface of the samples that were monitored by specially developed portal frame gauges.

These finite element results enable a fracture mechanics interpretation of the test results to be made that serves as the basis of a predictive model for thermal reflection cracking of surfacing thicknesses differing from the 100 mm used in tests. The predictive model is partially validated by limited full-scale observations of cracking on a 100 m section of untrafficked road after 7 years.

Finally, the effect of accelerating simulative tests from a 24 hours cycle to 0.1 Hz has been considered in this study where the crack growth rates and thus fatigue lives have been shown to be related to bitumen stiffness as defined by the SHELL Nomograph. Bitumen stiffness is a useful parameter for 'low stiffness' fatigue testing because it accounts for the influence of test temperature, test frequency and bitumen grade on fatigue life.

06011 **Latest Developments in the Analytical Methods for the Design of New Pavements and Strengthening Overlays in Belgium**
L. Heleven, J. Verstraeten, V. Veverka

The practical methods presented are primarily intended for project designers and those responsible for road networks (State, Provincial or Municipal authorities). The object of the proposed method for the structural design of new bituminous pavements is to avoid fatigue cracking of bituminous layers and excessive permanent deformation of road structures.

The practical solutions recommended offer a choice between two variants:
- flexible structures (bituminous layers, crushed stone base, granular sub-base),
- semi-rigid structures (bituminous layers, lean concrete base, granular sub-base).

The object of the proposed method for the design of strengthening overlays of old flexible pavements is the determination of the thicknesses of the strengthening layers and also the thicknesses of the layers to be eventually rebuilt. Several variants of the solution are proposed with a view to a technico-economic comparison.

The paper is a synthesis grouping the latest developments of analytical methods based on results of fundamental

researches presented to the former Ann Arbor Conferences (1967, 1972, 1977 and 1982).

06012 **Characterization and Structural Assessment of Bound Materials for Flexible Road Structures**
L. Francken, C. Clauwaert

In order to generalize pavement design and management systems, prediction methods have been developed at the Belgian Road Research Centre.

These methods allow the assessment of the dynamic modulus, the fatigue law of bituminous mixes on the basis of a limited number of input data describing the mix volumic composition and the binder characteristics. The general formulas proposed were obtained after a statistical analysis of a large variety of compositions.

The properties measured on mixes containing modified bitumens have been used to illustrate a procedure for the determination of equivalent thicknesses. A structural factor allowing the generalization of design methods can be derived in this way.

A stress analysis procedure based on the method of finite differences was used for the study of the stress distribution in cracked road structures or in the vicinity of buried joints.

06013 **A Design Procedure Based on Experimental Results**
H. Buseck, H. Hurtgen

Structural design of pavements essentially means that layer thickness and material properties be so selected as to ensure that the end of service life is not reached within a given time. End of service life in this context is defined by a rut depth limit. In the Federal Republic of Germany, the long-term behavior of most pavements , studies on test roads, those in a full scale testing laboratory, and laboratory tests, all point to rut depth as failure criterion. Fatigue of bituminous road materials has been a very rarely observed phenomenon.

Experimental design methods require that an adequate number of variables of the pavement in question be subjected to real traffic till the end of service life. Full scale pavement tests can shorten this time. However, transfer functions then have to be set up to translate the results of the experiment into real life conditions. In theoretical pavement design methods, the material properties determined in the laboratory are used in a model and the long- term behavior of the pavement is forecast based on this model. It is assumed that the model is able to describe reality. Verification by means of the real behavior of an experimentally designed pavement will not be possible before the end of design life is reached. The pavement design strategy proposed here, being largely based on experimental results, also makes use of a calculation model. However. the results of the model are calibrated on the behavior of a full scale pavement subjected to fatigue loading.

The model calculation can thus be verified within a relatively short time, although applying to a special case only. The authors believe that the probability of describing real-life conditions by a model are much higher if it also applies to the full scale pavement test. In addition, the use of permanent deformation, in terms of rut depth, as the only failure criterion is considered as sufficient and is also justified. The calculation model is thus greatly simplified, becoming more realistic at the same time.

Although full application of this method has yet to be made, the results obtained so far are considered worth presenting here. In this connection, the relationship between the permanent deformation of bituminous road materials and above all the number of load applications is of importance. It exists in the same form in laboratory tests, in the full scale.pavement test, and in the real life conditions of a test road. With this and its temperature dependency it is possible to forecast the long-term behavior of a pavement, provided normal pavement behavior can be assumed, i.e., without excessive stresses and strains on the unbound subgrade. If that is not the case. it should be detected by the calculation model beforehand to be prevented from occurring.

06014 **Application of Reliability Concepts to Pavement Design**
Paul Irick, W.R. Hudson, B.F. McCullough

This paper is an overview of the major aspects of pavement design reliability that were developed by the authors for inclusion in the 1986 revision, of the AASHTO Pavement Design Guide. Reliability (R) is generally defined to be the probability that a designed pavement will perform satisfactorily over a specified design period.

The measure of 'performance is taken to be the actual number of equivalent axle loads, N sub t, that the pavement carries during its performance period, i.e., the time during which a particular distress indicator, d, does not exceed a specified terminal value, d sub t. The indicator may be for singular distress such a cracking or rutting, or for composite distress such as roughness or serviceability loss. If N sub T is the actual number of equivalent axle loads tnat occur during the design period of T years, then reliability is the probability that N sub t will be at least as great as N sub T.

It is assumed that the design is based on two specific prediction equations or algorithms. The first is a function of design period traffic factors that gives predictions, w sub T, for actual design period applications, N sub T. The second is a function of load applications, other loading factors, environmental factors, and structural factors that gives predictions, ^d for the distress indicator, d.

If the second equation is solved for load applications with ^d = d sub t, the result is a design equation that gives predictions, W sub t, for actual performance, N sub t. In design practice, W sub t represents design applications, and is the product of a designer-selected reliability factor, F sub R > 1, and the design period traffic prediction, w sub T. The probability basis for F sub R is the set of all quadruples (N sub T, w sub T, W sub t, N sub t) that would result from (say) hundreds of independent pavement projects for which the same design procedure and reliability level has been used.

Probability distributions associated with these quadruples are assumed to be log-normal. Deviations between log W sub T and log N sub T are traffic prediction errors, deviations between log N sub t and log W sub t are performance prediction errors, and, by definition, the deviation between log W sub t and log w sub T is log F sub R. The algebraic sum of these three deviations is the overall process deviation, delta sub 0.

It is shown that R = Prob (delta sub 0 > 0). and that delta sub 0 is normally distributed with mean value log F sub R and

variance S^2 sub O, where S sub 0 is the standard deviation of the overall design-performance process. If delta sub 0 is transformed to a standard normal variate, z, and if z sub R corresponds to delta sub 0 = 0, then R = Prob (z > z sub R), and for a given value of R, the reliability factor is given by log F sub R = -z sub R S sub 0.

The process variance, S^2 sub O, is the sum of the two prediction error variances, and each of the latter can be decomposed into higher level variance components that represent replication variance and lack- of-fit of the prediction equation. For performance predictions, replication variance components are unexplained variance and variance attributable to differences between design levels and as-constructed levels of the prediction factors.

Rationale for reliability level selection is discussed, and an example is discussed for the application of reliability to flexible pavement design.

Research needs include evaluation of variance components for all pavement design equations in current use, and development of objective criteria for selection of reliability levels.

06015 **The Effect of Truck Tire Contact Pressure Distribution on the Design of Flexible Pavements**
C. Saraf, R. Marshek, H. Chen, R. Connell, W.R. Hudson

This paper presents the results of a study to determine the effect of truck tire contact pressure distribution on the response of a flexible pavement. An experimental procedure was developed to measure the tire contact pressure distribution under a treaded truck tire, This contact pressure distribution was used to determine the effect of increased tire Inflation pressure and wheel load on the response of flexible pavements. A 3D finite element program called TEXGAP-3D was used to analyze the pavement sections selected for this study.

The conventional analysis of flexible pavements is generally performed by layer analysis programs. Therefore, a layer analysis program called ELSYM5 was also used to analyze all the pavement sections used in this study. A uniform and circular tire contact pressure was assumed for this analysis.

The results of the TEXGAP-3D analysis were compared with the results of the ELSYM5 analysis to determine the effect of truck tire contact pressure distribution on the design of flexible pavements. Limited data used in this study indicated that for a given pavement section the conventional analysis of flexible pavements overestimated the tensile strain at the bottom of the surface layer. The percent increase in tensile strain due to increase in tire inflation pressure is also overestimated by the conventional analysis. However, the conventional analysis underestimated the percent increase in the surface tensile strain due to an increase in wheel load.

The vertical compressive strains at the top of the subgrade are underestimated by the conventional analysis. The increasing inflation pressure had negligible effect on the vertical compressive strain as Indicated by both the conventional (ELSYM5) and the TEXGAP-3D analysis. However, both analyses indicated that a 20 percent increase in wheel load resulted in about 19 percent increase in vertical compressive strain at the top of the subgrade.

06016 **Calculation of the Rutting of Structures - Castor Program Method for Prediction of Permanent Deformations in Asphaltic Structures**
Honore Goacolou

Asphaltic pavement structural design is generally based on criteria of two types. One concerns the fatigue behavior of the materials (failure), the other permanent deformations of the pavement profile (subsidence or rutting). A method of predicting the permanent deformations of asphaltic structures is proposed for use in connection with the latter problem.

The calculation of the permanent deformations is based on a finite-element numerical method (two-dimensional model). The behavior laws of the materials are of the linear elastic type for reversible deformations, while permanent deformations are described by laws of the viscoplastic type, which may or may not include a threshold of plasticity. The formulation of the model leads to the non-linearities resulting from the viscoplasticity being taken into account by forces equivalent to the antecedent viscoplastic deformations. In this formulation, the rigidity matrix is constant and only the "forces" change over time. The system of equations is solved at constant rigidity by an iterative method.

The calculation of the rut, over a reference interval, involves working out the diagram of the evolution of the input parameters and dividing it into homogeneous elementary intervals. A finite-element calculation is carried out for each interval; the resulting permanent deformations are multiplied by the corresponding number of passages (the permanent deformations are additive), then incorporated in the geometry of the structure by modifying the coordinates of the nodes of the mesh. After chronological processing of all of the intervals, the final mesh represents the rutted structure.

The input parameters of the model are:
- the master curves of the asphaltic materials;
- the laws of flow of the asphaltic materials;
- the vertical temperature distribution;
- the speed of the vehicles;
- the axle weight;
- the transverse position of passage of the axle;
- the elastic moduli and Poisson's ratios of the other materials.

The method is illustrated by a simulation of the LPC rutting tester, testing the susceptibility to rutting of asphaltic materials. The viscoplastic behavior of the test specimen under the passage of a rolling load is simulated using a law of flow in pure shear. The main results given by the CASTOR calculation program are presented:
- the initial, then deformed, meshes of the structure;
- the lines of creep of the materials;
- the level curves of a principal tensor characteristic of the permanent deformations.

Finally, two deformed meshes are compared, one obtained experimentally and the other produced by the calculation model.

06017 **Evaluation of Heavy-Vehicle Traffic and Its Application to Pavement Structural Design**
M. Siffert, B. Lescure

In-depth knowledge of traffic make-up and loading conditions is of primary importance for the proper design and management of highway facilities. Current methods of evaluating loads on roads and bridges and their effects are overly complex and inadequate. The piezoelectric ceramic cable has undergone extensive investigation and development in France for use as a traffic detector, or more precisely a load detector. More economical than traditional methods and involving easier maintenance, this detector can find broad applications in many fields. A traffic evaluation method based upon the real aggressiveness of loads and using of this type of detector will doubtless make it possible to improve the accuracy of pavement structural design methods and the definition of maintenance priorities.

06018 **Rut Depth Prediction: A Practical Verification**
B. Eckmann

This paper presents the contribution of the ESSO Research Centre at Mont-Saint-Aignan (France) to an overall research program monitored by the Road Engineering Division of the Rijkswaterstaat. Two test overlays of asphaltic concrete were therefore built in 1978 on National Highway No. 28 in The Netherlands. The main objective of the program was to check the ability of various design methods to predict the behavior of the test sections.

Within the framework of ESSO Road Design Technology, the rutting behavior of bituminous mixes is assessed by means of a specifically designed dynamic creep test. When recorded against the number of load cycles, the axial permanent deformation of the specimen shows a rapid initial growth followed by a steady creep rate regime. Rut depth prediction is derived from computed stresses and temperatures and with reference to the creep curves obtained at laboratory under various state of stress and temperature conditions.

In the usual ERDT rutting subsystem, initial creep is not taken into account. All the bituminous layers are supposed to be in a "linear phase" of creep. Calculations are thus simplified but provide only the rut depth evolution after the first period of rapid deformation. In this particular case, this was not sufficient as the short time elapsed since the overlay construction conferred a key role to the initial creep in the road test analysis.

The contribution of this early rutting stage was estimated while describing the first part of the experimental creep curves by analytical laws of the type epsilon = alpha.t(super) Beta (epsilon = permanent deformation, t = loading time). Like the creep rates, coefficients alpha and Beta are related to state of stress and temperature by means of a regression analysis.

By contrast with steady stage rut depth computations, the rutting development calculated at any time then depends on the deformation already undergone by the pavement. The computations are therefore made according to a stepwise procedure.

When compared to the rut depths actually measured, the calculated values proved to be excellent in one case and too low in the other case. These results are discussed through a sensitivity analysis applied to temperature and traffic data.

It could thus be demonstrated that the contribution of high temperatures, even when limited in time, is of paramount importance. This entails that a temperature record as detailed as possible is required for reconciling calculated rut depth values with actual field measurements.

Sensitivity to traffic was studied as a function of axle load and tyre pressure. It was namely found that, due to the effect of higher lateral stresses developed within the upper layers, a lighter axle may be more damaging than a heavier one (at constant tyre pressure). A load equivalency factor such as those derived from the fourth power law thus does not apply to rut depth prediction. Moreover, the process for backing up such an equivalent factor in the case of rutting remains to be explored and is likely to be more complex than for the fatigue case.

Due to the large number of input data which are to be known with high accuracy, a precise rut depth prediction appears to be difficult. But this does not lower the interest of rational methods such as the one described here.

We see it as being twofold :
- understand and emulate the relative importance of each environment and structural parameter. - provide a comparative basis for assessing the rutting performance of a given pavement versus a reference one, under given conditions for temperature and traffic. Along these lines, the ERDT approach for permanent deformation is confirmed by this conspicuous field test as an efficient aid to the pavement designer.

06019 **Design Practice for Bituminous Pavements in the United Kingdom**
N.W. Lister, W.D. Powell

A new method for the structural design of bituminous road pavements has been developed by the Transport and Road Research Laboratory. It is based on the systematic analysis of the performance of a large number of experimental pavements interpreted in the light of structural theory. The sub-base is designed primarily to carry construction traffic. Standard design curves are given for the thickness of roadbase required to carry the traffic expected to use the road during its design life, life being defined in terms of the timing of pre-emptive pavement strengthening.

The designs take into account the effect of variability in road performance and there is independent evidence of their validity. Probabilistic criteria for design against pavement deformation and fatigue cracking are established and a new procedure for predicting the internal deformability of bituminous pavement layers is introduced. The method offers the means of adapting the standard designs to take advantage of new materials and design configurations: this is particularly relevant for designs for very heavy traffic and for pavement reconstruction. Examples of developments that are leading towards changes in design practice are given.

06020 **Mechanisms of Surface Cracking in Wearing Courses**
M. Dauzats, A. Rampal

Because of the extent of the damage, the appearance of surface cracking in asphaltic concrete wearing courses in Europe and across the Atlantic has led to the development of models for the prediction of thermal cracking and to investigation of the parameters that influence its spread.

The method presented in this article, in the context of this approach, is suited to the needs of highway managers. It uses a combination of two models. One is an adaptation to French pavements of the thermal cracking prediction model developed by Y. Shahin. The discontinuities constituted by these surface cracks are entered into the second model, which uses

fracture mechanics to investigate the propagation of the cracks towards the roadbase under the influence of rolling loads.

The extent of cracking and the rate of crack propagation, as a result of thermal effects only, are estimated using the first model, which gives, from the climatic conditions of the site and the characteristics of the mix and asphalt used, or to be used, the degree of cracking per year in service.

This two-dimensional mechanistic model uses the finite-element method, which provides a good approximation of a cracking model and satisfactory stress intensity factor values. The rate of propagation is calculated by integrating Paris' law and determining the number of cycles required for the crack to reach the wearing course/roadbase interface. The investigation is carried out for three loading cases, and the damage to the wearing course is determined as a function of the transverse distribution of the traffic.

The method described is aimed at giving highway managers information that can help them to choose, according to the site and its climatic conditions, the class of asphalt that will give the least thermal surface cracking, or, in the case of existing pavements, to determine the depth of penetration of surface cracks into the pavement so that the appropriate maintenance work can be done.

06021 **Employing Paving Asphalt Temperature Susceptibility in the Structural Design of Asphalt Pavements**
Norman W. McLeod

Paving asphalt temperature susceptibility is defined, and a simple method for its measurement is described.

The influence of paving asphalt temperature susceptibility on pavement design and performance in hot countries without frost, and in cold climates with frost is described.
Requirements for paving asphalt temperature susceptibility that can be added to or incorporated into a paving asphalt specification are proposed and discussed.

It is shown that by the addition of suitable polymers, the temperature susceptibilities of paving asphalts can be changed dramatically. This development implies that what has always been an asphalt supplier's market could be changed to an asphalt user's market. In an Appendix, the validity of pen-vis number (PVN) as a measure of paving asphalt temperature susceptibility is examined, together with some of its implications for pavement design and pavement performance.

06022 **Estimation of Fatigue Life of Asphalt Pavement**
Kenji Himeno, Takashi Watanabe, Teruhiko Maruyama

In this study, a new fatigue failure criterion of asphalt mix is presented, based on the energy dissipation theory. When the mix stiffness modulus is low, fatigue test data cannot be obtained from laboratory cyclic bending test, thus the phase angle between the stress and the strain sinusoidal waves is measured, employing the cyclic wheel tracking test, and the new fatigue failure criterion is proposed which is valid for the wide range of mix stiffness modulus, estimating the energy dissipation in the mix.

Examining the new criterion, it is found that bending fatigue damage at bottom of the mix slab is comparatively large in spring and can be ignored in winter and summer. It was also found that fatigue failure can initiate at top of the mix slab when the mix stiffness modulus is low.

A new system to predict the load associated pavement fatigue life considering the external factors affecting the life, such as wheel load, transverse wheel position, pavement temperature, as random variables. In the system, pavement fatigue failure is assumed to initiate at both top and bottom of the slab, and the shorter one of the predicted lives is defined as its fatigue life. From the results of case studies applied for Japan national highways, the predicted lives were found to correspond well with field data obtained by government agency.

06023 **Catering For Long Term Changes in the Characteristics of Asphalt During the Design Life of a Pavement**
F. Hugo

Asphalt is subject to ageing. This causes hardening and volume change of the binder during the life cycle of a pavement. Both phenomena have already been extensively studied. However, with respect to the influence of these phenomena, certain aspects required investigation.

A laboratory procedure for simulating the ageing process was used to evaluate the variation in the engineering parameters of the asphalt during the life cycle of a pavement. Typical South African continuously and gap-graded asphalt mixes were tested. The engineering characteristics were determined for aged and unaged asphaltic mixtures at low, medium and high temperatures that is at -5 C, 25 C and 40 C.

By using elastic layered theory in conjunction with the analysis of stresses due to rapid cooling down of the asphalt layers it was confirmed that thin asphalt layers as used in South Africa would be prone to cracking under particular environmental conditions. This was found to be both load and non- load associated as well as due to the interaction of the two. In an attempt to validate previous findings and hypotheses a full-scale pilot study on experimental pavements is being carried out using a Heavy Vehicle Simulator in conjunction with a temperature chamber capable of varying the pavement temperature between -10 C and 50 C. The tests are being conducted on pavements especially prepared for this purpose and both continuously graded and gap-graded asphalt with and without precoated chips are being tested. The program also includes the testing of pavements which have been artificially aged by using heat and UV-radiation similar to a process utilised in the laboratory.

At temperate and high temperatures the variation in binder viscosity is most important since it causes the pavement to have variations in plastic behaviour in relation to depth. This in turn has been shown to cause residual stresses to build up. These stresses can either prolong or shorten the fatigue life of the asphalt depending upon the structural system and the location within the asphalt layer.

Results obtained to date have shown that the design of asphalt pavements should take into account the fact that the engineering parameters which influence the structural behaviour of such pavements, are subject to environmental influences. The parameters used in mathematical analyses have to be selected or varied to cater for changes throughout a single day and also for changes which are due to environmental influences during the life cycle of the asphalt. It will be

shown that the life cycle of a pavement needs to be analysed in separate phases covering inter alia the following periods: initial construction, early life, middle age, aged and rejuvenated or recycled. This should lead to a clearer understanding of distress mechanisms and phenomena such as so called "premature cracks". Interim guidelines are proposed for the design of asphalt mixes and pavements.

06024 **Evaluation of Fatigue Properties of Recycled Asphalt Concrete**
Elton R. Brown

Recycling of aged asphalt concrete pavements has been demonstrated to be cost-effective and to reduce the demand for natural resources such as aggregate and asphalt. Because of the advantages derived when using recycled materials, the capability to predict long-term performance is needed so that optimum benefits can be obtained. This study was undertaken to evaluate the flexural fatigue performance of recycled asphalt concrete mixtures and to compare these results to those measured for conventional asphalt concrete mixtures.

To make these comparisons, samples of aged asphalt concrete were obtained from three locations where recycling was planned. These samples were blended with new aggregate and new asphalt materials to produce six different recycled mixtures.

Two aggregate types, a crushed gravel and a crushed limestone, were used to produce two conventional mixtures and to blend with the reclaimed asphalt pavement to produce the six recycled mixtures. Three asphalt materials which were obtained to produce the various mixtures being evaluated consisted of AC-20 for preparing the conventional mixtures and AC-5 and a recycling agent for preparing the recycled mixtures.

The flexural fatigue properties ware evaluated for all mixtures. Tests were conducted on the asphalt binder (combined binder for recycled mixtures) prior to mixing with aggregate. Tests on the binder included penetration at 40F and 77F; ductility at 40F and 77F; softening point; viscosity at 275F, 225F, and 140F; specific gravity; and rolling thin-film oven test. Tests conducted on the asphalt concrete included all tests conducted during mix design and flexural fatigue test at 40F and 77F.

Test results indicate that recycled mixtures can be designed to perform as well as conventional mixtures when tested in flexural fatigue. The properties of the blended asphalt binder in the recycled mixture should be similar to the properties of a new asphalt binder to provide satisfactory results.

06025 **Higher Accuracy in Flexible Pavement Construction Design**
F. Lehovec, F. Luxemburk

This paper concentrates on stress in flexible pavement constructions derived from:

- horizontal forces acting on the wearing course,
- vertical forces, assuming an imperfect interaction between the top layer and road base.

To facilitate the calculation of stress and deformation in an n-layer system, TANLAY program has been written which operates on the following assumptions:
- The individual construction layers behave like perfectly elastic three-dimensional bodies characterized by modulus of elasticity E sub i, Poisson number mu sub i and layer thickness h sub i horizontal dimensions are unlimited,
- the sub-base behaves like an elastic half-space characterized by modulus of elasticity E sub n and Poisson number mu sub n,
- measure of interaction between the layers and sub-base can be prescribed in the range from perfect friction to perfect slip,
- the surface of the system is subject, on an area with radius a, to a uniform horizontal directional (shear) load.

However, under these assumptions the radial stress on the surface of the critical wearing course at the circumference of loading area is infinitely great.

In order to determine the magnitude of stress in these troublesome singular points the construction system was expanded by an additional layer situated in contact with the wearing course. Material characteristics of this layer (E, u) and its thickness are identical with those of a tyre tread. Under this simplification the stress of a number of road constructions was computed and their operational capacity, expressed as the number of design axle passages, was evaluated.

For calculation of stress and deformation in an n-dimensional system by vertical forces the LAYMED program is used. Theoretical premises in the LAYMED program are analogous to those in TANLAY. Only the loading is different. The LAYMED program assumes a vertical load distributed uniformly over a circular loading area.

In this case the investigation focused on determining the measure of interaction at the contact of top and road base layers. A number of constructions was investigated, with the interaction at the interfaces ranging from perfect friction to perfect slip. The obtained results have borne out the fact that whenever construction work fails to secure a perfect bond between construction layers, operational capacity and service life of the designed pavement are severely reduced.

06026 **The Behaviour and Mechanistic Design of Asphalt Pavements**
C.R. Freeme, M. De Beer, A.W. Viljoen

The mechanistic method of the design of asphalt pavements, as reported to the last Conference, has received a wide degree of acceptance by road authorities in South Africa. Additional work has enabled the application of the principles embodied in the method to lead to the development of more effective rehabilitation methods.

This paper describes the importance of understanding the behaviour of asphalt pavements, with the emphasis on its state of distress. The importance of the type of support under the asphalt layer is emphasized, whether this be granular or cemented layers. Typical moduli for these layers in the distressed state is given for use in mechanistic rehabilitation methods. A variety of distress mechanisms is also discussed.

The present state of the pavement can be assessed more accurately and rehabilitation strategies better selected by using the methods and information discussed.

06027 **A General Analytically Based Approach to the Design of Asphalt Concrete Pavements**
C.L. Monismith, F.N. Finn, G. Ahlborn, N. Markevich

This paper describes a general approach to the structural design of asphalt concrete pavement systems, making use of research which has been developed in the past 25 years. The approach is based on the assumption that pavement systems respond to loads elastically; however, the actual nonlinear responses of the materials comprising the pavement section are incorporated in an ad hoc but representative manner.

Analyses of representative pavement systems are made using an updated version of the ELSYM5 program developed originally in 1972. This updated version, termed ELSA, permits consideration of up to 100 loads applied to the pavement including 10 different load types (defined by tire pressure, radius of loaded area, or magnitude of load). The pavement structure can be represented by up to 10 different layers.

Examples of the use of the approach are presented and include:
1. Design of a new airport pavement system in the Middle East.
2. Analysis of the rutting potential in an airport pavement in the Middle East and modifications in asphalt mix design.
3. Assessment of increased tire pressures on the rutting potential of pavements in the southwestern United States.
4. Assessment of the potential of mixtures containing a modified asphalt to solve specific distress problems.

06028 **Developments to the Nottingham Analytical Design Method for Asphalt Pavements**
Janet M. Brunton, Stephen F. Brown, Peter S. Pell

The method of pavement design developed at the University of Nottingham uses theoretical analysis and mechanical properties of pavement materials in a procedure which is implemented by use of computers. The techniques have been described to previous conferences as they have evolved, so the present paper provides a summary, together with a description of developments which have taken place recently. Amongst the detailed matters considered is the improvement to the subgrade strain criterion, to take account of differing deformation resistance offered by various asphalt mixes and the elastic stiffness which should be assigned to granular sub-base. Comparisons are made between the results of the Nottingham design method and that recently proposed by the UK Transport and Road Research Laboratory.

New consideration has been given to the appropriate terminal pavement condition for design purposes and the concept of "design temperatures" has been evolved. While the Nottingham design method has, quantitatively, been developed for British conditions, it can be used for other environments and an example is given of how it has been adapted for North America.

06029 **Prediction and Prevention of Surface Cracking in Asphalt Pavements**
A.H. Gerritsen, C.A.P.M. Van Gurp, J.P.J. Van Der Heide, A.A.A. Molenaar, A.C. Pronk

In several relatively new road pavements premature cracking in the top layer(s) has occurred. It has been found that this type of cracking could be surveyed both in and outside the wheelpaths. According to the currently used mechanistic design procedures with linear elastic multilayer programs the greatest tensile strains are predicted in the bottom of the asphalt layers and not at the surface. To search for causes of this type of distress and to provide recommendations for the prevention, theoretical analyses, laboratory experiments and field studies have been conducted. In the theoretical analyses the currently used traffic models and fatigue Parameters have been evaluated. The tentative results show that radial shear forces under rubber tyres can attribute to surface cracking. Secondly it is shown that energy parameters can be useful in the structural analysis of top layers. Experiments have covered aspects such as mix composition, mix properties, fatigue, strength, thermal stresses and dynamic load induced residual stresses. The fatigue characteristics of the mixes appeared to be not sufficient mainly due to excessive hardening of the bitumen. The mixes have been tested for their response on low temperatures. Tests on stress relaxation could be described very well by the Burgers' model. This enabled the use of the model for investigating the influence of loading time, temperature, and load repetitions on the asphalt mix. Field Studies containing visual condition surveys and falling weight deflection measurements have been conducted to check the results of the laboratory experiments. Tentative recommendations are presented to prevent premature cracking of asphalt wearing courses.

06030 **Influence of Wheel Load and Inflation Pressure on the Rutting Effect at Asphalt-Pavements - Experiments and Theoretical Investigations**
J. Eisenmann, A. Hilmer

The presented paper includes a study of the influence of wheel loading and inflation pressure on the rutting effect at asphalt pavements. The statements are based on laboratory tests with single tire equipment as well as with twin tire equipment and on theoretical investigations. The tests were performed with a test facility which enables full-scale rutting tests with loading by real tires, test specimens of natural dimension, and practical temperatures. In the here described test series only the parameters wheel loading, inflation pressure, and tire arrangement (single tire, twin tires) were varied. The pavement system, the temperature gradient (according to the relevant temperatures of a hot summer day), and the speed in test were not changed.

The rutting development was measured by superimposed transverse surface profiles. The dependence of rutting on the influence parameters loading number, wheel load, and inflation pressure was determined by regression analysis.

The theoretical investigations were based on the elastic multi-layer theory using computer program BISAR of SHELL whereby deformation was separated from general strain. The calculated deformations were compared with the test results. With the results of theoretical calculation the test results could be completed or extended.

The tests and the theoretical investigations have shown that the wheel load, the inflation pressure, the average contact pressure between tire and pavement surface (depending on both factors), and the tire arrangement have an important influence on rutting effect. With regard to the design of heavy trucks these parameters need a particular consideration.

06031 **Asphalt Mix Design for Optimum Structural and Tyre Interaction Purposes**
G. Lees

In recent years there has been a noticeable trend towards redefining the desirable qualities of bituminous pavement

surfacing materials and towards the development of design methods aimed at achieving these qualities. Resistance to deformation, to cracking, to adhesion failure and to wear, and durability in the sense of resistance to adverse physical and chemical changes as a consequence of weathering effects upon either aggregate or binder, are the structural properties required. In addition, for wearing course compositions, adequate skid resistance over the anticipated speed range of vehicles , plus low noise generation, low spray generation, reasonably low tyre wear, low vibration characteristics and low rolling resistance, are the main aims in design and construction. All in this second group are concerned with the interaction in one form or another between tyre and pavement material.

Notwithstanding the need for research studies involving more fundamental and complex test methods, the requirement of industry for a quick and reasonably reliable test method has led to the adoption on a fairly world-wide scale of the Marshall test both for design and control of bituminous mixes. This paper aims to provide a closer link between the Marshall method and some of the more important findings from fundamental research studies. Some long held misconceptions concerning the Marshall test are discussed and a new approach to Marshall asphalt mix design proposed involving:
a) a rationalisation of Marshall test parameters,
b) determination of a Design Binder Content by the method of 'ranges' rather by the traditional method of 'averaging',
c) the need to design asphalt mixes for thin carpets by testing specimens of corresponding thickness,
d) the greater engineering relevance of designing according to limits of permeability rather than of air voids,
e) via the latter the possibility of inclusion of design of deliberately pervious ('drainage') asphalts into the Marshall method,
f) recognition of the importance of the different stiffness requirements of asphalt mixes for fatigue life, as between structurally thick bituminous pavements and structurally thin bituminous pavements.

06032 **Probabilistic and Reliability Analysis of the California Bearing Ratio (CBR) Design Method for Flexible Airfield Pavements**
Yu T. Chou

The California Bearing Ratio (CBR) design method for flexible airfield pavements was analyzed using a probabilistic approach. The design parameters considered were the load P (or the equivalent single-wheel load), the subgrade CBR, the tire contact area A, and the pavement total thickness t. The expected value and variance of the dependent variable performance factor alpha (which is logarithmically related to the number of passes to failure) were estimated by using the Taylor series expansion and the Rosenblueth method. Differences in computed results between the two methods were found to be small, although the derivation of the expressions for Taylor series expansion was very complicated. A procedure was developed to estimate the reliability of the designed pavement system based on known variabilities of design parameters. Results of the reliability analysis indicate that prediction of pavement performance is most influenced by variations of pavement thickness t and is least influenced by variations of tire contact area A. The effects of variations of wheel load P and subgrade CBR are identical. The weighting factors for parameters t, CBR, P, and A, in general, are approximately 1, 0.34, 0.34, and 0.01, respectively.

06033 **An Analysis of Load and Non-Load-Related Effects on Flexible Pavement Performance**
Tien-Fang Fwa, Kumares C. Sinha

The determination and knowledge of the relative effects of traffic and environmental factors have significant implications in pavement design, pavement performance monitoring and evaluation technology. In addition, this information would also assist in pavement maintenance and rehabilitation planning and decision making. The paper presents an analysis of the effects of load and non-load factors on flexible and overlay pavement performance by means of:
(a) a performance-based procedure to estimate quantitatively the relative effects (or responsibilities) of load and non-load factors; and
(b) statistical correlation and regression analyses to investigate how individual load and non-load factors influence pavement performance.

The analysis presented is based upon the data of the state highway system in Indiana. The data used included the following main categories: pavement inventory data, traffic data, pavement performance data, pavement routine maintenance cost data, and subgrade soil data. The AASHTO serviceability concept was adopted as a measure of pavement performance. A parameter, PSI-ESAL loss, was introduced as a quantitative representation of the performance of a given pavement. This quantity is calculated by integrating the PSI loss of the pavement over imposed traffic loading expressed in ESAL. To investigate the influence of individual load and non-load factors on asphalt pavements in Indiana, statistical correlation and regression analyses were performed to study the relationships between the results of performance analysis and individual factor effects. Based upon the results of the performance analysis, conclusions were drawn concerning the relative shares of load and non-load-related effects on the performance of asphalt pavements in Indiana. Statistical analyses provided further information regarding the relative importance of various climatic factors, traffic load and pavement characteristic variables as to how they affect the performance of asphalt pavements in Indiana.

06034 **Predicted and Field Performance of a Thin Full Depth Asphalt Pavement Placed Over a Weak Subgrade**
R.B. Smith, W.O. Yandell

The mechano-lattice method of analysis method, which assumes elastoplastic material behaviour is described and details are provided of both the bound and unbound options. Prior to this paper the method has been used successfully with a variety of flexible pavements, but this was the first opportunity for the method to be used on an asphalt pavement for which testing was particularly adapted to the requirements of the analysis procedure.

The asphalt pavement was 100 mm thick and overlay a weak imported subgrade, having four day soaked CBR values between 2% and 4%. Both the pavement and pavement materials were extensively evaluated during construction. Following construction, the pavement has been monitored and the results of rut depth determinations, roughness, and periodic visual assessment are presented.

Using the load/deformation behaviour of the constituent materials as input the mechano-lattice predictions were compared with the field performance after the passage of the equivalent of 350 000 standard axles (esa). Two prediction runs were performed. One was based on an asphalt modulus determined from a one second loading time and a relatively dry imported subgrade and the other based on an asphalt modulus determined from a one-tenth second loading time and a relatively wet imported subgrade.

The permanent deformation was overpredicted by approximately 50% for the dry imported subgrade condition and low asphalt modulus, and was close to the field value for the wet imported subgrade condition and high asphalt modulus. In

both cases the absolute rut depth was predicted as 18 mm. The field survey data did not allow for the absolute rut depth to be determined.

Output from mechano-lattice analysis and the asphalt moduli were used to predict the onset of cracking using the Shell method. In each case the onset of cracking was predicted to occur at about 100 000 esa. Initial cracking was noted in the outer wheelpath during a visual assessment after the equivalent of 105 000 esa.

06035 **Fundamental Properties of Recycled Asphalt Mixes**
V.P. Servas, M.A. Ferreira, P.C. Curtayne

Experience has shown hot mix recycling to provide a cost-effective rehabilitation option. To resolve some residual doubts about quality, recycled mixes have been evaluated in South Africa through a laboratory investigation and Heavy Vehicle Simulator testing.

The laboratory study was carried out to determine the initial engineering properties of asphalt mixes composed of different proportions of reclaimed material, yet meeting the design criteria of conventional mixes. It was found that the proportion of reclaimed material had no effect on permanent deformation and fatigue resistance. This study took no account of either the durability characteristics of recycled mixes or the effect of recycling additives. These factors are currently being investigated.

The Heavy Vehicle Simulator has been used to test recycled asphalt base layers. The results of this accelerated testing suggest that the field behaviour of recycled base mixes is comparable to that of conventional asphalt.

06036 **Dynamic Anaiysis of Multilayered Pavement Structures - Theory, Significance and Verification**
Michael S. Mamlouk

The loads applied by traffic and by most deflection measurement devices on pavements are dynamic in nature. Until recently, analysis of the data obtained from dynamic loadings have been based on either empirical approaches or static models. This paper discusses the state-of- the-art of the use of dynamic analysis (considering the inertial effect) and provides better understanding of the true response of pavements under dynamic loadings. The theoretical formulation and the significance of considering the dynamic response of pavement is presented. The dynamic analysis is significant when shallow bedrock or frozen subgrade is encountered. The dynamic analysis is also more important in case of harmonic loadings as compared to the case of impulsive loadings. The dynamic analysis technique is verified on in-service pavements using field measurements obtained by deflection devices under different conditions. Field deflections were predicted by the dynamic analysis closer than did the static analysis.

06037 **Structural Evaluation of Asphalt Pavements in the Eastern Province of Saudi Arabia**
Madan G. Arora, Faisal Saleem

In this paper, a framework for estimating the structural adequacy of in-service asphalt pavements is developed based on the Benkelman beam deflection measurements on typically selected highway pavements in the Eastern Province of the Kingdom of Saudi Arabia. Pavement condition survey was also conducted, side-by-side with the deflection survey, following the U.S. Corps of Engineers' procedure based on pavement rating (PAVER) technique. Field cores were extracted from asphaltic layers and tested for dynamic modulus under repetitive loading at varying temperatures simulating the on-site pavement conditions. Moduli of the supporting layers were determined by back-calculation by matching the observed beam deflections with the theoretically determined values using the BISAR computer software. Applications of the prevalent fatigue damage and subgrade rutting models to predicting the pavement life and overlay thickness requirement have been demonstrated for the prevailing in-service conditions in the Kingdom. The developed overlay design chart will be further refined as more data on deflection and performance of overlays of varying thicknesses become available.

06038 **A Field Verification of VESYS IIIA Structural Subsystem**
N. Paul Khosla

Presented in this paper are the results of the field verification of VESYS IIIA structural subsystem.

Five pavement sections in different geographical locations of North Carolina were selected for this study. The layer materials from these pavement sections were characterized in the laboratory by subjecting specimens of the given materials to a series of creep and dynamic load tests under environmental conditions representative of those experienced in the field. The characterization of asphaltic mixtures was done using the direct compression test and the diametral tension test.

Based on the input of the mechanical properties of the layer materials, the actual traffic volume, and the local environmental conditions, the performance of the pavement sections was predicted using the VESYS IIIA structural subsystem. The predicted performance parameters (rutting, cracking, and present serviceability index) were compared with the actual measured performance parameters.

The predicted performance using the mechanical properties, as determined by the direct compression test, matched quite well with the actually measured performance. On the other hand, the input of the mechanical properties, as determined by diametral tension test, almost always overestimated the performance of the pavements.

06039 **Diagnostic Evaluation of In-Service Pavements Performance Using Pavement Condition Data**
Waheed Uddin, John F. Nixon. B. Frank McCullough, J. Kabir

A combination of various pavement condition monitoring methods and equipment was used for diagnostic evaluation of in-service highway pavements' performance in Oklahoma. Condition monitoring data, analyses, and interpretation pertaining to the selected pavement sections are discussed in this paper. Pavement Condition monitoring data for this study included:
1) estimates of Present Serviceability Rating (PSR) based on ride quality measurement,
2) visual distress survey, and
3) nondestructive testing.

Results of PSR and visual distress surveys on the test sites were used to identify "good" (performing as intended) and "bad" (poorly performing and severely distressed) pavements.

The extensive nondestructive test data were collected in Oklahoma by operating both the Dynaflect and falling weight deflectometer (FWD) at the same locations, with the FWD immediately following the Dynaflect, providing a unique opportunity for side-by-side comparison of the two devices, and in situ moduli evaluated from their respective deflection basins. The mechanistic interpretation of dynamic deflection basins to ascertain in situ material properties and load carrying capacity was performed using self-iterative computer programs, FPEDD1 and RPEDD1. The methodology used in these programs ensures unique results of in situ moduli and eliminates the user-dependency aspect of the deflection basin fitting approach. The results were comparable. Neither of the devices appears to be significantly underestimating or overestimating in situ moduli.

The mechanistic analyses of dynamic deflection basins of both the Dynaflect and FWD did not provide any evidence of structural inadequacy. Fatigue was not the primary distress mechanism according to the results of distress surveys. Rutting and shoving were prominent among the primary distress manifestations on most of these pavement sites. Laboratory tests (Lottman tests and Boiling tests) and visual observation of core samples provided ample evidence to conclude that stripping in bituminous concrete surface and/or base layers is the most likely cause of premature distress on most of these in-service pavements. This case study shows that although pavement design may be structurally adequate, material problems and their interaction with load may become significant factors associated with pavement deterioration.

06040 **Verification of the Analytical-Empirical Method of Pavement Evaluation Based on FWD Testing**
P. Ullidtz, G. Battiato, B.K. Larsen, R.N. Stubstad

This paper is based on several years experience with practical use of analytical-empirical (or mechanistic-empirical) methods for pavement evaluation. The paper addresses problems related to the analytical part as well as to the empirical part of the method.

The analytical part consists of determination of layer moduli and calculation of critical stresses and strains. Many models exist but none of them deals with all the complexities of real pavements. The use of the very simple Odemark-Boussinesq method is described and examples of verification of this method are given.

The crucial part of the method is the empirical relations between pavement response and pavement performance. The paper demonstrates that deflection criteria for predicting performance are incompatible with strain or stress criteria. A tentative strain criteria for predicting decrease of asphalt moduli is then presented and compared to a few observed values. Finally, a stress criteria for predicting functional pavement performance (PSR) is verified using data from 157 pavement sections with a combined length of 253 km, and covering a wide variety of pavement structures, subgrade soils, climatic conditions and traffic loadings.

The paper concludes that the analytical-empirical method is a powerful tool for pavement analysis at the present time, but that further improvements and/or verifications are needed for the analytical and, particularly, for the empirical parts of the method.

06041 **Derivation of Pavement Material Variability From Nondestructive Testing**
Jacob Uzan, David G. Zeitoun, Raphael Baker

In pavement evaluation using nondestructive testing (NDT), a large amount of deflection bowls are analyzed in terms of the elastic moduli of the layers. The results are used to evaluate the material variability, which could serve in an overlay design procedure based on the concept of reliability.

The model currently used for interpreting deflection bowls is based on the random variable theory which neglects the spatial distribution of the elastic modulus of the material. Since the subgrade and pavement materials have a spatial distribution, the analysis of NDT could lead to an underestimate of the material variability. The random field theory, which is more adequate than the random variable theory, is presented and used to correct the NDT analysis. The theoretical approach is limited to the small variation range (i.e. coefficients of variation up to 30 percent).

Two cases - the Boussinesq and the two-layer system - are analyzed with the random field theory, and the covariance matrix of the deflection bowl is obtained and used to generate deflection bowls corresponding to the properties of the random field. These bowls are then interpreted with the current procedure and elastic modulus variabilities are computed. It is found that the current procedure for interpreting deflection bowls underestimates the variability of the subgrade, by a factor of 0.4 to 1.0. It is interesting to note that the average moduli of the Boussinesq layer and of the two layers are not affected by the type of theory used. The variability of the upper layer in the two layers system is also unaffected (for the small variation range).

Figures for correcting the variability obtained from NDT results are presented. The methodology is illustrated and discussed.

06042 **Accelerated Full Scale Testing of Heavy Duty Pavements - Experience with the Australian Accelerated Loading Facility (ALF)**
P. Kadar

The Accelerated Loading Facility has completed more than 2.5 x 10^6 loading cycles up to date, and provided valuable information on the pavement response to accelerated loading. Once the initial mechanical problems were overcome, the ALF applied an average of 50 000 load cycles per week. Three pavements were tested, each typical to the current design and construction practice of heavy duty pavements of the host State Road Authority.

The pavement performance and structural response was monitored by means of surface and subsurface deflections, permanent deformations, in-depth strains and visual observation of surface deterioration.

A method for assessing critical strains based on the measured surface deflection bowls and in-depth deflections was worked out, which makes it possible to continually monitor (and analyse) the structural performance of the tested pavements. Cross-reference between analytical approaches based on the equivalent layer thicknesses and on the surface

curvature index yielded consistent results, increasing confidence in both approaches.

All three tests indicated long pavement life under the given load conditions, consistent with the design life of the tested pavements.

06043 **The Circular Test Track of the Laboratoire Central Des Ponts et Chaussees (L.C.P.C.) Nantes - First Results**
P. Autret, A. Baucheron de Boissoudy, J.C. Gramsammer

The circular test track of the Laboratiore Central des Ponts et Chausses (Public works Research Laboratory) has been in service for two years. The properties and performance of this sophisticated machine are remarkable, especially as regards the applied load. The first part of the article gives a brief description of the installation and of the measuring apparatus and how it is used. The second part of the article deals with the role of the circular test track in highway research and with the first results obtained on asphaltic pavements. These results concern the factors of equivalence among axles, which vary both with the type of pavement and with the type of damage considered, the representation of flexible pavements by mathematical models, the laws governing rutting and cracking, and the deadlines for repair work in vim of the speed of evolution of the damage once the process has begun.

06044 **New Methods Developed in France for Road Network Survey and Maintenance**
M. Cuvillier, J.F. Godard, P. Retour

The present increasing use of pavement management systems and the high sensitivity of highways managers to maintenance policy are reinforced by setting up new devices to facilitate road data collection and compilation or to better know characteristics of existing pavements. This paper presents three new methods developed by the Laboratoire Central des Ponts et Chaussees (LCPC):
- the "PULSE RADAR"
- the "VIDEOROUTE"
- the "DECRIROUTE".

06045 **Strain Measurements in Bituminous Layers**
I.F. Scazziga, A.G. Dumont, W. Knobel

An international expert Group on "Full scale pavement tests", created by OECD in 1983 with the task to improve the use and benefits from accelerated load tests through international co-operation, carried out a joint program of strain measurements on the Italian test facility of Nardo in April 1984. The comparison of the results from various types of instrumentation used to measure strain in asphalt layers was intended to give an answer to the question whether it is possible to consider in an equivalent way strain values obtained through different techniques and finally also the conclusions of tests based on such results of strain measurements. Nine groups of researchers and technicians from 8 different countries participated in the common field experiment, placing their instrumentation in a special test section and carrying out simultaneous readings under the same transient loads. The sum of the results obtained in the course of 3 days by all the participants have been analyzed together with all the boundary conditions for the test. It was found that a major part of the dispersion in the results was due to variations in the test conditions, i.e. homogeneity of the test pavement structure, temperature, speed and exact position of the load. The different types of instrumentation used also showed a certain amount of scatter. However, a detailed analysis indicates that certain solutions are less subject to additional influencing factors such as stiffness of the gauge, method of preparation and placement, use of asphalt materials prepared in the laboratory. Knowledge of all gauge characteristics is thus an important factor in the estimation of its reliability and of the value of the results obtained.

06046 **Estimation of In Situ Elastic Moduli of Pavement Structural Layer with Failing-Weight-Deflectometer Deflection Basion**
A. Kasahara, H. Kubo, T. Sugawara

This paper describes the estimation method of the elastic moduli of a subgrade (E sub 3), a granular subbase (E sub 2) and an asphalt bound layer (E sub 1). In this study, SAS-BISAR system is fully utilized and the pavement is simplified into three-layer structure by using deflection data, i.e. D sub 0, D sub 300, D sub 750, (suffixes denote distances (mm) from the center of the loading plate), which are obtained by the testing device of FWD. SAS-BISAR system was accomplished by combining BISAR and Super Application System (SAS). BISAR is an elastic analysis method for multi-layer, and SAS is a statistical software, which was developed by SAS Institute in U.S.A. and has valuable functions for data management and drawing figures.

First, we attempt to find the most appropriate deflection variables for estimating the elastic coefficient of each layer of the pavement. The relation between D sub 750 and (D sub 300 - D sub 750) is useful to estimate the value of E sub 3. In a similar way, the relation between D sub 750 and (D sub 0 - D sub 300) and the deviation (D sub 0 - D sub 300) are required for the estimation of E sub 2. It becomes possible to estimate the elastic modulus of the whole asphalt bound layer (E sub 1) by using the relation between D sub 0 and E sub 1.

The elastic modulus of the whole asphalt bound layer, cited above, has a good agreement with the elastic modulus of the asphalt mixture which was obtained in the dynamic indirect tension test with a loading time of FWD. We propose the relatively simple estimating method of E sub 2 and E sub 3 with the known variable E sub 1. In this method, a diagram of the relation between delta sub 750 and (delta sub 300 - delta sub 750) is drawn by the use of SAS-BISAR system. Plotting D sub 750 and (D sub 300 - D sub 750), values which are actually measured, on this figure, E sub 2 and E sub 3 are estimated by interpolation. By the use of this method, E sub 2 and E sub 3 are estimated for various kinds of the asphalt pavement structure. The results are as follows:

1) Seasonal fluctuation in the bearing capacity of the asphalt pavement can be shown in terms of the change in the elastic moduli of the granular subbase and the subgrade.

2) It is possible to estimate the elastic moduli of the granular subbase and the subgrade even for some special types of pavement structure such as the pavement with insulation boards or with a thin asphalt layer.

06047 **The Verification of Design Methods - Test Sections**
M. Siffert

Pavement structural design, reconstruction and maintenance methods involve the use of theoretical models and varying degrees of experimental verification which should make it possible to adjust the parameters defined in the models and check, on real cases, the assumptions upon which the methods were based.

With the appearance of the first rational pavement structural design and reconstruction methods in France in 1965, a program of "test sections" was set up to allow closer analysis of pavement performance over long periods in order to determine the effectiveness of the methods used and to gradually improve their precision.

The sections were defined and selected in order to match real and representative cases. An experimentation plan was developed using many pavement surveying methods applied at adjustable intervals. These sections, most of which are between 10 and 20 years old, allowed the experimental verification of pavement behavior. It was thus possible to analyse the effectiveness of predictions provided by the theoretical model. Among the numerous results already made possible by this experimentation, we can mention the development of a structural surveying method, medium-and long term behavior laws for the represented structures, an assessment of the results of measurements and observations, the effect of environmental conditions (climate, drainage, etc.) on each type of structure, making it possible to determine the important effect of surface waterproofing, the limit values or thresholds on different survey test parameters, the overall trends in pavement damage, the search for surveying test indicators most sensitive to the structural evolution of pavements and their meaning, the improvement of methods of using the theoretical model (correlation coefficients), and so on.

06048 **An Integrated System for the Evaluation of Road Pavements**
P.G. Jordan, B.W. Ferne, D.R.C. Cooper

A high-speed road monitor (HRM) for surveying the surface condition and alignment of roads at traffic speed is described. This new computer-controlled equipment uses laser and inclinometer sensors to survey up to 200 lane kilometres per day of longitudinal profile, rutting, macrotexture, crossfall, gradient and horizontal curvature; usually it does this without interference to other traffic using the road. The development of a comprehensive computer-based system for processing the survey data to provide data summaries, exception reports and trend analysis is described. Levels of unevenness, and of change in unevenness are proposed for use in assessing aspects of road serviceability including structural adequacy.

The survey equipment provides a rapid and economic method of locating damaged sections of pavement so that more detailed and costly inspection and deflection surveys can be more efficiently deployed. Sometimes a regulating course may be all that is required to restore surface profile. A method of estimating the material required to restore a deformed surface is presented.

Measurement of deflection under a rolling wheel is firmly established in the United Kingdom as the basis for assessing structural condition and designing strengthening. An automated analysis system for deflection measurements is described that can assist in establishing priorities and designing cost-effective strengthening. The analysis system embodies empirical performance relationships derived from observations on pavements ranging from undesigned paved roads to pavements designed to carry traffic in excess of 100 million standard axles. An example is presented of a least-cost strengthening design provided by the system of analysis.

Prior to strengthening more detailed investigations of sections of pavement identified by rolling wheel deflection measurements are often carried out to identify the causes of deterioration and to establish where strengthening by overlay is appropriate and where reconstruction is needed. A falling weight deflectometer is being used to augment the information obtained from the excavation and materials testing.

The combination of these assessment techniques into an integrated system will allow the best use to be made of the limited resources available for the rehabilitation of road pavements.

06049 **Evaluation and Comparison of Various NDT Devices in Side-by-Side Testing on Indiana Highways**
J.K. Lindly, N.D. Pumphrey jr., T.D. White, V.L. Anderson

As part of a research program designed to provide an overlay design procedure for pavements in Indiana, four Nondestructive Deflection Testing (NDT) devices were compared side-by-side on 73 pavement sections in Indiana. The devices were the Dynaflect, the Road Rater 400, the Road Rater 2000, and the Dynatest Falling Weight Deflectometer (FWD). The 73 sections represent overlaid flexible pavements and both overlaid and non-overlaid JRC pavements. Brief descriptions of activities performed prior to field testing - including data base development, statistical experiment design, and test section selection - are presented, as are preliminary findings from the first of two planned test sequences. Comparisons of the deflection basins and the deflection variations within pavement test sections are made. Equations are presented correlating deflections from the FWD with deflections from the other three devices. Finally, variables are calculated from the deflections and are used as indicators of relative pavement strength characteristics. These indicators are analyzed to predict which of the NDT devices offer the most usable deflection data for investigating pavement structural properties.

06050 **Evaluation of Flexible Pavements and Overlay Design Based on F.W.D. Tests**
A. Marchionna, M.G. Fornaci, M. Malgarini

In this report a procedure is described that evaluates the remaining life of flexible pavements from tests carried out with the Falling Weight Deflectometer. A method was developed that allows an evaluation of pavement layers moduli using the deflections measured under the FWD load (PA.STR.EV. Program). A bituminous layers fatigue distress model was also developed that takes into account the effect of cracks propagation. Using this model it is possible to evaluate the allowable load repetitions related to different cracking stages of pavement surface. The input data required by the model are the tensile strains at the bottom of the bituminous layers. The stress/strain distribution induced by traffic loads was calculated using a finite element program (NOL.A.P.) that utilizes the elastic characteristics obtained from the PA.STR.EV. Program. The pavements are schematized as an elastic four layer body: a linear elastic law was adopted for the bituminous layers, a nonlinear elastic law was used for the unbound layers. Using these models it is possible to forecast the evolution of the pavement condition and to determine the pavement surface distress curve. Afterwards it is described a procedure that evaluates the percentage of the initial thickness of a bituminous layer affected by cracking. The fatigue distress model was used to calculate the residual life of the sound part of a partially cracked bituminous layer. The result was a diagram in which the percentage of residual life is linked to the percentage of cracked thickness. Finally this procedure allows the calculation of an overlay working life.

06051 **Performance of Flexible Airfield Pavements Subjected to High Traffic Volumes**
Starr D. Kohn, Ross A. Bentsen

Presently, the Federal Aviation Administration's (FAA) pavement design and evaluation procedure is based on the Corps of Engineers' CBR procedure. The Corps' procedure is based on accelerated traffic testing of pavement test sections. The highest traffic levels in the testing program were approximately 5,000 coverages of a given gear configuration for flexible pavements. Thus, the design curves in the current advisory circular (AC 150/6320-6C) have been drawn to include pass levels of 25,000 annual departures. However, the traffic levels at many of the major hub airports are receiving traffic in excess of this level. In order to accommodate the thickness design for these pavements, the design curves have been extrapolated to include pass levels of 200,000 annual departures. Since adaptation of this extrapolation procedure, some concern has arisen concerning the adequacy of the design procedure. In response to this concern the FAA initiated a study to determine the adequacy of this design procedure. The study included evaluation of in-service pavements currently receiving more than 25,000 annual departures. Flexible pavement sections at two major hub airports were surveyed and included in this study. This paper will summarize the findings of the field survey of these pavements. Included in the field survey was a visual condition survey using the "pavement condition index" (PCI) procedure and a nondestructive evaluation Using the Waterways Experiment Station's (WES) 16-kip vibratory testing device. Data from the condition surveys and nondestructive testing (NDT) will be presented.

06052 **Application of the International Roughness Index to Response Type Measuring Systems**
Michael W. Sayers, Thomas D. Gillespie, Cesar A.V. Queiroz

Characterizing the roughness of a road in a universal, consistent, and relevant manner has proven to be a persistent problem over the past 40 years. Two major problems are:
1) measuring methods have not been stable with time; and
2) measuring methods have not been transportable.

In response to these problems, The World Bank and The Brazilian Ministry of Transportation initiated the International Road Roughness Experiment (IRRE), held in Brasilia, Brazil, in 1982. The experiment and subsequent analyses included the participation of researchers and equipment from Brazil, England, France, Belgium, Australia, and the United States. Representative roughness measuring equipment was operated over test sites in the area around Brasilia that included asphalt pavements and unpaved roads. The data obtained were analyzed with the objectives of determining correlations between the various equipment and limitations on their use. The findings showed that it is possible for all of the equipment to measure roughness on the same scale, if the scale is carefully chosen. Thus, an International Roughness Index (IRI) was proposed for future work to eliminate much of the difficulty experienced in earlier studies.

The IRI is based on the concept of the ubiquitous response-type measuring system -- a vehicle equipped with a roadmeter. These systems are used throughout the world in both developing and developed countries. The IRI is defined, however, by a mathematical procedure that is applied to a measured profile, called a quarter-car simulation. The IRI can be measured directly by rod and level methods or by high-speed profilometers. In a validation study, all of the response-type systems that participated in the international experiment could be calibrated to the IRI without loss of accuracy.

06053 **Pavement and Material Evaluation by a Dynamic Cone Penetrometer**
Moshe Livneh, Ilan Ishai

This paper presents a non-destructive pavement evaluation method based on continuous measurement with depth of pavement layers and subgrade parameters, using a Dynamic Cone Penetrometer (DCP). The DCP pavement evaluation method was developed based on extensive laboratory and field correlation testing. In the laboratory, conventional and DCP tests were made on a wide range of undisturbed and compacted fine grained soil samples, with and without saturation. Compacted granular soils were tested in flexible molds with variable controlled lateral pressures. Field tests were made on natural and compacted layers representing a wide range of potential pavement and subgrade materials. Pavement evaluation tests were also performed for pavement and material evaluation and for correlation with pavement condition.

The correlative laboratory and field testing program resulted in a quantitative relationship between the CBR of the material and its DCP value. This relationship was highly correlated for a wide range of pavement and subgrade materials.

Based on the above extensive laboratory and field testing and analysis, a model was developed for realistic flexible pavement evaluation procedure. This is based on the DCP test through the entire pavement structure and down to the subgrade layers. The model relates the measured strength of individual pavement and subgrade layers and their relative contribution to the entire bearing capacity of the pavement structure.

The model finally resulted in an equivalent thickness of a designed conventional pavement. This equivalent thickness can be interpreted either to the residual pavement life, i.e., the number of coverages of existing load down to a given terminal serviceability, or to the required overlay thickness (or other pavement remedy) for obtaining the designed pavement life.

The experiments on subgrades and pavements have proved that the DCP has a high degree of repeatability under controlled conditions, and is sufficiently sensitive for use in practical pavement and material evaluation. The test was found to be simple and fast, allowing performance of scores of tests in one day.

Despite the asphaltic core extrusion needed for the DCP testing, the evaluation method can still be considered non-destructive. Moreover, it has a major advantage of measuring realistic pavement and subgrade layer parameters with no need for any supplementary destructive testing.

The paper presents the basic DCP test, the results of the correlative laboratory and field testing program, the models for highways and airport pavement and subgrade evaluation and results of the current method of pavement and subgrade evaluation using the DCP and its related models. A numerical example illustrates the practical use of the method.

06054 **On Improvements of the Existing VESYS-Concepts**
H. Beckedahl, A. Gerlach, H. Lucke, W. Schwaderer

The existing VESYS programs provide engineers not only with a new philosophy how to handle a management system by means of a performance predicting calculation program but also support design engineers with a suitable calculation

method. The programs enable us to calculate the progress of PSI (Present Serviceability Index) by means of theoretical treatments. Otherwise PSI could only be obtained by measurements.

About 8 years ago we started to scrutinize those VESYS programs which were available for us. A lot of special measurements were carried out to support our theoretical considerations. Instead of improving parts of existing programs we started to develop a new version which is called VESYS 3H (H stands for Hannover). In this program particularly the calculations of ruts and cracks had been changed. Measurements have shown that longitudinal roughness of roads is correlated to non-uniformities of the road bodies, which are spatially distributed by chance. So far, it seems to be very hard to predict slope variance.

06055 **Structural Design and Prediction of Asphalt Pavement Life-Time in Hungary**
Laszlo Gaspar jr., Erno Toth

After having mentioned the former main Hungarian research activities in the field of asphalt pavement structural design and life-time prediction, an evaluation method of highway network bearing capacity is presented. Its main advantages are as follows: it makes possible to perform a realistic evaluation, different permissible deflection values can be used, it utilizes the "traffic ratio", a correction because of actual surface damage mark is applied. It is expedient to evaluate every pavement condition parameter simultaneously. A 8-year long research work was being done connected with the deterioration process of asphalt pavements. Hereby the actual condition of some 30 selected highway sections of 500 m length were rated twice a year using several measurements and visual observation. The sections were divided into four classes according to their level of dimensioning (over-dimensioned, well-dimensioned, under-dimensioned, very under-dimensioned groups). Their still expectable life-times were determined by means of graphs where the subjective condition notes can be seen on the vertical axis and the time passed after construction or strengthening on the horizontal axis. The limits obtained are as follows: over-dimensioned sections 11-15 years, well-dimensioned sections 9-13 years, under-dimensioned sections 7-11.25 years, very under-dimensioned sections 6-9.5 years.

06056 **Heavy Vehicle Simulator Aided Evaluation of Overlays on Pavements With Active Cracks**
A.W. Viljoen, C.R. Freeme, V.P. Servas, F.C. Rust

Conventional overlay life estimates are often invalidated by the reflection of existing cracks in a pavement through an overlay. This is attributable to a lack of understanding of the factors influencing relative crack movements and their mechanisms. Inadequate knowledge of the ability of overlay techniques to tolerate induced strains originating from the discontinuities in the existing overlay pavement also contribute to the problem.

This paper identifies the factors and mechanisms and illustrates their effects by means of field data from actual pavements. The South African Heavy Vehicle Simulator was also used to evaluate a variety of conventional and innovative asphaltic overlays on a severely cracked concrete pavement of which the mechanisms and extent of relative crack and joint movements were determined prior to overlay placement. The results of this testing programme are discussed with special emphasis on the ability of the overlays to inhibit reflection cracking.

It is believed that the improved knowledge of the parameters involved in reflection cracking will contribute to more realistic prediction models and result in more cost effective rehabilitation strategies.

06057 **Evaluation of Mechanical Parameters of Inservice Pavements from Field Data**
M.G. Sharma, W.J. Kenis, M. Mirdamadi

In recent years, many analytical models have been developed to evaluate damage in flexible and rigid pavements. Most of these models determine each of the three primary modes of distress (rutting, cracking and roughness) separately and require as inputs, the material constants for pavement layers obtained from laboratory testing. It is very well known that laboratory-determined mechanical parameters do not reflect the in situ response of the material in the field. In addition, field condition surveys have indicated that accelerated damage to a pavement generally occurs when a primary distress leads to a secondary distress generated by increased traffic and/or severe environmental conditions.

The paper describes a material parameter identification model for the determination of mechanical properties of pavement layer materials from the field measured data such as the vertical deflections, rutting and cracking. The material identification model has been developed by considering the highway pavement as a layered elastic-plastic medium. The material parameters for the layers have been determined by solving a nonlinear optimization problem using the so-called Simplex method. The mechanical properties determined by the method are the elastic constants, permanent deformation and fatigue parameters for layer materials. The identification model has been used to determine in situ mechanical parameters for in-service highway pavements from New Jersey and some test pavements of AASHO and test pavements of Pennsylvania Transportation Research Facility. The field data on these test sections have been studied and damage function curves representing normalized rut depth and areal cracking values plotted against equivalent axle loads and deflection basins have been obtained. The developed identification model and the damage function curves and deflection basins were then used to back-calculate moduli and permanent deformation parameters for the layers and fatigue parameters for the base layer. The model requires inputting some initial value of material parameters and determines in situ parameters through a series of iterations until the field evaluated damage functions are close to corresponding predicted functions under a specified norm.

06058 **A Measurement of Routine Maintenance Effect on Flexible Pavements**
Tien-Fang Fwa, Kumares C. Sinha

This paper presents a procedure to measure the effect of routine maintenance on pavement performance. In the process of developing this procedure, quantitative measurements for both pavement performance and level of pavement routine maintenance were introduced. Consideration of these two quantities led to the defining of a third quantitative measure, known as the pavement routine maintenance effectiveness index, which provides a means to assess the effects of different maintenance policies and technologies on pavement performance. The index represents the change in pavement damage (measured in PSI-ESAL loss) for a unit change in pavement routine maintenance expenditure. In other words, the index provides a measure of the effect on pavement performance when routine maintenance expenditure is varied. It may also be viewed as a measure of the effectiveness of routine maintenance in improving the performance of a given pavement. Also presented in the paper is the application of the proposed procedure to analyze the effect of routine maintenance on flexible and overlay pavements in Indiana. In addition, factors such as traffic loadings and pavement characteristic variables, climatic and environmental indices were identified, and statistical correlation and regression analyses were performed to

study the effects of these factors on effectiveness of pavement routine maintenance work. The case study provided a test of validity of the proposed concept of measuring routine maintenance effect on flexible pavement performance.

06059 **Experimental Models for the Performance of Asphalt Concrete Overlays**
Paulo S.M. Coelho, Cesar A.V. Queiroz

The Road Research Institute of the National Highway Department of Brazil (IPR/DNER) has inventoried data about the performance of several experimental sections located in various roads. Fifteen sections among them were overlayed with asphalt concrete and have been systematically monitored since 1977. The available data refer to roughness, cracking, rut depths and Benkelman beam deflection and have been employed for the development of performance prediction models for overlayed pavements.

This paper presents the latest developed models, presently used by DNER in the design of overlays. These models may be used also as tools for the optimization of investments in pavement management systems.

06060 **Advances in Asphalt Overlay Design Procedures**
D.T. Anderson, C.K. Kosky

In the Road Construction Authority of Victoria (known as the Country Roads Board of Victoria prior to July 1983), the design of asphalt overlays for flexible pavements has for many years been based on the maximum deflection measured under a standard test load. Some limitations have been evident in procedures which relied solely on this principle, particularly with regard to the control of asphalt fatigue cracking. This paper describes theoretical and field studies which have resulted in modification of the former approach. Although maximum deflections appear to be related to vertical compressive strains in the pavement structure, they are not a reliable indicator of the potential for asphalt fatigue cracking.

A simple measure of the deflected shape of the pavement surface under a standard test load is now used to estimate the level of tensile strain in asphalt layers, and thereby predict asphalt fatigue performance. The adopted measure has been called curvature function and is defined as the arithmetic difference of the deflection between the tyres of a standard dual truck wheel (D sub 0), and the deflection which is produced 200 mm from D sub 0 in the direction of travel (D sub 200). D sub 0 and D sub 200 were selected as they can be readily measured by locally available deflection measuring equipment.

The paper includes details of the new procedures together with a worked example of their use in predicting the performance of pavements in terms of permanent deformation and fatigue cracking for different temperature environments. Experiences with use of the procedures since their introduction in 1982 are also discussed.

06061 **Development of a Pavement Maintenance Management System for Nigeria**
T.M. Oguara, N.D. Iriakuma

A simple pavement maintenance management system (PMMS) that provides a systematic procedure for prioritizing road pavement sections for maintenance and selecting an optimum maintenance strategy on a project-by-project basis is presented. Three models - priority, performance, and cost - are used to formulate the PMMS. In the priority model, pavements in a given jurisdiction are prioritized based on an overall pavement condition score (OPCS) derived from a combination of pavement surface distress (PSD) and quarter-car-index (QI) ratings. The performance model predicts the future condition of a given pavement by utilizing a one-step Markov chain probability process, while the cost model considers routine maintenance costs, construction costs, user costs, and salvage value. A present worth value criterion is employed to discount all future costs in determining an economic cost of a maintenance strategy, and an optimum strategy selection is based on least cost. The PMMS presented affords a systematic approach for pavement maintenance; the major benefit of which is the optimum use of available funds for maintenance and allocation of funds to road segments according to greatest need.

06062 **A Methodology for Life-Cycle Cost Analysis of Pavements Using Microcomputer**
Waheed Uddin, R. Frank Carmichael III, W. Ronald Hudson

Life-cycle cost (LCC) analysis of pavements is used for economic assessments of competing design/rehabilitation/ maintenance strategies and selection of cost effective alternatives. For each design strategy, total agency costs and user impacts are quantified. Costs are then computed over the analysis period for initial construction, rehabilitation and maintenance treatment, and discounted to a base year. This paper describes a methodology for comprehensive life-cycle cost analysis of pavements developed for microcomputer applications. The LCC1 microcomputer program is primarily a tool for comprehensive economic evaluation of competing design alternatives provided by users. The input data entry and manipulation is handled by user-friendly subprogram coded in BASIC language. The LCC1 program is unique for life-cycle cost analyses because of its flexibility and the options it offers to its users: creates and saves multiple input files provides default data, manipulates input data without going through an entire session, offers seven available optimization options for rank ordering the strategies, and considers multiple maintenance and rehabilitation treatments.

The subprograms for analytical and optimization procedures are coded in FORTRAN 77 language. The user inputs an array of design strategies (for initial construction or rehabilitation design). Several cycles of maintenance/rehabilitation actions can be included in a single strategy.

The LCC1 methodology does not rely on using one lump sum maintenance cost item. Maintenance treatments in eleven categories can be simulated in the LCC1. Similarly, seventeen rehabilitation options are available in LCC1. These include a do nothing policy, recycling, overlay, and reconstruction. Peripheral cost items like guiderail moving and drainage structure adjustment are also considered. The LCC1 methodology is also capable of computing user operating costs and added user costs due to traffic delays during rehabilitation and reconstruction. The program user may consider salvage value in life-cycle cost analysis. Present worth or annualized equivalent annuity method can be used to establish ranking of alternatives.

06063 **The Analytical-Empirical Method Used in a Pavement Management System**
P. Ullidtz, P. Simonsen, G. Lentz

At the Fifth International Conference a paper was presented by Ullidtz & Peattie [ISAP file 50046], outlining how the

analytical-empirical method could be used for performance prediction in a Pavement Management System (PMS). This paper presents the development that has taken place since then and that has resulted in a full PMS presently being used for more than 5000 km of highways in Europe.

An essential part of this system is still the analytical-empirical model for performance prediction. This model and some attempts at verification and improvements are described in some detail in a companion paper for this conference [ISAP file 60040]. This paper describes the basic elements of the PMS, consisting of:
1) Input data (functional, structural, constraints)
2) Data base ("point" and "section" data bases)
3) Data analysis (spreadsheet reports, benefit/cost, optimization)
4) Output data (predicted future condition, optimum budget)
5) Implementation (examples of feed back).

The system can be operated on a microcomputer. Most of the data (distress, roughness and structural data) are collected using automatic equipment storing the data on disc or tape that can be directly accessed by a microcomputer.

The paper describes an efficient optimization procedure that can be used even for large road networks, and provides examples of the use of spreadsheets for data reporting, Finally, some examples are given on the use of PMS data bases for research purposes.

06064 **Municipal Flexible Pavement Design and Life Cycle Cost Analysis System**
R. Frank Carmichael III, Stephen B. Seeds

A municipal flexible pavement design and life cycle cost analysis system (MFPS) for city streets is presented. The computer program structure is reported to show system capabilities and flow. Input variables are listed to show the thorough consideration of design. A number of designs for City of Austin, Texas, streets using traditional methods are compared with those made by the MFPS program. Design strategies can consider special urban street conditions such as curb and gutter costs, milling and inlaying for future rehabilitation work, roadbed soil excavation to maintain lot grades, and the effect of roadbed soil stabilization on construction costs. The use of non-destructive Dynaflect deflection testing to determine the stiffness coefficients of existing pavements and roadbed soils is described.

06065 **Implementing Pavement Management In the Rhode Island DOT**
R.F. Carmichael III, D.S. Halbach, W.R. Hudson, H.L. Bishop

The development of a statewide network level pavement management system is described. Emphasis is placed on implementation hurdles and their pragmatic solutions, Rhode Island Department of Transportation (RIDOT) has developed under contract to ARE Inc Engineering Consultants (ARE Inc) a Pavement Evaluation and Management System (PEMS). In numerous meetings and discussions with the assembled RIDOT Pavement Management Task Force and with many hours of individual discussions and exchange of correspondence with members of the Task Force and the RIDOT Planning Division staff, it became clear to ARE Inc engineers that a simple and straightforward first-phase implementation plan would serve best for PEMS in RIDOT. Therefore, the recommendations presented emphasize rapid practical applicability and economy of scale. It would have been possible to undertake a more complex and sophisticated first step in pavement management; however, this was not believed to be in the best interest of RIDOT. The final PEMS database and analysis software work on a Data General mainframe and are written in Fortran 77 and Data General macro command language, using the Data General SORT/MERGE utility.

06066 **Implementing Pavement Management at the Indiana Department of Highways**
R.F. Carmichael III, W.R. Hudson, K.J. Kercher

The infrastructure, requirements, and plans for implementing a statewide network level pavement management system (PMS) for the State of Indiana is described. Measurement equipment, computer hardware/software plans, organizational strategies, optimization options, and needs to coordinate with other Indiana Department of Highway programs are summarized.

The Indiana Department of Highways (IDOH), in the interest of protecting the State's highway investment, providing the best possible service at the least cost, and scheduling future rehabilitation and maintenance is developing a pavement management system (PMS). Many IDOH programs, data collection activities, research studies, and plans, both past and current, can support such a development.

06067 **Design and Evaluation of Resurfacing Alternatives for Pavement Rehabilitation**
B. Frank McCullough, W. Uddin, J.P. Zaniewski

For design and evaluation of pavement resurfacing alternatives, it is necessary to consider the existing condition of pavements and to establish decision criteria for triggering the necessary pavement maintenance or rehabilitation actions. This paper presents a methodology based on a systems approach for designing and evaluating alternative resurfacing strategies.

The PRDS-1 (Pavement Rehabilitation Design System) computer program incorporates this methodology. The program uses mechanistic analysis to generate numerous resurfacing design alternatives and perform economic evaluation. The evaluation technique is sensitive to both the performance and cost of these competing resurfacing alternatives. Cost factors include the initial construction costs, future maintenance and overlay costs, user costs associated with traffic delay during overlays, and interest costs. Linear elastic theory is used for structural response calculations. Resurfacing alternatives include bituminous concrete, jointed Portland cement concrete, and continuously reinforced concrete. Fatigue equations are used in the PRDS-1 to determine the number of load applications a pavement structure can carry before it reaches the limiting failure criterion. Overlay placement times are specified in the PRDS-1 in terms of percentage remaining life of the pavement structure. The PRDS-1 program limits the number of thickness design alternatives by omitting those which provide excessive lifetimes. All costs are discounted to present worth for an economic comparison of alternatives The top twenty strategies are sorted by the PRDS-1 program in order of increasing present worth. The details of these strategies are printed in an easily readable format.

The PRDS-1 program was used to evaluate typical Pennsylvania pavements. A factorial design was used to study the influence of several factors on predicted overlay thicknesses and associated life-cycle costs. These factors included

traffic at three level and three subgrade conditions. The required asphaltic concrete overlay thickness at each level of traffic was found generally insensitive to subgrade modulus.

06068 **A Computer System for Converting Pavement Condition Data To Inputs for Pavement Management**
Stuart W. Hudson, W. Ronald Hudson, John P. Zaniewski

This paper describes a computerized analysis methodology called MAPCON, which takes pavement condition data and produces results useful for pavement management. The MAPCON system was developed during a Federal Highway Administration research project, In the project, eight state highway departments were studied to determine the types of pavement condition data collected, procedures used for collecting data, the inputs to the States' pavement management systems, and computer programs used by the States to analyze raw pavement condition data. Several computer programs were inherited by the project from previous research performed at the Pennsylvania State University, These programs were tested and modified. New programs, and other existing programs were also identified, tested and modified. All of these programs (a total of 18) were incorporated into a microcomputer system. This system features menu driven program flow and fully interactive data input.

MAPCON guides the user through selection of analysis method, raw data entry, and data analysis, The path taken by MAPCON is determined by the user's answers to questions presented on the screen. The types of data analyzed by MAPCON include safety, serviceability, structural capacity, surface condition, or a combination of the latter three.

MAPCON presents a set of tools useful to pavement management and design engineers. The program converts raw pavement condition data to meaningful inputs for pavement management systems. It is available at the present time for implementation and use by highway agencies. Due to the wide variety of existing techniques and ever-changing technology, continued support for further research and development of MAPCON is desirable. Pavement technology is constantly changing and the MAPCON suite of analysis programs has the capability to change with the technology.

06069 **Road Mechanics in Highway Management**
J. Charbrol, D. Duran, J.P. Marchand, F. Prudhomme

Two of the main objectives of highway managers are:
- to give drivers high comfort and security conditions,
- to preserve the money invested in the pavement.
For this purpose, it is necessary to conveniently maintain the pavement structure, guaranteeing the durability of surface qualities, such as skid-resistance, roughness, etc.

COFIROUTE is a private company, which the French Government has entrusted for 35 years with the construction and management of a 680 km (as of December 31, 1986) toll highway network. COFIROUTE is working on a tool for maintenance works programming. This tool will take into account pavement specificities: design methods, materials and so on (traffic is, of course, quite different from the kind met on the state roads). This method combines:
- the analysis of pavement survey reports;
- the recent acquisitions of roads mechanics.

The basic idea consists of putting forward a connection between the pavement distress condition and the theoretical risk accepted when designing it. This relation must permit the choice of reference values of degradation index, designed to classify according to priority order, the pavement maintenance or rehabilitation works.

The first stage of calculating a Degradation Index, DI, taking into account the extent and severity of structural distresses.

The second stage consists in computing the theoretical risk of pavement. This one is modelised according to Burmister's scheme. This model was dealt with a computer program, ALIZE III, which provides stresses and strains at the base of each layer of the pavement. The comparison of the computed relative tensile elongation by bending with its admissible value in the most stressed layer gives the number of loads admissible by the concerned layer and the theoretical risk of the pavement.

For known traffic, expressed in number of standard 130 kN axles, by using a weight in motion system, we can calculate the probabilistic risk accepted when designing the pavement. The study, performed on a test-section of the COFIROUTE's network, put forward satisfactory correlation between the Degradation Index, DI, and the theoretical risk, R. This justifies the continuation of the study on other test-sections with different structure and traffic. This phase will purchase a first series of reference values of DI, permitting to classify, by priority order, sections that should be maintained or rehabilitated.

Finally, supposing that the first results are confirmed, an adjustment phase of the system on sections of significant length will be assumed before extending its use to the whole of COFIROUTE's network.

06070 **Design of Asphalt Pavements Using Lateritic Soils in Brazil**
Jacques Medina, Laura M.G. Motta

New developments of overlay design for flexible pavements composed of granular layers and asphalt concrete surfacing of main highways are presented. They were confirmed through measurements on experimental sections before and after overlaying conducted by the Brazilian Road Research Institute (Instituto de Pesquisas Rodoviarias).

Resiliency studies of lateritic fine sands used in low cost pavements have revealed new models of behavior concerning resilient moduli against stresses which are reported herein.

Progress on tropical soil classification for pavement design is presented. It distinguishes the lateritic behavior from the non-lateritic behavior, using new identification testing procedures.

The fundamental principles of pavement mechanics according to engineering experience and applied research developed in Brazil are enunciated. They are seemingly of interest to other tropical regions.

06071 **Strengthening of Thin Asphalt Pavements**
Henrik Broms

An overlay design method for strengthening thin asphalt pavements and gravel roads is developed. The method is based on deflection data and a two-layer elastic model, where the vertical compressive strain at the top of the subgrade is regarded as the critical response. The deflections are measured with the Falling Weight Deflectometer (150 mm radius of the loading plate) at the centre of the loading plate (y sub o) and at a distance of 450 mm from the centre (y sub 450).

The subgrade modulus is simply determined from the y sub 450-value, if the thickness of the granular base is less than 300 mm. The non-linear granular base modulus is replaced by an equivalent one-layer linear elastic modulus, which is governed by the subgrade modulus and the type of base material.

Measured deflections from a Swedish test road are shown to be in good agreement with those predicted by the two-layer model. The proposed failure criterion, developed from the AASHO Road Test data, can reasonably well explain the performance of two Swedish test roads with thin asphalt surfacings. The criterion leads to higher tolerable y sub o-values with increasing y sub 450-values.

The proposed overlay design method can be used for strengthening low-volume roads, if the existing pavement thickness is less than 300 to 400 mm. The deflections y sub o and y sub 450 and the thickness of the existing pavement are required as data inputs.

06072 **Methodology for Predicting Asphalt Concrete Overlay Life Against Reflection Cracking**
P.W. Jayawickrama, R.L. Lytton

This paper describes a new design methodology for the prediction of the reflection cracking life of asphalt concrete overlays. A mechanistic empirical approach is used in developing the present design procedure. The variables used and the form of the design equation were chosen based upon a mechanistic model which represents the actual process of pavement failure. An approach which makes use of principles of fracture mechanics and beam-on-elastic foundation theory is used in developing the mechanistic model. The mechanistically computed pavement responses are then regressed against observed distress on overlays to obtain the final design equations. The data collected on a large number of pavement sections located at various parts of the State of Texas and stored in the computerized data base at Texas Transportation Institute were available for the use of this research study. From these, 40 flexible pavement sections with bituminous concrete overlays were selected for the analysis.

From the correlations obtained in the regression analysis, it is evident that this methodology may be employed successfully in the design of asphalt overlays.

In the conclusion of the paper, the need to perform similar analysis on data collected from regions of varying climatic conditions is emphasized.

06073 **Evaluation of Fabrics, Fibers and Grids in Overlays**
Joe W. Button, Robert L. Lytton

A comprehensive assessment of engineering fabrics, synthetic fibers and polymeric and fiberglass grids applied to reduce reflection cracking in asphalt concrete overlays has been conducted. The experimental program included laboratory testing to evaluate stability as well as tensile, fatigue, creep and shear properties of asphalt mixtures containing these products. Computer programs were used to predict pavement service life under various conditions of traffic, subgrade and climate. Finite element theory and fracture mechanics were employed in the analysis. Pavement construction with fabrics, fibers and grids was observed and performance was evaluated.

Fabrics, fibers and grids have the capacity to delay cracking in asphalt concrete overlays; however, proper construction techniques are imperative to achieve improvements in performance. Fabrics must be applied with the proper quantity of asphalt tack and with an adequate thickness of a nonporous overlay mixture. Fibers in hot mix require additional asphalt as well as additional compactive effort to attain adequate density. Grids perform best when applied in conjunction with a conventional seal coat.

06074 **Low-Temperature Reflection Cracking Through Asphalt Overlays**
Ponniah Joseph, Ralph Haas, William A. Phang, L. Rothenburg

The problem of cracks in old, underlying pavements quickly propagating up through overlays is a serious problem in many areas. It is generally termed "reflection cracking" and is caused by thermal contraction cycles, by repeated traffic loads, or by some combination of the two mechanisms.

Overlay design methods should consider reflection cracking and should be able to evaluate the effectiveness of treatments such as interlayers, reinforcement, fabrics, and increased overlay thickness for any given situation. Fracture mechanics principles with strain energy and strength criteria can be effectively used. In particular, finite element analyses combined with a blunt crack band theory are employed in this paper to evaluate typical overlay situations under thermal cycling conditions.

These situations are for no treatment and with geogrid reinforcement, stress absorbing membrane interlayer (SAMI), and composite interlayer treatments. Temperature cycling and gradients are modelled from the Ste. Anne Test Road.

Results of the analyses illustrate that stress concentrations around the crack front can vary widely. Moreover, they can be significantly reduced with a SAMI or geogrid reinforcement. However, under very cold conditions, cracks may initiate at the top of the overlay and propagate down. The results also show that a composite interlayer offers potential for reduced overlay thickness compared to the other treatments.

A laboratory simulation study, involving specially designed equipment for thermal cycling down to -40C, has been initiated.

It will be used to verify or calibrate the analytical modelling, to screen treatments and to plan field trials. Example preliminary results show that a geogrid reinforced overlay was able to withstand 7 times more thermal cycles before fracture than the control overlay.

06075 **Project Level PMS Life Cycle Cost Model for Flexible Pavements**
G.R. Rada, M.W. Witczak

It is current engineering practice in the State of Maryland to design and construct pavements, and select maintenance and rehabilitation alternatives on subjective judgement and engineering experience. The success of this outcome is obviously tied into the experience base of the engineer making the decision. However, even if the engineer has a significant experience base to draw on, there is no presently available analytical tool used by the Maryland State Highway Administration (MSHA) to assist him in selecting the best strategy based upon the economics of life cycle costs.

To look at this problem, a research study was undertaken by the Department of Civil Engineering at the University of Maryland. The ultimate goal of the study was to develop a microcomputer based solution of the minimum life cycle cost for flexible pavement systems (hence design, maintenance or rehabilitation strategy) associated with a given project or particular highway section. This model represents the backbone of the project level PMS and, in combination with future research, could serve as the basis for the development of a fully implementable PMS approach.

In order to accomplish this objective, three major research tasks were completed. They are:

1) the development of a structural design-overlay methodology to accurately forecast serviceability as a function of time over the analysis period of any given pavement structure;

2) the collection, assimilation and recommendation of all relevant information regarding highway cost data for direct use in the life cycle cost model; and

3) the integration of the structural design-overlay methodology and highway cost models, from Tasks 1 and 2, to develop a microcomputer based solution of the project level PMS life cycle cost model for flexible pavements.

The resulting microcomputer program, called Life Cycle Cost Program or LCCP, provides the MSHA with a powerful analytical tool for use in the selection of the optimal strategy associated with a given project based on the life cycle cost criteria.

06076 **Analysis of Asphalt Concrete Layer Slippage and its Effect on Pavement Performance and Rehabilitation Design**
M.Y. Shahin, R. Kirchner, E. Blackmon

This research effort analyzed the slippage (or unbending) of asphaltic concrete layers in terms of:
1) Redistribution of critical stresses and strains in the pavement system,
2) Effect on pavement performance including fatigue life,
3) Understanding of the slippage cracking phenomenon, and
4) Impact of layer slippage on rehabilitation design.

06077 **Realizing Structural Design Objectives Through Minimization of Construction Induced Cracking**
A.O. Adb El Halim, W.A. Phang, R. Haas

The structural analysis of asphalt overlays is conventionally carried out for the in-service condition, over the traffic-serving life cycle of the pavement. However, there is a short period of time, during construction, when the overlay is quite different from its in-service condition but is not conventionally analyzed as a structure.

This paper contends that the overlay's long-term behavior and performance may in fact be significantly affected by the construction procedures, aside from the usual requirements for density and voids. In other words, the overlay may not be as structurally sound when put into service as normally assumed.

A theoretical analysis is first presented to compare stress, strain and displacement distributions for two representative overlays for both the construction and in-service situations. It is shown that there are major and significant differences. Then, the principle of relative rigidity is introduced and applied to the construction situation where a stiff compactor acts on a soft layer which has been placed on an underlying stiff layer. A coefficient of stability can be used to identify instabilities in this loaded system, and in turn to show that the critical interface for new overlays is at the top. This can result in the often observed roller cracking.

It is contended that the conventional circular roller therefore creates a curvature incompatibility between it and the distorted surface of the new overlay because of the large relative difference in stiffness. An experimental investigation was carried out on mixes compacted with such conventional equipment and a new Asphalt Multi-Integrated Roller (AMIR) to verify this contention and to propose a new approach to compaction. The results showed roller cracking to be eliminated when the AMIR compactor was used, and maximum bending strengths of the overlay material to be 30 to 70 percent higher.

These results, while preliminary, suggest that substantially better long term performance of overlays may be achieved by a new method of compaction.

06078 **Application of the Mechanistic Analysis Procedure to Pavement Rehabilitation - Two Case Studies**
S.V. Kekwick

Mechanistic analysis and design procedures have become an important part of highway pavement design and, certainly in South Africa, have led to significant improvement and advances over earlier designs. This is due , in large part, to the better understanding of material behaviour in pavement structures gained from many years of accelerated testing using the Heavy Vehicle Simulator.

With the development of the road infrastructure, present emphasis is turning towards rehabilitation of existing major roads and, consequently, to the application of mechanistic analysis in rehabilitation design. The major aim is, of course, implementation of the most appropriate rehabilitation action. This requires, firstly, a meaningful assessment of the existing structural condition of the road and, secondly, the realistic appraisal of possible alternative rehabilitation measures.

This Paper gives details of two recent rehabilitation investigations, and illustrates the application of the South African mechanistic design methods in assessing both the existing structural condition and the subsequent rehabilitation measures of the pavements. The two case studies demonstrate the use of conventional methods of initial pavement assessment and the use of an accelerated trafficking test programme.

The rehabilitation recommendations were adopted for each road and it is concluded that the procedures used enable a rapid assessment of the most appropriate rehabilitation strategy with a high degree of confidence.

06079 **The Use of Surface Deflection Basin Measurements In the Mechanistic Analysis of Flexible Pavements**
E. Horak

The Mechanistic design procedure in South Africa and the accelerated testing with the fleet of Heavy Vehicle Simulators (HVSs) provided a unique opportunity to verify an analysis procedure using measured deflection basins as basic input. It was possible to calculate various deflection basin parameters and relate them to behavioural changes of typical flexible pavements. Two basic flexible pavement types, bitumen base and granular base pavements, were identified. These pavement types were analyzed over a wide range of input parmeters found in practice. The deflection basin parameters calculated were related to the typical distress determinants, namely, subgrade vertical strain and maximum horizontal asphalt tensile strain. Deflection basin parameters were also related to other structural input parameters to facilitate proper material characterization. Remaining life can be calculated for these distress determinants and the choice of overlay thicknesses can be based on mechanistic analysis.

06080 **Airfield Pavement Evaluation and Strengthening Based on NDT and Aided By An Expert System**
G. Wiseman, J. Uzan, J. Greenstein

The paper presents the methodology presently used by the authors for the evaluation of the bearing strength of flexible airfield pavements as well as a procedure for determining the required overlay thickness. The methodology is based on nondestructive testing deflection measurements, the use of linear layered elastic theory to interpret the measurements in terms of layer elastic moduli and on CBR design curves. The method is related to the current ICAO requirements for the reporting of pavement strengths in terms of ACN-PCN.

A Knowledge Based Expert System is presented that should be useful in estimating reasonable in situ CBR values based on subgrade soil classification and environmental conditions. The system also includes guidance in determining the strength of an existing flexible pavement in terms of its PCN based on both nondestructive testing and experience with the aircraft using the facility. The expert system is used to check the NDT results.

An example is given illustrating the methodology. Sufficient detail has been included so that the reader can prepare his own version of the Expert System using a 'shell' and microcomputer of his choice.

06081 **Structural Evaluation and Overlay Design: Analysis and Implementation**
Stephen F. Brown, W.S. Tam, Janet M. Brunton

Increasing use of the Falling Weight Deflectometer for pavement evaluation has lead to more widespread data being available on in situ effective elastic stiffnesses of pavement layers. This parameter is a dominant one in evaluation using mechanistic methods. An improved back-analysis procedure is described, involving a computer program PADAL, that allows accurate and unique values of in situ effective stiffness to be determined for each significant pavement layer. The program has also been used to determine optimum radial locations for the deflection transducers used in FWD surveys on particular pavements. The evaluation procedure using PADAL forms part of a design method for remedial treatment of asphalt pavements using a mechanistic approach and two case studies are considered. The first of these involves an old structure with a granular base, while the second illustrates how the FWD and the associated computations can be applied to identifying damage to a new lean concrete base caused by construction traffic overloading.

06082 **Marginal Maintenance and Rehabilitation Cost**
James Sherwood, William Kenis, Charles Liu

User charge responsibilities (UCR's) for pavement maintenance and rehabilitation (M&R) were calculated using the efficiency-based cost allocation scheme. The steps necessary to satisfy the method involve use of the Economic Analysis of Roadway Occupancy for Maintenance and Rehabilitation (EAROMAR) model to calculate agency pavement M&R costs for various traffic volumes. The types of damage predicted are those most prevalent to both rigid and flexible pavements such as rutting, cracking, loss of Pavement Serviceability Index (PSI), faulting, and pumping. The M&R activities prolong the service life or restore structural capacity. Policy dictates the trigger values wherein the damage is repaired. The rate of change of pavement M&R costs with respect to vehicle equivalent single axle load (ESAL) level (marginal cost) is then determined by linear regression. The UCR's for various types of vehicles are calculated by multiplication of the marginal cost by the vehicle-ESAL factor for each vehicle class.

Reasons for the difference between the results of the Federal Highway Administration's (FHWA's) Research, Development, and Technology (RD&T), and the Massachusetts Institute of Technology (MIT) studies are discussed. The asphalt grade, vehicle-ESAL factor, pavement structural capacity, and overlay models are evaluated. Based on the FHWA RD&T runs, you can conclude marginal M&R costs are relatively independent of pavement type and environmental zone. The major finding is the relationship between marginal costs and pavement thickness; i.e., thicker pavements had lower marginal costs. Hypothetically, increased traffic has less effect on stronger pavement systems.

06083 **Pavement Management System for Municipalities with Emphasis on Planning and Cost Models**
P.C. Koning, A.A.A. Molenaar

This paper describes the pavement management system developed by the Working Group R1, Pavement Management Systems, of the Dutch Study centre for Road Construction for the maintenance planning in small municipalities. The members of the Working Group are from governmental as well as provincial and city roads departments, research institutes and private industry (contractors, consultants). The system is based on input coming from a road data inventory and a broad and/or detailed visual condition survey. Incorporated in the system are deterioration prediction models and maintenance strategy effect and cost models. Furthermore use is made of differentiated minimum acceptance levels in order to take into account the difference in importance of the road categories that can be discerned.

06084 **Volume II - Preliminary pages and Table of Contents**
n/a

Contains a table of contents for Volume II of the 6th Conference Proceedings. Volume II is mostly discussions and analysis of the papers presented and pubished in Volume I. However, two additional papers are published in Vol II.

06085 **Opening address: International Conferences - Twenty-five Years of Contributions To Asphalt Concrete Pavement Design and Rehabilitation**
C. L. Monismith

On this, the twenty-fifth anniversary of the International Conferences on the Structural Design of Asphalt Pavements, it is worthwhile to examine what the conferences have accomplished relative to asphalt pavement technology since their inception in 1962 and to look ahead as well.

While the conferences have contributed to the many facets of pavement design and rehabilitation, my discussion will be directed to the following areas:
- Analytically-based (mechanistic-empirical) design for both new pavements and overlays
- Material evaluation
- Pavement evaluation
- Pavement management

In part, my reason for presenting this evaluation is to urge that the conferences continue in the future on a more formal basis since they have served as an effective forum for exchange of information among the international community, impacting pavement research as well as the various facets of design. Moreover, their contents have reflected the changing requirements in pavement technology; for example, the emphasis of the conferences has been expanded to include not only its original concerns with new design but rehabilitation design and pavement management as well. Moreover, the requisite information generally has been presented at the conferences in sufficient time to be of use to the profession when it has been truly needed.

06086 **Keynote Address - Pavement Design**
Fred N. Finn

Oglesby and Hicks (1) note that the first hard surfaced roads were reported shortly after the development of the wheel in about 3500 B.C. The Old Testament (Isaiah 40: 3-5) includes the following statement, "I... make straight in the desert a high road. .." referring to a road constructed around 539 B.C. between Babylon and Egypt. The Romans are credited with building an extensive road system around 300 B.C. The Appian Way is often referred to by pavement engineers as a classic example of a long life cycle pavement having been in service for some 2,000 years. It is clear that roads have played an important role in our society for many years. We continue to improve design procedures to increase the reliability of performance.

Here we are at the Sixth Conference on Structural Design of Asphalt Pavements. Those of use who were involved in the First Conference had no idea that the Conference would be continued and develop a world-wide reputation as the center for the synthesis of technology related to asphalt pavement design. It is worth noting that the proceedings of the first conference were titled only International Conference on Structural Design of Asphalt Pavements and did not refer to it as the "First" Conference. Nevertheless, as Prof. Monismith has indicated in his opening remarks, these Conferences have enjoyed an International flavor and provide an important resource for researchers and practitioners.

In directing my comments toward pavement design, it is important to establish a framework for the term "design" as it relates to the structural design of asphalt pavements.

06087 **Keynote Address -- Pavement Materials**
P. S. Pell

Quantitative information on materials is required as input data to all analytical pavement design procedures and a knowledge of the basic properties and behavior of materials is essential for a proper understanding of the response of a pavement structure to various loading and environmental factors. The intention of this keynote lecture is to concentrate on the fundamental behavior of the four different basic types of material used in the layers of a flexible pavement structure, namely: bituminous, cement bound, unbound granular and subgrade soil.

All four types of materials are in reality complex both in composition and behavior most of them being inhomogenious, anisotropic, non-linear and non-elastic and some of their properties are time dependent and affected by environmental factors such as temperature or moisture content.

There are two aspects of material properties which have to be considered.
Firstly, the load-deformation or stress-strain characteristics need to be known so that analysis of the structure can be carried out to determine the critical stresses and strains. Secondly, the performance characteristics mainly under repeated applications of load which determines the likely mode of failure must be understood.

In order to analyze pavement structures consisting of such complex
materials analytical models of various degrees of sophistication are used. The simplest and most widely used approach is multi-layered elastic analysis and this requires input characteristics of elastic parameters such as elastic stiffness and Poisson's ratio for each layer. If finite element analysis is used to deal with, say, non-linearity this allows more complex material characterization, if visco-elastic analysis then characteristics such as creep compliance need to be determined.

Because of the nature of the materials, bituminous depending on time and temperature, soils and unbound granular depending on moisture content, density and stress levels, cement bound depending on degree of cracking, the selection of appropriate values of material characteristics for analysis is critical.

When considering the performance characteristics of pavement materials there are three main modes of failure:
1. Fatigue cracking of bituminous and cement bound materials.
2. Permanent deformation (rutting) of all materials both bound and unbound.

3. Other cracking of bound materials i.e. thermal and reflective.

In the time available it is not possible to give a comprehensive detailed review of each category of pavement material but an attempt will be made to give very much a personal view of what are considered to be the essential characteristics of each type of material emphasizing the fundamental behavior, the information req

06088 **Keynote Address -- Pavement Rehabilitation**
J. Bonnot

Pavement rehabilitation work has now become of key importance in the industrialized nations, which undertook the construction of modern highway networks twenty or thirty years ago. For specialists in pavement design and behavior, this has meant undertaking such work as pavement evaluations; the choice of maintenance and rehabilitation strategies at the network level; and the determination of the residual lives of sections of pave- ment and overlay design. These are the three major themes I should like to deal with, in an attempt to sum up the state of our knowledge as this sixth conference opens.

06089 **Keynote Address -- Pavement Management**
W. R. Hudson

This paper concentrates on the development of pavement management as a necessary part of the process of proving adequate pavements. It attempts to carefully show that pavement management in no way replaces or interferes with good pavement design, materials, and rehabilitation techniques. Rather, pavement management provides a methodology for synthesizing design, materials, and rehabilitation along with maintenance, life cycle economics, and optimization to maximize pavement life and benefits.

The first half of this paper provides historical background and perspective. The second half concentrates on developments in pavement management in the last decade. Major sections include:
1. a clear definition of project versus network level pavement management;
2. a review of significant progress in implementation of pavement management at the small to medium city level, but not a city-by-city report;
3. a review of state level PMS in the USA, Canada, and other countries but not on an individual basis;
4. an understanding of PMS as a sound basis for planning and coordinating pavement research, including a foundation for long-term pavement
performance monitoring; and
5. projections and predictions of the expected future of pavement management worldwide; ideas are presented on future directions in pavement management and benefits of more complete implementation.

06090 **Theme I Lecture: Pavement Design and Materials**
S. F. Brown, R. D. Barksdale

It is now 25 years since the first Conference in this series was held here at Ann Arbor and it identified the structural design approach to asphalt pavements as having real promise for the future. That Conference was carried out in the wake of the AASHO Road Test which was the first extensive and structured exercise in collecting detailed performance data on pavement response to repeated wheel loading from real traffic. This present Conference is being held as the U.S.

Strategic Highway Research Program (SHRP) is being launched, including its Long Term Pavement Performance Studies. This enormous undertaking will provide very substantial data on how pavements perform in the field. The approach to both AASHO and SHRP has been essentially empirical with statistical techniques used to plan experiments and to analyze data producing equations relating performance to a list of dependent variables. This philosophy is an elaborate version of that traditionally adopted in pavement design, which is to design and specify by experience.

The Ann Arbor Conferences have led the way internationally in demonstrating that there is an alternative approach based on engineering science and the concepts of blending theory with experiment and a knowledge of materials to produce a satisfactory engineering design. In the process, the discipline of "Pavement Engineering" has been born. This lecture largely takes the extensive developments in asphalt pavement engineering, prior to this Conference, for granted. The Keynote Speakers, whose experience extends over the 25 years since the first Conference, have already set the scene in this respect. Our objectives are to consider new developments, to identify promising work in the Conference papers associated with our Theme and to focus attention on future areas of research and development. Since engineering is always in an evolving state, research has to proceed in parallel with design and construction of real projects using the best avail- able technology. Our other task, therefore, is to identify techniques which are presently useable and implementable for engineering practice.

06091 **Theme I Workshop Report -- Design Concepts**
W. J. Kenis, R. May

Although empirical equations have been employed in the past to produce adequate designs of pavement structures, many reasons now exist for upgrading the concept of pavement design with mechanistic modeling. Materials used in pavement construction continue to change; wheel loadings that ride on these pavements continue to be altered in magnitude, pressure, and configuration; and finally, the pavement engineer is beginning to realize that the environment has a tremendous impact on performance. All of these vacillating factors are difficult to consider by "adjusting" coefficients of an empirical design algorithm. However, by an over- whelming consensus, a "rational" design procedure still requires an empirical "link" to actual performance; hence, the origin of the term mechanistic-empirical design. Luckily, with the rapid advancement of computer processing, memory, and availability; the time for advancing the mechanistic-empirical concept of design from research investigation to routine practical utilization has arrived.

The current problem is that there are so many variations of mechanistic structural analysis. Also, the ideal method of analysis for one form of pavement distress, e.g., cracking, is not necessarily the best procedure for predicting rutting, or other modes of distress. To examine the complexity of the situation, the following discussion will briefly describe nine major elements of a complete mechanistic-empirical design system. These element listed below are not intended to be all inclusive, but merely to illustrate how much formulation and development is necessary to establish such a system.

1. Constitutive Law

2. Material Behavior
3. Boundary Conditions
4. Form of Solution Technique
5. Primary Response Prediction
6. Pavement Distress Prediction
7. Model Verification
8. Model Calibration
9. Model Reliability

06092 **Theme I Workshop Report - Design Methods**
M. R. Thompson, F. Hugo

The workshop was structured to allow authors to present specific aspects of their papers. This served as an introduction to discussion by attendees. As a conclusion to the workshop, attention was focussed on Future Directions and Research and Development Needs.

The following design method were discussed either directly or indirectly:
- The University of Illinois method
- An extension of the Asphalt Institute Method
- The Transport and Road Research Laboratory (TRRL) method
- The Shell method
- The Belgian Road Research Centre method
- The University of Nottingham-Mobil method
- A general Analytical method by Monismith and co-authors.

06093 **Theme I Workshop Report - Loading And Environment**
R. C. Koole

The 6 papers in this session can be divided into two groups. One group contains four papers discussing characteristics and other aspects of traffic loading, and the other group contains papers on the interaction of temperature induced and traffic-induced stress and the binder properties. The workshop session was conducted in two parts. Before the break short author presentations were given that were followed by floor discussion. After the break a panel discussion with audience participation was held addressing three questions put forward by the Chair.

This report gives a short summary of the main points of each paper with comments, where deemed appropriate. Following that, a summary is given of the results of the discussion on the three topics.

06094 Theme I Workshop Report - Loading And Environment
J. N. Brunton
As suggested by the title of this workshop session, one of the major items discussed was traffic loading. All design methods for pavements need to recognize the importance of this parameter and consider, where appropriate, the number and magnitude of wheel loads, the distribution of traffic loads with daily and seasonal climatic variations, axle and tire configurations, contact pressures and areas, lateral wheel distribution and vehicle speeds. Three papers (2, 3, 4) presented in the workshop were specifically related to magnitude of wheel loads, axle and tire configuration and/or contact pressures.

Design methods generally express traffic in terms of standard design loads which are assumed to be uniformly distributed over one or more circular areas, see Figure 1 (5, 6, 7). However, it has long been recognized that the actual contact area is neither circular nor uniform. For example, in their paper to the 1972 Third International Conference, Hofstra and Valkering (8) recognized that the actual contact area for the pneumatic tire wheel used in their experiments was both non-uniform and more elliptical than circular in shape. To take this into account, in their calculations to compare measured stresses and trains with those predicted using elastic theory, the load was represented by four circular areas with uniform distributions.

06095 **Theme I Workshop Report - Materials**
L. E. Santucci, C. A. Bell

There are three major factors that are critical to the satisfactory performance of asphalt pavements. They are good materials, proper design, and quality construction, as shown in Figure 1. The Workshop on Materials concentrated on examining one of these factors (namely, materials), emphasis on conventional binders and mixes, recycled materials, and modified binders and mixes. We discussed in the Workshop some of the most significant changes (Figure 2) that have affected materials over the past 20 years since the Second International Conference was held here in Ann Arbor in 1967.

No doubt, the most memorable occurrence was the energy crisis in the early 1970's caused by the Arab oil embargo. Energy-related costs, including the cost of asphalt, escalated rapidly. Crude oil prices rose from a pre-1973 level of less than $3 per barrel to a high in 1982 of approximately $34 per barrel. Although crude oil prices have dropped significantly since 1982, they are still well above pre-1973 levels. Another significant change that resulted from the oil embargo has been the variability in crude oil supply. Although asphalt is manufactured in essentially the same way it has always been, a wider range of specification asphalts with different properties may be supplied to a given region. The properties, and hence behavior, of asphalts form different suppliers as well as asphalts from the same supplier are likely to vary over a period of time. At about the same time the energy crisis developed, a shift from penetration grading to viscosity grading of asphalts took place in the United States. Unfortunately, despite this shift, agreement on a uniform grading system for asphalts has not occurred in this country.

Modification of asphalts has increased significantly over the past 20 years. Sulfur, rubbers, polymers, carbon black, and chemical modifiers have all been \offered as ways to affect the performance of asphalt pavements. Antistrip and antioxidant additives are being used more widely. Pavement recycling processes and recycling agents were also introduced during this period.

06096 **Theme I - Chairman's Summary - Design Methods and Materials**
R. L. Lytton

The Sixth International Conference adopted a new format with each day featuring a different theme, a theme lecture, a plenary session, and four parallel workshops to permit more active participation by those in attendance.

Because of the variety of the material in each parallel workshop session, a certain degree of flexibility in organizing presentations and discussion was essential, and the workshop Chairman and Co- Chairmen were creative in the way they composed their sessions. It was suggested to each workshop chairman that after several brief illustrative presentations, the workshop should break up into smaller committees to consider more detailed aspects of each workshop topic. The purpose of this workshop structure was to encourage open discussion, free exchange of ideas, and as much participation by those in attendance as possible.

Where it was possible, the workshops broke up into three smaller committees to discuss the following questions for each subtopic:

1. What are the real advances in this subject area?

2. What are the barriers to putting these advances into practice?

3. What new developments are still needed?

06097 **Theme II Lecture: Pavement Evaluation and Performance**
R. G. Hicks, C. R. Freeme

This paper provides a critical review of the 26 papers in the conference dealing with pavement evaluation and performance. For each topic, the authors identify significant findings contained in the papers, gaps in current technology, and needs for implementation. It is expected the paper will result in a list of questions which need to be addressed by the workshop chairman (evaluation methods, data interpretation, and verification).

06098 **Theme II Workshop - Basic Concepts of Performance and Evaluation**
P. Ullidtz, I. Scazziga

First of all I would like to acknowledge my Co-Chairman Ivan Scazziga, who did an excellent job, and, then I would like to congratulate the organizers of this conference on the new format, with workshops and poster session. That has been a great success. The poster sessions to such an extent that I will suggest that we, at the next conference, have the poster sessions at the North Pole. The workshops that I have attended have also been extremely successful. Sometimes even too much so. When you have asked someone for a contribution to a workshop the enthusiasm has often been so immense, that when you asked for a contribution of 10 cents you got a dollar. In our workshop we probably tried to do too much in too short a time. We tried to have discussions of the papers assigned to the workshop, as well as discussion of the workshop topics. But the papers and the topics were not always directly related to one another. This should eventually be better coordinated in a following occasion.

06099 **Theme Ii Workshop Report - Evaluation - Field Testing**
J. W. Hall, Jr., R. R. Costigan

The approach followed in this workshop was to have short presentations on various topics of field testing followed by discussion periods. This summary of the workshop will discuss important topics discussed but will not identify individuals who made the comments or presented the discussions.

The subject of field testing for the purpose of pavement evaluation is a broad topic, and many types of test methods are practiced. The type of test is generally dictated by the evaluation methodology being used for analysis. Generally, evaluation methods can be categorized into the following groups:
> Inversion of Design
> Nondestructive Evaluation
> Accelerated Traffic Test Methods
> Condition Monitoring of In-Service Pavements

Test Methods discussed in the workshop included the following:
> Direct Sampling Methods
- CBR, test pits, etc.
- Kleg hammer
- Dynamic cone penetrometer (DCP)
- Automated cone penetrometer
> Nondestructive Testing
- Static deflections
- Steady-state dynamic deflections
- Impact load response
- Wave propagation
> Accelerated Traffic Testing
- South African Heavy Vehicle Simulator (HVS)
- Australian Accelerated Load Facility (ALF)
- French circular track
- British test track
> Condition Survey Methods
- Windshield surveys
- Walking surveys
- Automated equipment
- Distress types

06100 **Theme II Workshop Report - Pavement Evaluation: Data Interpretation**
C. K. Kennedy

A total of 16 papers were allocated to workshop session 3, Pavement Evaluation (Date Interpretation). These papers are

listed at the end of this report. Most of the papers are restricted to pavement evaluation but a number include aspects of Pavement rehabilitation.

It was concluded by the workshop session chairmen that the main trust of these papers involve the development of Mechanistic Pavement Evaluation, Performance and Strengthening Design Systems using non-destructive testing techniques. Although some of the papers allocated to the session do not fit easily under this heading, all papers contribute in some way to the broad topic and the chairmen considered the choice of heading reflected the area where the most significant state-of-the-art developments are taking place.

The session itself was organized around three topics which cover the principal elements of pavement evaluation, performance prediction and strengthening design systems:
i) back calculation procedures for evaluating layer properties
ii) methods for predicting remaining life, and
iii) systems to design remedial treatments.

Under each topic area a series of questions were set and one speaker invited to discuss an aspect of the topic. General discussion was then invited from the floor and finally broad conclusions and recommendations for future work reached.

The following sections describe briefly the deliberations of the workshop under each topic heading and include a summary supplied by the invited speakers of their formal presentations. The report concentrates on current difficulties of the methods and makes recommendation for areas where further work is required.

06101 **Theme II Workshop Report - Verification of Methodologies**
J. P. Mahoney, N. C. Jackson

Any discussion of verification of methodologies should start with basic definitions. These definitions include
1. verification: to establish the truth, accuracy, or reality of; to confirm,
2. methodology: a particular procedure or set of procedures.

These definitions were provided at the beginning of the workshop to assist the forty workshop participants in viewing the purpose, scope and focus of the activity.

More specifically, the verification of methodologies was related to the conference theme topic for July 15, 1987 which was Pavement Performance and Evaluation. Thus, verification within the theme topic was taken to be:

1. Pavement evaluation
(a) In situ material characterization

2. Pavement performance
(a) Structural design theory (or practice)
(i) Load equivalencies
(ii) Failure criteria (e.g. rutting, cracking)
(b) Compare predicted versus actual pavement behavior

The specific items shown for pavement evaluation and performance were obtained mainly from topics within the papers preselected for the workshop.

06102 **Theme III Lecture - Part I - Pavement Maintenance**
A. A. A. Molenaar

This session is dealing with two closely interrelated aspects which are pavement management and pavement rehabilitation. As clearly stated by Hudson in his keynote address to this conference (1) "Pavement management is a methodology for synthesizing design, materials and rehabilitation along with maintenance, life cycle economics and optimization to maximize pavement life and benefits". He also states that "pavement management in no way replaces or interferes with good pavement design, materials and rehabilitation techniques. In fact no adequate pavement management is possible without such good design and rehabilitation techniques, and pavement management can be seen as the umbrella under which all these design and rehabilitation activities are coordinated in order to achieve our goal which is to maximize pavement life and benefits. With this respect it is worthwhile to note that most of the papers assigned to this session are describing different parts of the overall pavement system.

Nine papers are related to overlay design and pavement evaluation, four papers are related to reflective cracking, two papers are dealing with performance models, three paper are devoted to life cycle cost analysis, one paper related to measuring the effect of routine maintenance, another paper describes tools that are available for data processing i.e. and finally two papers are dealing with the implementation of a pavement management system.

This session is therefore a truly kaleidoscopic picture of aspects related to pavement management.

06103 **Theme III Lecture Part II: Pavement Rehabilitation**
B. Liljedahl

IS THERE A NEED FOR ADEQUATE OVERLAY DESIGN METHODS7

My answer to this question is undoubtedly: Yes.

The investments in pavements all around the world represent a tremendous value and it is and will be a very important task to preserve these investments. In my opinion this cannot be done in an economical way if we do not have an adequate method for the design of the rehabilitation measures that are needed in this preservation.

It is also my opinion that the need is much more urgent today than it was in the beginning of the seventies. This is mainly due to the following four factors:
- The age and the aging of the existing paved road networks
- The increase in traffic loading

- The increase in the price of asphalt work
- Inadequate funds for maintenance and rehabilitation

As I think it is important that all people involved in roads are fully aware of what have happened to these factors during the last decades, I will use a part of my presentation for a closer look at them.

06104 **Theme Iii Workshop Report - Pavement Management Systems**
J. P. Marchand, H. Ros

Ladies and Gentlemen, I will give you a short summary of parallel session on pavement management concepts and economics. In his keynote lecture Ron Hudson stressed that "pavement management is not business as usual," Andre Molenaar explained in the theme lecture on Pavement Management that "a PMS is a multicolored non-figurative piece of art." To put things upside down: Hans Ros and myself we assume, we have been elected chairman and Co-Chairman because modern non-figurative art painting is not our usual business.

Eight papers had been assigned to the parallel session "PMS concepts and economics."

Five papers have authors from the USA and three of them from Europe (Denmark, France and the Netherlands).

A breakdown of the papers assigned on "PMS concepts and economics" have been made in:
- paper describing aspects of PMS
- General Framework of a PMS
- PMS papers with a focus on pavement condition and evolution.
- Papers dealing with life cycle costs analysis.

We have used this breakdown to come to three one-hour hocks in the parallel sessions, each block consisting of a short presentation by the authors and a discussion after the presentations.

06105 **Theme III Workshop Report - Pavement Management System Implementatio**
C. Queiroz, F. Carmichael

QUESTIONS / TOPICS FOR COMMITTEES

1. Network Level

What are the main obstacles to effective network level measurements of performance?

Why haven't network level optimization analyses been more widespread?

What are the brightest possibilities for enhancing network level PMS activities?

What are some specific recommendations for developing countries?

2. Project Level

What data/models are the most lacking/inadequate for project projections?
How can we get mechanistic modeling and the required materials testing more widely implemented?

Do project level PMS analyses justify the costs associated with field tests, laboratory tests, and complex analyses?

What are come specific recommendations for developing countries?

06106 **Theme III Workshop Report - Overlay Design Methods**
F. L. Roberts, M. Acott

Organization

The workshop session on overlay design methods is one of those sessions that was designated to be practice oriented, therefore, the eight papers were reviewed with the following questions in mind:

1. Does the method represent a technique that is currently being used by a road authority to design overlays on a regular basis?

2. Does the paper describe all or most of the important elements included in the overlay thickness design method?

All the papers were reviewed with these two questions in mind with the result that three papers were selected to be theme papers. The papers by Horak, and Anderson and Kosky were selected as the two that represented models of papers that were practical design methods. The paper by Kekwick is a case study of two projects and demonstrates the use of the design method described by Horak.

The remaining papers, while all excellent, were considered to be not as well-developed or documented and each author was asked to prepare comments to expand the description of several items in his paper or to contrast his approach to a particular factor with the approaches presented in the theme papers. Each author kindly agreed to follow this general formal in their discussion and was allowed approximately 10 minutes to discuss his paper.

Questions were received from the audience after each of the theme papers. These questions were very specific to each paper and general questions were held until the question and answer session at the end of all presentations.

06107 **Theme III Workshop Report - Overlay Design Concepts**
A. W. Viljoen, P. J. Strauss

Seven papers were assigned to this workshop session, three from the United States of America, two from Canada, and one

each from United Kingdom and Brazil. Four of these papers deal mainly with the problem of reflection cracking, and three of them address aspects related to the structural design of overlay. Table 1 lists the papers covered in this workshop and also briefly summarizes their contents. The workshop was divided into two subsessions: the first dealt with reflection cracking concept and the second with structural design concepts.

06108 **Theme III Chairman's Summary - Pavement Management And Rehabilitation**
R. G. Haas

The pavement management and rehabilitation portion of the Conference was introduced by a theme lecture from Dr. Andre Molenaar of Holland and Mr.Bo Liljedahl of Sweden. This was followed by five short presentations from other authors.

Parallel workshops were then held on the following topic areas:
1. PMS Concepts (chaired by Mr. J. P. Marchand and Mr. Hans Ros)
2. PMS Implementation (chaired by Mr.Frank Carmichael and Dr. Cesar Queiroz)
3. Overlay Design Methods (chaired by Dr. Freddy Roberts and Mr. Mike Acott)
4. Overlay Design Concepts (chaired by Mr. A. W. Viljoen and Dr. P. J. Strauss)

Reports on the results of these workshops follow. These reports present an excellent summary of the contributions from both authors and other participants, and they illustrate the tremendous interest in this subject area. It is not the intent of this summary to repeat those results; they speak for themselves. Rather, the opportunity exists to complement them by speculating what the future holds for pavement management.

First, it is useful to identify some of the major pavement management issues and needs to be resolved in the future so that we can improve both the process itself and its application. They are general but can be used as a context for identifying more specific organizational and technical needs, for integrating new technologies and research results such as SHRP, and for the likely evolution or improvement of the pavement management process.

06109 **Final Session - Paving The Gap**
Chairman / Moderator: B. A. Vallerga

For this session, intriguingly titled "Paving the Gap", the objective is to explore whether or not the results of the research so diligently carried out and reported at these International Conferences are reaching the stage of implementation. The belief that there is a "gap" existing between reported research findings and their application to the everyday practice of designing, constructing, evaluating and managing asphalt pavement systems appears to be widely held, although not in any way defined as to the extent of the "gap". At any rate, true to our propensity as pavement engineers to pave any such observed "gap", the title of this session appears to be highly appropriate.

We have, therefore, assembled here today a panel of seven speakers, knowledgeable and highly-experienced, as a group, in all the various aspects of asphalt pavement systems, to address this subject. Two of the seven, Messers. Jon Epps, Dean of the College of Engineering of the University of Nevada, Reno, (USA) and Jim Shook, Senior Vice President of ARE Consultants (USA), can be classified as "analytical" types who are well versed in the theoretical aspects of today's topic. Then, in the "practitioners" category, we have two representatives from governmental agencies noted for their contributions over the years to asphalt pavement systems, Messers. Bill Phang, Head of Pavements and Roadways, Ontario Ministry of Transportation and Communications (Canada), and Ray Forsyth, Materials and Research Engineer of the California Department of Transportation (USA). Lastly, in the "Builder/Constructor" category we have three speakers, Messers. John Gray, President of the National Asphalt Paving Association (USA); Job van der Plas of the Vereniging voor Bitumineuze Werken (The Netherlands); and, Roger Yarborough, President of the University Asphalt Company (USA).

The charge given to these panel members was, essentially, to express their respective viewpoints on the implementation of research results reported at this and all five previous International Conferences, with reference to the questions of:
A. Extent of Implementation
B. Effectiveness of Implementation
C. Feedback to Researchers

06110 **Discussion of Paper on Employing Paving Asphalt Temperature Susceptibility in the Structural of Asphalt Pavements**
Discussor: N. W. McLeod

Since my paper for Session 1 was written more than a year ago, new information on paving asphalt temperature susceptibility has been developed. This new information provides further support for the main theme of my paper for Session 1, that the introduction of meaningful paving asphalt temperature susceptibility requirements into our specifications for paving asphalts would open a whole new world of understanding about the performance, or service behavior, of bituminous paved surfaces and how they should be designed. I would like to enter this new information into the record.

06111 **Workshop Discussion on: Rut-Depth-Calculations by Using the Latest VESYS-3H-Program Version**
Discussor / Author: H. Beckedahl

In the last 15 years many authors have dealt with theoretical calculations of rutting. The improvements in the existing VESYS rut depth model were explained in reference [l]. It could be said that the research work on improving the rut depth model is not complete, because the VESYS rut depth model was not able to take Into account the transverse distribution of motor vehicle wheelpaths and the form of the rut profiles. Since then it has become possible to extend the rut depth model more successfully (see reference [2].

There' is a necessity to improve the 'old' rut depth model because of three shortcomings:
- Only the deepest point of deformation of the rut profile is taken into consideration. Therefore the calculated rut depth cannot be connected with the real standard of measurement (see figure 1).
- The form of the rut profile is ignored.
- It is impossible to calculate rutting with respect to the transverse distribution of wheelpaths which can be observed in reality.

06112 **Additional Contribution to the Question of the Progress of Longitudinal Profile Changes**
W. Schwaderer

In 1967 an extensive program was started to observe periodically more than 250 test sections of normal roads distributed all over the country. Every year a lot of special measurements were done. Particularly, the Present Serviceability Index (PSI), p, was measured on all lanes of each section at least once a year. In about 100 test sections automatic weighing systems had been installed which counted and registered the number of axle load applications within loading classes.

In 1977 the American VESYS-philosophy incited us to start another program which deals theoretically as well as experimentally with the progress of ruts and cracks and with the development of deviations of the longitudinal profile. Besides the theoretical treatments mentioned before by Dr. Beckedahl at this very moment we try to compare and to connect the findings of both these programs. We hope to be able to improve furthermore the now existing German version of the VESYS-program. This treatment includes additional physical considerations as well as conclusions from special experimental observations.

06113 **Workshop III - Discussion on: Design of Asphalt Pavements Using Lateritic Soils in Brazil**
Discussor / Author: J. Medina

Written Answer to Questions Directed to J. Medina and His Presentation.

(The paper discussed is ISAP file 06070.pdf

06114 **Workshop III - Discussion on: Different Thickness Due to Bearing Capacity of Subbase Traffic Loading and Temperature**
Discussor: R. L. Davis

Discussion of the paper: Influence of' Different Thickness Due to Bearing Capacity of Subbase Traffic Loading and Temperature by W. Arand.

(The paper discussed is ISAP file: 06006.pdf)

06115 **Discussion of: The Concept of Complex Stabilized Material**
P. J. Braunovic

Complex Stabilized Material (CSM), as interpreted by the author; refers to the concept of compound mechanism and chemism of a mix containing local material (a), stabilized with an admixture of pozzolanic properties (b), together with hydraulic cement (c), and, water (d). This homogenized mixture when compacted with an energy (C) it hydrates by aging (t) under normal temperatures (7') such when hardened it forms stable and durable pavement base course material.

An analytical expression of CSM can be given in the form of the unity of relevant factors which define CSM. The concept of C S M has been developed by comprehensive research program carried out for characterization of particular complex stabilized material composed of locally available limestone aggregate (80-90%), various products of blast furnace slag (10-20%), and hydrated lime (l-2%). Such a CSM should possess viscoelastic properties rather than typical soil-cement, aiming at releasing high shrinkage stresses in the early life of CSM base course.

The mechanical levels of CSM, i.e. the comparatively high tensile strength, and relatively low tensile moduli of elasticity obtained in the laboratory on CSM samples, tend to show that this material approaches to the hypothesis of "ideal stabilization" with respect to its resistance to shrinkage cracking, and consequently contributing to minimization of crack propagation through the pavement.

The mechanical or rheological properties of these CSM Models were subjected to qualitative and quantitative analysis using Hooke's Law of Elasticity and Burger's Viscoelastic theory. By comparing the properties of CSM with those of standard Soil-Cement, the subsequent analysis showed, that CSM compared favorably with SC.

06116 **General Discussion on the 6th Conference**
G. Nievell

Chairman, Ladies and Gentlemen I have been deeply impressed of the high technical level this conference has demonstrated. This is due to the highly qualified researchers who have contributed -- the high reputation, these conferences had in the past I only learned from literature surveys.

I am coming from a small country in Europe from Austria where I am running my own laboratory for testing construction materials and a consultancy engineering office for 10 years. Working in the field of asphalt, asphalt-mixes and asphalt pavement rehabilitation for almost 30 years I feel that this background will allow me to add some critical comments on this conference.

The main objective of this conference is in my view to transfer knowledge to engineers, administrators and construction firms. It should also be the forum where the state of art is defined and the goals and ways of further research shall be laid down. But all these activities should lead to the final target to construct highways which provide more security, and better riding quality, longer life spans and which ask for less maintenance cost in the frame of an efficient Pavement Management system.

It is the desire of those who organize and for those who sponsor this conference. If we want to reach this aim it is necessary to transfer the main outcomings in such a way that this technical communication is less sophisticated and has more transparency in order to be adopted by the engineers of the administration and the construction firms who have to apply these innovations of knowledge for the sake of our economies.

06117 **Calibration and Validation of the Model Based on Studies on Control Sections**
S.S. Jain, A.K. Gupta, S.K. Khanna

Calibration of the model normally includes a vast amount of field data to generate and exhibit the confidence in its field application and implementation programme. It has been possible to calibrate the developed model using extensive field data from a national sponsored R & D project of Ministry of Transport, Govt. of India. 46 road sections comprising varied

spectrum of geometry, location, traffic volume, rainfall, subgrade soil, pavement composition etc. were taken in the State of Uttar Pradesh, Himachal Pradesh and Punjab, all in Northern India, which resulted into 22 finalized test sections based on the preliminary study. The finalised test sections with cyclic studies were limited to 14 "Control Sections" for the overlay performance study under design conditions.

The details of the criteria for selection of control road test sections, measurement of surface deflection and measurement for deflection basin are already given in the paper submitted earlier. The elastic modulii values of the materials existing in the flexible pavement layers have been determined in accordance with the equations I and 2 as given already in the paper submitted earlier.

The model was calibrated to yield maximum deflection (characteristic deflection) equal to the mean value plus one times the standard deviation. The calibrated model yielded vertical compressive strain at the top of the subgrade and horizontal tensile strain in the bottom of wearing course layer under the load axis. The results were compared with permissible values given by Dorman and Matcalf (5) and Pell (6) for 10^5 applications of standard axle loads. The computed values along with the permissible limits are summarized in Table 1.1. It can be seen from the Table, that the existing pavement requires an overlay thickness to keep the critical strains within acceptable limits. Trial runs indicate that the overlay thickness is adequate to keep the strain values within permissible limits.

06118 **Mechanstic Pavement Design, a Probabilistic Approach**

M. L. Pigois

The use of mechanistic pavement design methods is restricted to research or special studies even though strains, stresses and displacements values computed by using elastic multi-layer computer programs are very close to the ones that can be measured at the bottom of asphaltic layers when the properties of the materials are well known and the loads and their positions closely monitored.

It is felt that despite the great variability of the road materials and the often very weak correlation between measured values characterizing the materials and the ones used in these programs, a mechanistic design could be used by engineers provided a probabilistic approach was substituted to the commonly used deterministic approach.

A computer program using such a probabilistic method for the computation of the loads and the fatigue life of the asphaltic layers has been developed. This program incorporates the solution of an elastic multi-layer system. The main features of this program are quite similar to the ones of a deterministic one except that each variable influencing the design (loads, climatic conditions, soils and road materials characteristics) are not defined by fixed values but by a frequency distribution. The program is run a great number of times and at each run a set of values is randomly selected taking into account the probability density of each variable. The frequency distribution of the fatigue life of the asphaltic layers is then analysed and its probability density function is compared to the probability density of the traffic established in the same way. This procedure allows to evaluate the risk of early failure.

A numerical example using this probabilistic approach is fully described.

06119 **Corrections For Volume I Papers**

The following papers are corrected:

(Note that corrections have been appended to the appropriate ISAP Acrobat file.)

06028.pdf
Developments to the Nottingham Analytical Design Method for Asphalt Pavements
J.M. Brunton, SF. Brown and P.S. Pell - pp. 366-377

06081.pdf
Structural Evaluation and Overlay Design: Analysis and Implementation
SF. Brown, KS. Tam and J.M. Brunton - pp. 1013-1028

06021.pdf
Employing Paving Asphalt Temperature Susceptibility in the Structural Design of Asphalt Pavements,
N. W. McLeod, pages 240 to 271, Volume I,

06120 **List of Registrants**

An alphabetical listing of 6th Conference participants, with affiliation, and address.

code	7th Conference -- Titles & Abstracts
07000	**7th International Conference on Asphalt Pavements - Volume contents** *anon.* A list of session titles and paper titles
07001	**Effects of different pavement rehabilitation types on the development of rut depth and fatigue cracking** *H Beckedahl, H Buseck, A Gerlach, E Straube, S Velske* Pavement rehabilitations vary in general any part of the wearability of the pavement substance, no matter what reason led to the rehabilitation. In Germany the VESYS-program has been extended to a pavement rehabilitation design program. The calculated rehabilitation effects are compared with the measured ones and the effects of different rehabilitation types including an asphalt binder course with low strength against permanent deformation are shown. Several asphalt mixtures were tested with different laboratory test methods. Two of them and some test-results are described in this paper.
07002	**Two-stage mechanistic approach to asphalt pavement design** *S F Brown, A R Dawson* A method is outlined for the design of asphalt pavements in two stages; the foundation under construction traffic followed by the completed structure under long-term loading. The results of research on soils and granular materials are incorporated to establish design criteria and allow for non-linear resilient behaviour. The method incorporates simple charts and equations and is illustrated by an example. The procedure is put forward as a framework for further progress and discussion rather than as a complete package.
07003	**Extending the use of the Nottingham Asphalt Tester** *F Bullen, J N Preston* Present mechanistic pavement design procedures do not take into account creep deformation in thick asphaltic concrete layers. The Nottingham Asphalt Tester (NAT) and similar apparatus may be used to remedy this deficiency however, the use of the NAT in pavement design is restricted by the need for extensive sample testing and accompanying preparation. The use of simple mathematical models is able to extend the use of the NAT by predicting the behaviour of specimens more representative of the actual pavement.
07004	**Interface systems to prevent reflective cracking. Modelling and experimental testing methods.** *L Francken, A Vanelstaete* This paper describes recent developments on design and evaluation of interface systems for the prevention of reflective cracking in asphalt overlays. The study deals with the following topics : - Characterisation of the system components (asphaltic and interlayer products) - Calculation models for the evaluation of the structural behaviour of such systems under thermal and traffic loads. - Laboratory simulations for the study of the effect of thermal loads. - Field surveys for the evaluation of their feasibility.
07005	**Thickness design of asphalt overlays on concrete pavements for airports** *Y Hachiya, K Sato, A Kawakami* Two design methods of asphalt overlays on the structurally sound concrete pavements have been developed. The current design method gives extremely thick overlays on the condition that the existing concrete slabs are structurally sound. One is based on a multi-layered elastic theory in case that there is no danger of reflection cracking occurring, and the other is founded on a finite element method when reflection cracking is suspected. Loading test data on experimental pavements have been taken into consideration in the process of establishing both methods. The proposed design methods give thinner overlay thickness compared with the current one.
07006	**Application of the visco-elastic properties of asphalt concrete** *P C Hopman, A C Pronk, P A J C Kunst, A A A Molenaar, J M M Molenaar* In this paper a visco-elastic approach to the rutting and fatigue behaviour of asphalt pavements is presented. For this the Burgers' model has been adopted and several laboratory tests have been performed to characterize the parameters in the Burgers' model both for fatigue and permanent deformation. From these tests it appears that the elements of the Burgers' model are dependent on the mode of loading (tensile versus compressive). Furthermore evidence has been obtained that values for the elements can be estimated from mix composition and bitumen characteristics. In order to be able to qualify the behaviour of a visco-elastic pavement structure, the pavement is characterized at this stage as a visco-elastic half-space, which is loaded by a moving point load. It appears that the velocity of the load and the viscous properties of the asphaltic material are important factors which control the deterioration of the construction. This study enables a further detailed insight in the mechanical behaviour of asphalt pavements. It will be used to develop a better correlation between the mix composition and the mechanical behaviour of the road.
07007	**Cracking in asphalt concrete pavements** *M M J Jacobs, A H de Bond, A A A Molenaar, P C Hopman* This paper describes the research efforts that are currently undertaken at the Road and Railroad Research Laboratory of the Delft University of Technology in the modelling of crack propagation in asphalt concrete mixes and the development of an overlay design method. From the research on crack propagation it appears that cracking in asphalt concrete mixes is a rather complex phenomenon. Micro crack zones, as well as small single macro cracks develop initially while later on these small macro cracks combine into one large macro crack. The incorporation of this complex crack behaviour in pavement

and overlay design models would make these models not suitable for every day use. However it is shown that the complex crack process can be simulated by a much simpler single macro crack process. This approach has been used to characterize the cracking of asphalt concrete mixes and to develop a set of design equations which allow the calculation of stress intensity factors at the tip of cracks entering from the existing pavement into the overlay. It is believed that procedures are provided that can be used in practical overlay design problems.

07008 **Performance of asphalt pavements at Bibi new test road in Japan related to their bearing capacity**
A Kasahara, K Himeno, K Kawamura, S Nakagawa

In order to transfer from the conventional and empirical asphalt pavement design method to theoretical one, it is important to ascertain performance of asphalt pavement designed based on the respective design method. For this purpose, Bibi New Test Road was constructed in July 1990 in National Highway Route 36 close to New Chitose Airport in Hokkaido area. To obtain the performance, measurements were made for the following items:
1) Weigh-in-motion,
2) Pavement distress, and
3) Surface deflection.

In particular, the relationship between elastic moduli in the asphalt pavement structure layer and a number of equivalent 49kN wheel load were determined, according to backcalculation of deflection data obtained by a falling weight deflectometer.

07009 **Rational concept in relating lab testing to pavement analysis**
M S Mamlouk

A laboratory investigation is performed to evaluate the modulus of typical asphalt concrete using fourloading conditions; diametral (indirect tensile) pulsating, axial compressive pulsating, triaxila compressive pulsating, and axial compressive harmonic. The diametral modulus was considerably higher than those obtained from compressive loads, especially at low and intermediate temperatures. The laboratory results were related to typical pavement field conditions. Since the stresses are mostly compressive in the pavement asphalt layer, a significant error might develop if the tensile lab modulus is used in the analysis. In addition, the temperature correction factors reported in the 1986 AASHTO guide to be used with non-destructive testing of pavements are too sensitive. More accurate pavement analysis and temperature correction factors can be developed if both tensile and compressive moduli are considered.

07010 **Integrating flexible pavement mix and structural design**
R W May, M W Witczak

Typically, asphalt concrete mix design and the structural thickness design of the pavement are performed separately. New analytical computer programs that allow the two design processes to be integrated into a rational system are described. The discussion is concentrated on the behavior and performance models used in evaluating the trial mixes for the intended pavement cross-section. Performance is examined in terms of fatigue cracking, permanent deformation, and low-temperature cracking. Finally, the performance of mixes in actual pavements is compared to the performance predicted by this system.

07011 **Fatigue of asphaltic mixtures and paving cracking**
J Medina, L Motta, S Pinto, R M Rodrigues

Fatigue test data of fifteen asphaltic mixtures under stress controlled diametric compression are presented. Creep testing under diametric compression is compared to repeated load diametric compression. Some results of strain controlled flexure tests are compared to stress controlled tests. Fracture parameters of Paris's law are obtained from the analysis of the diametral compression test. Models of crack propagation - vertical, horizontal, and reflection cracking - are presented. A model for pavement management system with its application is shown.

07012 **Resilient modulus of granular materials under repeated loading**
A Nataatmadja

Several models presently available for characterisation of granular materials under repeated loading are reviewed and a new simple elastic model is subsequently proposed. The model can predict the dynamic stress-strain relationship (yielding and locking) during loading and incorporates both the first invariant of stress and the repeated deviator stress. The model is dimensionally stable, requires only straightforward calculation for parameters, and offers a practical application in the analysis and design of flexible pavements as well as in the evaluation of material performance.

07013 **Guidance on the design of fine dense bituminous material**
E O Donnell, D Fordyce, K Khweir

A rational approach to the design of fine dense bituminous materials is outlined which extends current procedures. The approach is based on the characterisation of the dry compacted fine aggregate-filler structure. A profile of voidage allows for: an appraisal of the effectiveness of the packing of the blend, calculation of binder content at a target blend and an appraisal of mix tolerance to material ingredient variation. Placement performance is appraised using a stiffness-temperature profile defined using a high temperature triaxial cell and from compaction data. Service performance can be measured from current fundamental techniques.

07014 **The effect of maximum nominal aggregate size and the coarse/fine ratio to permanent deformation of continuously graded mixtures**
G Tsohos, A F Nikolaides, D Leondarides

Six typical gradings of asphaltic concrete mixtures for surface course and two types of bitumen (40/50 and 60/1OOpen) were examined in order to investigate their effect to permanent deformation. The evaluation was carried out using the unconfined creep test. The results show that mixtures with high coarse aggregate content and large maximum aggregate size possess better resistance to permanent deformation. A minimum coarse/fine aggregate ratio of 1.O is justified and proposed for better deformation performance of the mixtures. The effect of using harder bitumen is only apparent on rich mixtures. Air voids is a critical factor and there should be a limiting permissible value depending on the maximum

aggregate size.

07015 **The case for tapered pavement sections**
A H Rhodes

This paper assesses the potential for using tapered pavement sections on dual two-lane and dual three-lane roads. The taper is formed by varying the depth of the base layer which is overlayed by a conventional surfacing. The study demonstrates that either the design life of a conventional pavement section can be almost doubled by redistributing the base material to form a tapered section, or the base material can be reduced by at least 20 per cent without reducing design life.

07016 **Micromechanical modelling of asphalt concrete in connection with pavement rutting problems**
L Rothenburg, A Bogobowicz, R Haas, F W Jung, G Kennepohl

Rutting of asphalt concrete can be modelled using discrete element techniques that are able to simulate the interactions of individual aggregate particles binded with bitumen. The particles are treated as elastic elements and the binder as a linearly visco-elastic material. Creep displacement of the particles involves a viscous flow of the binder, whose rate is affected by binder viscosity, film thickness, contact stress and other parameters. The binder within voids is treated as a compressible Newtonian fluid. Simulations are carried out by numerically solving Newton's equations of motion for individual particles. Results of the simulations illustrate the effects of cohesive and frictional contacts on creep behavior. Rutting occurs when the number of frictional contacts is below a certain minimum.

07017 **Critical condition mechanistic analyses for structural evaluation and rehabilitation design**
B E Ruth, L Guan, M Tia

A computer program for the REhabilitation Design of Asphalt Pavement Systems (REDAPS) was developed to mechanistically analyze and design flexible pavements. The analysis segment of the program uses non-destructive deflection test methods (e.g., FWD or Dynaflect) in combination with asphalt mixture properties to assess the effect of thermal contraction and load induced stressing conditions during periods when the pavement is at its worst structural support (critical) condition. Description of the key functions built into the program are presented along with the testing requirements needed to provide input parameters for the asphalt concrete pavement layer(s).

07018 **Use of the Pencel pressuremeter in pavement design**
P J Sanders, E Horak

The paper describes the use of a special pressuremeter and associated in-situ equipment for shear strength measurement and compares test results with those of a Heavy Vehicle Simulator (HVS) and laboratory shear tests on one site. Results are given for tests on a subgrade and a crushed mine dump rock basecourse. From the limited data the pressuremeter shows promise for use in mechanistic design and provides data that can be used to predict stress-dependant elastic moduli. An iterative technique to predict elastic moduli under wheel loads is also described using equations derived from pressuremeter test results and multi-layer linear elastic analysis.

07019 **High modulus asphalt mixes - Laboratory evaluation, practical aspects and structural design**
J P Serfass, A Bauduin, J F Garnier

High Modulus asphalt mixes can be obtained using various technologies, the main ones being special very hard bitumen, asphaltite-modification and polyethylene-modification. The laboratory characterization of these types of High Modulus mixes is presented and discussed. It comprises gyratory compaction test, compressive and tensile strength, determination of static moduli, rutting resistance, complex moduli, fatigue response, and low-temperature behaviour. Practical aspects are briefl y dealt with. In-place characteristics and performance are then analyzed, special attention being paid to linking laboratory- and site- results. Examples of pavement condition evaluation and modulus backcalculation are given. They show that practice matches research.

07020 **Modelling strain distributions in flexible pavements for variable loads and tire contact pressure distributions**
H F Southgate, K Mahboub

A modified Chevron N-layer program permitted application of 150 discrete loaded areas and contact pressures to a given flexible pavement structure. This paper presents sensitivity analyses for three loadings:
a) variable loads and pressures,
b) variable loads and constant pressure, and
c) constant load and constant pressure.

Static load analyses indicated that the severest combination of load and location corresponds to the variable load, variable tire contact pressure, for the location under the edge of the tire. Tire-pavement interaction proved to be too important to be neglected in the pavement response analyses.

07021 **Water conditioning of asphalt concrete mixtures using the environmental conditioning system (ECS)**
R L Terrel, S Al-Swailmi, A Al-Joaib, W L Allen

As part of the SHRP contract, the Environmental Conditioning System (ECS) was developed to evaluate the water sensitivity of asphalt paving mixtures. The ECS includes cyclic hot-cold conditioning following partial saturation under flow-through vacuum. The integrity of the mixture is monitored by measuring dynamic resilient modulus (MR) and permeability after each cycle. Repeated loading can be applied continuously or only during M, measurements. The ratio of original (dry) to conditioned (wet) M, appears to be a good indicator of expected deterioration. Also, visual observations of stripping and change in permeability provide a further indication of asphalt-aggregate compatibility.

07022 **ILLI-PAVE based conventional flexible pavement design procedure**
M R Thompson

The basic concepts and the development of a CONVENTIONAL FLEXIBLE PAVEMENT THICKNESS DESIGN PROCEDURE are presented. The proposed procedure is based on resilient soil and material testing procedures, the ILLI-

PAVE structural model, and design algorithms developed from an extensive ILLI-PAVE data base. Traffic (Equivalent Single Axle Loads), subgrade modulus, location (pavement temperature effects), asphalt concrete modulus and design reliability are considered. Comparisons of ILLI-PAVE, SHELL, and the Asphalt Institute thickness requirements are made.

07023 **Development and validation of realistic pavement response models**
J Uzan, M W Witczak, T Scullion, R L Lytton

In this paper constitutive models are presented for both the resilient modulus and Poisson's ratio of granular materials. They are based on an extensive review of laboratory test data and incorporate the dilation effects which have been measured to exist at high stress ratios. These constitutive equations have been incorporated into a finite-element computer code. A comparison is made of the influence of using either a fixed or varying Poisson's ratio on the induced layer stresses. Validation is attempted using deflection data from instrumented test sections. The proposed nonlinear equations show a distinct improvement over the linear approach in matching both surface and depth deflections.

07024 **The Shell pavement design method on a personal computer**
C P Valkering, F D R Stapel

A version of the Shell Pavement Design Manual has been developed for use on personal computers. The Manual, based on a rational method for the thickness design of flexible pavements, was published in 1978 in the form of a series of design curves. The separate computer modules of the new version provide for the prediction of material properties and for the calculation of the critical stresses and strains. The method now has greater flexibility in that the user can introduce his specific material properties, traffic or climate without extensive interpolation effort.

07025 **Structural design of road structures with unbound granular bases and subbases**
E Vos, P J Galjaard, A P Allaart

A mechanistic approach of the structural contribution of unbound granular bases and subbases has been developed. It is based on a non-linear elastic constitutive model, the parameters of which can be determined with cyclic load triaxial tests. The model has been implemented in the finite element code DIANA. Validation has been carried out by comparison of calculated and measured asphalt strain data of full scale test pavements. For full depth asphalt structures and structures with unbound granular base courses a good compatibility has been found. Comparison has been made between the results of the developed non-linear elastic approach and traditional linear elastic analysis. Consequences for practical road design are discussed.

07026 **A reliability analysis of flexible pavement design**
Q S Zhang, Li Yun

Based on the Design Code (JTJO14-86) for Highway Flexible Pavement issued in 1986 by the Ministry of Communications of China, this paper has put forward a method of analysing the reliability of flexible pavement with multi-indexes. It has carried out a probability statistics and simulation analysis for the design indexes and parameters, thus obtaining their probability distribution. Also, it has calculated and analysed the reliability and sensitivity of pavement structure by using different mean parameters and coefficients of variation. Finally, it has discussed the application of reliability analysis in areas of construction and quality control.

07027 **Aging of asphalt-aggregate mixtures**
C A Bell, Y Ab Wahab, J E Klliewer, D Sosnovske, A Wieder

This paper presents the development of laboratory aging procedures for asphalt-aggregate mixtures as a part of project A-003A of the Strategic Highway Research Program (SHRP). A short-term oven aging method to represent aging of the mixture when it is hot during the construction process is described. Alternate long-term aging methods are considered, involving oven aging, or forcing oxygen through a specimen. The development of tests to evaluate the extent of aging is also described together with the extensive data gathered (to date), and a description of testing yet to be done. Finally, a validation program is outlined, which compares the aging of mixtures in the field with that achieved in laboratory made specimens.

07028 **Assessing the nonlinear behavior of subgrades and granular bases from surface deflection basins**
R Bonaquist, M W Witczak

Linear elastic basin analysis methods often yield unrealistic layer moduli when stress dependent subgrade soils and unbound base materials are encountered. The objective of this study was to develop and verify a method for assessing the nonlinear behavior of subgrade soils and granular base course materials from surface deflection basin measurements. The method that was developed is not a rigorous nonlinear solution, but uses numerical integration of the Boussinesq point load solution to estimate stresses and to calculate deflections using stress dependent moduli. Field derived nonlinear modulus relationships were developed with this method for a silty sand soil, and a dense graded crushed aggregate base.

07029 **A new initiative in measuring the fatigue performance of bituminous materials**
M J Brennan, F Clancy

Cylindrical test specimens are manufactured using a double acting static load of 100 or 125 kN. The specimens are tested in uniaxial sinusoidal loading with zero mean stress. Failure is defined by the complete fracture of a specimen. The materials that have been tested include SBS modified and unmodified bitumen macadams, EVA modified and unmodified rolled asphalts, graves-emulsion, asphaltic concrete, heavy duty macadam and polymer modified slurry seal. The paper presents the results of statistical comparisons between the performances of the different materials together with analyses of the effects of test temperature, aggregate grading, bitumen content and rest periods.

07030 **Performance of bituminous road pavements in Malaysia**
K P Chong, R B I Hasnur, J K Han

The primary mode of pavement distress in Malaysia is cracking in the bituminous surfacing due to a reflection of cracks from existing pavement and age-hardening of the bituminous materials. Rutting is not a major problem except at highly stressed areas such as on climbing lanes and junctions. Extensive research has been carried out by the Training and

Research Institute, Public Works Department of Malaysia, to address the problems of pavement distress accordingly. Some early findings from the research work are discussed and presented in this paper.

07031 **Full scale pavement testing in the Netherlands**
L J M Dohmen, A A A Molenaar

Response studies have been carried out on several test pavements, equipped with strain measurement devices. From the results it appears that the actual strain under a circular, uniformly distributed load as produced by a falling weight deflectometer can easily be predicted with linear elastic multi layer programmes, like e.g. BISAR. The agreement between the measured and calculated strain due to a moving dual and single wheel was less then was obtained from the F.W.D. tests. The measured strains were lower than the predicted ones. It is believed this is mainly due to the non-uniform contact pressure distribution but effects of visco-elasticity might have attributed to this as well.

Furthermore it appeared that there was a very good agreement between the asphalt layer stiffness back calculated from deflections profiles and the laboratory determined mix stiffness.

07032 **Effect of polymer modified bitumen on rutting and cold cracking performance**
J Eisenmann, U Lempe, U Neumann

The paper presents extensive laboratory tests to determine the influence of different kinds of polymer modified bltumen in opposition to a usual bitumen as it appears in practice. Tests were run to investigate each binders' performance in asphalt courses at high and low temperature and under dynamic load repetitions. Full scale tests were run in a special device to estimate the influence of the used binders on rutting. The results of the different tests show a good conformity that is partly proved by theoretical studies.

07033 **Effects of asphalt properties on low temperature cracking of asphalt pavements**
H Kanerva

The effect of the following asphalt properties on low temperature pavement cracking are studied: penetration at 0, 5, 10 and 25C, viscosity at 60 and 135C, Fraass brittle point, softening point R&B, ductility at different temperatures, force-ductility at OC, sliding plate-stiffness at -10C and OC, glass transition point (DSC), impact strength at different temperatures and cracking temperature on a glass plate. All these properties are correlated with a cracking temperature measured in a laboratory using the restrained stress beam test. Based on the data from nine asphalts, the penetration at 5C of the TFOT residue together with PI are the best predictors for the cracking temperature of the mixture.

07034 **Technology and in-situ trial of a noise absorbing pavement structure**
E U Hiersche, H-J Freund

The porous surface bituminous wearing courses which are employed for traffic noise reduction are capable of reducing rolling noises of traffic by approximately 3 dB(A). A pilot study and trafficable pavement test section showed that a full depth of 45 cm and an air void content of 20 - 25 Vol.- % is necessary to reduce rolling noises by approximately 7 dB(A) and engine and driving noises by 6 dB(A). Bitumen and Cement, as well as synthetic materials (as a wearing course alternative of bituminous subsection) were utilized as binding agents. After a service life of approximately 2.5 years further investigations (in regard to materials, construction and cleaning procedures) of the bituminous mix design were carried out.

07035 **The performance and behaviour of bitumen emulsion treated road bases in South Africa**
E Horak, F C Rus

Emulsion treatment of granular bases is used mostly as a rehabilitation option in South Africa. Emulsion treated bases (ETBs) have been used on an ad hoc basis in South Africa in the past. Considerable work has gone into the mix design of ETBs, but in general, the modelling of ETB pavements lacks performance data. Accelerated testing with the Heavy Vehicle Simulator (HVS) fleet in South Africa has proven to be the ideal way of evaluating and modelling the performance of ETB pavements. Experimental sections and previously constructed ETB sections were tested. The outcome of these tests has contributed significantly towards the increased use of ETBs in South Africa. Research on ETB with natural gravels are also reported on.

07036 **The impact and management of the Heavy Vehicle Simulator (HVS) fleet in South Africa**
E Horak, E G Kleyn, J A du Plessis, E M de Villiers, A J Thomson

Accelerated testing of pavements is accepted as an important decision tool in road design and behaviour analysis world-wide. Accelerated testing with the Heavy Vehicle Simulator (HVS) system in South Africa has enhanced an understanding and knowledge of material, pavement behaviour and modelling specific to the South African environment. The HVS system proved to be a unique and cost-effective decision tool and facilitator of cooperation between researchers, practitioners, clients and administrators. The impact of the HVS system in South Africa is clearly demonstrated by the extent of successful technology transfer projects.

07037 **The structural performance of the thinly surfaced road pavements**
D A B Hughes, C D F Rogers, H A R Faddaoui

The performance of a number of surface dressed, unbound pavement structures has been assessed under repeated standard axle loads. The structures consisted of variable thicknesses of sand and gravel and well graded crushed limestone subbases overlying a clay subgrade. Transient surface deflections, to define the deflection bowl, permanent surface deflection and radius of curvature were measured. Well defined and consistent patterns of the various performance indicators were found, with good correlation between radius of curvature, measured by a curvature meter, and Surface Curvature Index. Interesting trends were found in the transient surface deflection measurements.

07038 **Mechanistic performance modeling: a contradiction of terms?**
A M Ioannides

Most current pavement performance prediction models incorporate a two-step approach. Mechanistic structural responses

	are passed to statistical/empirical "transfer functions," predicting distress as a function of load repetitions, It is argued that algorithms like the AASHO PSI equation, the ESAL concept, and Miner's hypothesis are descriptors of past pavement performance and are unreliable as predictors of future perfomance. Predictions of current programs are, therefore, erratic. The constructs noted should be replaced by more fundamental approaches, calibrated using laboratory and field observations. Pending such changes, mechanistic performance modeling will remain a contradiction of terms.
07039	**Full-depth asphalt pavement fatigue under accelerated loading** *G W Jameson, K G Sharp, N J Vertessy* This paper describes the recent Accelerated Loading Facility (ALF) trial conducted in Australia on full depth asphalt pavements nominally 120 mm thick. The aim of the trial was to investrgate the fatigue performance of dense-graded asphalt. Extensive laboratory and field testing was conducted to complement the ALF trial. Relationships were established between back-calculated asphalt stiffness, determined from Falling Weight Deflectometer deflection bowls, pavement temperature and the severity and extent of surface cracking. The asphalt stiffness was found to decrease markedly with an increase in the number of loading cycles before surface cracking was apparent. Fatigue relationships, derived for various extents and severities of surface cracking, suggested that, for the trial mix tested under ALF loading, the Shell fatigue relationship was associated with about 50% of the loaded area having severe fatigue cracking.
07040	**Primary response under heavy truck traffic** *W J Kenis, G Rohde* The Federal Highway Administration's Test Road located at the Turner-Fairbank Highway Research Center (TFHRC) in McLean, Virginia, is an experimental in-service roadway used for monitoring the primary response of the pavement. The Test Road was constructed and first tested in August 1990. It contains two full scale flexible pavement test sections. It will accommodate truck traffic at speeds up to 73 Km/h. The main feature of the test road is the strain and deflection instrumentation located in the pavement. This paper presents an analysis of information obtained from the deflection devices.
07041	**Measuring pavement deflections using laser imaging** *H Lee, D I McLean, H Oshima* The paper demonstrates the feasibility of automatically measuring pavement deflections using a laser imaging method. A sheet of laser light, created using a cylindrical lens, is projected on a concrete slab at a small angle to create a straight line image. The straight laser line bends as the slab is deflected. The shifted laser images are captured using a video camera and then digitally processed to determine the vertical deflection. Deflections obtained using the proposed laser imaging method closely match the measured deflections using LVDT's at various points along the length of the slab. It is concluded that this automated deflection measuring procedure using a laser sheet is a precise and inexpensive method of measuring pavement deflections at multiple locations
07042	**Assessment of radar technology for determining the thickness of pavement layers** *M Livneh, M H Siddiqui* Use of GPR is proposed as a non-destructive technique for pavement thickness determination, and its possibilities and limitations are discussed. It is found that for the zero product variability case the maximum error anticipated in determining asphalt layer thicknesses may be at the 15-20 percent level, mainly due to the biased errors resulting from the measuring method of the relative dielectric constant. The error can be reduced to about 10 percent when several readings are taken for each measuring point. For the heterogeneous case, the maximum error anticipated in determining asphalt layer thicknesses can be higher. However, this can be avoided if the relative dielectric constant is determined for each measuring point.
07043	**Use of radar technology for pavement layer evaluation** *K R Maser, T Scullion, R C Briggs* This paper describes the use of non-contact Ground Penetration Radar to measure asphalt surfacing thicknesses at speeds ranging from 8 to 64 km/hr (5 to 40 mph). On four SHRP sites in Texas it was determined that by using radar alone it was possible predict asphalt thicknesses to + or - 7.6 mm (0.32 ins). However when a single calibration core was taken on each site the accuracy improved to + or - 2.8 mm (0.11 ins). The accuracy in predicting granular base thickness was + or - 25 mm (0.99 inches). The impact of using actual layer thicknesses on FWD analysis is demonstrated.
07044	**Reflection of model and measurement errors on stiffness estimates** *K Matsui, T Inoue, T Sanpei* Some problems encountered in backcalculation of pavement structure are examined in this paper. The problems considered are errors in layer thickness, Poisson's ratio, deflection measurements and possible existence of rigid bottom. The effect of errors on stiffness estimates are presented by both simulation and analysis. Optimal design sensitivity is introduced in the analytical approach. The effect of rigid bottom is also presented in terms of the sensitivity of layer stiffnesses with respect to the thickness change of the layer overlying the rigid bottom.
07045	**Mechanism of longitudinal surface cracking in asphalt pavement** *S Matsuno, T Nishizawa* Longitudinal Surface Crack (LX) is one of the major problems of the asphalt pavements in Japan. This type of cracking is basically different from the scope of current structure design concept. In this paper, our assumption, that LSC is induced by tensile strains in the pavement close to the tire edges at high temperature, is discussed based on visual condition survey and FEM analysis. From the visual condition survey conducted in highway sections, it is confirmed that LX occurs more in the sunshine than in the shadow cast by overpass bridges. The FEM analysis shows that large tensile strains occur in the pavements close to a tire edge at high temperature and that the strain is concentrated at the tip of a small crack induced at the surface.

07046 **The evaluation of six modified binders for retardation of crack reflection through laboratory studies and field work**
F C Rust, K Coetser, B M J A Verhaeghe

Three bitumen-rubber binder technologies and three polymer-modified binders were evaluated both in field trials and extensive laboratory work to assess their ability to retard reflection cracking. The work conducted included the measurement of crack activity and fatigue testing under simulated crack movement. Laboratory results and field performance data were related in a model to assist in the selection of surface treatments for the retardation of reflection cracking.

07047 **The appraisal and evaluation of an asphalt base pavement on a sandy subgrade**
P J Sanders, G Verwey, C J van der Merwe

The paper describes the appraisal of a pavement using a variety of test measurements and life prediction methods. When the pavement was built over 20 years ago the base consisted of a crushed mine dump rock layer. Since then two asphalt overlays and a chip and spray surfacing have been laid, effectively forming an asphalt base. The pavement is to be rehabilitated and upgraded to take increased traffic flows, hence the pavement investigation. The pavement is shown to perform well under Heavy Vehicle Simulator loading and has a significant residual life.

07048 **Field and laboratory evaluation of specialist high performance binders**
A F Stock, L Planque, B Gunderson

The circular test track facility of the University of Canterbury was used to compare the performance of four specially prepared polymer modified binders and one high stiffness binder, with that of a conventional binder in an asphalt concrete mix. The study showed that the special binders outperform the conventional binder by a significant margin, and also that there is variation in performance between different polymer systems.

07049 **Modelling of pavement performance**
P Ullidtz, R N Stubstad

Pavement structures are amongst the most difficult civil engineering structures to treat using analytical (or mechanistic) methods. Since the very first "Ann Arbor" conference in 1962, a lot of effort has been put into changing pavement design from being a purely empirical craft to being part of the engineering science.

Some success has been achieved in applying the analytical-empirical method to day-to-day engineering problems, but the gap between research and practice is far from closed. An important reason for this is the complexity of the problem. Models are necessarily simplifications of reality, but oversimplifying often leads to a lack of realism, which again leads to a rejection of the model for practical use.

This paper presents a model called PERS (for Performance and Economic Rating System) that tries to strike a balance between simplification and realism, giving the user the possibility to verify or calibrate the model to conform to practical experience. It is hoped that this approach may contribute to paving the gap.

07050 **Quality of bitumens in asphalt hot-mixes with emphasis on the durability of constructed premix surfacings**
E J van Assen, M Vlok, F C Rust

The chemical and physical properties (quality) of bitumens and the durability of hot-mix surfacings placed in various locations have been investigated over a four-year period. Performance-related properties of the residual bitumen subsequently recovered, were identified and quantified by comparing asphalts from early failures to those which have performed well. There is a significant relationship between ductility and chemical composition of the residual bitumen and the durability of new hot-mix surfacings. A rapid test for the semi-quantitative estimation of asphaltenes in bitumen is described. The method based on the Oliensis spot test, can be used for on-site bitumen quality control.

07051 **Impact of season on the structural condition of asphalt pavements**
C van Gurp

Results of a study on the effect of season on the structural condition of asphalt pavements and subgrade response in non-frost areas is presented. Changes in subgrade response and deflection were measured with a falling weight deflectometer. Each of the 60 test sites was visited 15 times in a two-year period. Moisture content and groundwater table level were recorded at each visit. Analyses of the moduli show a sine shaped variation throughout the year. The influence of the subgrade soil type on this variation is presented. Repeated triaxial tests were performed at some subgrade soils. The results indicate that use of meteorological data, and measuring deflections can result in reasonable estimates of the subgrade modulus at any date in the year.

07052 **An assessment of the increased damage potential ot wide based single tires**
R Bonaquist

In 1989, the Federal Highway Administration (FHWA) initiated a research program to assess the impact of wide based single tires on flexible pavement response and performance. This study was conducted at the FHWA Pavement Testing Facility. Using the Accelerated Loading Facility pavement testing machine to simulate traffic loading, pavement response and performance data were collected for comparable dual and wide based single tires. Comparisons of the response and performance data for the two types of tires were used to assess the relative damage potential of the wide based singles.

07053 **Seven years experience of pavement evaluation**
J M Brunton, R J Armitage, S F Brown

Since the back-analysis program PADAL was written in 1985 extensive experience has been gained in the practical implementation of the program and the associated rehabilitation design techniques based on analytical methods. A number of case studies are discussed which cover a range of pavement types and conditions. Comparison of measured and back-analysed effective stiffnesses are made, and correlations between stiffness and deflection parameters presented. Consideration is given to non-linearity of the subgrade. A simple procedure for assessing load transfer across joints in rigid pavements when designing bituminous overlays is also illustrated.

07054 **Development of an overlay design method for flexible pavements on lateritic soils**
G Claros, W R Hudson

A mechanistic-empirical overlay design method (in terms of cracking and rutting) applicable to Nigerian conditions is presented in this paper. The basic steps of the new overlay design procedure include field evaluation of existing pavement (with condition and deflection surveys), in situ materials sampling and testing, laboratory testing, analysis of the existing pavement to determine remaining life, and the structure layers design method. The procedure was tested during the evaluation of over 3,500 kilometers of roads in Nigeria.

07055 **Developments in the failure criteria of the South African mechanistic design procedure for asphalt pavements**
M de Beer

Effective implementation of the widely accepted mechanistic design method for asphalt pavements requires calibrated failure criteria and transfer functions. This paper describes various criteria developed and verified in South Africa in association with the full-scale accelerated testing of pavements, using the Heavy Vehicle Simulator (HVS) technology. Criteria such as the effective fatigue failure; compression (crushing) failure; erodibility of lightly cementitious (stabilized) pavement materials, and subgrade strain are discussed. Aspects of in situ pavement response measuring techniques are discussed, and include dynamic pavement characteristics; asphalt creep response; temperature and load correction, as well as effects of vehicle speed on pavement response.

07056 **The circular test track facility and road maintenance studies on flexible pavements**
A de Boissoudy, J C Gramsammer, J P Kerzreho

We describe the behaviour of three thin bituminous overlays placed on flexible pavements which have been first damaged by the Nantes circular test track and we compare their behaviour with that of equivalent newly-made pavements. The pavements are modelised with the help of the rational method and we use a simplified law to describe rutting evolution. We show, among other things, the important part played by the sealing effect in the case of overlays and how the law, chosen for flexible pavement rutting, confirms the validity of the limits usually selected for the vertical strain of untreated courses. It seems that a 50% increase can be chosen in the case of overlaid pavements in relation to newly-made ones. Let us note that the French routine design method already applies it.

07057 **Analysis of asphalt test pavements with a subbase of expanded polystyrene foam**
M Duskov, R Bull-Wasser

Flexible pavement structures with an EPS sub-base were investigated by measurements on six full-size test pavements and by a numerical analysis using a finite element program. The measurement program included registration of horizontal tensile strain at the bottom of the asphalt layer, surface deflections, compaction degree in the gravel layer, and rut depths during long-term loading tests. Numerical analysis is performed by the DIANA program which contains a non-linear material model. The pavement structures are compared with each other and calculated stresses and strains are compared with allowable material values.

07058 **A system for evaluating the impact of truck characteristics and use on flexible pavement performance and life-cycle costs**
E G Fernando, R L Lytton

Florida COMPAS is a project level pavement management tool for evaluating the effects of different forecasted truck characteristics and use on flexible pavement performance and life-cycle costs. This is accomplished through a comprehensive approach involving the combined application of models for load-shift analysis, vehicle simulation, load equivalency calculations, performance prediction, overlay design, and life cycle cost estimation. This comprehensive pavement analysis system is described in this paper together with examples that illustrate program applications.

07059 **Use of subnormal local aggregates in high modulus asphalt mixes**
H Goacolou, A Dimitri, F Prudhomme, L A George

The construction of the A 71 Motorway in France raised the problem of the use of local materials which could only give a low percentage of standard crushed aggregates. The use of High Modulus Mixes (HMM) with better mechanical properties than those of the standard base course mix allowed an optimal use of the local pit and a considerable reduction in aggregate extraction and elaboration. Laboratory and in situ test results are discussed and shown to confirm the pavement design initial assumptions.

07060 **The effects of dynamic axle loads on the response and life of flexible pavements**
M S A Hardy, D Cebon

In order to assess the influence of dynamic wheel loads on pavement wear it is necessary to understand the way in which such loads are carried by the structure.

A method for calculating the transient response of road surfaces to dynamic wheel loads is presented. The key assumptions of this method, the system's dynamic linearity and structural isotropy, are investigated and the theory is validated by experiments on an instrumented test track.

The theory is then used to:

i) Investigate road response to static and dynamic loads;

ii) Investigate the conditions under which dynamic road models are required for accurate response predictions;

iii) Examine theoretical road damage due to dynamic loads.

07061 **Prediction of airfield pavement response employing nondestructive testing procedures and elastic layered theory**
D R Hiltunen, J R James, R Roque, A J Bush III

The deflections of airfield pavements predicted using elastic layered theory are compared with deflections measured under actual aircraft loads. The predictions are made using elastic moduli backcalculated from falling weight deflectometer data. The deflections under actual moving aircraft loads were determined via velocity transducers (geophones) placed both on and within the pavement system. In all cases analyzed, the predicted deflections agree well with the measured deflections in the vicinity of the wheel load. The predictions become progressively worse, however, for increased distances from the load. It is felt that the discrepancies observed are due to nonlinear effects in the subgrade materials.

07062 **Comparative tests of FWD and Lacroix Deflectograph**
W Th Hoyinck, J M M van der Loo, J Mulderij, R Kuijper

Parallel tests of the FWD and Lacroix-Deflectograph were carried out in order to explore the possibilities of using both types of equipment side by side in everyday practice. This paper provides the necessary tools to convert certain parameters from LAC to FWD and vice versa. It also presents a new approach to the theoretical analysis of LAC deflection bowls. Subsequently, the results of this analysis are compared with the FWD analysis. Strain levels appear to compare favourably, both for direct LAC analysis or after conversion to FWD profiles.

07063 **New concepts on load equivalency measurements**
M Huhtala, J Pihlajamaki

The equivalencies of 100 kN and 115 kN were compared within the OECD/FORCE circular track test and the "powers" of the fourth power law were calculated. A comparison of the effects of different tyres and the lateral wander effect is based on response measurements made at Virttaa. The strains in pavements in transverse and longitudinal directions are different if measured by non-elastic gauges. That phenomenon was studied also with computer simulation based on Burgers' model.

07064 **Towards improved procedures for the mechanistic analysis of cement treated layers in pavements**
G J Jordaan

The horizontal tensile strain at the bottom of cement treated (CTB) layers in pavements is generally used to assess the expected behaviour of such layers. However, this strain parameter alone does not adequately allow for the description of the observed behaviour of many pavements containing cemented layers. In this paper measurements of an accelerated pavement test with the Heavy Vehicle Simulator, are used to develop an approach for the mechanistic analysis of CTB layers which is in line with the observed behaviour. This procedure includes the modelling of the CTB layer using a relatively low effective elastic modulus, a test to establish the position of maximum strain which is not always at the bottom of the CT6 layer and an adjustment of the fatigue curve for CTB layers to allow for field performance.

07065 **Evaluation of various field measurement techniques for the assessment of pavement interface conditions**
P Lepert, J P Poilane, M Bats-Villard

A brief overview of the construction and maintenance faults which causes lacks of bond between the road base and the bituminous wearing course (one of the major causes of distress of treated base pavements) is presented. Experiments were carried out on special test sections, with different interlayer conditions, to compare the ability of existing NDT equipments to support a definite diagnosis of such a flaw. Results from these equipments are compared. A new dynamic testing method is presented: it was applied on the test sections, and proved to be one of the most efficient methods to detect lacks of bond. Finally an equipment applying the method is described: the COLIBRI system.

07066 **Fatigue of asphalt materials for Norwegian conditions**
J Myre

Fatigue cracking is a frequent failure mechanism causing extensive structural damage of flexible pavements. This study presents results from fatigue testing in the laboratory. The project involved three types of fatigue test apparatus. Based on this study fatigue criteria have been established for asphalt mixes commonly used in Norway. The influence of load environmental and mix variables have been studied. The experimental work has also resulted in development of one single fatigue criterion for all examined mixes.

07067 **Determination of pavement aging by high frequency body and surface waves**
S Nazarian, M Baker, R C Boyd

An economical field methodology for determining the degree of aging of the AC layer is presented. The assessment of aging involves relating the propagation velocities of shear and compression waves to elastic modulus and Poisson's ratio of the layer. These parameters are directly related to the stiffness and brittleness of the AC layer. The ultrasonic wave propagation techniques have the potential to yield valuable information with respect to aging of AC layers. Much research is needed to establish relationships between temperature, environment, stiffness, Poisson's ratio and aging. The methods described here may facilitate the development of these relationships.

07068 **Towards a performance specification for bituminous roadbase**
M E Nunn, G Bowskill

Work on the development of an end-product or performance specification for bituminous roadbase material is described. Practical methods of measuring the most important structural properties are being identified and assessed. The study has so far concentrated on evaluating a method for measuring the load spreading ability or elastic stiffness of the roadbase and has found the indirect tensile test to be suitable.

07069 **Pavement deflection analysis on sections where the subgrade vary in stiffness with depth**
G T Rohde, R E Smith, T Scullian

This paper deals with an improved method of analyzing nondestructive deflection measurements. From the shape of a measured deflection bowl the depth to an apparent rigid layer is determined. This apparent rigid layer then accounts for bedrock, subgrades stiffening with depth, or both during the backcalculation of layer moduli. The procedure, incorporated in the layered elastic backcalculation program MODULUS4, has been validated by laboratory tests and results from instrumented pavements. The paper covers how to determine the depth to an apparent rigid layer and illustrates typical changes in stiffness with depth expected in clay and sandy subgrades. Results from a deflection analysis on an

instrumented pavement section are also presented.

07070 **The use of linear elastic analysis to predict the nonlinear response of pavements**
R Roque, P Romero, D R Hiltunen

A comprehensive analysis was performed to determine whether linear elastic layer analysis can be used to accurately predict the nonlinear response of pavements. The analyses showed that fairly accurate predictions of deflections, stresses, and strains resulted within the surface layer when a single effective layer modulus was used to represent the surface and base layers. However, it was found that the upper portion of the subgrade must be modeled as a separate layer in linear elastic layer analysis to approximate the effect of stress dependency on response. Effective layer moduli determined at design wheel load levels resulted in accurate prediction of nonlinear pavement response at load levels of + or minus 25% of the design wheel load level at which the moduli were determined.

07071 **Towards analytical mix design for large-stone asphalt mixes**
F C Rust, J E Grobler, P A Myburgh, F Hugo

Increasing traffic volumes and axle loads in South Africa has recently resulted in traffic loading beyond the current design classes. In addition, there is a strong lobby to increase the legal axle load limit. A need was expressed by the Southern African Bitumen and Tar Industry for an investigation into Heavy Duty Asphalt Pavements. A project focusing on the use of large-aggregate asphalt mixes (37.5 mm and 53 mm) was defined. This paper addresses the development of an analytically based design procedure for large-aggregate asphalt and its application in thirteen trial sections. In addition, the physical and engineering properties of the various materials are discussed and related to the constructability of the mixes. The performance of these trial sections under accelerated trafficking are related to laboratory results.

07072 **Relationships between climatic conditions and the structural parameters of flexible pavements.**
A A Shaat, M A Kamal, N S Matter

An extensive programme of Deflectograph deflection testing of typical highway sections is being conducted since early 1990 by the authors in co-operation with the Research and General Services, Roads Service of the Department of the Environment in Northern Ireland. This paper describes the technique being developed for quantifying the variations in pavement effective stiffnesses due to environmental (seasonal) effect. Monthly collection of deflection data, ground water-table variation, moisture content and temperature distribution in bituminous layer etc. are being carried out on 200 m in-service flexible pavement test sections. The analysis of this data will provide reliable information about the seasonal variation in strength of the tested pavements.

07073 **Field performance, laboratory testing and predictive models for modified binders used in reflection cracking**
P J Strauss, E Kleyn, J A du Plessis

Cracks in flexible pavements allow surface water to enter and wherever marginal material has been used in foundation layers, structural failures are to be expected. Design and construction of overlays on cracked pavements are therefore aimed at avoiding reflection cracking. The development of modified binders has greatly improved the rate of success in this regard, but it also has emphasized the lack of understanding of and design methods to design against reflection cracking. This paper discusses the modelling of crack behaviour, the sensitive parameters in predicting performance and actual field experiences of different strategies. The conclusion is made that although fatigue principles are to be applied in predicting performance, cracks develop under brittle failure and re-heal during periods of warmer weather which complicates predictive models.

07074 **Evaluation of the rehabilitation design of a BTB pavement and the effects of artificial ageing using accelerated wheel load testing**
C J van der Merwe, H L Theyse, E Horak, F Hugo, J A du Plessis

A number of flexible rehabilitation design methods that are used in South Africa were evaluated by Heavy Vehicle Simulator (HVS) test loading. The predicted mechanisms of failure and structural life of a Bituminous Treated Base (BTB) pavement were compared to actual test results. All design methods required shift factors to correlate the test results with the respective design performance predictions. The effects of accelerated ageing by heat were then studied under full scale HVS testing, as well as scaled down laboratory testing using the ITT's 1:lO model Mobile Load Simulator (MLS). Shift factors were found to be affected by and dependant upon the mode of failure.

07075 **Harmonisation of Falling Weight Deflection evaluation procedures**
C Van Gurp, W Th Hoyinck, A Van de Streek, B Thewessen

A novel procedure for the structural evaluation of falling weight deflection data on all types of asphalt pavements in The Netherlands is presented. Results of repeatability and reproducibility experiments in FWD comparisons are given. These tests point at the influence of the pulse load shape on the magnitude of the deflection. The FWD test procedure and the obligatory additional testings are described. Backcalculated moduli are adjusted for thermal gradient effects and normalized to a reference air temperature. The data processing procedure shows how the results of FWD testings and the other testings should be combined for a proper structural evaluation. A brief description of the effects of lateral wander and travelling speed of truck traffic is given.

07076 **Thermal cracking resistance of asphalt concrete: an experimental approach**
T S Vinson, N M Jackson, D-H Jung

Low temperature and thermal fatigue cracking of asphalt concrete pavements are serious problems in many regions of the world. Based on research conducted to date under the Strategic Highway Research Program (SHRP), thermal stress restrained specimen test (TSRST) results for 5x5x25 cm beam specimens at a rate of cooling of lOC/hr provide an excellent indication of low temperature cracking resistance and TSRSTs performed under cyclic cooling provide an indication of thermal fatigue cracking resistance. The energy rate integral (C*-Line Integral) and direct tensile strength do not correlate to thermal cracking resistance.

07077 **The elasto-plastic behaviour of crushed stone bases in flexible pavement structures under accelerated testing**
H Wolff, E G Kleyn, A T Visser, M de Beer

A model based on the S-N curve principle is developed to predict rutting in crushed stone bases from Heavy Vehicle Simulator (HVS) testing. The model is intended for use in the mechanistic analyses of pavements together with Miner's damage law. The benefit in terms of less rutting over the lifetime of the pavement by compacting the crushed stone base to 89 instead of 84 per cent of apparent density is illustrated by the development of the model. The model is developed for the equilibrium moisture condition of crushed stone bases only, as an important aim of pavement design and management is to prevent ingress of water into the pavement layers.

07078 **The distribution of stresses at the interface between tyre and road and their effect on surface chippings**
A R Woodside, J Wilson, G Xin Liu

Contact stresses induced at interface between tyre and road surface may cause crushing, polishing and abrasion of surface chippings. Two computer-aided testing systems are used to measure the contact stresses under static and dynamic conditions using various loads and inflation pressures. The effect of different surface texture depths is assessed and the contact forces on individual chippings obtained. Results indicate that a surface chipping of 1 mm macro-texture endured a contact force of twice that induced on a chipping at zero texture depth. These stresses are also analyzed mathematically.

07079 **Evaluation of field measurements of the Ankara-Eskisehir flexible experimental road**
R Yuce, U Anliatimer. E Bostanci

This study includes some of the field results for the Ankara- Eskisehir Flexible Experimental Road which was constructed in 1988 and 1989. Since September 1989, axle load repetitions, surface deflections, rut depth and crack measurements, air and plant temperatures and aggregate stock moisture contents are recorded to find correlation in between selected parameters. The MAPCON computer program is used to estimate the appropriate modulus of elasticity values for each layer to match the deflection bowl obtained under a 50 kN FWD load, whereas the ELSYM5 computer program is used to determine the critical deflections, tensile stresses and strains created in the pavement structure. It is attempted to determine the remaining fatigue life of the flexible pavement by the use of the design time concept and a flow chart is proposed for the design of flexible pavements.

07080 **Treatment of reflection cracks in Queensland**
M A Caltabiano, R E Rawlings

This paper details the steps undertaken to arrive at a recommended code of practice for the treatment of reflection cracks in Queensland. The process followed firstly identified the problem, then used a detailed experimental site on the Bruce Highway at Beerburrum to trial the use of a range of treatments, conducted a parallel research program to further understand the mechanism of cracking, and finally confirmed the results through a series of trial sites before establishing a recommended code of practice.

07081 **Mastering the quality of bituminous pavement courses**
M L Gallenne, E Layerle

The experiment that led to the monitoring of spreaders is part of a joint action by the USAP (Association of toll Motorway Companies) and contractors, with two objectives: to establish correlations between execution processes and pavement properties (evenness, density, and macrotexture) and to develop a system for the real-time monitoring of placement (contribution to operating assistance).

07082 **Design and construction of sandwich pavements for airports on soft ground**
Y Hachiya, T Ogishima, K Sato

For constructing new facilities at Tokyo International Airport and New Tokyo International Airport, sandwich type pavements have been proposed. The principle of this pavement structure is to decrease the subgrade vertical stress by introducing a stiff subbase right on the subgrade. As the sandwich pavement is not included in the current airport pavement design manual in Japan, detailed research including construction of various test pavements has been conducted. The design procedure developed through these experiences has been used successfully on two projects. This paper describes the whole process of adopting the sandwich pavement design method for airports.

07083 **End-result smoothness specifications for acceptance of asphalt concrete pavements**
W R Hudson, T Dossey, R Harrison, D G Goulias

This paper documents the development and evaluation of end-result smoothness specifications for asphalt concrete pavements in Texas. Based on available equipment and prior studies, the California Profilograph was selected as the instrument for use in developing the specification. Because there are several types of California profilographs, the study team compared two instruments by two different manufacturers. This paper presents the results of this comparison, along with a methodology for defining a recommended specification.

07084 **Evaluation of heavy duty asphalt pavements for rutting**
P S Kandhal, S A Cros, E R Brown

34 pavements across Pennsylvania were evaluated to identify the material properties, mix design parameters, pavement construction properties, and in-service properties which are responsible for premature rutting. Cores were tested to determine pavement properties. The mix was recompacted by three different compaction methods, and analyzed for voids and strength. Transverse surface profiles of the pavements were taken to determine maximum rut depths. Correlation analysis, and linear regression analysis methods were used to analyze the effect of 60 independent variables on rutting. Threshold values of significant independent variables were also established.

07085 **Improving the properties of asphalt pavements through the use of Amir Compactor: laboratory and field verification**
A E H Omar A El Halim, R Haas, W Phang

Results of previous research work carried out in the field of asphalt compaction showed that under currently designed rollers, construction induced cracks are inevitable. As a result a new compactor, Asphalt Multi-Integrated Roller - AMIR,

	was designed and built. The new roller overcomes the problems associated with current rollers and as a result produces pavements without construction cracks. The use of laboratory AMIR models confirmed the analytical findings and suggested that elimination of "hair checking" during compaction can significantly improve the mechanical properties of the compacted mix.
07086	**Asphalt concrete pavement preservation with cold in-place recycling** *D F Rogge, T V Scholz, R G Hicks, D Allen* Since 1984, the Oregon Department of Transportation (ODOT) has utilized cold in-place recycling (CIR) as one alternative to conventional asphalt concrete pavement preservation techniques. Through September 1990 over 800 Km of pavement have been recycled with most projects showing good success. This paper describes the project design and selection process for CIR. Also presented is a summary of the field performance. Recycled pavement condition, ride data, and mixture properties are presented. Expected service lives and the economics of CIR versus hot mix preservation techniques are discussed.
07087	**Performance-related specifications for asphalt concrete** *J F Shook, M A Diaz, M Stroup-Gardiner* This paper reports the results of a study to continue development of performance-related specifications (PRS) for asphalt concrete pavement by conducting a laboratory experiment to study the relationships between materials and construction (M&C) variables and fundamental response variables. The most relevant relationships between M&C variables and performance responses have been selected for presentation in this paper. All these relationships are expressed in algebraic form, and their statistical information is included. Also, included in this paper is a demonstration PRS for asphalt concrete developed using a computerized spreadsheet program. The description of the spreadsheet program addresses many of the significant factors that ought to be considered in assessing contractor bonus/penalty.
07088	**Application of new compacting technique for deep lifts and large aggregate asphalt mixes** *O J Svec* Conventional asphalt compaction is characterized by geometric and material incompatibilities at the interface between the drums and the hot asphalt mix. As a result, surface and internal cracks are frequently generated during the compacting process. To avoid these problems, a new concept for compaction was introduced. Subsequently, a prototype was built as a joint project between the NRC and a Canadian manufacturer. This prototype was termed "Asphalt Multi-Integrated Roller" - AMIR, and its performance tested in four experimental trails and one commercial project This paper describes the results of AMIR compaction of two large aggregate and two standard mixes compacted in deep lifts with or without geogrid reinforcement.
07089	**The construction and performance of polymer modified asphalt concrete pavement** *J A Scherocman, O W Schlitz* The use of polymer modified asphalt concrete mixes has increased in the United States in the last few years. The use of stone mastic asphalt mixes was also recently introduced. The mix designs used to construct three polymer modified asphalt concrete pavements, one in Germany and two in the United States, are described. Also discussed is the performance of these mixes during limited time under traffic.
07090	**Opening Ceremony** *various*
07091	**The Ann Arbor Conference: Thirty years contribution to asphalt technology** *M W Witczak, J F Skok*
07092	**Paving the gap, in design, construction, and performance - Parts I and II** *A A A Molenaar*
07093	**The SHRP final products - performance based specifications** *T W Kennedy, G A Huber*
07094	**Pavement design and materials - Past, present and future** *J P Mahoney, C A Bell*
07095	**Construction - Moderator's report** *M Acott, J Samanos*
07096	**The Construction Products Directive and Asphalt Specifications** *C A Loveday*
07097	**Impact of construction on performance** *L Domenichini*
07098	**The Partnership Contractors - Administration as regards innovation for asphalt pavement in France** *J Bonnot*
07099	**Pavement behaviour and performance: Highlights - Parts I and II** *W D O Paterson, E Horak*
07100	**Materials and mix design** *J S Moulthrop, R B Leahy, T S Shuler*
07101	**Field testing and performance measurements** *P Kadar, J Bethune*
07102	**Case studies** *I F Scazziga, G T H Sweene, P Ullidtz*

code	ISAP 8th Conference Titles & Abstracts
08001	**Long-Life Flexible Roads** *M. Nunn* A longer design life for flexible pavements, which carry the heaviest volumes of traffic, will yield a lower whole life cost. This will require strategies for design that decrease the need for maintenance and thereby cause less disruption to the road user. This paper reviews the current philosophy and criteria for design and considers information on the performance of roads that has been collected since the last revision of UK design standards, in 1984. This has demonstrated that the deterioration of thick, well-constructed, fully-flexible pavements is not structural, and that deterioration generally occurs at the surface in the form of cracking and rutting. The evidence suggests that fatigue and structural deformation originating deep within the pavement structure are not the prevalent modes of deterioration. It also shows that changes that occur to the structural properties of the bituminous materials over the life of the road are crucial to the understanding of its behaviour. These changes can help to explain why conventional mechanisms of deterioration do not occur. They imply that a road built above a minimum strength will remain structurally serviceable for a considerable period, provided that non-structural deterioration in the form of cracks and deformation are detected and remedied before they have a serious impact on the structural integrity of the road.
08002	**UK Design of Flexible Composite Pavements** *A. Parry, S. Phillips, J. Potter, M. Nunn* The UK pavement design guide has recently been updated to include new options for the construction of flexible composite pavements for heavy traffic. They are summarised in this paper. These new designs, along with those they supersede, are based upon the principal that the flexural strength of the cement-bound roadbase should be greater than the combined traffic and thermal warping stresses experienced during service. The thickness of the asphalt layers is required to limit these stresses and to reduce the severity of reflective cracking. A study of the construction and maintenance history of in-service flexible composite pavements, which have carried up to about 100 million standard axles, has revealed that the current designs are capable of carrying at least this traffic load. Ongoing studies which should lead to further improvements in the design of these pavements are identified and the results to date summarised.
08003	**New Tools for Rational Pavement Design** *B. Eckmann* The paper presents two developments aimed at the supporting of rational pavement design. In the field of probabilistic design, the possibilities of the ROSENBLUETH approximation have been evaluated. This technique consists in replacing a continuous data distribution by an equivalent discrete distribution (2 or 3 data points), which leads to considerable gains in calculation times. The validity of this approach is shown to be related to the shape of the "transfer function" which relates the considered input parameter to the calculated pavement response (e.g. a stress). The potential of the method is illustrated by an example. The NOAH software is a very powerful computation tool by which the user can investigate the sensitivity of pavement performance (as related to calculated stresses and strains) to variations of any of the involved input parameters (structural, environmental, loading). It incorporates the ROSENBLUETH method and many other specific facilities such as a built-in "Formula Generator". This confers NOAH an extreme flexibility so that it can easily be used by pavement engineers working according to different design methods.
08004	**Pavement Design and Management Guide** *R. Haas, T. Kazmierowski* A new Pavement Design and Management Guide, produced under the auspices of the Transportation Association of Canada, provides an up-to-date, comprehensive consolidation of knowledge in the field for a new generation of users. It promotes good practices among the owners of pavements and incorporates the best available technology within a systematic, organized framework. The Guide is intended to serve the needs of engineers and technologists in public agencies, industry, academia and consulting. The Guide has ten major chapters which cover (1) an introduction to and focus of the document, (2) procedures and technologies for acquiring and processing identification of data, (3) identification of maintenance and rehabilitation treatments, (4) carrying out needs analysis and priority programming, (5) description of pavement materials and their characterization, (6) structural design and economic evaluation, (7) role of construction, (8) role of maintenance, (9) implementation guidelines, and (10) issues, opportunities and future prospects.
08005	**Development of Performance Models for Ontario's New Mechanistic-Empirical Pavement Design Method** *Z. He, G. Kennepohl, Y. Cai, R. Haas* Ontario's OPAC design method, developed in the early 1970's, was mechanistic-empirically based. A key feature was the performance modeling approach which separated traffic and environment associated deterioration. A new, comprehensive "OPAC 2000" has been developed as the successor to the original OPAC. This new pavement design method is also mechanistic-empirically based, with separate load-associated and environment associated performance models. However, the updated models have been calibrated from an extensive, long-term performance data base (incorporating age vs PCI, layer thicknesses, ESALs, etc.). Moreover, they have been regionally adjusted using a clustering technique. As well, reliability analysis has been included based on the second moment approximation method to obtain variance estimates for the parameters. Validation checks indicate very reasonable results. While the framework of OPAC 2000 will be summatized in terms of the major modules and subsystems, including a comprehensive economic analysis module, the paper concentrates on the performance modeling effort and results. It is suggested that even though the calibration has been carried out with the Ontario data base, the approach is generic in that the model form is transferable and could be calibrated to other regions.

08006 **Computer Aided Overlay Design System for Flexible Pavements**
F. Bayomy, F. Al-Kandari, W. Nassar

This study presents a mechanistic-based overlay design system and its implementation in a computer program named "FLEXOLAY" for the state of Idaho. The concept adopted is based on analyzing the pavement distresses in terms of rutting and fatigue and determining an overlay thickness using strain-based fatigue and rutting models. The developed design procedures consider the past and the expected future traffic to calculate the required overlay thickness. Evaluation of existing pavements is performed by nondestructive testing using Falling Weight Deflectometer. Effect of seasonal variation is considered by employing seasonal adjustment factors for pavement layers moduli to account for each season. Seasonal factors for different climate regions in Idaho have been established and used in the environmental data base of the computer program. The program allows for entering other seasonal factors for other locations. The user has the flexibility to enter different shift factors based on local experience.

08007 **Progress and Pitfalls for a DOT-Developed Mechanistic Design Procedure**
J. Corley-Lay, Y. Qian

For thinner asphalt concrete sections, the horizontal tensile strain at the bottom of the asphalt layers obtained using Jung's technique was found to be in reasonable agreement with Thompson's AUPP. It also was in good agreement for thinner sections with backcalculation of layer moduli and using these moduli in an elastic layer program to obtain the horizontal strain. Jung's method appears to overpredict strain in thick asphalt sections.

Seasonal ratios of strain calculated using Jung's method to the strain at the initial testing period were calculated. Similar seasonal ratios were obtained for pavements of similar type and subgrade stabilization type. The seasonal ratios could be used to incorporate seasonal effects for the wet-no freeze zone of North Carolina using three seasonal periods.

Fitting time series to the backcalculated moduli of the asphalt layers and to the subgrade moduli as suggested by Ali and Parker resulted in the most direct method to incorporate seasonal effects and calculate remaining life.

Serious difficulties were demonstrated in correctly estimating the time to failure and order of failure of three similar design sections.

08008 **Research on the Design Method of Asphalt Pavement**
Y. Menyu, Z. Qisen

China has moved its national economy into a continuous upwards and stable development stage since this country implemented economic reform and "open door to foreigners policy" in the mid-1980s. This has brought a good opportunity for booming its road construction and improving highway transportation. Over the last 10 years, a large quantity of high graded highways or freeways has been built within the country. As a result, a significant change has been made from backward traffic condition to a better highway transport facilities.

In order to meet the standards of high graded highways required by Ministry of Communications of China, we organized a research group, consisting of many scientists and engineers from universities, highway research institutes and highway design agencies, to study the design method of asphalt pavement at semi-rigid base conditions. Based on the study, the previous version of the Code of Flexible Pavement Design gf Highway, JTJO14-86, was revised and now it is renamed as Code of Asphalt Pavement Design of Highway, JTJ014-97. The new code will come into effect on the first of October, 1997. The key points and major contents of the new code is described explicitly.

08009 **Dynamic Loading Effects on Flexible Pavement Performance**
B. Pidwerbesky, B. Steven, J. de Pont

Research was conducted at the Canterbury Accelerated Pavement Testing Indoor Facility investigating the influence of dynamic axle loads on pavement response and deterioration. Measurements from an earlier pavement showed that the SLAVE units subject the pavement to realistic dynamic loading.

Two tests have been undertaken, comparing the effect of steel multi leaf, twin parabolic spring and air suspensions on pavement deterioration. The second test was part of the Organisation for Economic Co- operation and Development Dynamic Interaction between Vehicles and Infrastructure Experiment (OECD DIVINE project). The results to date show a good correlation between the dynamic wheel forces and pavement distress. The modes and level of pavement distress are dependent on the particular suspension characteristics. Analysis ranks the suspensions from worst to best as steel, parabolic and air.

The results have provided the first measured evidence of a direct link between peak dynamic loads and pavement damage reported thus far.

08010 **Distribution of Tire Contact Pressure of Vehicles and Its Influence on Pavement Distress**
K. Himeno, T. Kamijima, T. Ikeda, T. Abe

This study places an emphasis on precise measurement of distribution of tire contact pressures. Komatsu Corporation has developed a new device using piezo electric ceramics sensors, which measures weight distribution within a contact area of a tire in motion. From the measured data at all the pixels, distribution of contact pressure and its average value can be obtained. The measurement was performed in summer in Tsukuba, Japan, varying tire type, traveling speed, air pressure, and wheel load.

Based on the measured data, effect of the difference between the modeled uniform and the actual distributed pressures on the pavement distress, especially fatigue cracking, is discussed, employing the multilayered elasticity theory and energy dissipation theory for prediction of the initiation of cracking.

08011 **Investigation of Flexible Pavement Response to Truck Speed and FWD Load Through Instrumented Pavements**
S. Dai, D. Van Deusen, M. Beer, D. Rettner, G. Cochran

Falling weight deflectometer (FWD) and truck tests have been conducted on the Minnesota Road Research project (Mn/ROAD) in an effort to (1) study truck speed effects on flexible pavements, (2) compare pavement response under FWD and truck loads; and (3) investigate the effects of wheel path offset on the pavement response.

Three flexible pavement sections were used for this study. The truck tests were performed at various speeds ranging from 1 0 to 103 km/h.

The results showed that on a smooth pavement (IRI=O.97 m/km) strains in the bottom of the pavement continuously reduced with the truck speed. While on a relatively (relative to the smooth pavement) rough pavement (IRI=l.74 m/km), strains in the bottom of the pavement decreased as the speed of the truck increased to a speed about 65 km/h, but the strains increased when the speed was further increased from 65 km/h to 103 km/h. The effects of the pavement surface roughness were also investigated and the influence of truck suspension type was discussed.

08012 **Mechanistic Determination of Equivalent Damage Factors for Multiple Load and Axle Configurations**
J. Prozzi, M. de Beer

The increase of the maximum axle load limit in South Africa sparked renewed interest into methods of quantifying traffic load associated damage on pavements. Extensive research with the Heavy Vehicle Simulator (HVS) over the past 20 years has led to improved fundamental understanding of pavement performance and has permitted the development of Equivalent Damage Factors (EDFs) for single-axle loads. A major limitation of this approach is that it does not directly facilitate the calculation of EDFs for multiple axle contigurations, i.e. tandem or tridem axles.

This paper describes a method for extending the existing HVS-based method to the determination of EDFs for multiple axle configurations. This, in principle, facilitates the development of guidelines on permissible axle loads and tyre inflation pressures for different axle configurations. The method assesses the effects of: wheel load, contact stress, single and dual wheels, and single, tandem and tridem axle configurations. The method, therefore, enables determination of EDFs for the accurate estimation of equivalent traffic loading for design purposes and performance analysis enhancing life predictions and management decisions.

Initial determinations indicated the advantage to road friendliness of grouping axles together into tandem or tridem configurations. Additionally, the use of dual-wheel instead of single-wheel axles could result in the axle load being increased by up to 30 percent without any increase in pavement damage.

08013 **Determination of Pneumatic Tyre/Pavement Interface Contact Stresses under Moving Loads and Some Effects on Pavements with Thin Asphalt Surfacing Layers**
M. de Beer, C. Fisher, F. Jooste

This paper describes the quantification of three-dimensional tyre/pavement contact stresses for vehicle tyres. The Vehicle-Road Surface Pressure Transducer Array (VRSPTA) system was developed to measure contact stresses under moving loads, i.e. Stress-In-Motion (SIM). Prediction equations for quantification of these stresses, based on tyre inflation pressure and loads for seven (7) different tyre types, are given. Tyre inflation pressure predominantly controls the vertical contact stresses on the pavement at the tyre centre, whereas the tyre load controls those at the tyre edges.

Analysis indicated that during instantaneous overloading / under-inflated conditions the maximum strain energy of distortion (SED) in the asphalt surfacing occurs close to the tyre edges, while under instantaneous uniform vertical stress conditions the SED is within the asphalt surfacing at the tyre centre. In addition to improved load/contact stress idealization for modelling, this finding may have important implications for the design of relatively thin asphalt surfacing layers for pavements.

08014 **Measured and Theoretical Comparisons of Traffic Loads and Pavement Response Distributions**
B. Chadbourn, D. Newcomb, D. Timm

The correlations between traftic load distributions and tensile strains in flexible pavements are discussed in this paper, and these relationships are compared against theoretical strains computed from layered elastic theory. Six flexible pavement test sections at the Minnesota Road Research Project (Mn/ROAD) were selected for the analysis presented in this paper. Wheel-weight data from the weigh-in-motion station at the Mn/ROAD site were taken for a number of time periods during 1995. Weight data distributions were then matched to temperature-corrected transverse strains measured at the bottom of the asphalt concrete in the test sections. Finally, a layered elastic analysis was performed, the results of which were compared to actual measurements under traflic. It was found that the measured strains and the strains computed from the analytical model matched well when the loads were modeled as dual wheels with constant tire pressure and a varying load magnitude.

08015 **Modification of the Austrian Guideline for Standardized Asphalt Pavements**
R. Blab, C. Molzer, J. Litzka

The Austrian guideline regulating pavement design is currently being revised in the light of increasing heavy vehicle traffic and changes in the technical equipment of heavy freight vehicles. To calculate the expected traffic load for the design period the modification will not longer employ the well-known Fourth Power Law. Instead the damaging impact on the pavement structure (with fatigue as the criterion) is determined in a direct approach from the fatigue effects due to the passage of different axle loads and axle configurations.

A comprehensive sensitive analysis examines the key components of fatigue caused by single and twin tyres and different axle configurations on asphalt pavements by taking into account their lateral distribution in the cross section of a road lane. Detailed data for lateral distributions of loads evaluated due to field measurements and comprehensive information on the distribution of axle loads and heavy vehicle types found in Austria's federal road network provide the basis for computation of mean equivalency factors for different vehicle types and characteristic collectives of heavy freight vehicles. These are used to determine the relevant design load for routine design purposes and will be incorporated in the modified Austrian design guideline for asphalt pavements.

08016 **Maximizing Shear Resistance of Asphalt Mixtures by Proper Selection of Aggregate Gradation**
R. Roque, S-C. Huang, B. Ruth

A better understanding of the influence of aggregate gradation on the shear resistance and volumetric properties of asphalt mixtures is needed to maximize the shear and rutting resistance in asphalt mixtures. Eighteen mixtures were prepared with different coarse aggregate (> 2.0 mm) gradations ranging from Stone Matrix Asphalt (SMA) to those corresponding to the maximum density line. The Gyratory Shear (Gs measurements indicated the gradation of the coarse aggregate fraction (>

2.0 mm) was related to the shear resistance of the mixtures. Coarseness, shape, and position of the gradation curve relative to the maximum density line affected the shear resistance. Mixtures including both coarse and fine aggregate fractions verified the test results obtained from the coarse-aggregate only mixtures. It was evident that coarse aggregate gradations controlled the shear resistance of the mixtures even though fine aggregate dilated the coarse aggregate structure. Crumb rubber modified (CRM) asphalt binders were generally found to have little effect on the air void content and shear resistance (Gs) of coarse- graded (e.g., SMA) mixtures.

08017 **Design and Fatigue Behaviour of Emulsified Bitumen Macadams for Highway Reinstatement**
H. Khalid, K. Eta

A mix design method has been developed for Emulsified Bitumen Macadam materials (EBMs) used in trench reinstatement operations as wearing and base course layers in flexible pavement constructions. The method considers the effect of mixing, compaction, curing, strength development and moisture sensitivity. The influence of polymer-modified emulsions on the stiffness and permanent deformation characteristics of the EBMs has been investigated. EVA and SBS copolymers have been incorporated into a conventional 100 pen emulsion at various levels in the investigation, and the resulting EBM properties were compared to the specifications advocated by the Highway Authorities and Utilities Committee (HAUC) to arrive at suitable mixes that are capable of performing adequately in service.

The conventional and selected modified EBMs were then used in a laboratory study to evaluate their fatigue behaviour, together with an equivalent hot-applied mix containing 200 penetration grade bitumen. Controlled stress three-point bending fatigue tests were conducted to arrive at strain/fatigue life relationships for the hot and cold-lay mixes. Linear elastic theory was then applied to evaluate the response of the materials to traffic loading in a typical flexible pavement model using BISAR-PC Program developed by Shell. The calculated strains were used to determine the life of the pavements with candidate mixes from the developed fatigue relationships. Structural equivalency factors for the cold-lay materials in conjunction with the hot-applied mixes were computed from the resulting fatigue lives. The fatigue analysis revealed that certain modified EBMs have the potential to perform equally to, or even better than, the equivalent hot-applied material.

08018 **Recent Activities of RILEM TC 152-PBM "Performance of Bituminous Materials"**
L. Francken, E. Eustacchio, U. Isacsson, M. Partl

A general overview on recent activities of the Technical Committee "Performance of Bituminous Materials" TC 152-PBM of the International Union of Testing and Research Laboratories of Materials and Structures (RILEM) is given, including a state of the art study on testing and appraisal of polymer modified road bitumens. All activities are within the framework of performance related mixture design and part of a basic general testing methodology. Results of three large interlaboratory tests on binder rheology and both design and repeated mechanical loading of mixtures are presented, showing general agreements and suggesting advanced methods to be implemented in the near future. The tests provided new information in addition to already known principles in the field of bitumen and bituminous materials testing methods. This opens the way for further developments to obtain better performance related standards and more durable roads.

08019 **A Reliability-Based Mix Design and Analysis System for Mitigating Fatigue Distress**
J. Harvey, J. Deacon, A. Taybali, R. Leahy, C. Monismith

A reliability-based mix design and analysis system has been developed for mitigating fatigue distress in asphalt pavements. Design decisions consider not only fundamental mix properties but also the level of design traffic, the temperature environment at the site, the pavement structural section, laboratory testing and construction variabilities, and the acceptable level of risk. This paper describes the mix design and analysis system, discusses its calibration, illustrates its use, and assesses the consistency of current California design practice vis- a-vis the control of fatigue distress. It reveals possible inconsistencies in current California design practice, discusses effects of construction variability, highlights advantages of rich-bottom pavement structures, and illustrates the integration of mix and structural components into a reliability-based mix design process.

08020 **Properties and New Developments of High Modulus Asphalt Concrete**
J-P. Serfass, P. Bense, P. Pellevoisin

The use of High Modulus Asphalt Concrete (HMAC) for base and subbase has steadily increased for the last fifteen years. Several technologies are suitable: selection of very hard bitumen, addition of asphaltite, addition of polyolefins. Rich or lean mixes can be designed. Richer mixes are easier to compact and less sensitive to water. The resistance to rutting and the stiffness moduli are similar, irrespective of the richness. The long term in-place behaviour can be rated as satiafactory. A new type of HMAC has been designed to obtain high fatigue resistance. It contains a high amount of binder, which is a composite of very hard bitumen and polyolefin. The first trial sections are being monitored. HMAC for binder and wearing courses began to be used recently. They are designed to reach not only high stiffness and excellent rutting resistance, but also sufficient surface macrotexture. The observation of the first sections laid shows no rutting under extremely heavy traffic and an overall satisfactory performance to date.

08021 **Design and Evaluation of Large Stone Asphalt Mixtures**
J. Button, E. Fernando, W. Crockford, B. Coree

A mixture design procedure was developed for large stone mixtures with maximum aggregate sizes of 25 mm to 63 mm. The design procedure makes use of existing contractor stockpile gradations with the intent of maximizing the load carrying role of the stockpile containing the largest aggregate. Evaluative laboratory test procedures were developed and tested. A full scale test pavement demonstrated the effectiveness of the procedure.

08022 **Effect of Tack Coat on Bonding Characteristics at Interface between Asphalt Concrete Layers**
Y. Hachiya, K. Sato

The effect of a tack coat on the bond between asphalt concrete layers was investigated. First, the stresses at the interface caused by aircraft loads were calculated. Second, the effect of using a tack coat was evaluated by examining samples taken from in-service airport pavements. Third, laboratory tests were conducted to investigate how bonding characteristics were influenced by dirt adhering to the existing surfaces. Finally, measures to ensure sufficient bonding were developed.

The following conclusions were obtained. The interval between the construction of the wearing and binder coarses

	influences the bond strength: the strength decreases as the interval increases because dirt accumulates on the binder course. Adhesion between the courses can be improved by applying a tack coat. The curing time of the tack coat, however, also influences the strength, and the strength after one hour of curing is much less than that after 24 hours of curing. However, satisfactory strength can be obtained by using a newly developed tack coat. In addition, the structural integrity of the surface course can be ensured by introducing a thick lift construction procedure.
08023	**Longitudinal Joint Construction Techniques for Asphalt Pavements** *P. Kandhal, R. Mallick* Thirty hot mix asphalt (HMA) test sections were constructed in Michigan (1992), Wisconsin (1992), Colorado (1994), and Pennsylvania (1995) to evaluate the effectiveness of twelve different longitudinal joint construction techniques. The performance of these test sections was evaluated in 1996 after one to four years in service. The joints with high densities generally show better performance than those with relatively low densities. The Michigan joint technique (12.5 mm vertical offset and 12:1 taper) appears to have the best potential of obtaining a satisfactory longitudinal joint. The cutting wheel and the edge restraining device techniques have good potential but are too much operator dependent to obtain consistent results. Among the three different joint rolling techniques used in all four projects, rolling the joint from hot side generally gave the best performance followed by rolling from hot side 152 mm away from the joint. Paver manufacturers should consider modifying the paver design to obtain a Michigan type, high density unconfined wedge in the lane paved first. Highway agencies should specify minimum compaction levels to be achieved at the longitudinal joint
08024	**Development of Performance-Related Specifications for Porous Pavements in Oregon** *K. Dunn, J. Gray, R. Hicks, J. Gower* The State of Oregon has employed the use of porous asphalt concrete surfaces (E and F-mixes) since the 1970s. The use of porous mixes has increased substantially in the past five years. Previously, no work had been done to evaluate whether the quality control/quality assurance (QC/QA) procedures used for dense-graded mixes were appropriate for open-graded mixes. This study consisted of a literature review, expert survey, and field survey of selected projects to determine the relative importance of the constituents (e.g., asphalt content, gradation, voids, moisture content) on the long-term performance of the pavement. The overall objective achieved by this study was the development of a basis for an improved QC/QA specification for porous pavements in Oregon. Specific objectives achieved include: 1) evaluation of experiences of others to control quality of open-graded mixes, 2) conducted a field survey of selected projects in Oregon to determine what factors most affect pavement performance, 3) recommended modifications to existing specifications which would include pay adjustments, and 4) developed a plan for implementing the resulting recommendations. This study found that the factors to be controlled during the production of porous pavements include asphalt content, gradation, and moisture content.
08025	**Quantifying the Impact of Construction Specifications on Asphalt Pavement Performance Life** *A. Noureldin* Asphalt content, aggregate characteristics, pavement layers thicknesses and their degree of compaction, and initial pavement smoothness are key quality control aspects in asphalt pavement construction. These measurable items are routinely checked during the constmction process. The overall pavement performance life may be significantly affected when the specified values of those items are not achieved in situ. Quantification of their impact on pavement performance is essential for quality roadway construction, and rational pay adjustment factors. This paper presents an approach to estimate the expected loss (or gain) in pavement performance life resulting from any in situ deviation in the above performance related characteristics from the specified values.
08026	**Field Management of Hot Mix Asphalt Mixtures** *J. Scherocman, D. Decker* The purpose of this report is to discuss the factors that contribute to the differences that occur in the properties of a Hot Mix Asphalt (HMA) mix designed in the laboratory and the properties of the "same" mix produced in an asphalt batch or drum mix facility. Emphasis is placed on the causes for the differences in the mix volumetric characteristics between the lab and the field with the understanding that laboratory mix design is only a starting point which must be verified through the HMA plant production. Major areas considered are: aggregate, asphalt binder, plant production process, hot mix storage, and hauling of the mix. This publication provides a ranking system to prioritize the importance of each factor in contributing to the differences which may exist. Therefore, this document is intended to serve as a reference to assist HMA producers in understanding variables affecting volumetric properties.
08027	**Introducing Quality System to Asphalt Mixing Plants - The Israeli Experience** *S. Nesichi, I. Choustere, M. Divinsky* Significant increase in the national asphalt hot mix production required development of the quality system in asphalt mising plants. The paper describes the quality system in detail and presents original statistical elaboration with respect to the problem under study. A major component of the quality system is a Quality Mark (QM) characteristic which is a statistical estimation for the quality of the produced asphalt mixture. Analysis of the actual data evidences that optimal quality characteristic can be derived with provision for the individual quality estimations for the diagnostic parameters such as Bulk Density, Bitumen Content, Filler Content, etc. The prediction model for the QM characteristic is presented and its advantage and sensitivity are demonstrated. The results of the analysis allow to distinguish the quality level of the plant production processes on the basis of the QM characteristic as well as prepare its quantitative estimation. The approach shows essential efficiency. and can be recommended in practical applications of quality estimations for

asphalt mixing plant production.

08028 **Evaluation of Flexible Pavements in the Middle East**
F. Chan, R. Armitage

The paper presents data from a number of sites in the Middle East where detailed pavement evaluation has been performed; generally utilising the FWD, DCP, coring/pitting and, sometimes high-speed ground radar, to determine pavement layer thickness and condition. This data has enabled both empirical and mechanistic design methodologies to be used and compared. Emphasis is made to one particular project in Qatar, where over 3000 FWD test points were analysed and relationships between deflection levels, stiffnesses, predicted lives and Modified Structural Number were developed. Data from the detailed assessment of a heavily trafficked pavement in the United Arab Emirates (U.A.E) is also given to illustrate the importance of material characterisation when developing maintenance measures. The results from the FWD were used in conjunction with performance related laboratory test results, predominantly using the Nottingham Asphalt Tester, NAT. The NAT enables stiffness, deformation resistance and fatigue cracking resistance properties of bituminous materials to be determined.

08029 *Pavement Response Due to Dynamic Axle Loads*
M. Huhtala, J. Pihlajamaki, P. Halonen

This paper describes the results of primary response measurements carried out to study the effects of dynamic loadings of vehicles on pavements. The measurements were made at the Virttaa test site in Finland as part of the OECD/DIVINE project. Two instrumented pavements and two artificial bumps were used to excite body bounce and axle hop. Instrumented vehicles were from Canada, the United Kingdom and Finland. The strains at the bottom of the bituminous courses were in almost direct proportion to the dynamic wheel loads on thick bituminous pavement. They were similar if there were air or steel suspensions or if the dynamic load was caused by body bounce or axle hop. On thin bituminous pavement the size of the changing tire imprint plays an important role and dynamic wheel loads have only a slight effect on the strains.

08030 **The C-SHRP Lamont Test Road: Five Years of Performance Monitoring**
L. Dunn, J. Gavin

As part of the Canadian Strategic Highway Research Program's study entitled "Performance Correlation for Quality Paving Asphalts" a full scale test road was constructed in 1991. The Lamont Test Road (LTR) was constructed in order to assess the low temperature transverse cracking performance of seven markedly different asphalt cements. Extensive field and laboratory testing and ongoing performance monitoring was undertaken.

This paper documents: the asphalt cement selection and physical properties; the quality assurance results; the results of subsequent SHRP Superpave laboratory grading of the asphalt cements; the results of the LTR's performance after five winters of service and; the temperature monitoring during the first three winters and subsequent weather station data for the remaining two winters.

08031 **Characterization of Stone Matrix Asphalt Mortars**
E. Brown, J. Haddock

Stone Matrix Asphalt has been used for over 20 years in parts of Europe and Scandinavia. Recently, it has gained more recognition in the United States. The mixture has been successful due in part to its durability. This durability is provided by a mortar that consists of asphalt binder, fine aggregate, mineral filler, and a stabilizing additive.

This paper details research aimed at applying the Superpave binder test methods and specifications to SMA mortars. It was found that the use of the Dynamic Shear and Bending Beam Rheometers does seem to be viable with mortars.

Data obtained with the Dynamic Shear and Bending Beam Rheometers suggests that specifications for SMA mortars can be established if the current Superpave binder specifications related to these two pieces of equipment are multiplied by a factor of 5.

08032 **The Construction and Performance of Stone Mastic Asphalt Pavements in the United States**
J. Scherocman

Stone mastic asphalt (SMA) pavements were first built in the United States in 1991 using technology obtained from Europe. It was determined, however, that significant differences exist in the aggregate properties and mix design methods used. In addition, differences in the plant production methods and in the laydown and compaction procedures are present. This resulted in a number of problems in constructing the stone mastic asphalt pavements that are discussed. To date, after up to six years of service under traffic, the performance of the SMA pavements has been excellent.

08033 **Development of a Stone Mastic Asphalt Design Method for South African Conditions**
L. Louw, C. Semmelink, B. Verhaeghe

Thin asphalt layers (of less than 40 mm thickness) are often used for surfacings in South Africa. As these layers are placed on either stiff (cemented) or flexible structures it is important that they be rut resistant, durable and have good fatigue properties. Stone Mastic Asphalt (SMA) has been gaining worldwide acceptance as a stable, durable and fatigue-resistant surfacing mix. The objective of this project was to develop a SMA design method suited for southern African conditions. This paper discusses:
- the recipe mix design methods prescribed by the various road authorities;
- basic principles of volumetric design;
- a theoretical model to determine the volumetric properties of SMA mixes, and
- various compaction methods, including the gyratory compactor and the Marshall impact hammers.

In the design of SMAs the applicability of grading envelopes is compared with volumetric properties. The laboratory results are compared with those obtained from the model. The K-mould apparatus, a dynamic triaxial loading and data acquisition system, was used to determine the rut resistance ie. dynamic creep and effective stiffness (Esec) of the material.

08034 **Effect of Surface Seals on Aging of Underlying Asphalt Concrete**

J. Button

Asphalt surface seals are defined herein as slurry seals, micro-surfacings, and chip seals (seal coats). The objective of this study is to estimate, by laboratory testing, the relative aging abatement effects of surface seals on the upper 13 mm of an asphalt pavement.

A surface seal can retard oxidative hardening of an underlying asphalt concrete layer by 0 to 2 years, depending on the situation. However, most of the oxidative aging in the upper stratum of an asphalt concrete pavement occurs during the first 4 years after construction. Therefore, in order for a surface seal to significantly delay oxidative hardening of the underlying pavement, it must be placed during the first two years (approximately) of the pavement's life. Ultraviolet (actinic) light penetrates asphalt cement only a few microns and, therefore, does not contribute materially to hardening of the uppermost 13 mm of an asphalt concrete pavement. For practical purposes, these three surface seals will protect the top 13 mm of an underlying pavement from oxidation as if they were impermeable to air and water.

08035 **Study of Maintenance Treatments for Asphalt Pavements**
D. Morian, S. Gibson, J. Epps

During the conduct of the Strategic Highway Research Programs (SHRP) on highway operations, flexible and rigid pavement preventive maintenance treatments were placed on pavements in the United States and Canada. The placement and performance monitoring of these Specific Pavement Studies (SPS-3 and SPS-4) has been conducted under the SHRP and Federal Highway Administration (FHWA) Long Term Pavement Performance Program (LTPP). Field performance reviews of the preventive maintenance treatments have also been conducted by Expert Task Groups (ETG) organized by the Pavement Division of the FHWA.

This report summarizes the results of the ETG performance surveys conducted after 5 years of service and the results of the preliminary analysis of LTPP Database data for the SPS-3 experiment.

08036 **Full Scale Performance Trials and Accelerated Testing of Hot Mix Recycling in the UK**
J. Potter, J. Mercer

This paper reviews the research carried out on the hot-mix recycling of bituminous materials over more than a decade in the UK. Results from trials on public roads and full-scale accelerated load testing of recycled roadbase in the TRL Pavement Test Facility are summarised and discussed. Hot rolled asphalt wearing course has been recycled in-situ using the Remix method with up to 80 per cent of the original surfacing material in the mix. In off-site mixing plants, recycled bituminous roadbase has been produced with up to 60 per cent of reclaimed material in the mix. Their performance in the road has been assessed by measuring longitudinal profile, transient deflection, depth of rutting, surface texture and resistance to skidding. Performance-related laboratory tests have also been carried out. In general, the trials indicate that the performance of recycled materials is as good as that of equivalent conventional materials. The results of the research have been implemented in the UK Specifications.

08037 **Progress in Hot-In-Place Recycling Technology**
R. Terrel, J. Epps, M. Joharifard, P. Wiley

The concept of recycling asphalt pavements has been attempted using a range of methods for more than eighty years. Starting with simple concepts of crushing old pavements for use in highway fill, the technology has progressed through numerous phases. The most recent began in the mid 1970s when both central plant and in-place methods were initiated. Hot central plant recycling and cold in-place recycling (CIR) has gained general acceptance by many agencies. Hot in-place recycling (HIR) has been used for nearly 50 years but public agencies have been slow to implement the technology. However, recently developed equipment and procedures have made HIR a very viable alternative for pavement rehabilitation.

HIR methods began with various equipment that used flames which impinged directly on the pavement surface then progressed through several evolutions of heating methods including infrared. The current state-of-the-art is a hot-air system that overcomes the previous limitations of shallow depth of heating, burning of the surface, and creation of objectionable smoke.

This paper includes a technical description of HIR equipment and methods and test results from early projects using the more modern, efficient equipment. The data and early performance evaluation show that the 100% recycled asphalt concrete was aged insignificantly and had laboratory test properties equivalent to virgin hot mix.

08038 **A Theoretical Model of Long Term Flexible Pavement Performance**
A. Collop, D. Cebon

A new 'whole-life' pavement performance model (WLPPM) has been developed that is capable of making deterministic pavement damage predictions due to realistic traffic and environmental loading. The WLPPM is divided into three main areas: (i) dynamic vehicle simulation, (ii) pavement primary response (stresses, strains etc) model, and (iii) material damage (surface rutting and fatigue cracking) model.

The WLPPM is used to investigate the relationships between 'hot spots' (due to peak dynamic tyre forces), and 'weak spots' (due to initial pavement stiffness variations) and long-term flexible pavement damage. The effects of spatially repeatable patterns of loading on long-term flexible pavement performance are also investigated. A method is described for simulating vehicle fleets with varying degrees of 'spatial repeatability' of dynamic tyre forces using a small number of dynamic tyre force histories. Results indicate that thinner pavements are most sensitive to the level of spatial repeatability exhibited by the vehicle fleet. Pavement damage predictions made without assuming an appropriate level of spatial repeatability can be in error by 20-150%, the higher values being for thinner pavements that fail by fatigue damage.

08039 **Resin Modified Pavement: A Composite Paving Material**
G. Anderton, R. Ahlrich

Resin modified pavement (RMP) is a composite pavement surfacing that uses a unique combination of asphalt concrete and Portland cement concrete materials in the same layer. The RMP material is generally described as an open-graded asphalt concrete mixture containing 25 to 35-percent air voids which are filled with a resin modified portland cement

grout.

The RMP process was developed in France in the 1960s under the trade name "Salviacim" as a fuel and abrasion resistant surfacing material. RMP was introduced into the United States pavements industry by researchers at the U.S. Army Engineer Waterways Experiment Station (WES) beginning in 1987. WES researchers were hoping to develop a cost effective and easily-constructed alternative to portland cement concrete. Numerous full-scale field applications have since followed.

This paper gives a general description of the RMP process, including discussions of structural and material designs as well as construction techniques. Performance of significant field applications and the projected future of RMP are also discussed.

08040 **Calibrating Mechanistic Flexible Pavement Rutting Models from Full Scale Accelerated Tests**
W. Kenis, W. Wang

This paper summarizes research conducted at the Federal Highway Administration (FHWA) to validate and calibrate two different flexible pavement mechanistic permanent deformation models. The research uses internal calibration method and demonstrates applications of the method using rutting performance data generated from selected full scale accelerated pavement tests.

Since 1970, the FHWA has sponsored research both nationally and internationally on a wide variety of topics dealing with flexible pavement performance modeling. Some of these efforts led to the development of the VESYS mechanistic flexible pavement analysis system. This system is capable of performing pavement primary response analysis and performance prediction. A recent version, VESYS 5, includes two flexible pavement rutting models, "system rutting" and "layer rutting" models, along with other pavement performance models to predict pavement performance for different pavement materials under daily traffic loading and under different climatic seasons. Also under the FHWA sponsored programs, several full-scale pavement testing programs have been developed to better understand and quantify pavement performance under controlled tragic loads. Among those full-scale testing programs, a permanent, outdoor Accelerated Loading Facility (ALF) was constructed at FHWA and has been in operation since 1986. The ALF tests are conducted under controlled conditions, therefore, it provides a valuable source of data for validating, calibrating and improving currently used flexible pavement performance models.

In this study, selected sets of field performance data from FHWA's ALF testing program were used to validate and calibrate the two flexible pavement rutting models used in VESYS 5. A procedure for mechanistic model calibrations using of full-scale test data was established. It was further shown that the calibrated rutting model can be used to predict the rutting performance of other flexible pavements.

08041 **Finite Element Simulation of Damage Development in Asphalt Concrete Pavements**
A Scarpas, R. Al-Khoury, C. van Gurp, S. Erkens

An extensive experimental and analytical investigation is being currently carried out on the mechanisms leading to the initiation and propagation of fatigue damage in the top layers of asphalt concrete pavements when subjected to various types of loading. One of the major goals of the investigation is the development and finite element implementation of a triaxial, strain rate sensitive, history and temperature dependent constitutive model for asphalt concrete under arbitrary states of stress.

Because of the hierarchical formulation of the model, the analyst can activate, at will, those features of the model which he considers relevant to his specific interests. Explicit procedures are suggested for the experimental determination of the parameters. As a minimum, only uniaxial test results are needed for determination of the basic parameters. An actual example of such a procedure is presented.

In its current, prototype formulation, the model has been implemented in the finite element code CAPA3D. Results of the utilization of CAPA-3D for the investigation of the dynamic non-linear response of asphalt concrete pavements are reviewed in the last part of this contribution.

08042 **Theory, Validation and Application of the Visco-Elastic Multilayer Program VEROAD**
P. Hopman, R. Nilsson, A. Pronk

VEROAD is a linear visco-elastic multilayer program. The acronym VEROAD stands for Visco-Elastic Road Analysis Delft. The program takes fully account for both the viso-elasticity of the asphalt material and the movement of the wheel. Thus the actual time dependent displacements, stresses and strains and the permanent deformation are obtained, fully three-dimensionally. From these quantities others can be derived: the dissipated energy due to the passage of a wheel, the effect of lateral wandering on permanent deformation, the principal stresses, the rotation of the principal stresses, etc.

The underlying theory is described shortly. The program has been validated by comparing the longitudinal and transversal strains measured in full scale tests with those calculated by using VEROAD. The agreement can be called excellent. The field of application is obvious. It ranges from analyzing full scale test results to pavement design, from mix design to analysis of the damaging effects of different wheel configurations. In the article also attention is paid to the experimental determination of the material parameters to be used in VEROAD.

08043 **Bimodular Analysis of Asphalt Pavements**
M. Mamlouk, P. Khanal

When wheel loads are applied on the pavement surface, both tension and compression are developed in the asphalt concrete layer. Laboratory tests were conducted on asphalt concrete specimens under different dynamic loading and temperature conditions. Largely different tensile and compressive moduli were obtained, especially at high temperatures.

A nonlinear finite element multi-layer program that can account for the bimodular nature of asphalt concrete (BIMODPAV) was developed. The program applies traffic loads in increments, checks the stress state at each element, and selects the appropriate modulus accordingly using the modulus values obtained from the lab tests. The BIMODPAV program was further used to analyze stresses, strains and displacements in typical pavement sections under different conditions. The results indicate that pavement response parameters calculated by the bimodular analysis are significantly different from those calculated by assuming a single modulus value. Using single-modulus analyses erroneously over-predict fatigue

and rutting pavement lives as compared to those obtained from the bimodular analysis. The effect of bimodularity is most significant for pavements with a thick asphalt layer and/or at high temperatures. The mechanistic analysis technique developed in this study allows pavement to be designed in a more scientifically-based manner.

08044 **Finite-Element Dynamic Analysis of Distressed Asphalt Pavements**
W. Uddin, Z. Pan, P. Noppakunwijai, C. Plaxico, R. Hackett

Three-dimensional finite-element pavement-subgrade models are developed in this study to simulate falling weight deflectometer (FWD) loading on highway pavements. Reasonably good agreement is found between FWD deflections measured on selected pavements and computed dynamic deflections for pavement models subjected to the FWD load pulse and contact simulation. Effects of loading force-time history and pavement cracking on the surface deflections response of an asphalt pavement are also presented. The creep modulus of asphalt mix is predicted using a micromechanical model which calculates the viscoelastic response from creep compliance test results of the binder and elastic properties of the aggregates.

08045 **Evaluation of the Interaction Between the Asphalt Concrete Layers by a New Dynamic Test**
M. Crispino, B. Festa, P. Giannattasio, V. Nicolosi

To study the dynamic interaction between flexible pavement layers a special equipment was designed and built and a testing methodology was also developed. Theoretical analysis and initial testing have demonstrated qualitative aspects of the phenomenon. On such basis it was suggested to represent the horizontal interaction between flexible pavement layers as a structural restraint following Kelvin's model. The representing parameter has been defined by the authors as: Interlayer Reaction Complex Modulus KI*. The statistical characteristics of the test developed were evaluated, together with the values of the norm (absolute value) and of the phase angle (between load and deformation) of the vector KI* at two different temperatures. Statistical analysis has shown that test reliability is adequate for research purposes but still low for normalization. The test and the parameter KI* appear to be suitable for the representation and evaluation of the interaction between asphalt concrete layers for flexible pavements.

08046 **Modelling of Granular Materials Using the Discrete Element Method**
P. Ullidtz

With the Discrete Element method it is possible to model materials that consists of individual particles where a particle may roll or slide on other particles. This is interesting because most of the deformation of granular materials is due to rolling or sliding rather than compression of the grains. This is true even of the resilient (or reversible) deformations. It is also interesting because the Discrete Element method models resilient and plastic deformations as well as failure in a single process.

The paper describes two types of calculations. One on a small sample of angular elements subjected to a pulsating (repeated) biaxial loading and another of a larger sample of circular elements subjected to a plate load. Both cases are two dimensional i.e. plane strain.

The repeated biaxial loading showed a large increase in plastic strain for the first load pulse at a given load level. Additional load pulses at the same load level gave decreasing plastic strain rate, in agreement with what is normally observed on granular materials. The resilient modulus was much lower than the stiffness of the elements and was decreasing with increasing deviator stress. At high deviator stresses the stiffness of the assembly of elements was less than one percent of the stiffness of the elements. This is also in good agreement with observations on granular materials.

Plate loading showed a distribution of vertical stress that was close to the stress in an elastic continuum. Very little stress concentration was observed, but this might change if angular elements were used. The horizontal stresses on the other hand were quite different from the horizontal stresses in an elastic continuum. Modulus and Poisson's ratio calculated at different points of the particulate medium, from the stresses and strains, showed large variations. Dilation of the material was frequent.

08047 **Mechanical Properties of Unbound Base Course**
J. Belt, T. Ryynanen, E. Ehrola

A laboratory-scale pavement testing facility with a moving vehicle load can be used to simulate reliably the stresses caused by traffic in the road structure and is therefore well suited to the testing of materials and structures. The measuring system developed here can be used to determine reliably both elastic and permanent deformations within the structure, which, in turn, can be used to determine relative strains.

The mechanical properties of the unbound base course and their significance for the performance of the whole road structure depend on the thickness of the bound layer and the quality of the material. When the asphalt concrete (AC) layer is thin, it would be good to have grading with Fuller's "n" value equal to 0.4 or 0.5 in the unbound base course. When the bound layer consists of very soft asphalt, in turn, it would be good to aim at a grading curve with "n" = 0.5. A large maximum grain size in the base course minimizes both permanent and elastic strains.

Compaction of the unbound layers also has a distinct effect on the mechanical properties of the layer. A high degree of compaction minimizes permanent strains. Effective compaction, however, results in grinding of the materials. The compaction of unbound rough materials and their grinding during compaction can be evaluated with the Intensive Compaction Tester gyratory compactor both quickly and inexpensively.

08048 **A Comprehensive Constitutive Model for Granular Materials in Flexible Pavement Structures**
R. Bonaquist, M. Witczak

This paper summarizes research leading to the development of a comprehensive constitutive modeling approach for granular bases, subbases, and subgrade soils. The model that was developed is based on the flow theory of plasticity. It rationally considers both the resilient and permanent deformation response, and accounts for the effects of repeated loading and saturation and drainage conditions. The model can be used to predict pavement performance, to select pavement layer thicknesses to resist permanent deformations, and to select material properties to assure adequate performance. This paper describes the conceptual model development. It also presents results from a laboratory evaluation of the constitutive model using three materials covering the range of materials typically classified as granular in pavement construction. Finally, the modeling concepts are applied to practical pavement design problems.

08049 **Assessing Seasonal Variations in Cohesive Subgrade Soils**
W. Khogali, K. Anderson

In 1990, an investigation was initiated to measure seasonal variations in subgrade stiffness of cohesive soils in Alberta. The main objective of this study was to identify and select suitable strength indices for measuring seasonal variations in pavement response.

The study consisted of two phases: a field investigation phase and a laboratory testing program. The field phase involved instrumenting an in-service pavement section in Alberta with thermal conductivity sensors to measure temperature and soil suction. This data coupled with Falling Weight Deflectometer deflection tests performed within the instrumented section were used to accomplish the research goals.

The laboratory program consisted of extensive repeated load testing on remolded samples of the subgrade material taken from the instrumented site. Results obtained from these tests were used to develop predictive resilient moduli relationships.

Both field and laboratory phases produced novel and practical approaches for quantifying the influence of seasonal variations on subgrade strength.

08050 **Mechanical Behaviour of Soils and Unbound Granular Materials, Modelling of Flexible Pavements - Recent Advances**
J. Balay, A. Gomes Correia, P. Jouve, P. Hornych, J-L. Paute

Different European Laboratories (Administration, Universities) were awarded a laboratory twining project between 1990 and 1993, under the "Science" programme, which closure has taken place with Euroflex '93 Symposium (Lisbon, 1993). This research aims to harmonise and develop rational procedures to take into account the mechanical characteristics of soils and unbound granular materials, to apply into the design of flexible pavement structures.

A round-robin test programme for unbound granular materials carried out by different laboratories enable to establish reliable test procedures for characterisation of elastic and plastic behaviours of these materials. The procedure for elastic behaviour is summarised in this paper. Concerning the modelling of flexible pavements structures, the behaviour of unbound granular materials was described by a non linear elastic constitutive law (Boyce), with which a classic plasticity criterion was added (Drucker-Prager) in order to give a stress field in the material compatible with its strength.

This model was implemented in FEM codes: CESAR LCPC-2D and 3D, and Noel 8-2D of University of Nantes. The results of FEM-2D (single wheel) and FEM- 3D (dual wheel) calculations realised for most representative flexible pavement structures are presented.

08051 **Pavement Subgrade Performance Study in the Danish Road Testing Machine**
H. Ertman Larsen, P. Ullidtz

Most existing pavement subgrade criteria are based on the AASHO Road Test, where only one material was tested and for only one climatic condition. To study the validity of this criteria and to refine the criteria a co-operative research program entitled the "International Pavement Subgrade Performance Study' was sponsored by the FHWA with American, Finnish and Danish partners.This paper describes the first test series which was carried out in the Danish Road Testing Machine (RTM).

The first step in this program is a full scale test on an instrumented pavement in the Danish Road Testing Machine. Pressure gauges and strain cells were installed in the upper part of the subgrade, for measuring stresses and strains in all three directions. During and after construction FWD testing was carried out to evaluate the elastic parameters of the materials. These parameters were then used with the theory of elasticity to calculate the stresses and strains at the position of the gauges and to compare these values to the stresses and strains recorded under the rolling wheel load.

Plastic strains resulting from 50,000 applications of each of two load levels (20 kN and 40 kN) were recorded, as well as the permanent deformation of the pavement surface. A simple model describing the plastic strain bas been developed.

The test showed that currently used subgrade strain criteria are conservative if used with the measured strains in the subgrade. If used with strains calculated from FWD tests using linear elastic theory, however, the strain criteria seem to give a reasonably good prediction of the bearing capacity of the pavement. The differences between measured and theoretical values appear to be due to inhomogeneities in the pavement, to the non-linear elastic subgrade modulus, and to a modulus gradient in the subgrade.

08052 **A Regression Model for Better Characterization of Resilient Properties of Subgrade Soils**
A. Puppala, L. Mohammad

Subgrade soil characterization in flexible pavement design is necessary for estimating the structural capacity of flexible pavements and then determining tbe pavement layer thicknesses. Several non-linear and linear models have been used to characterize the subgrade soils. The current bulk and deviatoric stress models have limited applications since they are essentially developed for a particular soil type. Few other models are restricted by the multiple collinearity problems in the regression analysis. A regression model with confining and deviatoric stresses as attributes is adopted in this paper to analyze the repeated load triaxial test results. This model is simple, easy to analyze the repeated load triaixial test results and does not have any structural type collinearity problems. This paper presents the regression model analysis results on different subgrade soils including mixed soil types. The repeated load triaxial tests conducted on granular, cohesive and mixed soil types at various moisture content levels are first analyzed to determine the model constants. The model constants are then correlated with the basic soil properties. The correlations are evaluated in their reliability in predicting the resilient properties of the same subgrade soils. This evaluation, which is fairly successful, showed that this approach can be used to predict the resilient properties of similar type soils. This approach will save significant project costs since core sampling and resilient modulus testing tasks can be averted.

08053 **Specimen Preparation and Repeated Load Triaxial Testing of Subgrade Soils**
S. Baltzer, L. Irwin

This paper presents part of the research work being performed under the "International Subgrade Performance Study"

sponsored by the Federal Highway Administration (FHWA). The objective of the subgrade study is to define one or more predictive models that will relate rutting to soil type, stress/strain level, and soil moisture conditions. Full-scale instrumented flexible test pavements will be constructed in the Frost Effects Research Facility at the U.S. Army Corps of Engineers Cold Regions Research and Engineering Laboratory (CRREL) and at the Danish Road Institute (DRI). Accelerated loading will be used to simulate traffic, and pavement performance will be measured. As part of the research work, repeated-load triaxial testing of both resilient and plastic properties of the subgrade soils will be performed. Characterization of resilient properties is being done at Cornell University. Special testing equipment and procedures for specimen preparation have been developed. The procedure produces specimens with a uniform density and moisture gradient. The test plan for repeated-load triaxial testing of resilient modulus, and plans for model building from the results are described.

08054 **Asphalt Mix Fatigue Behavior Experimental Structures and Modeling**
H. Odeon, J-C. Gramsammer, C. Caroff

An extensive research program on asphalt mix fatigue was conducted jointly by the LCPC (French transportation research laboratories) and Scetauroute (French highway engineering agency) between 1990 and 1994. The program included tests on the LCPC circular fatigue test track and a theoretical analysis of the behavior of structures. This article looks into the parts of the program dealing with the fatigue tests and modeling. The aim of this program was to clarify the behavior in the laboratory and on pavements of asphalt mixes differing only in the type of asphalt. Additionally, it involved adding constituents to improve the design method in the case of high-modulus asphalts. On the fatigue test track more than 7 IO^6 load sequences were applied to twelve structures over the course of three experiments. The experimental pavements revealed similar behavior in asphalt concrete of the same thickness, and the good performance of high-modulus materials whenever proper thicknesses were used. The model made it possible to determine a correlection coefficient in connection with rigid materials for the French pavement design method and brought out the value of controlled-force tests.

08055 **Fatigue Behavior of Asphalt Mixes: Influence of Laboratory Test Procedures on Fatigue Performances**
C. de La Roche, N. Riviere

Since 1990, the LCPC carried out three "semi-scale" experiments on its test track aimed at studying the fatigue behavior of asphalt mixes in the aspect of the influence of the nature of asphalt.

The large amount of laboratory tests carried out on the six different tested materials show that, if the modulus is a value relatively independent of the measurement method, the fatigue behavior in the laboratory strongly depends on the test procedure (frequency, temperature, two or three points bending, controlled force or displacement, with or without rest period). The results obtained don't allow to choose one type of fatigue test as more relevant than another one in all cases.

A systematic study carried out in laboratory in order to better define the data obtained from the fatigue tests highlights the energy dissipated in the form of heat during the continuous tests. It also points out that the differences in the results between the continuous and discontinuous tests are probably not attributable to an actual healing of the material during the rest periods.

08056 **Comparison of Fatigue Criteria for Flexible and Semi-Rigid Pavements**
J. Judycki

The paper presents comparison of fatigue criteria which are used in mechanistic methods of pavement design. The following criteria were considered: (a) for fatigue cracking of asphalt layers and structural rutting (subgrade strain): LCPC and SETRA (France), Nottingham University (United Kingdom), Road Research Centre in Belgium, Shell and The Asphalt Institute (USA) and (b) for fatigue cracking of bases treated with hydraulic binders: CSIR (South Africa), Road Research Centre in Belgium, University of Illinois (USA). The aim of the comparison was to select suitable fatigue criteria for the revision of the 20-year old Polish catalogue of typical pavements which was required due to significant increase in traffic volume and in axle loads.

In the paper the fatigue formulas for all the considered criteria were given and fatigue curves were compared. Pavement structures with different base courses were designed for a range of traffic volumes with regard to various fatigue criteria and Polish design considerations. The designed structures were compared with pavement structures included in the old Polish catalogue of typical pavements which performance can be evaluated as acceptable. On this basis the following criteria were selected as suitable for Polish conditions: (a) for fatigue cracking of asphalt layers and structural rutting (subgrade strain) - The Asphalt Institute (USA), and (b) for fatigue cracking of cement treated bases - CSIR (South Africa), Road Research Centre in Belgium, University of Illinois (USA). New typical pavements structures were designed according to the selected fatigue criteria.

08057 **Possibilities of a Semi-Circular Bending Test**
M. van de Ven, A. de Fortier Smit, R. Krans

The possibilities of a Semi-Circular Bending (SCB) test on semi-cylindrical specimens is investigated as an alternative to the Indirect Tensile Test (ITT) to determine the flexural strength, stiffness and fatigue behaviour of asphalt concrete. Finite element analysis relations for the stresses and deformations under SCB have been derived. Based on these relations the tensile strength and fatigue behaviour of two asphalt mixes were determined with laboratory tests. These results have been compared with ITT results on the same mixes.

It can be concluded that the SCB gives results comparable with ITT for the tensile strength. The determination of stiffness requires accurate measurement of the relatively small vertical deformations under loading. Fatigue tests can also be carried out. The SCB test can be used as a mix design test for performance related specifications and a reliable quality control test for mix production and road construction. A standard test set-up is proposed.

08058 **Stiffness and Fatigue Characteristics of Some Asphalt Wearing Courses Used in South Africa**
N. Kong Kam Wa, H. Theyse, B. Verhaeghe, E. Knottenbelt

This paper deals with an extensive research program into the upgrading of the fatigue transfer functions of asphalt mixes in use in South Africa. Parts of the program have recently been completed and the aim of the paper is to summarise and discuss the results obtained to date. Two stages of the program are discussed in this paper: a comparison of stiffnesses of asphalt mixes obtained from different sources, and the evaluation of the fatigue life of laboratory asphalt mixes and

development of laboratory fatigue regression models.

In the first of the above-mentioned stages, stiffnesses of asphalt mixes were determined in the laboratory (using the Indirect Tensile Test) and from two theoretical stiffness prediction models (Shell method and Asphalt Institute method). Attempts were also made to backcalculate field stiffness using the Multi-Depth Deflectometer (MDD) results of four Heavy Vehicle Simulator (HVS) field tests. In the second stage fatigue tests were undertaken in the third- point beam fatigue test apparatus in the constant strain mode at various strain levels. Regression models were developed for the following independent variables: strain, temperature, initial flexural stiffness, load frequency, aggregate grading and binder type.

The findings indicate that the Shell BANDS- program and the Asphalt Institute's equation (AI) can be used for an approximate determination of asphalt stiffness, provided that the methods are used correctly. There is also some indication that there is a correlation between the resilient modulus obtained in the Indirect Tensile Test and the actual effective field stiffness, but this has to be verified by further studies. In the second part of the investigation it was found that the fatigue regression models obtained from this study gave a higher life than other models such as those of the Asphalt Institute, TRRL and NCHRP. The coefficients of determination obtained were, however, very good.

08059 **Fatigue Analysis of Asphalt Pavements with Thick Asphalt Mixture Layer**
T. Nishizawa, S. Shimeno, M. Sekiguchi

In the prevailing structural design of asphalt pavements, fatigue cracking at the bottom of asphalt mixture layer is considered to be a major failure mode of the pavement structure. In Japan, however, such failure has rarely been observed in the asphalt pavements with thick asphalt mixture layer including asphalt stabilized base course which has been in service for more than 20 years. Failure modes of the asphalt pavements are rutting and surface cracking. The asphalt stabilized base courses in such pavements have been alive without major repairing. Therefore, the concept of the structural design should be reconsidered in terms of the fatigue cracking.

We conducted fatigue analysis for various asphalt pavements with thick asphalt mixture layer in Japan. Radial strains at the bottom of asphalt mixture layer and vertical strains at the top of subgrade were calculated. Then, fatigue damages were estimated by applying the calculated strains to fatigue curves presented in the manual. In the analysis, wheel load distributions were taken into account by employing the Miner's law. The results of the fatigue analysis showed that the fatigue crack at the bottom would occur in the asphalt pavements with thick asphalt mixture layer in less than 10 years. The results do not agree with our field experiences mentioned above.

We made an assumption that, at the strain level of less than 200 micro, asphalt mixture would not fatigue because of the healing effect. Being based on the assumption, we conducted the fatigue analysis again. The results of the analysis seemed to be quite reasonable and agree with our experiences in Japan.

08060 **Variability in Roadbase Layer Properties Conducting Indirect Tensile Test**
S. Said

Knowledge of variabilities in the properties of asphalt pavement layers is valuable in the structural evaluation of pavements. Mix composition and construction procedure influence the mechanical properties of bituminous layers. Fatigue and stiffness characteristics are two of the most important parameters in input data to pavement evaluation models. In this study, more than 300 cores from 15 test sections were drilled from roadbase layers for determining mix composition, fatigue and stiffness properties. These cores have been tested at different temperatures when conducting the Indirect Tensile Test (ITT). The ITT, which is probably most suitable for examining specimens from pavement layers, has proved to be sufficiently accurate for routine use, such as determination of mix properties, and also in quality control. A good correlation has been found between laboratory based and field based fatigue curves for the roadbase mix.

Statistical fatigue relationships based on the laboratory measurements are also presented and the effects of the variabilities in the mix properties are illustrated. It is hoped that knowledge of the characteristics of bituminous pavement layers with their variations and the use of ITT in routine measurements may contribute to further utilization of pavement evaluation models by road engineers.

08061 **Comparison of 2 and 4 Point Fatigue Tests and Healing in 4 Point Dynamic Bending Test Based on the Dissipated Energy Concept**
A. Pronk

At the 4th Eurobitume Symposium a fatigue life definition was introduced, which was based on the dissipated energy concept (Hopman et al, (1989)). This new definition is based on a change in a material related aspect (dissipated energy per cycle) instead of a specimen property. It was shown that, using the dissipated energy law and this new fatigue life definition, the results were exchangeable for strain and stress controlled fatigue tests even at different frequencies. These experiments were only carried out in a 4 point dynamic bending test. In this paper the results are presented of a comparison of fatigue lives measured in 2 and 4 point dynamic bending tests. In spite of the new fatigue life definition, the results are not comparable for both tests. This may be due to the composition of the mix at issue and the small dimensions of the specimen in the 2 point bending test.

Also the healing phenomenon is studied in the 4 point bending test. Rest periods between loadings ought to enlarge the fatigue life considerably. After a resting period the stiffness modulus is largely restored. If instead of resting periods (with zero loading), load blocks are used with a smaller load amplitude, it is shown that during these pseudo rest periods the stiffness modulus will increase. Depending on the duration of the pseudo rest period and the amplitudes of the loadings, this increase will be followed by a decrease in stiffness modulus. These findings confirm the opinion that healing already takes place during the fatigue process and should be taken into account in the interpretation of the fatigue measurements and the characterization of the fatigue properties. Based on the dissipated energy concept a model is proposed taking into account the healing phenomenon. This model should enable a more fundamental description of the asphalt fatigue properties including healing.

08062 **Development of Performance Prediction Models for Dry-No Freeze and Dry-Freeze Zones Using LTPP Data**
K. Senn, D. Frith, M. Yapp, L. Scofield

The Long Term Pavement Performance (LTPP) program is currently in the eighth year of a twenty year project to monitor and collect pavement data on approximately 800 general pavement studies (GPS) sections across the United States and Canada. This paper focuses on GPS 1 sections (asphalt surfacing on a granular base) located in the Dry-Freeze and the

Dry-No Freeze zones of the Western United States. Approximately 50 sites were selected from these two zones.

Using data collected from the LTPP sites, this paper presents the analyses used to develop pavement performance prediction models. Performance is measured in terms of individual distress types, such as roughness and fatigue cracking. A discussion of the problems inherent in such a process is also included.

The authors concluded that although it was possible to recognize performance trends, developing meaningful prediction models was not feasible for GPS sections. It was recommended that future analysis along similar lines focus on specific pavement study (SPS) sections.

08063 **Development of Deterioration Models for Cold Climate Using Long-Term Pavement Field Data**
H. Jamsa, H. Spoof, L-G. Wagberg, N-G. Goransson, W. Hudson

The paper describes the results of the Long-Term Pavement Performance (LTPP) study carried out in Finland and Sweden on the GPS-1 experiment (asphalt concrete on granular base). The main results include new pavement deterioration models which are based on a failure time approach using censored data on 64 test sections. A large number of independent variables were examined to identify factors which explain most of the pavement deterioration on wheel paths (traffic related distress) and on a whole pavement surface (traffic and climate related distress). The most important factors explaining deterioration included tensile strain at the bottom of the asphalt layer, or the surface curvature index calculated from FWD measurements and the freezing index. In addition to deterioration models, a new neural network approach to calculate tensile strains on the basis of measured deflection bowl and asphalt layer thickness is introduced.

08064 **Comparison of Accelerated Pavement Test Results with Long Term Pavement Behaviour and Performance**
F. Jooste, S. Kekwick, E. Sadzik, G. Rohde

A comparison was made of pavement behaviour and performance as measured during an accelerated pavement test conducted by the Heavy Vehicle Simulator (HVS) in 1980, and actual behaviour and performance of the same pavement section measured in 1996. Behavioural aspects such as deflection, Dynamic Cone Penetrometer shear strength, moisture and density were found to correlate reasonably well with measurements made during the accelerated pavement test 16 years earlier. Rutting measured in 1996 compared well with rut depths measured during the accelerated pavement test at a similar number of equivalent standard axles. Rut development as measured during the accelerated pavement test also compared well with predictions made with the World Bank's Highway Design and Maintenance Program (HDM). Results obtained indicate that, for the pavement section studied, environmental effects did not significantly change the behaviour and performance of the pavement.

08065 **Performance Prediction of Accelerated Loading Facility (ALF) Trials Using Elastic, Visco-Elastic and Elasto-Plastic Analysis**
W. Yandell, G. Behzadi

Most current methods of flexible pavement design take only the stiffness of materials into account in terms of the resilient modulus and the theory of linearized elasticity is utilzed to determinee the principal criieria of rutting and fatigue life. The need to incorporate elastic and vlsco-elastic or plastic models into practical flexible pavement design procedure is now well founded. The main purpose of this research is to demonstrate the importance of plastic parameters and their attendant residual stresses and strains on pavement life.

The elastic and plastic behaviour of materials from three Accelerated Loading Facility (ALF) sections were characterized using a repeated load triaxial apparatus. The Mechano-Lattice (ML) elasto-plastic, Visco-elastic (VESYS) and linear elastic (adapted CIRCLY) analysis were used to predict the performance of three ALF trials. It was found that the predicted rutting by Mechano-Lattice in all cases was close to the field and was superior to VESYS and adapted CIRCLY methods. VESYS and Mechano-Lattice analysis have shown that in Somersby section no cracking should occur before 7.3 x 10^5 repetitions of 80 kN load. This is supported by ALF test results. The CIRCLY analysis has shown that cracks will happen before the above repetitions. By ML analysis it is observed that if residual stress accumulation was ignored, bottom lateral cracks would commence according to CIRCLY predictions, but residual compression stress cause the transient stresses to reduce as passes continued.

08066 **CALTRANS Accelerated Pavement Testing (CAL/APT) Program - Test Results 1993-1996**
W. Nokes, J. Harvey, L. du Plessis, F. Long, P. Stolarski

Results to date (Fall 1996) from the Caltrans Accelerated Pavement Testing (CAL/APT) Program are discussed and include those for the Phase I program and initial results from the Phase II program.

The Phase I program involved a study of the comparative performance under Heavy-Vehicle-Simulator (HVS) loading of Caltrans dense-graded asphalt concrete (DGAC) and asphalt-rubber, hot mix, gap-graded (ARHM-GG) as overlays on a fatigue-cracked asphalt pavement and an evaluation of pavement rutting from channelized traffic resulting from simulated Automated Vehicle Control Systems (AVCS).

The initial part of the Phase II program includes an evaluation, under HVS-loading, of the performance of two pavements, one containing an asphalt-treated permeable base (ATPB) and the other an aggregate base (AB), designed and constructed according to Caltrans procedures. The HVS testing of pavements for the Phase I program was performed in South Africa while the Phase II program is being conducted at the University of California at Berkeley (UCB) Richmond Field Station.

Laboratory tests have been performed for both phases at UCB involving evaluations of the stiffness and permanent deformation characteristics of the various pavement components and fatigue characteristics of the asphalt mixes. These results have been used to analyze the performance of the HVS-loaded pavements.

By combining the results of both the HVS and laboratory tests, interpretations of pavement performance are described and recommendations for pavement design and construction have been made to Caltrans.

08067 **The Impact of the Heavy Vehicle Simulator (HVS) Test Programme on Road Pavement Technology and Management**
F. Rust, S. Kekwick, E. Kleyn, E. Sadzik

The political and socio-economic changes in South Africa over the past five years have had a significant influence on the South African HVS programme. From a fleet of three production machines operating solely in South Africa since 1978, only

	one now remains in the country, while the other two are used in the CalAPT programme in California. Nevertheless, the SA HVS programme has, in turn, had a marked impact on the development of pavement engineering technology in South Africa and has demonstrably effected significant savings to the country. In particular, the focus of the programme has been redirected to address the issues currently facing the South African road building industry. This Paper gives an overview of the history and current status of the SA HVS programme and highlights the impact of the programme on both technological advances in pavement engineering and cost savings to the industry.
08068	**Mechanistic Evaluation of Fatigue Damage Growth and Healing of Asphalt Concrete: Laboratory and Field Experiments** *Y R. Kim, H-J. Lee, Y. Kim, D. Little* Fatigue damage growth and healing of asphalt concrete are studied in this paper using laboratory and field experiments. The field study was performed using the stress wave technique on asphalt pavement sections with varying degrees of damage. The elastic modulus of an asphalt concrete layer is calculated from the stress wave data using the dispersion analysis based on Short Kernel Method. The laboratory study employs two fundamentally different approaches to modeling the mixture fatigue behavior; continuum approach and micromechanical approach. The continuum approach applies the elastic-viscoelastic correspondence principle to eliminate the time-dependence from the hysteretic behavior of asphalt concrete under cyclic loading. Pseudo stiffness, stiffness after the application of the elastic-viscoelastic correspondence principle, decreases following a characteristic S-shape curve due to the fatigue damage growth when plotted against number of loading cycles. This curve is vertically shifted when rest periods are introduced, resulting in a longer fatigue life. The same trend is observed from the field study between the elastic modulus and the number of loading cycles. Work potential theory, a continuum damage theory based on thermodynamics of irreversible process, is then applied to the laboratory data to model the changes in pseudo stiffness due to fatigue damage growth and microdamage healing. The resulting model is found to be mode-of-loading independent and capable of predicting the changes in stress-strain behavior under compound loading histories with multi-level loading and varying durations of rest. A validation study is performed on the fatigue performance prediction model using the data obtained from uniaxial fatigue testing of AAD and AAM mixtures under constant stress/strain amplitude cyclic loading histories with and without rest periods. Finally, a micromechanical approach is presented which describes a fracture process as a balance between the energy imparted to the system and the energy taken up by the newly created crack surfaces. Different microdamage healing behavior of AAD and AAM mixtures described by the coefficients in the continuum damage model is explained by the difference in micromechanical properties between the two binders, such as total cohesive surface energy and different proportions of the Lifschitz-Van der Waals and the acid-base components in the surface energy.
08069	**Fatigue Life Prediction Using Visco-Elastic Analysis** *G. Rowe, S. Brown* Several pavements were tested with a wheel tracking device to determine the fatigue performance. The use of the visco-elastic method (with a dissipated energy criteria) was compared to elastic analysis for those pavements tested. Strains measured in test tracks show that, in the longitudinal direction, compressive strains occur which are followed by a tensile peak and then compressive strains again, whereas, in the transverse direction, the strain is all tensile. If a visco-elastic model is employed, non-symmetrical stress/strain responses can be calculated. Further analysis illustrates that using asphalt material properties associated with a visco-elastic model the effect of multiple wheel passes on the strain response could be explained with reasonable accuracy. Analysis of pavements produced a similar ranking to the performance obtained in the test pavements and indicated that as temperature is increased, life decreases, consistent with fatigue calculations by other techniques.
08070	**Using Paris' Law to Determine Fatigue Characteristics - Discussion** *S. Erkens, J. Moraal, A. Molenaar, J. Groenendijk, M. Jacobs* This paper consists of three parts, which are related to a new fatigue characterisation method that was developed at the Road & Railroad Research Laboratory (RRRL) of the Delft University of Technology. The basic idea behind this method is the use of Paris' law to determine the fatigue properties of an asphalt mix. In the first part of the paper the background of this method will be discussed. In this section a theoretical justification of the use of Paris' law to describe fatigue cracking will be presented, as well as experimental data to support that justification. In the second part of the paper this method will be described. An overview of the types of tests as well as the data processing procedure will be presented. For a more elaborate presentation of the complete method, the reader is referred to Jacobs (1995), Erkens et al. (1995) and Sabha et al. (1995). In the third section the modifications that resulted from additional research at the RRRL, intended to modify the procedure for application on another asphalt mix are discussed. From this paper it can be concluded that crack growth covers a major part of the fatigue process. Thus, Paris' crack growth law provides an approximation of the overall fatigue life. Furthermore, it is shown that the parameters in the crack growth law can be determined using simple tests. The fatigue characteristics that were predicted using this approach, agreed well with actual fatigue data.
08071	**The Rehabilitation of the N1 Freeway Between Cape Town and Paarl** *M. White, J. van der Walt, C. van der Merwe, E. Pretorius* This paper describes the rehabilitation of three different pavement types existing within a 35 km section of a heavily trafficked dual carriageway freeway between Cape Town and Paarl, South Africa. This freeway was originally constructed between 1968 and 1973 and the first stage of the rehabilitation was carried out in 1985. A further detailed investigation of the structural and functional condition of these pavements using the South African mechanistic pavement design approach was carried out in 1993. Various rehabilitation measures were selected to best suit the three different pavement types and the second stage of the rehabilitation was carried out in 1995 within a limited budget. The freeway pavement should now be able to carry the projected twenty year design traffic loading of 6.5 x 10^6 equivalent 80 kN axle loads. A rut resistant, continuously graded asphalt surfacing was used and rolled in, precoated stone chips were added to provide a skid resistant surface.
08072	**Design of (Reinforced) Asphaltic Overlays** *A. de Bondt, A. Scarpas*

In the field a designer faces a lot of problems when the effectiveness values of overlay alternatives have to be assessed; especially if the existing pavement is cracked or jointed. Since the effectiveness of alternatives such as applying modified bitumen, fibres, stress-relieving systems or reinforcing systems is site dependent, designers have to consider more than one alternative in their analysis and implement the optimum one. In the paper a design methodology is presented which focusses on the reflection of cracks from an old surface into and through an overlay. It is the result of a six-years project at Delft University of Technology encompassing field measurements, laboratory testing, theoretical development and numerical simulations. Within the methodology the evaluation phase is build-up in such a way that its results can be used directly for the design phase.

08073 **Thin Asphalt and Double Seal Rehabilitated Lightly Cemented Pavements: Evaluation of Structural Behaviour and Life Cycle Costs**
W. vdM Steyn, M. de Beer, A. Visser

A multi-year Accelerated Pavement Testing research programme was initiated to study the behaviour of rehabilitated Lightly Cemented Pavement (LCP) structures. The aim of this work was to quantify the structural behaviour of these rehabilitated pavements, and to optimise the life-cycle cost for the road agency.

The main findings were that the rehabilitated LCPs tested in the study only failed in terms of permanent deformation due to pumping of fines in the wet condition (G1 crushed stone and thin (< 50 mm) asphalt rehabilitation options) and bleeding of the double seal (double seal rehabilitation option).

The economic analysis of these rehabilitated LCPs, indicated that the double seal rehabilitation option is the most economical option for traffic classes with equivalent traffic demands less than or equal to 10 million equivalent standard axles, while the G1 crushed stone rehabilitation option was the most economical option for 10 to 30 million equivalent standard axles.

08074 **Testing and Analysis of the TxMLS Test Pads at Victoria, Texas**
D-H. Chen, M. Murphy, C. Pilson, W. Hudson

Hundreds of Falling Weight Deflectometer (FWD) tests were conducted to characterize the material properties of the test pad under accelerated trafficking. Cores were obtained to verify pavement thickness and to determine material properties in the laboratory. In addition, FWD tests were performed on an instrumented pavement section, and pressure cell and MDD data were simultaneously collected. Structural analysis of the pavement was performed by examining results from numerous sets of layer moduli. FWD deflections were used to determine layer moduli through backcalculation. Theoretical stress and strain were then computed using multi-layered elasticity based programs. The theoretical stress and strain were then compared to the measured pressure and strain. Furthermore, pavement life was computed using distress models suggested by the Asphalt Institute and then compared with the actual termination life determined in the field. The findings are presented in the paper.

08075 **A Rational Evaluation of Pavement Performance Using the Texas Mobile Load Simulator (TxMLS)**
F. Hugo, T. Scullion, N-K. Lee, K. Fults, T. Visser

The paper gives an overview of findings from the first three MLS test pads. Distress occurred as both rutting and cracking. However, the extent of each distress type varied between the test pads. This was unexpected since they had similar structural compositions. Changes in pavement response and material characteristics were monitored during testing using NDT. Tools used for measuring performance included a profilometer and a procedure for capturing and monitoring cracks. A diagnostic evaluation showed that the differences were probably related to varying subgrade strength, and poor performance of the lime treated limestone river gravel base and the asphalt surfacing due to water ingress and aging.

08076 **Validation of Some Superpave Design Parameters by Wheel Testing with the Scale Model Mobile Load Simulator**
M. van de Ven, A. de Fortier Smit, R. Lorio, R. McGennis

The validation of SUPERPAVE has become an important issue. The SUPERPAVE parameters selected for validation were aggregate grading and Fine Aggregate Angularity.

The Model Mobile Load Simulator (MMLS) and a Simple Shear Tester (SST) were used for the validation. The results of these tests are compared with South African specification tests.

It was concluded that it is difftcult to design a fine aggregate mix which satisfies the SUPERPAVE level 1 requirements for low design traffic. Small variations in the nominal maximum aggregate size of a mix may change the restricted zone of that mix. The result of this for a particular mix tested was that it passed through the restricted zone but performed well nonetheless. Fine Aggregate Angularity had a significant effect on the rutting susceptibility of a mix tested. This effect, while apparent under MMLS loading, was less apparent in the results of dynamic creep and SST testing. The dynamic creep and SST tests were found to be performance indicators. These tests, however, should be supported by actual performance tests, such as the MMLS test.

08077 **Long Term Ageing of Pure and Modified Bitumen: Influence on the Rheological Properties and Relation with the Mechanical Performance of Asphalt Mixtures**
L. Francken, A. Vanelstraete, A. Verhasselt

This paper presents a study of the behaviour of eight road binders (one reference bitumen and 7 modified bitumens) used in porous asphalt wearing courses of an experimental road built in 1985. The complex moduli as well as different other characteristics of the binders were determined on the original binders and mixtures. A relationship between the complex modulus of binders and that of the corresponding mixtures has been validated for the case of modified bitumens. The complex moduli as well as different other characteristics of the binders were determined after different exposure times in a laboratory simulated long term ageing test. For some of the binders, these results were compared with the results obtained on tbe binders extracted from cores on the mixes, in service for 12 years. It was investigated whether the complex moduli of the aged mixes could be estimated on the basis of that of the aged binder, with the help of the relationship between the complex modulus of the binders and mixtures.

08078 **Do Superpave Binder Tests Reflect Long Term Pavement Performance Better Than Traditional Tests?**
M. Partl, H. Fritz

Recovered binders from a Swiss long term pavement performance (LTPP) study have been investigated with dynamic shear and bending beam rheometer to evaluate whether superpave binder tests reflect LTPP better than traditional tests. In addition, tests were performed to quantify changes that may occur due to long-term storage at room temperature. The results show that the new superpave binder tests are valuable tools to assess binders from old pavements but should be further analyzed, for example, by master curves and Black diagrams. It was found that on a large scale basis superpave binder tests lead to a ranking similar to traditional tests, especially for warm temperature characteristics. As, on the other hand, traditional tests are often the only link to original pavement data, this type of tests should still be performed in parallel for LTPP studies. Finally, it was found that long-term storage may reduce the penetration considerably.

08079 **Effect of Polymer Modifiers on Dense-Graded, Heavy Duty Pavement Mixtures**
R. Freeman, J. Newman, R. Ahlrich

This study was initiated to investigate some potential benefits of polymer modification on dense-graded, heavy- duty pavement mixtures, The following polymers were used to modify asphalt binders and mixtures: an ethyl vinyl acetate (EVA), a low-density polyethylene (LDPE), a styrene butadiene styrene (SBS), an hydrogenated SBS, and a finely ground tire rubber. Each of the polymers was blended with one or more of the following asphalt cements: an AC-10 and three sources of AC-20. Both conventional and recently-developed test methods were performed on the binders and mixtures to study the effects of the polymer modifiers at both low temperatures and high temperatures. Standard Marshall mixture design procedures did not optimize the mixtures containing tire rubber and dense-graded crushed limestone. The effect of polymers on low-temperature properties was dependent on the modifier/polymer combination. Ground tire rubber was particularly effective at these low temperatures. The high-temperature performance of an AC-20 mixture, produced with crushed gravel, was improved by modification with an SBS.

08080 **Evaluation of Design and Construction Effects on Asphalt Pavements Performance Through a Portable In-Situ Shear Test Device**
A. El Halim, I. Rickards, R. Haas, R. Abdel Nabi

One of the main objectives of SHRP has been the development of more reliable testing methods for assessing the field performance of asphalt pavements. The methods and equipment developed by SHRP indirectly evalute field performance and mechanical properties by the laboratory testing of samples. A concentrated research effort was directed to extending the SHRP methodology by developing a portable, in-situ shear strength test device. This device was designed and fabricated at Carleton University, and is known as the Carleton In-Situ Shear Strength Test device (CISSST).

This paper presents a description of the development and details of the device, its use in the field and the results of a variety of field situations. The results show the profound effect of road geometry (in-situ shear strength of up to 60% higher on a straight line as compared to curved sections), the effect of taking cores to the laboratory for testing (in-situ shear strengths can range up to 300% higher), and the effect of traffic on the in-situ shear strength.

08081 **Volumetric Considerations in Testing, Construction, and Performance of HMA Pavements**
M. Stroup-Gardiner, D. Newcomb, R. DeSombre, R. Olson

Volumetrics describe the relationship between the mass of matter and the volume it occupies. Density, a quotient of mass to volume, is the most commonly used parameter for HMA mix design, quality assurance, and quality acceptance. The proper use of density measurements depends strongly upon the ability to accurately and precisely measure both the desired volume and mass of the mixture. Three independent studies were conducted to investigate the variability of density measurements (i.e., various measurements of bulk specific gravities), control of volumetric proportions during construction, and the influence of in-place densities on pavement performance.

08082 **Asphalt Content by the Ignition Method: Virginia's Experience**
B. Prowell, R. Schreck

In 1995, the Virginia Department of Transportation (VDOT) adopted the ignition method as an alternative to chlorinated solvent extraction for quality control and acceptance of hot-mix asphalt. The production of trichloroethane was outlawed in the United States on December 31, 1995, as part of the 1990 Clean Air Act Amendments.

Implementation of the ignition method was accomplished through a training program jointly sponsored by VDOT and the industry. Approximately 75% of the industry began using the method in 1995.

Field data from four standard VDOT mixes were evaluated. The mixes were produced at different plants and contained different types of aggregate from different sources. Test data from the ignition furnace, solvent extraction, and nuclear asphalt contents are provided.

As a result of VDOT's favorable experience with the ignition method, this method is mandatory for all VDOT QC/QA.

08083 **The Retained Thickness Index: A Quick Tool for Network Evaluation**
W. Hoyinck, C. van Gurp, M. Jacobs, J. Hiemstra

This paper presents the approach of the Retained Thickness Index (RTI) for the assessment of the residual structural integrity of asphalt pavements on the network level. Lacroix Deflectograph deflections and distress identification served as major input variables. The procedure makes use of the whole deflection basin and is not restricted to application of the maximum deflection only. The approach provides additional data on cracking origin (top-down or bottom-up) and crack propagation, and can be used in combination with the commonly used analysis methods.

The Retained Thickness Index is based on the flexural rigidity, inferred directly from the deflection bowl, and the occurrence of cracking observed in the wheelpaths. Both input parameters can be collected quite quickly.

Verification of the model was performed in 1996 on some fifty test sections of the SHRP-The Netherlands programme. This paper describes an attempt to fine tune the methodology. To this end some thirty test sections on the county network of Gelderland were made available, which is gratefully acknowledged by the authors. Analysis of Deflectograph testing, cracking surveys and asphalt coring on cracks attributed to establishing the accuracy of the predictive method.

08084 **Backcalculation of Pavement Layer Moduli Using Genetic Algorithms**
S. Kameyama, K. Himeno, A. Kasahara, T. Maruyama

A new method was developed to backcalculate pavement layer moduli from pavement surface deflection, measured by an FWD, using genetic algorithms, It was found that layer moduli can be accurately estimated by backcalculation using this method, with surface deflection calculated by the theory of elasticity for layer structures as the input condition. This method was also applied to data of asphalt and concrete pavements, measured by the FWD. The results showed that backcalculated moduli could sometimes be estimated even in the case where an appropriate solution could not be obtained by conventional backcalculation methods.

08085 **Performance-Based Asphalt Mix Properties in Relation to Preventive Pavement Maintenance**
A. Loizos, J. Fatseas

In the present work the major findings concerning the data analysis of a Long Term Pavement Performance study, focusing on the evaluation of the asphalt mix performance in relation to preventive pavement maintenance, are presented and discussed. The performance study comprised laboratory tests for both the original and the in-service bituminous materials, as well as destructive and nondestructive tests on the in-service pavements. The stiffness of the existing asphalt concrete layers was estimated using laboratory mechanical tests, traditional component analysis, as well as backanalysis based on FWD tests. In addition, the fatigue strength of the existing asphalt mixes was estimated. After a longer time period the pavement remaining life predicted through the fatigue analysis was validated by performing FWD tests on the non-maintained pavements, as well as pavement condition distress assessments. The results of the analysis showed that the interpretation of the asphalt mix performance based on FWD tests can give useful information for possible rational pavement preventive maintenance requirements. The laboratory estimated asphalt mix properties are to some extent still necessary for supporting the relevant engineering judgments for the interpretation of the FWD-based backanalysis.

08086 **Evaluation of Spring Thaw Load Restriction and Deflection Interpretation Techniques**
D. Van Deusen, C. Schrader, G. Johnson

A study was undertaken to evaluate criteria used to predict when to place and remove springtime load restrictions. The objectives were to (1) evaluate current springtime load restriction procedures, (2) investigate pavement strength changes in relation to springtime freeze-thaw events, and (3) suggest a more rational method for determining when to remove the load restrictions.

Mn/DOT load restriction placement and removal dates for a ten year period were tabulated and compared to predictions based on the existing model. Data collected from eight different flexible pavement test sections, including falling-weight deflectometer, resistivity probe, and in situ strain gauge data, were used to assess environmental effects on pavement strength.

It was found that, while the existing procedure works well for predicting the onset of thaw, the predicted thaw durations were higher than field observations. Deflection tests indicated that the period of minimum strength coincides with the approximate time that thawing is complete.

08087 **Comparative Studies of Deflectometry with Benkelman Beam and FWD Supported by Mechanistic Analysis and Repeated Load Testing**
L. Motta, J. Medina, J. Macedo, C. Albernaz

Deflectometry of two road experiments in Brazil was made using both the Falling Weight Deflectometer (FWD) and the Benkelman beam (BB). Deflection basins measured by these two instruments were compared to computed basins obtained through the finite element method and using resilient moduli results of repeated load testing. Measurements were made in different layers of pavement structures under construction. Noureldin's simplified procedure for backanalysis was used together with Benkelman beam measurements.

08088 **Comparisons Between Laboratory and In Situ Determined Asphalt Concrete Moduli**
N. Thom, R. Elliot, L. Cheung

One of the key parameters for analytical design or evaluation of a pavement is the stiffness modulus appropriate to each layer. This paper discusses both the laboratory determination of stiffness modulus, by means of the Indirect Tensile Stiffness Modulus (ITSM) test, and in situ determination, by means of the Falling Weight Deflectometer (FWD). Their complimentary roles are highlighted by means of several examples. The role of ITSM testing in allowing proper temperature correction of FWD data is presented. A comparison of laboratory and in situ moduli is seen to provide information on crack severity, material variability and debonding.

Finally, these stiffness modulus tests are set in the context of a full pavement evaluation and their role in providing vital evidence on overall pavement condition is shown.

08089 **Long-Term Performance Study for Asphalt Pavements**
L. Sun, X. Liu, Z. Xu

Based on the analysis to the pavement data collected in 5 Districts covering about 12,000 km long highway, a pavement performance equation with a general form has been developed, and with the equation, the effects of the pavement structural component, pavement bearing capacity, traffic and environmental condition on the pavement performance have been analyzed. The study results show that the pavement surface course thickness has a major effect on the pavement performance, the following are ESAL, deflection and base course type, and that in the early stage of performance curve, the surface course thickness plays a dominant role, while in the later stage, the effects of deflection become more significant than in the early stage. The analysis shows that in the 5 Districts mentioned in this paper, the service life difference of pavements due to the climatic condition reaches up to 22%.

08090 **The Separate Effects of Traffic Loading and Environment on Rutting and Cracking Trends of Asphalt Pavements**
D. Mfinanga, H. Ochiai, N. Yasufuku, H. Yokota

Road pavements deteriorate with traffic loading and environment but the separate effects of these factors are not yet well defined especially with age or environment. This paper aims at finding the separate effects of these two factors on asphalt pavement rutting and cracking. It is believed that this will lead to better modeling of pavement deterioration by clearly understanding and treating the two factors as separate entities. A methodology was devised to separate the two effects, in

which pavement age is used to represent the cyclic effect of environmental forces, and analysis was carried out. Results show how each of these factors influence pavement rutting and cracking and provide a further understanding of the influence of some of pavement parameters on pavement rutting.

08091 **Pavement Performance Test for Innovative Design Method**
V. Rikovsky, I. Gschwendt

In 1987 was published the Catalog of flexible and cement concrete pavements prepared on the base of analytical-empirical design method. This papers deals with an improved design procedure for asphalt pavements on the base of new theoretical knowledge and experiences with modified and new road building materials and result of asphalt pavements behavior on circular test track (CTT VUIS-CESTY Research company Bratislava). The CTT has been used for test on six pavements structures under 11.5 kN axle load. The research program resulted in development on classification of used materials and innovation of design method using fatigue strength as a criterion.

08092 **Five-Year Performance Evaluation of Asphalt Pavements at Bibi New Test Road**
S. Nakagawa, A. Ogasawara, A. Kasahara

In order to transfer from the conventional and empirical asphalt pavement design method used in Japan to a mechanistic design method, a test road was constructed on National Highway 36 in Hokkaido, in August 1990. The test road, called the Bibi New Test Road has eight different pavement structures. Since its construction, traffic monitoring, and surface distress and deflection surveys have been regularly conducted. Performance data have been obtained regarding surface distress and deflection for up to 6.2 million of equivalent 49kN wheel load. The performance curves in relation to the surface distress were approximated by the exponential function with correlation coefficients of 0.98 and greater. The Structural Suitability Index (SSI), based on fatigue damage to the asphalt mixture, was proposed as an index of structural adequacy. The SSI performance curves were approximated by the exponential function with correlation coefficients of 0.93 and greater.

08093 **A Comparative Study of Performance of Different Designs for Flexible Pavements**
N. Khosla, N. Kim, S. Satish, Y. R. Kim

This paper describes the results of a comparative study of performance of different pavement designs in North Carolina. Testing was carried out at an instrumented test facility constructed on the US 421 Bypass near Siler City, North Carolina. The experimental stretch was about seven and a half miles long and was composed of 12 pavement section types, two of each type in two directions of traffic (having different expected traffic loads), for a total of 48 sections. Based on field measurements, such as stress, strain, and distress survey analysis, the performance of the various sections were analyzed. Subgrade stabilization was found to provide the maximum assistance to the pavement sections. Sections with asphalt concrete bases performed better than sections with aggregate base courses. Cement- treated base course sections performed the worst. Also, in this study, it was noticed that almost all the rutting was limited to the asphalt concrete layers.

08094 **Pavement Performance Modelling using LINTRACK**
J. Groenendijk, L. Dohmen, A. Maagdenberg, A. Miradi, A. Molenaar, C. Vogelzang, M. de Beer

Accelerated load testing (ALT) facilities like the LINTRACK are believed to be an essential tool in the development of improved performance models for asphalt pavements. It should however be realized that even such facilities are only capable of modelling real life conditions in a simple way. For that reason ALT studies undertaken in the Netherlands have the primary goal to improve response and damage models, which in turn can be used for performance predictions. This paper first describes the main features of the ALT studies performed in the Netherlands on a thick (150 mm) and thin (70 mm) asphalt pavement on a sand subgrade. These show that the current Dutch design model is unable to fully describe the behaviour of these pavements. Therefore, three suggested improvements to this design model are described:

1) Mix-wise prediction of fatigue characteristics for practical conditions from simple tests.

2) Calculation of strains and stresses using a linear visco-elastic multi-layer approach.

3) Modelling of the wheel load, using a rectangular, non-uniform three-dimensional distribution of contact stresses.

08095 **Subgrade Strain Criterion for Limiting Rutting in Asphalt Pavements**
B. Pidwerbesky, B. Steven, G. Arnold

The subgrade strain criterion for asphalt pavements was investigated by instrumenting pavement layers and underlying subgrades. Vertical compressive strains under wheel loads were recorded under accelerated and normal rates of loading. Four test pavements in the Canterbury Accelerated Pavement Testing Indoor Facility (CAPTIF), Christchurch, New Zealand, and one in-service pavement were included in the research. The asphalt surfacings were 2.5 mm to 85 mm thick, the subsurface granular layers were 135 mm to 300 mm thick, and the subgrade CBR ranged from 4%to28%.

Vertical compressive strains measured in the unbound granular layers and subgrade of flexible pavements are substantially greater than predicted values. Vertical compressive strains in unbound granular layers under thin asphalt surface layers can be equal in magnitude to the subgrade strains. A new subgrade strain model is developed and presented in this paper, which substantially reduces the required thicknesses of overlays.

08096 **Permanent Deformation and Fatigue Properties of Polymer Modified Asphalt Mixes**
S. Maccarrone, A. Ky, G. Gnanaseelan

An investigation was undertaken to evaluate permanent deformation and fatigue characteristics of polymer modified asphaltic mixes. The investigation included a laboratory testing program and a field evaluation of performance using an accelerated loading facility (ALF). Binders evaluated included the polymer types commonIy used in Australia for hot mix applications. Mix testing included wheel tracking at 60°C to examine permanent deformation and beam testing for fatigue characterisation.

Results of ALF traffickmg shows the permanent deformation of the polymer modified mixes is lower than conventional mixes both in magnitude and in rate of deformation. Laboratory wheel tracking is shown to correlate weII with ALF results. Compaction has a large influence on both fatigue and elastic properties of asphalt mixes. Using the Shell fatigue relation

as an indicator of field fatigue performance of bituminous mixes, relative fatigue multipliers for the various polymer modified binders were estimated. Finally binder parameters which best correlate with permanent deformation and fatigue properties are discussed.

08097 **Study of Rutting of Wearing Courses on the L.C.P.C. Test Track**
J-F. Corte, Y. Brosseaud, J-R Kerzreho, A. Spernol

In the last years three experiments have been carried out with LCPC accelerated loading facility to investigate the rutting resistance of different wearing courses. As far as asphalt concretes were concerned, attention was paid to the influence of the nature of the binder, keeping the other parameters constant. The reference mix was selected with a given proportion of rounded sand and a 50/70 pen grade pure bitumen. The performance of this material was compared to mixes with polymer modified binders, special bitumen and bitumen with additives. These materials were used in a 8 cm thick surface layer. A comparison was also made with a high modulus asphalt concrete as a bounding layer covered by a very thin bituminous concrete. Depending on the experiments the loading axles were single large wheels or common dual wheels. A heating system was tested to increase the temperature in the pavement upper layers. Data were obtained on the influence of the material type, loadings, and temperature on rutting.

08098 **Determination of Viscoelastic Properties from Indirect Tension Test**
W. Zhang, A. Drescher, D. Newcomb

This paper presents two test procedures, the constant load and haversine load, for determining the viscoelastic properties of asphalt concrete using the indirect tension (diametral compression) test. Equations for calculating the creep compliance and complex compliance from test result are derived. Locations of change in length measurements are recommended. Details of data reduction algorithms and the pros and cons of the two procedures are discussed. A series of laboratory tests were conducted on two groups of specimens to illustrate the methodology and verify the analysis.

08099 **Mechanistic-Empirical Modelling of the Permanent Deformation of Unbound Pavement Layers**
H. Theyse

This paper describes recent research the aim of which was to develop permanent deformation design transfer functions for unbound pavement layers from Heavy Vehicle Simulator (HVS) test data. Two types of data generated during an HVS test are used to develop the permanent deformation models on which the design transfer functions are based. These are the in-depth deflection and permanent deformation data obtained from the Multi-Depth Deflectometer (MDD) measurements taken at regular intervals during an HVS test. Test data from a number of HVS tests, selected from the moderate and wet regions in South Africa, were used for the development of the permanent deformation models.

A multi-dimensional, conceptual model for permanent deformation was developed and calibrated with HVS test data for pavement foundation and structural layers of different material qualities. These models provide permanent deformation design transfer functions at different expected performance reliabilities for unbound pavement layers in South Africa.

The use of these design transfer functions is illustrated by a number of examples. The design approach allows each of the pavement structural layers and the pavement foundation to contribute to the total deformation or surface rut of the pavement structure.

08100 **Predicting Ruts Caused by Soft Subgrade**
N. Thom

Rut prediction, whether stemming from deformation in asphalt or soil, has always been a particularly difficult area for the pavement engineer. This paper centres around a predictive technique for soils and granular materials and presents two examples where the technique has been used and appears to be a sufllciently accurate tool for achieving meaningful results. One example is of trafficking at a laboratory scale, the other relates to airfield pavement design. The derivation of the model itself is described and the means of obtaining model parameters discussed. Finally its role in pavement design is examined and recommendations made for its use.

08101 **Implementation of LAMBS Technology: A Partnership Approach**
A. Thomson, B. Nothnagel, P. Myburgh

This paper describes a carefully managed process of introducing new research outputs into practice. Specification of LAMBS (Large Aggregate Mixes for Bases) on five major road construction projects, provided a unique opportunity to structure the implementation process so that this new product could be successfully implemented, and so that the LAMBS technology could be refined as a result of the lessons learned. It demonstrates that significant advantages attach to a cooperative process which forestalls adversarial actions and promotes more cost-effective application of professional skills. The liaison process, which included a diverse group of participants, is outlined, and the achievements of the group are described. These include improvement of the LAMBS technology, development of new contract procedures, and enhancement of asphalt production and paving expertise in the field of large aggregate mixes. The partnership approach used provides a model for successful implementation of new technology.

08102 **Framework for the Development of a South African Product Performance Guarantee System for the Asphalt Industry**
B. Verhaeghe, J. Maree, G. Rutland, R. Vos

The paper deals with the development and implementation of a Product Performance Guarantee System (PPGS) in the South African asphalt industry. The proposed system comprises the formal management of product performance guarantees, in which acceptance criteria are based on the performance of products rather than on their compliance with current prescribed specifications. The system supports aspects such as innovation in materials and design, conditions for acceptance based on performance indicators, as well as formal quality management systems and their development and implementation in the industry. The development and implementation of PPGS are currently proceeding incrementally.

08103 **Comparison of Superpave with Conventional Pavement Design**
R. May, R. Anderson, D. Perdomo

This paper contains an evaluation of Superpave Mix Analysis performance modeling for three pavement projects. Test results of the Superpave Shear Tester (SST) and the Indirect Tensile Device (IDT) are presented, along with calculated material properties and performance projections for each section. Pavement performance is estimated in terms of fatigue

cracking and permanent deformation.

The asphalt concrete overlay constructed at each site was designed using the Superpave Mix Design procedure with materials selected based on the aggregate and binder criteria included in the Superpave system for the traffic and climate of the location. Material properties were affected by binder content and temperature.

Superpave predictions were compared to the results determined using the Asphalt Institute's DAMA analysis program and the AASHTO design equation. Although these determinations are based on varying assumptions, behavior and distress modeling, material characteristics, and design parameters, there was agreement in some cases. Specific inconsistencies are discussed.

08104 **Use of the K-Mould in Determination and Analysis of the Elastic and Shear Properties of Road Materials for Flexible Pavements**
C. Semmelink, F. Jooste, M. de Beer

This paper describes a laboratory test system for the rapid determination of the elastic and shear properties of road building materials, including asphalt. The system includes a dynamic loading and data acquisition system, commonly referred to as the "K-mould". The computer-controlled loading and data acquisition systems are described briefly. Typical material parameters such as stress dependent elastic modulus and Poisson's ratio, cohesion and friction angle are determined from a single test specimen. Some typical results and their application are discussed in this paper. The paper also discusses methods that were used to validate the laboratory-derived results. This was done by evaluating deflection basins measured by Multi-Depth Deflectometer (MDDs) and also by comparing with Falling Weight Deflectometer (FWD) results.

08105 **Effect of Asphalt Mixture Master Compliance Modeling Technique on Thermal Cracking Performance Evaluation Using Superpave**
W. Buttlar, R. Roque

One of the main components of the Superpave mixture design and analysis system, originally developed under the Strategic Highway Research Program (SHRP), is a mechanics-based thermal cracking performance prediction model (TCMODEL). Thermal stresses are predicted by TCMODEL based upon a viscoelastic characterization of the asphalt mixture at low temperatures. The sophisticated viscoelastic stress analysis performed carefully tracks the stress history of the mixture, and consequently, mixture properties must be known at very long loading times. The time-temperature superposition principle has been employed to allow the required properties to be obtained from creep tests of relatively short duration. However, the techniques originally used in Superpave to construct the creep compliance master curve have been found to be problematic (Buttlar and Roque, 1996a). New analysis techniques are presented which were found to produce accurate performance predictions with as little as 100 seconds of creep testing and without the need for supplementary binder data.

08106 **The International Society for Asphalt Pavements and Its Mandate**
R. Haas

It is my pleasure to welcome all of you to this 8th Conference on behalf of the International Society for Asphalt Pavements. Our Society is now 10 years old. It was formed at the time of the 1987 Ann Arbor Conference. As you know, however, these Conferences actually go all the way back to 1962, and even though 1972 was in London, 1982 in Delft, 1992 in Nottingham, 1997 of course in Seattle and 2002 in Copenhagen (which will be described in the closing Plenary Session), we still refer to them colloquially as the Ann Arbor Conferences.

Proceedings of these Conferences represent one of the most extensive repositories of knowledge and information in the asphalt pavement field.

In summary, our basic mandate is to ensure the continuity of these premier international events in the asphalt pavement field, to support other regional or international forums and conferences in the intervening years, and to promote the exchange of information world wide on key issues and technology in the asphalt field. We strive to recognize practical problems facing the industry and to cooperate with national, regional and local groups.

08107 **Paving The Gap: Research Into Practice**
P. Teng

The Federal Highway Administration's (FHWA) Pavement Technology Program has the primary goal of developing, delivering, and deploying the improved technologies that will ultimately lead to better performing, more durable, and more cost-effective pavements. The program covers five areas: asphalt; portland cement; analysis, evaluation, and management; advanced research; and long-term pavement performance. The Asphalt Pavement Technology Program is dedicated to unifying and accelerating the evolution of asphalt pavement structural design, asphalt mix design, and performance-related specifications. To roll out these technologies in the next 5-6 years, FHWA is working closely with its State, industry, and academia partners.

08108 **Future Issues Facing the Hot Mix Asphalt Industry**
M. Acott

This paper will describe some of the critical issues facing the HMA Industry. I have had the benefit of input from the South African Bitumen Association (SABITA) - Piet Myburgh and Rob Vos, the Australian Asphalt Pavement Association (AAPA) - Ray Farrelly and John Bethune, the European Asphalt Pavement Association (EAPA) - Max von Devivere, plus our involvement in many study tours that visit NAPA or tours we have initiated. While I am presenting this international perspective, and may include some personal asides, the thrust of this paper is supported by these associations. The not-so-surprising conclusion is that we have many common issues and approaches. The bottom line is that we are now in an era of significant change for the Hot Mix Asphalt (HMA) Industry. It will go down in the history books!

08109 **The Asphalt Global Community**
E. Miller

The need exists today more than ever for a strong Asphalt Global Community. Environmental issues, crude supplies, politics and policies, emerging technology, and the impact of rapidly-expanding world communications all drive the demand

for an improved international exchange of knowledge in asphalt pavements. Each individual, each country, and each association must take the time to determine where and how they fit into this global community. Whether it be through an improved International Society for Asphalt Pavements or through some other newly-formed Asphalt Global Alliance, a blending of technology and an exchange of scientific information will continue to occur. The problem, if any, is the sporadic nature of the exchange. The Asphalt Institute supports an increased pace in establishing more formal communications bridges via a global networking system and an increased focus on research and marketing to expand the use and improvement of asphalt pavements.

08110 **Achievements and Challenges In Asphalt Pavement Engineering**
S. Brown

This series of international conferences has facilitated the development of mechanistic methods for the design and structural evaluation of asphalt pavements over the past 35 years. While the record is one of real achievement, stimulated by initiatives such as the U.S. Strategic Highway Research Program, there are still problems to solve and challenges to face including that of implementing the results of research. The major achievements are outlined and the latest developments discussed. These include more realistic theoretical modelling and the availability of higher qdality data from modem testing facilities both in the laboratory and in the field. The need to incorporate the principles of soil mechanics more effectively in the design and evaluation of pavement foundations is identified. The continued extensive use of the CBR concept is questioned and the need for application of more relevant parameters is encouraged. Several other procedures which have long been used are critically reviewed and attention is drawn to innovative ideas including new concepts for modelling asphaltic materials. The theme of "Paving-the-Gap" between research and practice is considered and examples given of success. The importance of structural evaluation is emphasised and the need to develop faster, more convenient data gathering facilities is considered. The concept of "Smart Roads" incorporating appropriate low cost instrumentation could help in this context.

08111 **Charge to the Conference**
J. Maree

The theme of this conference, Paving the Gap - between theory and practice, is an issue with which ISAP conferences have grappled for at least the past decade. While considerable progress has been made to close this gap on several fronts, it can safely be said that we have not been entirely successful in coordinating the ideas and work of those who seek constantly to improve asphalt technology and pavement engineering with the needs and operations of the implementers and users, and hence this theme remains relevant and deserving of closer scrutiny. The aim of this paper is to raise some questions related to the gap which may still exist between theory and practice in the hope that, in attempting to find answers to the questions raised, this conference will come closer to bridging the divide.

08112 **Industry Issues for the 21st Century - An International Perspective on Asphalt (Bitumen) Supply**
A. Gilmour

In most of the world, the bitumen industry is set to undergo some substantial changes because of increasing pressures coming from within the oil industry, from governments and from the road industry. There is little doubt that the oil and bitumen industries will be able to respond effectively to ensure that the needs of governments and the roads industry for a wide range of competitively priced bitumens are met. Some of the R & D necessary to achieve this has already been successfully carried out but much remains to be done and continued efforts will be needed over the next five years to generate the most efficient solutions for the next century.

It is important to remember that a large majority of the bitumen used in the world is produced in refineries where bitumen represents less than 10% of the total product output. This is unlikely to change substantially in the future as it normally represents the lowest cost method of producing quality bitumen feedstocks.

08113 **European Perspective on Aggregate Issues**
H. Gormsen

European perspective on aggregate issues is a difficult subject for one main reason: Europe is not one single country, but consists of many countries with individual traditions, experiences and aggregate specifications. And on top of that as all over, the geology differs from place to place. It must be said, that aggregate specifications will be harmonized as part of the general harmonization program in Europe, which is going on to prevent barriers to trade among the member countries of the European Union.

In general I believe, that seen not only in an European perspective but also in a global perspective there are two overall issues:

- The need for high performing infrastructure
- Protection of the environment

08114 **Contracting Opportunities in the Twenty-First Century**
C. Potts

I am pleased to have this opportunity to speak to you. I will tell you a little bit before I start so you can see as where I am coming from. APAC is a large Hot Mix Asphalt (HMA) producer, actually the largest HMA producer in the United States. We are also the largest concrete paving company in this country as well as being a large aggregate producer. So we have a vested interest in every side of the business.

We are a wholly-owned subsidiary of Ashland, Inc. which is a large energy company. So we have a big investment in the liquid asphalt and the petroleum side of the business. In this presentation, I have been asked to give a vision of the future of what I see the industry, especially from the contracting standpoint.

It's a great opportunity because you are just asked to give your opinion, and you don't have to worry about documenting a lot of facts and giving a technical presentation. I heard some presentations yesterday, and people wanted to see the data, to see the tables, to see the proof. I don't need to give you any proof. All I have to do is tell you what I think. You can agree with me, or you can disagree with me. It really doesn't matter one way or the other. I am just giving you my opinion. Everyone in here has an opinion of what the future is going to be in the paving industry. Any of you could stand up and make this presentation.

08115 **Cost Effectiveness of Asphalt Pavement Preservation and Maintenance for Reduced Life-Cycle Costs: An International Perspective**
G. Kennepohl, J. Bethune, J. Maree

Rapid loss of useful pavement service life, loss of asset value and the need for funding to reconstruct has become a serious concern and challenge, which is addressed in this presentation. Described are the status of asphalt pavement preservation and maintenance strategies as well as a critical assessment of measures to reduce life-cycle costs through preventive maintenance and pavement preservation.

The review of the evolution of maintenance strategies from routine corrective measures to managed pavement distress prevention and preservation has shown that substantial user cost reductions can be achieved. The authors demonstrate, on hand, of case histories from Australia, North America and South Africa, the cost-effectiveness of advanced pavement maintenance strategies, new development and innovations as well as needs and trends for implementing pavement preservation.

08116 **Optimized Pavement Structure**
H. Goacolu, J. Gramsammer

Most road structures have traditionally been built with layers whose mechanical performance decrease with depth. In the case of treated materials, the structure bends and as a result the upper and lower parts are under the greatest stress. The durability of the structure depends mostly on the characteristics of the material used for the lower part, i.e. the lowest performance material.
The original design of the structure is intended to optimise the use of materials by putting the highest performance materials in the areas which receive the greatest stress.

This road structure is a three layers complex including:
- in the centre, an economical material with modest but sufficient mechanical performance,
- a thin layer of several centimetres on either face made of high performance materials which protect the structure from fatigue.
The article describes the theoretical functioning of this structure and its evaluation using the fatigue test track at the Central Laboratory of Ponts et Chaussees (LCPC).

08117 **Recent Development on Recycling Asphalt Pavements In Japan**
T. Ikeda, M. Kimura

The Government of Japan has intensively developed the technology to reduce and reuse construction by-products. As for asphalt pavement, the study and trials dated back to 1950s and technical guidelines for recycling asphalt pavement were published in the middle of 1980s. This paper presents current policy on waste management of the Japanese Government and revision of the technical guidelines based on data obtained from test pavements. This paper also mentions data on new issues, re-recycling and recycling modified asphalt.

08118 **PARIS: A Collaborative European Approach to Pavement Performance Measurement and Analysis**
G. Sweer, H. Jamsa, L. Dohmen, H. Spoof, J. Potter

The PARIS project is a collaborative European research effort aimed at development of pavement deterioration models for use in pavement management systems. The models to be developed will be based on data on the observed long term performance of over 800 test sections in 15 European countries. These field data will be augmented by data from Accelerated Loading Tests in three of the participating countries. This paper gives an overview of the project. Details are presented on the test sections involved, on the normalisation of local distress data to a common European format, on the database used for storage of the data and on the analysis system to be applied.

08119 **Roughness Characteristics of GPS Flexible Pavements in the LTPP Program**
R. Perera, C. Byrum, S. Kohn, C. Richter

The Long Term Pavement Performance (LTPP) program in the United States was designed as a 20 year study of pavement performance. One aspect of the LTPP program is the monitoring of over 800 General Pavement Study (GPS) test sections that were established on in-service pavements in all fifty states of the United Sates and in Canada. A major data collection effort at the GPS sections is the collection of profile data that is performed annually. This paper presents the results of a study conducted to investigate the changes in roughness on:

(i) GPS-1 experiment sections, which studies asphalt concrete pavements on granular base, and

(ii) GPS-6B experiment sections, which studies asphalt concrete overlays of flexible pavements.

The changes in roughness at test sections was investigated by using the International Roughness Index (IRI) as the roughness parameter. The test sections were classified according to environmental zones and the IRI trends for the group of test sections included in each zone were studied. Correlation analysis was conducted for GPS-1 sections in the dry freeze and the wet freeze zone between IRI and the factors that have an influence on roughness development. This paper presents a model that was developed to predict IRI for GPS-1 sections in the dry freeze zone. For the GPS-6B sections, the reduction in IRI due to the overlay was examined.

08120 **WesTrack Full-Scale test Track: Interim Findings**
J. Epps, S. Seeds, C. Monismith, S. Ashmore, T. Mitchell

A federally-funded multi-million dollar hot-mix asphalt (HMA) pavement research project is currently underway to further the development of performance related specifications (PRS) technology and to provide early field verification for the latest Superpave asphalt mixture design procedure. WesTrack refers to a full-scale road test experiment in which various asphalt mixes are being loaded in an accelerated fashion to determine the effect on field performance of "off-target" mix properties. The track is located near Reno, Nevada, and the experiment is being carried out by a team made up of consulting firms, universities and road contractors.

This paper provides background for the project including the nature of the experiment, the experimental factors, structural

and mix design, track construction, vehicle loading, driverless vehicle technology, performance monitoring and laboratory testing. It also presents information on the interim performance of the test sections, summarizes the planned approach to developing the pavement performance prediction models and describes the anticipated performance related specification system.

08121 **Warranteed Hot Mix Asphalt Pavements: A Cooperative Solution for Agencies and Industry in the United States**
G. Huber, J. Sorensen

The use of warranties as applied to hot mix asphalt pavements is just beginning in the United States. Whereas manufacturers of most products offer warranties against defects that affect performance of the product, the application of warranties to paving materials in the United States is not yet commonplace. Introduction of warranties has been hampered for both technical reasons and administrational reasons. Technically, the link between manufactured material and performance on the road is not well understood. It was believed that costs would be lowest if the owner agency carried the risk of performance. Therefore, contractors have been content to use method specifications and leave the risk with the owner. Administrative rules have generally prevented warranties on federally funded projects.

Administrative barriers have been removed and recently the attitude towards warranties in the USA has been changing. Visits to Europe have investigated methods used to warrant pavements and potential benefits to transportation agencies and the industry have been identified. Technically, the effect on pavement performance of asphalt mixture design, materials and workmanship as well as construction is better understood.

This paper discusses recent experiences with the implementation of asphalt pavement warranties in the United States including warranties, performance, asphalt pavement, and innovative contracting.

08122 **Superpave Support and Performance Models Management: Evaluation of the SHRP Performance Models System**
M. Witczak, H. von Quintus, C. Schwartz

A principal result of the Strategic Highway Research Program was a set of pavement performance models for predicting low temperature thermal cracking, fatigue cracking, and permanent deformation in asphalt pavements under environmental and traffic loadings. The Federal Highway Administration, as part of its Superpave implementation plan, awarded a contract to the University of Maryland and a team of subcontractors to provide a comprehensive and unbiased evaluation of the original SHRP pavement performance models. The principal conclusions from this evaluation are:

(a) the SHRP Superpave system provides an excellent framework for firture modifications and enhancements to the models;

(b) the existing non- load related thermal fracture model predicts field behavior reasonably well, although some minor modifications and enhancements to the model are necessary;

(c) the performance prediction models for load related fatigue fracture and permanent deformation perform poorly, and substantial corrections and enhancements to these models are imperative if they are to be sufficiently reliable for acceptance and use by industry;

(d) although some of the problems in the load related distress models are the consequence of technical and other constraints during the original SHRP research effort, many are the direct result of problems in the asphalt material characterization models and associated test procedures; and

(e) the necessary corrections, modifications, and enhancements to the models will mandate new field calibration and validation.

Detailed evaluation findings supporting these conclusions are presented in the paper. Future plans for the enhancement and implementation of the Superpave performance models are also briefly described.

08123 **Addendum to Pavement Performance Modelling Using Lintrack**
J. Groenendijk, A. Molenaar

Volume 2, page 1517: The caption for Figure 20 should be:
Vertical Contact Stresses, New R164BZ tyre, 100 kN, 700 kPa (instead of ... Longitudinal...)

Volume 2, page 1518: The caption for Figure 22 should be:
Longitudinal Contact Stresses, New R164BZ tyre, 100 kN, 700 kPa (instead of... Vertical...)

Volume 2, page 1523: 2nd column, first line should be:
XminCe = -30.4 -1.55*F + 8.68*10^4 * F*p -2.02 * V = 0.470 (instead of ... -8.68*10^4...)

08124 **Addendum to Field Management of Hot Mix Asphalt**
J. Scherocman, D. Decker

The attached figures provide a snapshot of recommendations and observations made by the National Center for Asphalt Technology (NCAT) based on an analysis of data collected in the Federal Highway Administration's Demonstration Project Number 74. Demo Project 74's objective was to compare volumetric properties of field-produced mixtures with laboratory-design values.

08125 **Best Paper and Poster Awards**
R. Terrel

The co-chairs of the Conference appointed an awards panel to select the best papers and posters. The papers were evaluated based on their technical merit and quality of writing. An additional consideration was how timely and appropriate the subject was for the Conference theme. The oral presentation was not a part of the evaluation, since all panel members could not be present at all sessions. Session chairs had the opportunity to read the papers carefully, and were invited to nominate the best paper in their respective session. In addition, each member of the awards panel was offered the same opportunity to nominate papers from any or all sessions.

code	ISAP 9th Conference Titles & Abstracts
09000	**9th International Conference on Design of Asphalt Pavements - Table of Contents** A listing of the Sessions, the titles of papers, and the authors.
09001	**Results of the Rilem Round Robin Test on Binder Rheology** *A. Vanelstraete and D. Sybilski* Road and Bridge Research Institute, Warszawa, Poland ABSTRACT: In 1998 the RILEM Technical Committee TC 152 PBM-Task Group TG1 "Binders", which is now under the responsibility of the new RILEM TC PEB "Performance Testing and Evaluation of Bituminous Materials" initiated a second round robin test on binder rheology. The objective of this round robin test is to compare the results of dynamic rheometer (DSR or equivalent) and bending beam rheometer (BBR) measurements of different laboratories and on different binders. The aim of the test is to determine the repeatability and reproducibility of the test methods, to give recommendations for improvements in order to come to a reliable standard testing method. DSR - and BBR-measurements were performed on four different binders: one straight run bitumen, two SBS - modified binders (one low and one high modification) and an EVA - modified binder. In the first phase, the tests were performed on the original binders. In the second phase of this round robin test, the influence of RTFOT-ageing and long term ageing was studied by DSR and BBR measurements. Measurements of the softening point of the binders were also performed before and after ageing. DSR-measurements were also performed on a reference fluid, in order to find out if this material was suitable for calibration purposes. Detailed instructions were given concerning handling of the binders, calibration of equipment and testing. Questionnaires with details on the precise handling and testing procedures were distributed among the different laboratories as well. This paper concerns the analysis of the results of both phases of the round robin: the measurements on the binders prior to ageing and the measurements after RTFOT and RTFOT + PAV - ageing.
09002	**Long-term Ageing - Simulation by RCAT Ageing Tests** *A. Verhasselt* The ageing of bituminous binders in service is an important factor in the long-term performance of bituminous materials. Relevant simulation by accelerated ageing can be achieved if the test is conducted at a temperature below 100°C. Comparison between the RCAT (Rotating Cylinder Ageing Test) developed by BRRC and the PAV (Pressure-Aging Vessel) test recommended by SHRP has shown that the reactions involved in these two ageing techniques are very similar (as opposed to what is observed with the RTFOT method). In this comparison, seven bituminous binders (two bitumen's and five polymer-modified bitumen's) were examined and results obtained for IR spectra, technological characteristics and rheological properties (DSR and BBR) were considered. Ageing time equivalence between the two test methods is, however, not a constant. The origin of this seems to lie in strong migration to the surface in the case of a static test and/or in degradation of the polymer; these types of behavior were demonstrated in a PAV-like test under nitrogen. With RCAT, a homogeneous sample of about 450 g of aged binder can be produced in one test run, and used for subsequent characterization and/or for further tests on asphalt mixes. In the marketed version of the RCAT apparatus, it is also possible to run, on a 550-g sample in the same device, a short-term ageing test at 163°C similar to the RTFOT test. The next step is to establish the equivalent ageing time for this application; this is now under way. With this apparatus, it will thus be possible to perform either the short-term ageing test and the long-term ageing simulation on separate samples of about 500 g of bituminous binder, or to perform the short-term ageing test followed immediately by long-term ageing simulation on the same sample. Enough material can be recovered after ageing to make some tests on asphalt mixes prepared with aged binder.
09003	**Determination of Asphalt Binders Viscosity From Other Rheological Parameters** *M.O. Marasteanu and D.A. Anderson* The dynamic modulus of asphalt concrete is an essential parameter in any pavement design method. However, laboratory determination of the dynamic modulus of asphalt concrete is very expensive and time consuming. The new AASHTO 2002 pavement design method addresses this issue by using asphalt binder viscosity as one of the parameters in predicting asphalt concrete dynamic modulus. In addition, many studies indicate that asphalt binder viscosity is a better parameter in evaluating the rutting potential of asphalt concrete. The Superpave asphalt binder specification provides a direct method for measuring the viscosity of asphalt binders at mixing and compaction temperatures only. Currently there is no accepted method to determine the viscosity or zero shear rate viscosity at service temperatures. This paper investigates a number of different approaches of calculating viscosity from other viscoelastic parameters and proposes the use of a simple method based on rheological master curves.
09004	**Project for Developing Performance Related Standards in Europe; Evaluation of Test Methods to Characterise Bituminous Binders** *A. Stawiarski, D. Jamois, W. Teugels, A. Madella, B. Lombardi and C. Robertus* The paper presents the results of the Eurobitume evaluation of candidate test methods for assessing the following binder properties, which are linked to the key asphalt pavement performance requirements: - rheological property at elevated service temperature, in relation with permanent deformation, - combined rheological and failure property, in relation with low temperature cracking, - short term and long term binder ageing behaviour, - binder stiffness modulus, in relation with asphalt structural strength, - binder fracture behaviour, in relation with fatigue cracking. The paper gives recommendations on which tests could be selected for standardisation as common European methods and for their possible use in future binder specifications. This work represents a contribution from the European bitumen industry to the project in progress, under the umbrella of CEN TC 336 Bituminous binders, for developing in Europe the next generation of performancerelated standards for bituminous binders.
09005	**Uncertainty and Appropriate Use of CBR Design for Airfields** *D.R. Alexander, R.B. Freeman and C.R. Gonzalez, L.N. Lynch*

The performance of recent pavement test sections instigated a review of the origin and use of the California bearing ratio (CBR) airfield pavement design procedure. The study involved inspection of the uncertainty associated with design solutions, given the uncertainty in the empirical equation itself. Variability in design thickness solutions, as produced by uncertainty in criteria, is reasonable. Variability is largest for relatively thin structures and/ or those that are subjected to relatively high load repetitions. Use of the CBR design equation for predicting remaining pavement life (i.e., load repetitions), given a pavement structure and traffic characteristics, leads to much higher uncertainty. The CBR equation evolved from research aimed at producing a thickness design tool and was not specifically developed for the purpose of evaluating pavements. It is best used for the purpose for which it was originally intended.

09006 **Asphalt Complex Moduli Determination Via FWD Test**
R. Al-Khoury, A. Scarpas and C. van Gurp

This paper addresses the development of a technique capable of identifying (viscous) pavement parameters in elastic-viscoelastic layered systems via non-destructive tests and techniques of wave propagation. The spectral element technique is adopted for determination of the stress-strain relationship in viscoelastic materials like asphalt pavement structures. The mathematical formulation of spectral elements for Burgers viscoelastic material model is highlighted. Some aspects of the forward calculating model and the inverse technique are presented. The first model can be used for proper assessment of deflections, stress, strains, etc, whereas the inverse technique is suited for detailed analysis of deflection histories and the identification of the material's Young's moduli and complex moduli for layer systems. Examples are provided. It is shown that the proposed methodology leads to robust and computationally efficient forward and inverse calculations.

09007 **Structural Design of Airport Asphalt Pavements on Soil with High Water Table**
Y. Hachiya, O. Takahashi, H. Kanazawa and K. Akimoto

Many airport projects have been constructed on ground reclaimed from the sea. At these sites, not only the subgrade, but also the pavement can be submerged because the water table generally remains high. When heavy loads are repeatedly applied to this pavement, severe damage to the pavement can result. The following three topics were studied to develop a structural design method for airport asphalt pavement at such sites: the condition of the pavement at an airport constructed on reclaimed ground, the influence of water on the pavement, and methods for constructing airport asphalt pavement at these sites. As a result, water-resistant airport pavement can be constructed if the following measures are used: reduce the design CBR of the subgrade, use asphalt stabilized material for the base, and install a drainage system surrounding the pavement.

09008 **Measuring of Dynamics Wheel Loads**
E. Doupal, R.Calderara, R. Jagau

This presentation will provide a brief information on using high-accuracy weigh-in-motion (WIM) traffic data for the evaluation of the dynamic axle loading influence affecting the pavement deformation and rutting. The measuring method is based on quartz crystal WIM sensors. This technology enables not only accurate axle load determination, but also evaluating the dynamic wheel loads separately. WIM data are used for a wide variety of applications. One of the most important applications is the estimation of the current and future loading of bridge constructions and road pavements. This paper presents several practical applications of such measurements, data reliability and recommendations for their use. The WIM measuring systems equipped with long term stable and temperature independent sensors collect the required pavement loading and dynamic effects data in real time. These data can be used for experimental checking of pavement modeling methods and for their improvement.

09009 **New Guidelines for the Design of Flexible Pavements for Australian Conditions**
G. Jameson, K. Sharp and D. Potter

This paper summarises the work undertaken to revise the guidelines for the design of flexible pavements for the 2002 edition of the Austroads Pavement Design Guide, which has recently been issued as a final draft for public comment prior to its release in 2002. The 2002 edition of the Pavement Design Guide incorporates substantial improvements that have resulted from Australian and overseas research into materials characterisation, traffic assessment, pavement performance studies and design methodology.

09010 **The Design, Creep and Fatigue Performance of Stone Mastic Asphalt**
G. Stephenson and F. Bullen

Stone Mastic Asphalt (SMA) is recognized as an ideal surface layer in heavy traffic situations, due to good rut resistance properties which is attributed to the stone on stone contact of the mix skeleton. Methods of ensuring that the stone skeleton is not overfilled with mastic were investigated in this research. In Queensland, Australia, thin surfacing layers (< 40mm for SMA10) are used, often over old, weak pavements that exhibit high deflection. Under such conditions, fatigue failure of SMA, rather than rutting, may be the limiting design factor. This paper reports on an investigation into using an applied vacuum as a confining pressure in the dynamic creep test. The fatigue performance of typical Queensland SMA mixtures was investigated using UMATTA equipment. The fatigue properties of SMA incorporating flyash, hydrated lime and ultra fine dust as the mineral filler and a SBS polymer modified binder are also investigated. The study included Queensland dense graded asphalt as a reference for quantifying any benefits obtained by using the various SMA mixtures. Some fatigue relationships for the SMA mixtures studied are proposed and the benefits of using SMA in combined creep-fatigue situations investigated. The testing programme demonstrated the effect of the type of filler and binder on the stiffness and fatigue life which has significance for generic specifications where a range of fillers are permitted.

09011 **A Damage Approach for Asphalt Mixture Fatigue Tests**
D. Bodin, C. de la Roche, J -M. Piau and G. Pijaudier-Cabot

Fatigue performances of asphalt pavement material are assessed using laboratory fatigue tests. It is proposed to apply damage mechanics to these tests to describe the stiffness decrease induced by microcrack development in the material samples. An isotropic nonlocal damage model is chosen as well as a cyclic time integration scheme for finite element implementation. Parameter identification is performed using tension compression fatigue test results. Validation on bending tests leads to good results in terms of damage field evolution and well describes the stiffness decrease before the macrocrack formation.

09012 **Determining Asphalt Concrete Fatigue Property**
J -P. Michaut and J. Bilal

Assessing the mechanical characteristics of bituminous materials required to design pavement calls for arduous, long and expensive tests. In addition, the results at the end of the tests - when compared to specifications - are not certain. When the mechanical characteristic called fatigue performance is required, the designer must start by studying different mixes. Once the formula has been selected, fatigue tests are carried out to verify if the formula fulfils the requirements. When the results do not comply, the entire study must be redone, which is a loss of time and money. To simplify and facilitate mix design studies, equations have been determined to ensure - in our mind - sufficiently precise fatigue deformation values for the bituminous materials. This value can then be used in pavement design models. This article covers the elaboration of these equations drawn up from a fatigue data file compiled by the company and from other published results. These equations take account of the elements that are used by every mix designer, e.g., binder and compaction ratio. Backed by these equations combined with sound knowledge of the parameters required with these types of asphalt mix, the designer is now able to carry out fatigue tests that comply with the required specifications without having to worry about the results.

09013 **Laboratory Evaluation of the Effects of Aggregate Gradation and Binder Type on Performance of Asphalt Mixtures**
H.J. Lee, J.Y. Choi, Y. Zhao and Y.R. Kim

This paper presents findings from a laboratory study on the performance of seven different asphalt mixtures. These mixtures were developed by systematically changing aggregate gradations and binders to investigate the effects of these mixture variables on performance. Dynamic Shear Rheometer (DSR) and Bending Beam Rheometer (BBR) tests were conducted on the binders to obtain temperature susceptibility. Axial creep, triaxial repeated permanent deformation, and uniaxial tensile fatigue tests were performed on the mixtures. Fatigue data were analyzed using the viscoelastic, continuum damage approach. The results from all the experiments were investigated together to evaluate the effects of different gradations and asphalt modifications. It was found that the Styrene- Butadiene-Styrene (SBS) modified binder improved the fatigue cracking and rutting resistance of the mixtures regardless of the aggregate gradation. The ranking of the performance among gradations was dependent on the distress type. In general, however, the dense gradation showed better cracking resistance and the coarse Superpave gradation showed better rutting resistance.

09014 **WAM-Foam, Asphalt Production at Lower Operating Temperatures**
B.G. Koenders, D.A. Stoker, C. Robertus, O. Larsen and J. Johansen

Reducing asphalt production temperatures has significant benefits from both cost and environmental perspective. The hot mix asphalt industry has been aware of this for many years. The biggest challenge however has always been to achieve adequate asphalt mix quality at lower or ambient operating temperatures. Recently, new production processes at temperatures between 80 - 120°C have attracted much interest because of the possibility to approach or even obtain hot mix quality. In the Warm Asphalt Mixture (WAM) process using foamed bitumen this region is explored using conventional production and laying equipment. The WAM-Foam process has been tested in the laboratory and in road trials. The results show that for dense asphalt wearing courses the properties and the performance can be comparable with hot mixture. Additionally the benefits to the environment were confirmed by measured reductions in energy consumption, emissions and fume exposure.

09015 **Foamed Bitumen Mix: Soil or Asphalt?**
A. Nataatmadja

The research described herein involved characterisation of a range of foamed bitumen mixes in the laboratory. The test results suggest that although foamed bitumen mixes can have some engineering properties which are comparable to those of hot-mix asphalt concrete or other stabilised soil mixes, they have some unique and distinct characteristics. With its low bitumen content and high air void content, the resilient modulus of foamed bitumen mix is affected by curing methods and moisture. Furthermore, it is also shown that while the stiffness of foamed bitumen mixes may be as high as that of typical asphalt mixes, it is much less sensitive to temperature variation. Similar to that of conventional asphalt mixes, however, the resilient modulus of foamed bitumen mixes varies with the applied strain.

09016 **The Use of a Designed Foamed Bitumen Stabilised RAP in an Urban High Street**
K. Khweir, D. Fordyce and G. McCabe

An analytical design approach and performance-based specification was used with a roadway refurbishment in Scotland. The approach was taken as the roadbase used was a foamed bitumen stabilised RAP. In the refurbishment the mixture was fully compacted and production variables had only a limited impact on material performance.The most significant factor influencing material performance was found to be material moisture content. It has been suggested that the load spreading capability of such stabilised RAP mixtures can be compared to conventional hot applied bitumen mixtures through the use of a single equivalence factor. The data from this work would suggest this is not the case and the use of a single factor should be used with caution.

09017 **Performance Prediction of Cold Foamed Bitumen Mixes**
K.J. Jenkins, M.F.C. van de Ven, A.A.A. Molenaar and J.L.A. de Groot

As the use of foamed bitumen mixtures in road pavements continues to grow on a global scale, so the need for performance functions that may be used in the design of pavements incorporating these materials becomes increasingly important. The challenge of modelling the behaviour of these mixes is complicated by the variety of foamed mixes that are produced and the range of properties that prevail. This paper focuses on the performance of cold foamed bitumen mixes that have low binder contents (generally less than 2,5%) and a model that could be used in pavement design. Mixes with and without active filler (cement) have been considered. Due to the lightly bound nature of these materials, the shear properties of the foamed mix were adjudged to be critical parameters for the prediction of permanent deformation under repeated loading. A model was developed on the basis of triaxial testing carried out on foamed mixes comprising a range of aggregate types, including marginal and recycled materials. This included monotonic and dynamic triaxial testing on large foamed and granular specimens (300mm phi x 600mm high) and intermediate specimens (150mm phi x 300mm high). The model was then validated using accelerated pavement tests (APT) with the Model Mobile Load Simulator MMLS on a layer treated with foamed bitumen using Cold in-place Recycling (CIPR). Through triaxial testing, the performance properties of the foamed mixes in terms of permanent deformation under repeated loading, can be related to the shear properties of the

same material. This provides a link between laboratory mix design and field performance. Stress dependent models incorporating shear parameters, can be used to define the resilient foamed mix behaviour under dynamic loading. The ratio of deviator stress at failure under monotonic loading and the deviator stress in the pavement structure has been identified as a critical parameter for rut prediction. Using finite element methods that incorporate non-linear elements, these models can be applied in pavement analysis. The applicability of the rutting performance model has been verified using the NOLIP finite element analysis programme and guidelines for (lightly bound) foamed mix layer design now exist.

09018 **Influence of the Surface Energy Status of Aggregates On the Performance of Asphalt Hot Mix**
O. Harders and I. Noesler

Aggregate selection for asphalt production is mostly governed by economic factors. This includes transportation costs, availability, capacity and seasonal effects. The storage time of the aggregates after crushing can vary remarkably. The surface energy of freshly broken minerals is changing over the time due to reorganisation of polar component and absorption of water and dust at its surface. This process takes some months to stabilise. The knowledge about the actual status of this energy is most important for application of bitumen emulsions as it has an influence on the breaking time and absorption. It can also have an influence on the performance of asphalt hot mix formulations. A work program included the investigation into the influence of different sources of minerals and granular sizes as well as the general behaviour of asphalt compositions. The interaction with different sources of bituminous binder was another topic of the investigation. The different surface activities were addressed by the methylene blue (MB) test and the performance of asphalt compositions was evaluated with a rolling wheel rut tester at 50°C under water.

09019 **The Characterization of Pavement Layer Interfaces**
S.A. Romanoschi and J.B. Metcalf

The primary objectives of the research were to derive constitutive models for the interfaces of flexible pavement layers, and to determine the effects of interface condition on pavement performance. A simple constitutive model was derived for the asphalt layer interfaces using data provided by laboratory direct shear tests at several normal load levels. In the model, the shear displacement is proportional to the shear stress until the shear strength of the interface is reached. When tack-coat is not applied between asphalt layers, the interface shear strength and stress-displacement relationship depend on the magnitude of the normal stress acting at the interface. Field shear tests at several levels of normal load were used to study the bond between asphalt surface layers and granular or soil-cement bases. The interface constitutive models were integrated into the ABAQUS finite element model to prove the significant impact of the interface condition on pavement life.

09020 **The Importance of Good Bond Between Bituminous Layers**
B.A. Hakim

Deflection testing using the Falling Weight Deflectometer (FWD) and the Deflectograph are often carried out on new pavements as a quality control measure to ensure that the pavement can carry the future traffic loading. Analysis of FWD data has indicated low bituminous stiffness and low residual life for some newly constructed pavements. Therefore, theoretically the pavement was not fit for purpose and strengthening by an overlay was needed. However, de-bonding between bituminous layers was noted in the majority of cores extracted from the pavement, where the layers were separated during coring under the torque applied by the rotary core barrel. Lack of bond between pavement layers will produce higher deflections under surface loading, since the layers will act independently in the absence of shear continuity at the interfaces. Lower bituminous layer stiffnesses are usually predicted from FWD test results if poor bond exists between different sub-layers. Therefore the back-analysed stiffness is an apparent value for the combined bituminous layers, which reflects the in-situ behaviour accounting for poor bonding, and is not a unique property reflecting material condition. The FWD data were re-analysed using a new method to predict both the pavement layer stiffness and the bonding condition between bituminous layers. The bond stiffness at the interface is considered as a variable affecting the FWD deflections and is therefore backanalysed in a similar manner to a layer stiffness. The results indicated better bituminous materials but with poor bond between the layers, and a good quality foundation. This was consistent with the laboratory Indirect Tensile Stiffness Modulus results carried out on the bituminous core samples. The implication of lack of bond between bituminous layers on pavement deterioration mechanisms and residual life prediction are discussed in this paper.

09021 **Experimental Investigation of Fracture and Healing of Bitumen at Pseudo-Contact of Two Aggregates**
F. Hammoum, C.De La Roche, J -M. Piau and C. Stefani

The study presented here aims at highlighting the bitumen part in the fatigue of bituminous mixtures, due to cohesive failure in binder. In order to do so, a specific test Repeated Local Fracture of Bitumen has been designed [de La Roche and al., 1999]. It aims at understanding cohesive failure and healing phenomenon of binder. This article reports the analysis of the test results, regarding crack initiation and growth within the sample. Such events appear as steps in a load versus displacement curve. These observations are confirmed with the help of acoustic emission. Successive tests performed after different rest period duration show that binder healing depends on temperature and rest period duration. The developed test seems a very promising tool to study bitumen part in fracture and healing of bituminous mixtures.

09022 **Healing Characteristics of Asphalt Mixture Under High Temperature Conditions**
K. Uchida, T. Kurokawa, K. Himeno and T. Nishizawa

In order to evaluate the healing characteristics of asphalt binders and asphalt mixtures, new test methods were developed. These methods include two procedures, one is to measure the bonding strength between asphalt surfaces and another is to measure a flexural strength of a specimen which is healed after artificially cracked and then estimate the healing potential which is defined as a ratio of the flexural strength of the cracked and healed specimen to that of a virgin specimen. In the latter procedure, loading time, temperature and degree of ageing can be variable. Using the methods, effects of loading time, temperature and degree of age on the healing characteristics were investigated. Also, cracking process at the surface of asphalt mixtures was observed using a modified wheel tracking test and discussed in terms of the aging and healing of asphalt mixtures.

09023 **Fracture of Bitumen Films**
J.A.F. Harvey and D. Cebon

This paper investigates the adhesive properties of bitumen films. Tensile tests on bitumen butt joints and double cantilever beam specimens, over a wide range of test conditions are described. The test results are treated using a fracture mechanics approach. It is found that the failure strain of bitumen is generally independent of equivalent strain rate, in both the brittle and ductile regimes, whereas the 'normalised toughness', G/2h is rate independent in the brittle regime and rate dependent in the ductile regime (G is the strain energy release rate, 2h is the film thickness). The toughness of a typical paving bitumen is quantified, both for brittle fracture and ductile failure, and a mechanism map classifying the failure mechanisms as a function of temperature and strain rate is presented.

09024 **Alternative Bitumens for Road Building**
A. Inman and E.E. Larsen

The rheological properties of bitumen deteriorate with time, this phenomenon is commonly called ageing. The main cause of this deterioration is oxidation. The oxidation of bitumens has long been a known problem in road building. The main factors that affect the rate at which bitumens deteriorate are the asphalt mix properties, exposure to elements, temperature, bitumen film thickness, and the bitumen ageing resistance capability. We have over a period of time investigated this phenomenon in connection with asphalt recycling projects in Africa and the Middle East.

The investigations carried out were based on the calculation of the Viscosity Index of the bitumens from asphalt mixes where recycled asphalt and rejuvenators were added. The bitumens were artificial aged by employing the Thin Film Oven Test (TFOT, ASTM D 1754) for 5 hours and a modified test of TFOT for 24 and 30 hours. The modified test method for TFOT for 24 and 30 hours was developed in cooperation with a Danish research laboratory.

The Investigations indicated that the long term ageing of these bitumens was dramatically less than conventional bitumens and this lead us to seek alternative bitumens for road building. In 1999 a road was designed in Tanzania where a Propane Precipitated bitumen was to be employed. The bitumen is supplied by a lubrication oil refinery. This paper presents the findings of the above mentioned investigations along with results of the bitumen investigation for the Propane Precipitated bitumen.

09025 **A Constitutive Material Modelling Methodology for Asphalt Mixtures**
G.D. Airey, S.T. Dunhill and A.C. Collop

This paper presents a methodology for the experimental characterisation and modelling of asphalt mixtures using an elastic-visco-plastic constitutive model. The recommended methodology has been successfully used in the paper to characterise two standard UK wearing course mixtures. The characterisation of the mixtures is undertaken through a series of monotonic uniaxial compression and tension tests. Due to the significant influence of strain rate and temperature on the response of asphaltic materials, the tests have been carried out at three temperatures and three displacement rates. Two different test configurations have been used for the compression and tension tests comprising cylindrical and necked specimens respectively. The basic model parameters required for the constitutive model have been calculated solely from the results of the monotonic uniaxial test data. Relationships are presented to describe the material parameters for the two standard asphalt mixtures as functions of peak strength, strain rate, temperature and plastic work.

09026 **Viscoelastic Rutting Model with Improved Loading Assumptions**
R. Blab and J.T. Harvey

A 3-dimensional FE model of a road pavement is presented, in which the temperature- and loaddependent performance of flexible pavements is characterized by a generalized Maxwell model and improved loading assumptions are used based on measurements of tire-road contact stresses. A method has been developed that permits the derivation of the required viscoelastic model parameters from dynamic shear tests. The model was evaluated using simulation calculations for a specific test structure on which rutting tests had been performed with a Heavy Vehicle Simulator (HVS). This evaluation demonstrated good agreement between the deformations predicted by the theoretical model and the deformations actually measured.

09027 **Design Aspects for Wearing Courses on Orthotropic Steel Bridge Decks**
T.O. Medani, A. Scarpas, M.H. Kolstein and A.A.A. Molenaar

Preliminary analyses have shown that linear elastic theory is not applicable for the analysis of surfacings on orthotropic steel deck bridges. It is believed that an improved nonlinear material models need to be implemented. The ACRe material model developed at Delft University of Technology can successfully describe the different aspects of the behavior of asphaltic materials (e.g. elasticity, visco-plasticity, cracking). In this contribution the model parameters for a mastic asphalt mix have been estimated. There are tools, which can be used to better understand the interaction between the different components of the structure and the influence of specific structural material parameters on the response. These tools comprise accurate non-linear material models and smart and powerful finite element based programs. Furthermore, it is expected that such tools, after the necessary simplifications, will lead to more useful procedures that can not only be used efficiently at the design phase but also at the construction phase (quality control). Delft University of Technology, the Netherlands

09028 **Permanent Deformation of Asphalt Concrete Pavements: Development of a Nonlinear Viscoelastic Model for Mix Design and Analyses**
F. Long, S. Govindjee and C.L. Monismith

Truck loading is increasing worldwide, resulting in more permanent deformation of asphalt concrete pavements. It is therefore necessary to ensure pavements can withstand this loading without rutting, which requires improvements to mix design and analyses. This paper discusses the development of a nonlinear viscoelastic constitutive model to describe the rutting behaviour of asphalt concrete. The model focuses on those properties that dominate asphalt concrete deformation; viscoelasticity and shear deformation. The model was formulated with laboratory test data, and includes both strain and temperature dependence using time-temperaturestrain superposition. To validate the model, finite element simulations of a laboratory test and of a pavement were compared to real data. The model predicts the laboratory test and pavement behaviour fairly well. The model is also used to evaluate the SHRP performance-based mix design procedure. The effects of different tyre types were found to have a significant effect on the development of rutting.

09029 **The Application of Shakedown Approach to Granular Pavement Layers**

G. Arnold, A. Dawson, D. Hughes and D. Robinson

The concept of shakedown was developed for describing the material and structural response to the repeated application of a cyclic load. In this paper the concept is applied to describing the behaviour of unbound granular materials in the repeated load tri-axial permanent strain test. Behaviour was categorised into 3 possible shakedown ranges A, B or C, where A is a stable shakedown response and C is incremental collapse while B is intermediate. From this data test stresses near or at the boundary of shakedown range A and B were determined to define a shakedown limit line stress boundary in p (mean normal stress) - q (principle stress difference) stress space. The shakedown limit line was applied as a yield criteria in the finite element model of the field trial to predict whether or not shakedown occurs in the UGM for a range of asphalt cover thicknesses. For comparison the lower and upper bound shakedown theorems were also applied to the field trial cross-sections.

09030 **Modelling of Granular Layers in Pavement Constructions**
S. Werkmeister, R. Numrich and F. Wellner

The shakedown approach was used to characterise the deformation behaviour of Unbound Granular Materials (UGM) in pavement constructions. In this paper it is shown that the application of the shakedown concept to UGM as used in pavement construction is possible, although adaptations have to be made. The essence of a shakedown analysis is to determine the critical shakedown load for a given pavement. The Dresden material law was introduced for modelling the permanent and resilient deformation behaviour of UGM-layers in pavement constructions under consideration of the shakedown ranges. A design method has been developed that utilizes test results from the Repeated Load Triaxial Tests to establish the risk level of permanent deformations in the UGMlayers. The non-linear resilient material law was implemented into the Finite Element Program FENLAP for the UGM-layer. These Finite-Element-Program was used to check, using a part of the German pavement design guideline, if the critical stress level for the UGM-layer (between stable and unstable behaviour) is exceed.

09031 **The Effect of Mix Design Technology on the Rutting Characteristics of Asphalt Pavement**
G.A. Huber, W. Pine, J.F. Corte, F. Moutier and P. Langlois

Permanent deformation of asphalt pavements has been the focus of mix design systems since the early part of the twentieth century. Today, one of the main objectives of mix design remains the prevention of rutting. Several main types of mix design are in use in the world. Each method approaches the problem of rutting using a different set of criteria that include type and effort of compaction, and selection of volumetric criteria and asphalt content. After 1950, the Marshall method of mix design was used widely throughout the world. In the 1960's and 70's, LCPC developed an approach to mix design significantly different than the Marshall method. In the 1990's the Superpave method of mix design was developed and is being implemented in the United States. The Province of Quebec developed a hybrid mix design system using Superpave equipment but applying LCPC design principles. In 2000, mix designs were independently done on the same set of materials using the four design methods and were built at the LCPC test track at Nantes, France. The sections were loaded during the summer of 2000 and rutting was monitored. This paper gives an overview of the mix design methods and a summary of the independently performed designs.

09032 **Effects of Fine Aggregate Properties on Rutting Resistance**
J. W. Button, D-W. Park, A. Chowdhury, Dallas N. Little, E. Masad

The objective of this laboratory study was to compare rutting resistance of hot mix asphalt (HMA) containing fine aggregates with different angularities. Permanent deformation was measured using the Asphalt Pavement Analyzer (APA). HMA mixtures were designed following the Superpave specifications, to the extent possible, and prepared using the Superpave gyratory compactor. A few mixes did not meet all Superpave specifications. Six different mixtures were prepared using the same gradation. In all mixtures, crushed limestone was used as the coarse aggregate. Six different fine aggregates were used: crushed granite, crushed river gravel, crushed limestone, sub-rounded natural sand, blend of 85% granite with 15% natural sand, and blend of 70% limestone with 30% natural sand. Angularity of the fine aggregates was measured using Superpave fine aggregate angularity (FAA), direct shear test, compacted aggregate resistance (CAR), and different image analysis techniques. FAA varied from 39.0 to 48.0; the other measured values of angularity varied similarly. Findings from APA testing indicate (1) HMA mixtures containing natural sand with a FAA of 39 and those containing river gravel fines with a FAA of 44.3 yielded statistically equivalent rut depths, (2) HMA mixtures containing crushed limestone fines with a FAA of 43.5 and those containing granite fines with a FAA of 48.0 yielded statistically equivalent rut depths, (3) HMA mixtures containing crushed limestone fines with a FAA of 43.5 yielded significantly lower rut depths than similar mixtures containing river gravel fines with a FAA of 44.3, (4) HMA mixtures containing a fine aggregate blend with a FAA of 41.9 gave essentially the same rut depth as similar mixtures containing a fines blend with a FAA of 46.8, (5) FAA is not sensitive to rut resistance of HMA mixtures. Further, certain fine aggregates with FAA values lower than 43, but with relatively high particle surface texture, can produce mixtures with relatively good rut resistance, (6) Angle of friction derived from direct shear tests and some of the image analysis parameters showed very good correlations with rut depth.

09033 **Asphalt Mixture Design on the Criteria of Shear and Crack Resistance of the Pavement**
G.N. Kiryukhin

An asphalt mix design on the criteria of shear and crack resistance calls for determining the main rheological and strength properties of the pavement asphalt concrete characterising its deformation and damage depending on its stressed-strained state and temperature-time conditions of loading, determinations being carried out under laboratory conditions. Algorithms for determining the asphalt concrete shear resistance at the maximum design temperature, residual deformation for a design service life of the pavement and its crack resistance due to the combined action of tensile stresses in the pavement are proposed. The design method makes it possible to choose an efficient composition of asphalt concrete on two criteria of shear resistance and a complex criterion of crack resistance of the pavement.

09034 **Use of Gyratory Compaction for the Design of Asphalt Mixes**
L. Francken and L. Didier

After presenting the basis principles of the Belgian volumetric mix design method [BRRC, 1997], this paper describes experimental work carried out in order to improve the method and enlarge its field of application. Gyratory tests were carried to determine input data needed by a packing model used to evaluate the distribution of volumes within asphalt

mixtures. The sigmoidal compaction curve proposed by Moutier [1996] was used to fit the experimental results obtained on different road mixes. The improvements proposed to the model take into account on one hand the grading curve and characteristics of the granular mix components and on the other hand the energy or rate of compaction. Results of this study will be incorporated in the PRADO [Francken & Vanelstraete, 1993] mix design software together with a set of tools for predicting mechanical characteristics and performance laws.

09035 **Use of the Concept of Pore Pressure in Unsaturated Soils for Evaluation of Rutting Potential of Asphalt Paving Mixes**
R.B. Mallick, M.R. Teto and J.E. Haddock

Rutting is a common problem in hot mix asphalt (HMA) pavements. For characterizing HMA, a theory has been developed on the basis of the concept of pore pressure in unsaturated soil mechanics. It is hypothesized that in a mass of HMA, the mastic acts similar to water in a partially saturated soil mass. It is proposed that a measure of increase in lateral pressure that is generated in a mix during gyratory compaction can give a good indication of the generated pore pressure in the mix - the more the lateral pressure, the more is the generation of pore pressure. Results from tests with a variety of mixes show that there is an increase in pore pressure, and hence reduction in shear strength with increase in asphalt content and at air voids lower than 2 percent, and that compared to dense graded HMA, SMA mixes remain relatively insensitive to low air voids.

09036 **Provisional Validation of the New South African Hot-Mix Asphalt Design Method**
A.T. Visser, F. Long, B.M.J.A. Verhaeghe and A. Taute

South African asphalt technology practitioners recognised the need for an updated and expanded hotmix asphalt (HMA) design system. This resulted in the launching of a three-year project aimed at developing new HMA design guidelines for South Africa. This new design system is centred on spatial design concepts and established knowledge of mix design, with additional validation of expected performance being attained through laboratory tests and prediction models. The aim of the paper is to present the initial results of a evaluation programme in which the new method was carried out in parallel with established practice. The paper presents the experimental programme and the results of the parallel testing. Aspects that were considered were rutting, durability, moisture sensitivity and permeability, as well as constructability issues. The new method provides the designer with greater insight and flexibility to overcome problems such as tender mixes, difficulties with construction and inability to achieve density and impermeability.

09037 **Repeated Simple Shear Test for Mix Design: A Summary of Recent Field and Accelerated Pavement Test Experience in California**
J. Harvey, I. Guada, C. Monismith, M. Bejarano and F. Long

The repeated simple shear test at constant height (RSST-CH) is a laboratory test to evaluate mix rutting performance. The test was developed as part of the SHRP program, which ended in 1993. The test is designed to isolate the primary mechanism for rutting of asphalt mixes: permanent shear deformation at elevated temperatures under repeated loading. The RSST-CH is a candidate for use as a simple performance test and performance prediction test. Since its development, the RSST-CH has been used for a large and varied number of field projects and for mixes used in accelerated pavement test sections in California. The projects include mix designs and forensic investigations. Representative examples presented in this paper include:

- Mix designs for a warranty pavement for a state highway in the mountains near Redding California

- Comparison of RSST-CH results with rutting performance under the HVS for asphalt-rubber and conventional overlays

- Mix design (conventional and polymer modified binders) binder content selection for the I-710 freeway reconstruction near Long Beach, California and evaluation of these materials for rutting with the Caltrans Heavy Vehicle Simulator

- Comparison of RSST-CH results with rutting performance under truck trafficking at the Westrack accelerated pavement testing experiment.

The performance prediction methods used for these projects are reviewed. The use of other tests performed using the shear tester, such as the shear frequency sweep, and shear stiffness from the RSST-CH are also compared with observed performance on field and HVS sections. Based on the case histories, this paper summarizes use of the RSST-CH for mix evaluation and design, and the design criteria used for mix design and pavement evaluation.

09038 **Evaluating Tensile Strength of Asphaltic Paving Mixtures Using a Hollow-Cylinder Tensile Tester**
G.G. Al-Khateeb and W.G. Buttlar

A Hollow-Cylinder Tensile Tester (HCT) was recently developed to obtain fundamental tensile properties of asphalt paving mixtures at low and intermediate temperatures. The HCT was developed as a surrogate test device for the Superpave Indirect Tensile Test (IDT), and can measure creep compliance, tensile strength, dynamic modulus, and resilient modulus. Because the HCT is a simple, portable, and rugged test device, it is a very useful and powerful tool for mixture design, control and forensic evaluation. This paper investigates the use of the HCT and IDT to measure the first failure and ultimate tensile strength of asphalt paving mixtures. As expected, ultimate tensile strength was found to be highly test-dependent. In a carefully controlled study involving four different polymer modification levels, the HCT ultimate tensile strength was found to be strongly dependent upon modification level, as opposed to the IDT ultimate tensile strength, which was weakly correlated to modification level.

09039 **Evaluation of Stability and Sensitivity of Hot-Mix Asphalt Mixtures Using Gyratory Shear Strength**
B. Birgisson, D.D. Darku, R. Roque and B.E. Ruth

At the time of development, the SuperPaveTM gyratory compactor was developed only to densify mixtures. Since the advent of the SuperPaveTM gyratory compactor, a number of SuperPaveTM compatible gyratory compactors have been developed that measure the gyratory shear strength during compaction. This paper explores the use of the gyratory shear strength parameter obtained in SuperPaveTM compatible compactors as an index of mixture sensitivity and stability, while maintaining the SuperPaveTM mixture design framework. Eight different mixtures were prepared and evaluated, including four fine-graded and four coarse graded mixtures, as defined by whether the gradation curve passes above or below the restricted zone, respectively. The aggregates used all had known rutting performance histories in asphalt

mixtures in Florida. The results show that the gyratory shear strength can be used as an index to evaluate both the stability of hot-mix asphalt mixtures, as well as the sensitivity of mixtures to asphalt content.

09040 **Development and Validation of a Pavement Response Evaluation Model**
R.V. Siddharthan, P.E. Sebaaly, M.M. El-Desouky and M. El-Mously

The paper provides the following relative to a recently developed finite-layer based pavement response evaluation model:
(1) verification of its predictive capability and
(2) demonstration of its applicability.

The model incorporates important pavement response factors such as the noncircular contact area, complex contact stress distributions, vehicle speed, and viscoelastic material characterization. The verification of the proposed approach and the ensuing computer program was undertaken using:
(1) results from ELSYM5, a widely used pavement response model and
(2) field measured strain responses from a well instrumented road test carried out under a variety of loading conditions (load level and vehicle speed).

A very good agreement was observed in all cases. This paper also documents many important pavement responses computed by the proposed model under a variety of loading conditions. Pavement responses for a conventional single axle with dual tires traversing two types of pavements with different contact stress distributions have been reported.

09041 **Non-uniform Tire Pressure Effects on Surface Initiated Cracks with Everflex: a Three Dimensional FEA Tool for Flexible Pavements**
H. Wu, J.P. Mahoney, G. Turkiyyah, L.M. Pierce, J. Uhlmeyer, R. Mulvaney

This paper presents a preliminary examination of the causes of surface initiated cracking. Of special interest are non-uniform tire pressure effects. These effects are examined via EverFlex--a three-dimensional finite element analysis tool for flexible pavement systems. The interactive and computational features of EverFlex are also presented. A case study is presented based on Minnesota Road Research Project sections.

09042 **Evaluation of Non-uniform Tyre Contact Stresses on Thin Asphalt Pavements**
M. De Beer, C. Fisher and F. J. Jooste

Improved quantification of the shape and distribution of actual tyre-pavement contact stresses resulted in enhanced definitions of 3D-tyre-pavement contact stresses for the design and analysis of flexible pavements. It is now possible to describe the 3D-load/stress regimes with a series of discrete load values that were measured using Stress-In-Motion (SIM) technology, as well as being predicted from trained Artificial Neural Networks (ANNs). This paper illustrates the importance of these new load/stress inputs in pavement design on pavements with relatively thin asphalt surfacings, typically used in southern Africa. This investigation concentrates on the quantification of several pavement response parameters as a result of non-uniform and non-circular shaped contact stresses at different asphalt moduli, compared to the traditional circular uniformly loaded tyre patch. The Finite Element Method (FEM) was used for the detailed analyses. In addition, the responses of an un-cracked and cracked pavement structure were also compared, under circular and rectangular loading shapes of varying levels of loads and contact stresses using a customised semi-analytical FEM code. The response data were benchmarked with multi-layered linear elastic theory, and also indicated the importance of both the load shape and level of contact stress on pavement performance. The importance of using and managing actual tyre-pavement contact stress data for more rational design and analysis of pavements incorporating thin asphalt layers is highlighted.

09043 **Prediction of the Behaviour of a Flexible Pavement Using Finite Element Analysis with Non-Linear Elastic and Visco-Elastic Models**
P. Hornych, J -P. Kerzreho and S. Salasca

In the past few years, LCPC has been implementing in its finite element code CESAR-LCPC a module for pavement modelling, including non-linear models for asphalt materials and unbound granular materials. This program has been used to model results of a full scale experiment on a flexible pavement, with a granular base, performed on the LCPC accelerated pavement testing facility. The experimental results indicated that the response of the pavement depends strongly on the level of load and on the water content of the unbound granular layers. The modelling of the pavement was performed in 3D, and several modelling hypotheses were successively tested : linear elasticity, a non-linear elastic model for the unbound layers (Boyce model) and a visco-elastic model for the asphalt concrete (Huet-Sayegh model). The most complete model, coupling non-linear elasticity for the unbound materials and visco-elasticity for the asphalt concrete, led to realistic predictions of the pavement response for different levels of load and different loading speeds.

09044 **Effects of Frost Heave on the Longitudinal Profile of Asphalt Pavements in Cold Regions**
S.Kameyama, M. Kato, A. Kawamura, K. Himeno and A.Kasahara

Longitudinal profile of an Expressway in a cold region of Japan was measured weekly during winter using inertial profiler. The International Roughness Index (IRI) calculated from the measured profiles was analyzed to determine its seasonal changes during the coldest period. While the IRI of segments including embankments and bridges changed little during winter, the IRI of some of the segments, including cuts, was approximately double what it was in fall. A tendency of increasing IRI with increasing freezing index was observed in these segments. This indicated that the IRI's increase in winter was affected by frost heave. Multiresolution decomposition using a wavelet was applied to the longitudinal profile to analyze the wave characteristics of the profile affected by frost heave. It was found that the component of the decomposed profile whose wavelength was 4 through 16 m greatly increased as the freezing index increased.

09045 **Development of a Rational Design Procedure for Pavements Subjected to Frost Action**
G. Dore, N. Rioux and P. Pierre

In northern climates, frost action is a major cause of pavement deterioration. In current pavement design approaches, modern analytical tools are commonly used to assess the adequacy of pavement structures with respect to the effect of traffic. However, in most design methods, procedures to take environmental factors into consideration are still essentially empirical. At the most, some design methods include procedures by which material properties vary as a function of

moisture and temperature. A new method for the verification of pavement structures with respect to the effects of freezing and thawing is proposed. The method is based on a four steps iterative procedure. In the first step, the mechanical and thermodynamic response of the pavement structure to traffic and climatic conditions are calculated. The calculated responses are then used to predict performance, through distress specific models, in the second step of the procedure. The results are compared to the specified project objectives in the third step. If the objectives are not met, the fourth step of the procedure includes a decision three to help enhance the pavement structure. A preliminary version of the method is being implemented in the province of Quebec. It has been validated for typical Quebec road network conditions through the collection of specific performance data from typical road sections. The validation project has also included the development of operational procedures to measure the new parameters required by the method.

09046 **Seasonal Variation of Moisture and Bearing Capacity in Roads with a Thin Surface Dressing Wearing Course**
S. Erlingsson, G. Bjarnason and V. Thorisson

Road structures in Iceland undergo annual freeze-thaw cycles, giving rise to environmental fatigue of the structure. In order to better understand the effect of environmental factors on the response and durability of the road structure, seasonal variability of moisture and temperature have been monitored for three years in the base and the subbase layers of three old test road sections in SW Iceland. Structural stiffness has further been measured regularly using the Falling Weight Deflectometer (FWD). The volumetric moisture content varies significantly, depending on seasonal variance (freeze-thaw) as well as the precipitation. Both a long-term seasonal variation and a short-term variation can be seen. The amount of moisture increases during short thawing periods during the winter and during the spring thaw period. During rainy periods the moisture in the layers increases, especially in the upper base course layers of the road, but is reduced quickly after the rainfall stops. From the FWD results the deflections and back-calculated moduli show good correlation with the measured moisture content in the pavement structure.

09047 **Top-Down Cracking, Damage and Hardening in Practical Flexible Pavement Design**
N.H. Thom, Y. Choi and A.C. Collop

This paper presents an approach to design against traffic-induced fatigue cracking, which allows topdown cracking, damage and hardening to be taken into account. The resulting computer-based prediction method makes use of recent laboratory research data on crack propagation and damage growth, both modelled in terms of calculated strain under load. Predictions relate first to damage growth, making the assumption that this is in the form of micro-cracks, which accumulate and grow in every part of the pavement experiencing tension. When cracks can no longer be considered small, strain in the region of the crack tip is related to propagation rate. The analysis methods used to obtain strain under load are sufficiently accurate for sensible usage, but incorporate engineering simplifications, avoiding the need for finite elements computations. Calculation of strain near the surface allows prediction of top-down cracking. Computation is incremental, first as damage accumulates and then as individual cracks grow.

09048 **An Improved Tool for Structural Design of Flexible, Composite and Rigid Structures**
D. Leonard, L. Francken

New structural design software is presented that deals with flexible, composite and rigid structures. The pavement design is based on a trial-and-error process involving the use of the linear elastic multilayer model for flexible and composite pavements and the strength of materials (Westergaard's theory) for the rigid ones. Evidence of illogical results in terms of fatigue performance using current pavement design philosophy for composite pavements are shown. Therefore, a new way of design is proposed to clear this issue.

09049 **Thin Asphalt Pavements on Soft Soil**
C.A.P.M. van Gurp and A.J. van Leest

This paper presents results of a study on the development of an integrated design and structural evaluation procedure for thin asphalt pavements. The procedure incorporates geotechnical design features, pavement design and evaluation, and the assessment of the reinforcing effect of geosynthetics in unbound road bases. The methodology uses the strain at the bottom and surface of the asphalt layer, the compressive strain at the top of the bound road base, the stress state at middepth of the unbound road base, the strain at the bottom of the bound road base, and the vertical compressive strains at the top sub-base and subgrade as design criteria. For the design of structural overlays, the load-carrying capacity of the pavement structure is expressed by the so-called Modified Structural Number, SNC, to circumvent the tedious procedure of backcalculation of layer stiffness moduli. An especially developed software tool called 'QUASAR' enables easy and very quick use of the multitude of equations to assess the structural condition of asphalt roads and to determine the required strengthening.

09050 **In-Place Densification of Hot Mix Asphalt and Verification of Superpave**
B.D. Prowell, E.R. Brown and M.H. Huner

In order to determine the optimum asphalt content for hot mix asphalt, the correct laboratory compaction effort needs to be applied during the design phase. The laboratory compaction effort for the Superpave mixture design system has been subject to refinement since first being introduced in 1994. The objective of this study was to verify the accuracy of the existing gyration table for the Superpave gyratory compactor. The verification includes data from two major research efforts, an evaluation of 40 field projects and the evaluation of 46 test sections of an accelerated loading test track at the National Center for Asphalt Technology. The results indicate that modified binders reduce the rate of pavement densification. The data appears to validate the currently specified gyration levels for low design traffic levels. Significant differences were found between the compactive efforts of different brands of Superpave gyratory compactors. These differences may be attributed to different internal angles applied to the samples.

09051 **Measurement of Edge Effects on Pavements with Thin Asphalt Surfacing**
J. Aksnes, I. Hoff and H. Mork

A full-scale pavement test has been performed at Sandmoen near Trondheim. Two different pavements were constructed, one of them were instrumented for the measurement of load responses at different depths and offsets from the pavement edge in the base and subbase layers. Results from controlled traffic and plate loading are reported in this paper. Vertical stress has been successfully measured both under the base and the subbase layers. The results show an increase in vertical stress towards the pavement edge. This effect is evident at the bottom of the base layer for load positions closer

than one meter from the edge. Increasing horizontal stress at the bottom of the base layer is recorded when a load is applied on the pavement surface. Deformation measurements show large plastic strains in granular materials, especially near the pavement edge. Parts of these strains recover when the load position is changed.

09052 **Reflective Cracking in Asphalt Overlay on Existing PCC**
F. Zhou and L.Sun

Reflective cracking is the main premature pavement distress of the asphalt overlay on existing PCC in China. A new anti-reflective cracking measure-Special Steel Grid (SSG) was developed to retard the reflective cracking. The preliminary test results showed that the SSG1 strongly reinforced the asphalt concrete and performed the best. In order to investigate the process of initiation and propagation of reflective cracking and validate further the effect of SSG1 on retarding the reflective cracking under repeated loads, both laboratory scale test pavements and field test roads were constructed. Both results indicated that SSG1 could effectively retard the occurrence of reflective cracking. And the double reflective cracks were observed in both laboratory and field. Furthermore, 3-D FEM was used to analyze the 3-D stress field in composite pavement structure (AC/PCC) in order to explain the observed phenomena. It was found that the interface debonding and associated horizontal tensile stress made the double reflective cracking initiate and propagate vertically in asphalt overlay. Finally, the optimal thickness of asphalt overlay for old PCC with different foundation was recommended based on the results of both 3-D FEM and field test roads.

09053 **Laboratory and Field Experimental Investigations About the Properties of a Bituminous Thin Layer with Porous Aggregate**
A. Bucchi, G. Dondi and A. Simon

A presentation and a critical analysis are made about the physical and functional characteristics of an ultra-thin porous layer. This work in particular deals with experimental tests carried out on a bituminous mix having part of the aggregate constituted of expanded clay. This mixture represents an improvement of the usual antiskid layer with discontinuous grading, concurring to obtain a lightening of the mixture and an increase of the skid resistance. The experimental study allowed to analyse the methodologies of employment of the gyratory compactor and the procedures of volumetric design. The analysis has concurred to verify also the possibilities of production and the performances of this bituminous mix. The comparison between the preliminary laboratory tests and in-situ tests for skid resistance, permeability and void index, allows to verify the data obtained during the optimisation study. The results obtained during construction also provided valuable indications on the parameters for design and quality requirements.

09054 **Temperature and Density Differentials in Asphalt Concrete Pavement**
K.A. Willoughby, J.P. Mahoney, L.M. Pierce, J.S. Uhlmeyer and K.W. Anderson

The Washington State Department of Transportation (WSDOT) has conducted an examination of open-textured areas in hot- mix asphalt paving over four construction seasons, 1995, and 1998 through 2000. These study programs examined over 60 production paving projects to determine the cause of these open-textured areas in the finished pavement. In 1995, examination of these areas revealed that a potential cause may be temperature differentials in the mat. The 1998 study program eliminated aggregate segregation as the only cause. WSDOT focused on the types of equipment being used (material transfer devices/vehicles, pavers, rollers, etc.) to investigate any patterns of temperature differential occurrence in 1999. In 2000, nuclear density testing through the open-textured areas was performed to determine the severity of density differentials in the mat. The bottom line is that pavements that experienced large temperature differentials during placement produced substantial density differentials in the finished mat.

09055 **Factory Production Control According to the New PREN 13108-21**
E. Eustacchio and G. Klimisch-Ibler

The European Standard prEN 13108-21 "Bituminous mixtures - Quality - Part 21: Factory Production control" describes how mixing plants shall operate their production control. In an Austrian research project six mixing plants of different age and design were investigated to show the effects of a quality management system as described in prEN 13108-21 on the results of mixture control. It is intended that the results of this project help to estimate future quality costs and their effects on the price of bituminous mixtures. On the other hand the results should assure that the frequencies set in prEN 13108-21 are realistic and that mixing plants are able to fulfil the requirements of this FPC system.

09056 **Performance Requirements on Asphalt Mixtures/Layers in Asphalt Contracts**
N. Ulmgren

New forms of contracts, where requirements are expressed in performance characteristics on the asphalt mixtures or on the built in asphalt layers instead of the traditional recipe approach have been introduced in Sweden since a couple of years. The performance parameters that are at first hand used in these contracts are abrasion, stability, bearing capacity and water sensitivity all measured on the mixtures or on cores from the built in layers. All these functional methods are at hand as prEN-standards. Both parties are new to these new forms of contracts and the client has to learn how to express his needs in functional terms and the contractor has to learn to produce a suitable mixture and pavement and take full responsibility for the results for a longer period of time. In the paper the development of criteria for contracts stipulating performance characteristics on the asphalt mixtures or on the built in asphalt layers are described. The paper also gives an account of the experience so far as of how the different laboratory methods may give a rightful forecast of the performance of the asphalt materials in the road.

09057 **Alternative Contracting Models for Maintenance and Rehabilitation of Pavement Networks**
R. Haas, C. Raymond, J. Yeaman and L.C. Falls, I. Rickards

The privatization of maintenance and rehabilitation for road networks can be in the form of several types of alternative contracting models. These range from privatized or outsourced maintenance, to public-private sector partnerships, to competitive or legislated highway maintenance to privatized highway asset management and maintenance, all generally involving terms of five years or less. Another type of model involves long term performance based contracts with terms of ten years or more. The allocation of risk between the public sector owner and the contractor varies with type of model. Any public sector owner contemplating privatization should carefully assess the pros and cons of each type of model as well as a number of influencing factors. The paper contends that despite a number of issues involved, the long term performance based contracting model offers the best potential for innovation and cost savings. Finally, it presents recommendations toward maximizing these benefits.

09058 **User Delay Impacts of Alternative Traffic Plans for Maintenance and Rehabilitation Interventions**
S.L. Tighe and R. Al Assar

Whether or not user delay costs due to maintenance and rehabilitation (M&R) interventions should be included in life cycle analysis is a controversial subject. However, there is a growing awareness or acceptance by public agencies that they should be considered either directly, in life cycle analysis, or at least indirectly in terms of the "down time" represented by delays. In fact, there is some contention that this down time is no different than that occurring when workers are not on the job due to illness, etc.A number of quite sophisticated user delay models have been developed which calculate slowing plus queuing delays, and the associated costs. A comprehensive model was developed in Ontario's, Ontario Pavement Analysis of Costs (OPAC) 2000 pavement design system, as reported at the 8th Conference in Seattle in 1997. This paper first identifies the available models, their principal features and their limitations. Among the limitations for most of the sophisticated models is the extensive requirement for input data, which in turn makes them cumbersome to use. The real issue suggested in the paper is twofold: (a) obtaining quantitative numbers on delay times and costs of sufficient reliability for the life cycle analysis, and (b) being able to evaluate the alternative traffic plans, including detours. To address these issues, the paper shows how user delay calculations can be simplified to yield approximate but still sufficiently reliable numbers for life cycle comparison of alternative M&R strategies as well as comparisons of a wide range of alternative traffic plans.

09059 **Selection of Pavement Maintenance By Use of Accelerated Load Testing**
C.B. Nielsen, J. Rosenberg and J. Raaberg

A three-year research project was commenced in 1998 at the Danish Road Institute to establish a basis for evaluating the flow rutting and weathering resistance of specific types of Danish asphalt pavement materials. The objective of the present paper is to combine the definition of road classes, with respect to flow rutting and weathering resistance, with an empirical model to estimate the development of rutting in the asphalt pavement. The empirical model is based on Accelerated Load Testing in the Danish Asphalt Rut Tester (DART). Different maintenance strategies are evaluated from an economic and technical point of view and the benefit from accelerated load testing is assessed.

09060 **Towards a Performance Related Seal Design Method: New Empirical Test Method Using Scaled Down APT and Theoretical Performance Model**
T. Milne, M.F.C. van de Ven and K.J. Jenkins

Practice has shown that bituminous road surfacing seals, with "straight" or modified bituminous binders, do not always behave as expected or predicted. An investigation towards a performance related seal design method was thus initiated at the Department of Civil Engineering, University of Stellenbosch during 1998. Part of this investigation focuses on the development of a new empirical test method using the scaled down accelerated pavement tester (model mobile load simulator) for seal performance prediction. The development of the new empirical test method is provided, with the findings of the first series of test results, where the performance of straight and modified single seals is compared. Current research is examining comparative performance of the different seal binders at road surface temperature at or approaching softening point (50ºC). The range of seal binders tested includes bitumen roller EVA, SBS and SBR modified binders, and the 80/100 penetration grade bitumen control. The development of a theoretical model aimed at assisting with the prediction of road surfacing seal serviceable life is discussed. The empirical test results will be used to assist in the evolution of seal design improvements where applicable, and in the calibration of the theoretical model. The comparison of empirical and theoretical model parameters relating to applicable performance aspects of the road surfacing seal is made. Aspects examined through literature search and original research include the seal components (aggregate, binder), pavement, environment and imposed load, and seal design and performance.

09061 **Compaction of HMA Using a High Frequency, Double Drum Vibratory Roller**
J.A. Scherocman, Y. Nohse and K. Hokari

The purpose of this research is to determine the relationship between roller speed, vibratory frequency, and number of roller impacts per meter and the effect of this relationship on the density obtained for a hot mix asphalt (HMA) pavement layer. Roller test sections were constructed in Japan, California, and Kentucky using various combinations of roller speed (two or three levels), roller vibratory frequency (two or three levels) and number of roller passes (two levels). It was determined that for a given vibratory frequency, as roller speed increased (number of impacts per meter decreased), density decreased. It was also determined that, in general, for a given roller speed, density increased as the vibratory frequency increased (impacts per meter increased).

09062 **Very Thin Asphalt Concrete as Runway Wearing Course. Quality Control by Mean of Microscopy Techniques**
H.C. Korsgaard and H.H. Bunner

In 1998 the first part of the main runway, 04L-22R, at Copenhagen Airport was successfully tendered for the resurfacing of the approximately 30.000 m2 wearing course. The works included the milling off of the top 20 mm of the old wearing course and the construction of a new 20 mm thick wearing course type where the asphalt paving machine is spreading 1,2 - 1,4 kg/m2 of emulsion in front of the open graded asphalt concrete being paved. The rest of the runway has successively been resurfaced during the period from 1999 to 2002 using the same method. The tender documents were based on the new type of specifications, which are based purely on functional requirements in this case including end-performance requirements after an eight-year warranty period. Amongst other topics the requirements used in the specifications are described below. During construction of the new wearing course, the client controlled the work intensively in order to be able to evaluate the actual quality of the new pavement and in order to be able to predict the development of the performance of the pavement using the first test results as a platform for the comparison with future measurements. For these purposes traditional laboratory test methods as well as new test methods like thin section microscopy were used. This has placed Copenhagen Airport A/S in a position making it possible for Copenhagen Airport to assess whether the maintenance methods and the maintenance efforts of the contractor during the eight-year warranty period are satisfactory or not in relation to the functional requirements of the new wearing course. The output of the traditional laboratory analysis as well as the output of the analysis of thin section microscopy during the four-year period is described below. The use of this pavement type has resulted in unexpected advantages. One of the unexpected advantages is that compared to conventional pavements for runways almost no rubber from the wheels of the aircraft fastens to the pavement surface and therefore no derubberisation work has been necessary after four year's use. Another unexpected advantage is that much less de-icer material is needed for the de-icing of the pavement compared to traditional runway pavements.

09063 **The Rehabilitation of the Ricchieri Highway in Argentina with SMA and Thin-SMA Technologies**
P.E. Bolzan

The present paper describes the application of Stone-Mastic Asphalt (SMA) and thin-SMA technologies that were used for the rehabilitation of the Ricchieri highway near the international airport of Buenos Aires, Argentina. This dual carriageway connects Buenos Aires city with the international airport and carries more than 120,000 vehicles per day. Due to the presence of reflective cracking (composite pavement sections), rutting, and lack of sufficient skid resistance, the road authorities conducted an investigation into the functional and structural conditions. From the rehabilitation techniques available, a variable thickness flexible overlay of SMA application was selected. The main goal was to cover both the functional and the structural needs with a single layer application together with some localised repairs. As a result a new heavy duty, high skid resistance wearing course surface has been obtained with a single application on a heavily trafficked highway. At present the performance of both SMA and thin-SMA layers are excellent.

09064 **The Effect of Reconstruction on the Stiffness, Balance and Stress Dependency of Pavement Layers**
P.W. de Bruin, A.T. Visser and G.J. Jordaan

Pavement reconstruction / rehabilitation usually involves the re-use and retension of existing pavement layers. Often, these layers are retained as sub-layers with the addition of strength in terms of new layers on the top of the pavement. Hence, in order to accurately analyse the behaviour of the rehabilitation effect, both the old as well as the new pavement layers need to be characterised accurately. Currently, little or no information or guidelines are available to assist the researcher or design engineer to accurately predict or simulate the elastic properties of the rehabilitated pavement. The objective of the paper is to demonstrate the effect of rehabilitation actions on pavement properties such as balance, pavement structure behaviour (stress-stiffening and / or stress-softening etc) and stress dependency. An experimental section of road was evaluated before and after rehabilitation and the stiffness and associated stresses were determined in situ for the different uniform sections for modelling purposes along the road. It was found that the elastic modulus changed dramatically with the addition of new layers, even if the layer was not disturbed.

09065 **Cold Mix Recycling of Milled Pavement Material for the Construction of Low-Volume Roads in Saudi Arabia**
A. Al-Dughaim

Due to the vast network of low-volume roads in the Kingdom and the important social and economic benefit provided by them, the Ministry of Communications (MOC) is keen on the enhancement of low volume road sector through the application of appropriate technology. Cold mix recycling is one of the techniques to economically upgrade the existing low-volume tracks and to construct good quality new low-volume pavements. A substantial quantity of milled material (asphalt) is generated from the rehabilitation and maintenance projects of the existing pavements. Several hundreds kilometers of low-volume roads have been constructed by performing cold mix recycling of the milled material generated from these projects. Both emulsion and cutback asphalt have been used as recycling agents in preparing cold mixes. The roads constructed in Riyadh and Hail districts are evaluated through visual condition survey and laboratory characterization. The paper concludes that most of these cold mix recycled roads have shown good performance. They are also economical and provide environmental benefits. It is recommended that more detailed evaluation of the milled material should be performed.

09066 **Development of Asphalt Overlay Performance Models From the C-LTPP Experiment**
S. Tighe, R. Haas and N. Li

The Canadian Long Term Pavement Performance (C-LTPP) study, initiated in 1989, involves 65 sections in the 24 provincial sites that received rehabilitation comprising various thicknesses of asphalt overlays. This paper describes the impacts of the various alternative rehabilitation treatments on pavement performance in terms of roughness progression under comparative traffic loading, climate, and subgrade soil conditions. Factor effects, including climatic zone, subgrade type and traffic level were also evaluated. Some findings are that: (a) in wet, high freeze zones, thinner overlays show a higher rate of roughness progression than thicker overlays, regardless of subgrade type; (b) in dry, high freeze zones, roughness progression for medium and thick overlays is relatively small; (c) in wet, low-freeze zones, thinner overlays combined with a fine subgrade show the highest rate of roughness progression. The methodology developed in this study for pavement roughness evaluation can be applied to performance trends analysis of other LTPP data.

09067 **Pavement Evaluation and Strengthening Design: Sixteen Years Experience**
B.A. Hakim, S.F. Brown and R.J. Armitage

Practical implementation of analytical pavement evaluation and strengthening design using the Falling Weight Deflectometer (FWD) and associated techniques has resulted in many developments in the past sixteen years and represents an excellent example of "paving the gap" between research and practice. This paper presents case studies to illustrate the techniques in various applications. Use of the Nottingham Asphalt Tester (NAT) to assess the mechanical properties of bituminous layers from tests on cores is commonly carried out to support FWD findings and for use in pavement strengthening design. Non-linearity of subgrade material crucially affects FWD measured deflections and, hence, the back analysed results. Therefore, determination of subgrade stress levels and the consequent stiffness variations with depth result in more realistic designs. Other case studies are described to illustrate:

- Whole life cost and pavement design optimisation for clients such as Design Build Finance and Operate (DBFO) consortia, using mechanistic techniques.

- Practical implementation of end-product performance testing such as FWD, Dynamic Cone Penetrometer (DCP) and Dynamic Plate Bearing Tester (DPBT) on foundations, and NAT on bituminous samples, to support applications of mechanistic design techniques.

- Use of the FWD to improve the design of rehabilitated concrete pavements using the 'crack and seat' technique with bituminous overlay.

- Use of a new analysis technique for prediction of bond stiffness between bituminous layers from FWD data, to assist in detailed structural evaluation.

09068 **Implementation of Falling Weight Deflectometer Technology and Development of Analytical Pavement Design in Thailand**

S. Lekso, T. Ruenkrairergsa and C. Phromsorn

Thailand has experienced an exceptionally rapid economic development over more than 10 years, leading to major infrastructure problems and costly rehabilitation of the road network at short intervals. The Thai Department of Highways aims to reduce the maintenance costs through more appropriate pavement evaluation and design. A contract agreement for the "Implementation of Falling Weight Deflectometer Technology and Development of Analytical Pavement Design Project" was signed between the Department of Highways, Thailand and the Danish Road Directorate in October 1998. Funding for the project was provided through a Danish Mixed Credits Loan for the total costs of the project. The duration of the project was three years ending in December 2001. The project has included intensive testing of 130 road sections by the Falling Weight Deflectometer and by Benkelman Beams. In addition, the pavement structures were checked and samples brought to the laboratory for further tests. The activities were summarised in ten research tasks. The present paper describes the activities used in the successful implementation of the new technology in the highway organisation and examples of the results. The technical content of the project is published in fourteen Technical Reports and Manuals available at the Department of Highways, Thailand.

09069 **In-Situ Assessment of Stiffness Modulus for Highway Foundations During Construction**
P.R. Fleming, J.P. Lambert, M.W. Frost and C.D.F. Rogers

Several portable field devices that measure stiffness modulus are reviewed in detail in this paper including the German Dynamic Plate Test (also known as the Lightweight Drop Tester), the TRL Foundation Tester (UK), the Prima (Denmark) and the Humboldt Soil Stiffness Gauge (USA, also known as the GeoGauge). Laboratory and field data are presented which explain the many important influences on the measured data and demonstrate comparative performance with respect to the Falling Weight Deflectometer. These field data show significant scatter and site specific correlation. A strategy for compliance testing during construction, as part of a performancebased specification approach for the UK, is suggested. Conclusions are made regarding the devices' relative merits and limitations, and considerations for their introduction into contractual use for routine assessment during construction.

09070 **Back-Calculation of Pavement Layer Moduli and Forward-Calculation of Stresses and Strains**
W. Zhang and P. Ullidtz

The "analytical-empirical" (or "mechanistic-empirical") method is widely used in pavement design or evaluation. The method has three steps:
1. Determine the moduli of the pavement layers
2. Calculate the critical stresses or strains under the design load(s)
3. Compare critical to permissible values (or use stresses or strains in a deterioration model)

If the pavement layer moduli are determined from an inverse analysis (backcalculation) of Falling Weight Deflectometer (FWD) data, then the first two steps in this procedure constitute the "analytical" part. This paper deals with these two steps in relation to deflections, stresses and strains measured under a FWD. In step 1 and 2 above, the pavement "response" is calculated using a theoretical model, in terms of deflections in step 1 and of stresses and strains in step 2. All theoretical models involve simplifications with respect to reality and even the most "sophisticated" theoretical model must be verified against real pavement structures. To verify a theoretical model, the stresses or strains calculated in step 2 may be compared to measured stresses or strains. During the past ten years this has been done on three instrumented pavements in the Danish Road Testing Machine and on three in situ pavements in Sweden. Strains at the bottom of the asphalt layer and stresses and strains at the top of the subgrade (which are frequently used in design methods) were measured and compared to theoretical values. Three different theoretical models were used to first backcalculate the layer moduli and then forward calculate the stresses and strains. The models were: Layered Elastic Theory with linear elastic materials, the Method of Equivalent Thicknesses with a nonlinear subgrade and the Finite Element Method where any layer may be non-linear elastic. For the strains at the bottom of the asphalt, reasonably good agreement was mostly found with all theoretical models, although some comparisons gave very large differences. For the strains at the top of the subgrade, the assumption of linear elastic materials gave very poor agreement. A reasonably good agreement could be obtained with a non-linear elastic subgrade. In most cases the best agreement (and the most reasonable values for layer moduli) was found using the Method of Equivalent Thicknesses.

09071 **Asphalt Pavement Performance Research Project in Lithuania**
A. Braga, V. Puodziukas

Currently there are three PMS systems used in Lithuania- HDM-III, HDM-4 and DAVASEMA (Lithuanian PMS). HDM pavement performance models are used in all of them. With the purpose of calibration and adaptation of those models in 1997 Lithuanian Pavement Performance Research Project was executed. The research data gathered in four years of the Project gives opportunity to do some conclusions on asphalt pavement performance in Lithuania. The first stage attempts of the adaptation of input data and calibration of HDM models to local conditions are described in this article.

09072 **Modelling Flexible Pavement Performance Using Canadian Historic Data**
T. Kazmierowski and L. Ningyuan

The Ministry of Transportation of Ontario (MTO) has recently completed the development of a Second- Generation Pavement Management System (PMS2). One of the advanced features built in the system is a number of performance prediction models used for analysing short-medium term pavement needs at the network level for maintenance and rehabilitation treatments planning purposes. Data samples recording more than 25 years of field pavement performance history were used in modelling deterioration characteristics of flexible pavements for each functional class of road. These models range from simple polynomial curves to sophisticated sigmoidal performance models. Substantial efforts were put into this phase of model analyses, including data source and pre- process, model analysis, and using engineering judgement to assess the impacts of various pavement rehabilitation treatments on overall pavement performance. Some major findings and recommendations from this study may be useful for highway engineers and practitioners in the areas of pavement life-cycle analysis, multi-year rehabilitation programming and economic analysis of thin asphalt pavements versus thick asphalt pavements.

09073 **Implementation of Ground Penetrating Radar Technology in Asphalt Pavement Testing**
T. Scullion and T. Saarenketo

Over the past decade Ground Penetrating Radar (GPR) applications have been under development within both the Texas Department of Transportation (TxDOT) and the Finnish National Roads Administration (FNRA). In the mid 1990's GPR systems moved into mainstream usage, improved software was developed and training schools were conducted. TxDOT now has 4 complete air launched GPR systems for pavement evaluation. GPR technology is now used on a routine basis as the first step in planning the rehabilitation of flexible pavements. In Finland GPR has been implemented in the area of quality assurance testing of new asphalt overlays. Using a limited number of calibration cores the GPR data are used to compute the inplace air void content profile of new overlays. In the 2000 construction season a penalty system was implemented based on these GPR results, and the feedback from both FNRA and the contracting community has been positive. This paper will provide an overview of these development and implementation efforts. The basics of GPR will be presented together with a discussion of the methods used to convert GPR waveforms into information useful to pavement engineers. A number of successful case studies will be described. GPR was initially promoted as a rapid layer thickness measuring tool. It certainly provides useful thickness information for the upper layers of flexible pavements. However as will be described in the case studies GPR can provide substantially more information than simply layer thickness.

09074 **Step-Frequency Radar Applied on Thin Pavements**
X. Derobert, J-M. Simonin, L. Laguerre and C. Pichot

In the field of road construction and maintenance, the need for information on the thickness of very thin road layers is not being satisfied by means of commercial impulse ground penetrating radar (GPR), due to the inability of such devices to operate over ranges of several gigahertz. As a result, research has focused on the design of a step-frequency radar technique, capable of working with very high-frequency synthetic pulses. The principle of the step-frequency technique is presented herein. An ultrawide band antenna (within the family of Vivaldi antennas) has been developed for road applications; it was created using "stripline" technology and yields a bandwidth greater than one decade, over a severalgigahertz range. GPR dynamic measurements were obtained from selected road construction and maintenance test sites (e.g. the Circular Pavement Fatigue Test Track, composed of a number of known structures). Results have shown improved resolution in comparison with a commercial impulse GPR system. Indeed, thin asphalt surfacing thicknesses can be measured from raw stepfrequency radar data in instances when very thin asphalt surfacing requires signal processing for thickness measurements.

09075 **Performance-Based Pay Factors for Asphalt-Concrete Construction Reflecting Fatigue and Rutting Effects**
J.A. Deacon, C.L. Monismith, J.T. Harvey and L. Popescu

This paper describes a rational and feasible method to quantitatively establish pay factors for new asphalt concrete pavements. The approach uses performance models for fatigue and rutting based on the analysis of accelerated pavement tests from the Caltrans Heavy Vehicle Simulator (HVS) and the Federal Highway Administration Project WesTrack. For rutting, the influence of asphalt content, air-void content, and aggregate gradation are considered. For fatigue, air-void content, asphalt content, and asphalt concrete thickness are included. Costs are established using a cost model considering only agency cost consequences of delaying or accelerating the time to the next rehabilitation. For the as-constructed mix the relative performance RP (ratio of off-target ESALs to target ESALs) is determined for both fatigue and rutting. The shortest RP for the combined RP's for mix and pavement characteristics considered for a specific distress mode permits determination of the pay factor from the cost model.

09076 **The Benefits of User-Friendly Suspensions**
A.C. Collop and D. Cebon

This paper examines the effects of 'road friendly' heavy goods vehicle suspensions on long-term flexible pavement performance. A deterministic Long Term Pavement Performance Model (LTPPM) is used to calculate pavement damage due to realistic traffic and environmental loading. The traffic is modelled first as a fleet of steel sprung heavy goods vehicles and second as a fleet of 'road friendly' air suspended vehicles. Two generic types of flexible pavement construction are considered representing a major road and a minor road. Pavement life predictions are compared for the two cases and with results from a simple road damage analysis based on the 'fourth power law'. It is concluded that changing to a fleet of 'road friendly' vehicles would not significantly affect the life or maintenance costs of thicker asphalt pavements (motorways and trunk roads) whereas the life of thinner pavements (minor roads) would be increased significantly if the vehicle fleet changed to road friendly suspensions.

09077 **The Combined Effects of Tire Contact Stresses and Environment on Surface Rutting and Cracking Performance**
L.A. Myers, C. Drakos and R. Roque

This paper will describe how the combined effects of tire contact stresses and environmental conditions may control the surface cracking and rutting performance of pavements. Measured tire contact stress data will be used in conjunction with a range of environmental conditions to evaluate their effects on near-surface stresses that are conducive to rutting and cracking. Findings to date have indicated that temperature gradients during cooling periods are most conducive to surface cracking. The work has also shown that an overall shear stability evaluation during critical high temperature periods may need to be conducted to better assess the near-surface rutting potential of a particular mixture in given environment.

09078 **Asphalt Pavement Deterioration Models for Mild Climatic Conditions**
A. Loizos, J. Roberts and S. Crank

There is currently significant international activity in model development, including the EU PARIS and RIMES projects, and the models within HDM-4. However, due to climatic and material variations across Europe, more models are needed. The Paper describes the ongoing adaptation of a suite of innovative performance models, based on HDM-4, for asphalt pavements for use in mild (Mediterranean) climates and operating conditions. The models have significant changes and additions to improve their realism, consistency, explanatory power and sensitivity, and are being implemented within a Road Infrastructure Management System (RIMS) being developed for the Greek Government. It is hoped that the work will be a positive contribution to HDM-4 development. The Paper provides an overview of the requirements of a satisfactory modelling system, a description of the modelling of structural degradation, and aspects of the models for cracking, rutting and roughness.The Paper compares the models with the official HDM-4 models in terms of a study for crack modelling using Greek SHRP LTPP data.

09079 **Performance Models for Deep in Situ Recycled, Bitumen Stabilised Pavements Under Accelerated Traffic**
F. Long, H.L. Theyse, S. Robroch and J. Liebenberg

This paper describes research to assess the use of foamed bitumen and bituminous emulsion treated materials with deep in situ recycling (DISR) technology. The paper discusses Heavy Vehicle Simulator (HVS) and laboratory test results on these materials. The results showed that the treated materials have higher resistance to permanent deformation than fatigue. The HVS sections failed after the addition of water, exhibiting erosion and pumping. The laboratory test results show that treating the material with bituminous binders and cement increases the permanent deformation resistance, and if enough binder is added, the flexibility of the material improves. The HVS data are used to develop preliminary structural design models for effective fatigue and permanent deformation, and to determine damage factors. The materials are more load sensitive in fatigue than permanent deformation.

09080 **Asphalt Concrete Response: Experimental Determination and Finite Element Implementation**
S.M.J.G. Erkens, X. Liu, A. Scarpas and A.A.A.Molenaar, J. Blaauwendraad

At the previous conference the beginning of an extensive experimental and analytical investigation into the mechanisms leading to the initiation and propagation of damage in asphalt concrete pavements was reported. The objectives of this Asphalt Concrete Response (ACRe) project were twofold, firstly a 3-dimensional, strain rate sensitive, temperature and loading history dependent constitutive model would be formulated and implemented in the finite element package CAPA-3D. Secondly, the necessary experimental set-ups, testing procedures and dataanalysis methods for determination of the model parameters would be developed. At the time the prototype formulation of the model was reported, along with preliminary test results and the way in which the model parameters were determined on the basis of the experimental results. A simulation of the dynamic non-linear response of a pavement was included to demonstrate the possibilities of the approach. In the past years, the project progressed rapidly, with continuous interaction between the two objectives: on the one hand the model dictated what should be measured in a test, while on the other hand, the response observed in the tests set the requirements for the model. This led to regular adaptations in the numerical formulation as well as the development of highly accurate test set-ups for parameter determination. Throughout the project, test results were compared to model predictions to verify applicability. In this contribution both, the numerical and the experimental aspects of the project will be presented in detail.

09081 **ILLI-PAVE Based Flexible Pavement Design Concepts for Multiple Wheel-Heavy Gear Load Aircraft**
M. Thompson, F. Gomez-Ramirez and M. Bejarano

ILLI-PAVE, a structural axi-symmetric non-linear finite-element pavement analysis software, has been enhanced to characterize flexible pavement response and performance under Multiple Wheel-Heavy Gear Load aircraft using Mechanistic-Empirical concepts. Several analysis techniques using the Principle of Superposition (PS) are applied to account for response interaction (stresses, strains and deflections) from multiple wheel loads. It has been shown that, for engineering purposes, the PS is valid and can be used to determine load-induced stresses and deflections of MW assemblies provided the SW responses are accurately computed or measured. To characterize Flexible Pavement performance using Mechanistic-Empirical concepts, fatigue-cracking and subgrade permanent deformation models have been adopted. The horizontal strain at the bottom of the asphalt layer is used to assess fatigue-cracking damage. For subgrade rutting, a Subgrade Stress Ratio criterion (SSR = applied stress iA soil strength) is used.

09082 **New Evaluation of Pavement Performance Through Mechanical Fatigue Testing**
P. Des Croix

Mix mechanical fatigue testing is almost thirty years old in our laboratory. The classical fatigue approach is to record the number of cycles for failure versus initial stress or strain. The standard fatigue law has the following form: delta = A Nsuper-B, with delta = (strain) or (stress). A new approach based on damage theory approach is presented in this paper leading to a new law: fatigue damage rate asubF versus strain amplitude level eta. Typical results are shown with a standard mix formulation with pure and modified bitumen. With this new approach, the procedure appears as independent of the type of loading (as far as an "homogeneous" testing procedure is considered). The testing time (as it is no more necessary to go up to the failure of the sample) can also be reduced.

09083 **Crack Growth Behavior of Asphalt Mixtures and Its Relation to Laboratory and Field Performance**
R. Roque, B. Birgisson, B. Sangpetgnam and Z. Zhang

Laboratory and field studies have resulted in a more complete understanding of the cracking behavior of asphalt mixtures and of the cracking mechanisms associated with asphalt pavements. This work has also led to the development of a viscoelastic fracture mechanics-based crack growth law that is capable of fully describing both initiation and propagation of cracks in asphalt mixtures for any combination of loading and temperature conditions. The model requires the determination of only four fundamental mixture parameters that can be obtained from less than one hour of testing using the SuperPaveTM Indirect Tension Test (IDT). These parameters can account for micro-damage, crack propagation, and healing for stated loading conditions, temperatures, and rest periods. This paper summarizes the developments leading to the model, and descri-bes the model and its potential use in the areas of mixture design and optimization, performance-based specifications, and pavement design.

09084 **RILEM - Interlaboratory Tests on Performance Prediction of Pavements**
M.N. Partl and H. Piber

First conclusive results of an ongoing international RILEM test programme are presented where performance predictions of different laboratories based on their own test methods and models are compared. Slabs and technical data of two motorway test sections were provided to 16 laboratories participating on a voluntary basis. This paper focuses on rutting and fatigue predictions for a period of 10 years. It was found that the predicted rut depths varied over a wide range. Compared to rutting, the fatigue predictions were in better agreement. However, the conclusion that fatigue models are more accurate could not be drawn. For both rutting and fatigue prediction, none of the laboratories followed a procedure and methodology which was directly comparable. This made clear that further exchange and co-ordination of research efforts is extremely necessary.

09085 **Evaluation of Pavement Performance Performance of Bituminous Roadbase Layers**
S.F. Said, R. Fredriksson, H. Carlsson and H. Jansson

Four different bituminous roadbase mixes were used in a new segment of a highway. The bituminous mixes were modified stone mastic asphalt called Viacobase D, which is used as a large aggregate roadbase mix, grouted macadam, which is

coated with open graded asphalt concrete called Runbase, conventional bituminous gravel mix, type AG25/B180, which was used in the reference sections, and a modified AG25/B180, which has a high content of stone particles. Pavement performance was studied 1995 - 2001 through measurements of deflection, rut depth and unevenness and manual distress identification, as well as traffic counts. A number of cores were taken for studying performance-related (functional/mechanical) properties of mixes in the laboratory. The evaluation is based on pavement performance. Furthermore, similar structures were tested in a Circular Test Track. In addition to evaluation of the roadbase layers, the purpose was to validate laboratory and field methodologies for predicting distress in flexible pavements, in particular roadbase layers.

09086 **Study on the Performance-Based Design Method of Flexible Pavement**
S. Lijun, Z. Hongchao, L. Fangyan, L. Liping and L. Hui

Along with the increasing traffic volume, vehicle's speed and axle load, serious initial failures occurred on the heavy-duty asphalt pavements in recent years. The rapid deterioration attracted more and more attention on the conventional road technique. To improve the pavement design methods, field investigation and mechanistic analysis have been conducted, and six new types of distress were addressed herein. The research indicates that the conventional pavement technique only be suitable for the ordinery pavement design but not the heavy-duty pavements. On the freeway, the dynamic hydraulic pressure under the moving-vehicles' tires became an unneglectable factor causing the initial failures. The non-uniformly distributed load is another important factor which will cause the local damage, and the other important factor is the overload. According to the pavement structure behavior equation covering the whole life cycle, which is eatablished in this paper, a new bitumen pavement design method based on performance was developed.

09087 **Highway Pavement Performance Models**
L. Gaspar

Since 1991, 62 Hungarian pavement sections have been yearly monitored to develop pavement performance models for various combinations of traffic-pavement type-subsoil strength. The condition evaluation technique and its application areas are presented. The investigation of resurfaced and redressed trial sections allowed to evaluate the actual condition improving effect and the cost-effectiveness of various intervention types. The time-series condition data of the 5-year monitoring of several main and secondary road sections of altogether 3000 km length will be used to validate the performance models based on the measuring results of 62 trial sections.

09088 **Bitumen Rubber Asphalt: Report on the Long Term Performance in South Africa**
C.J. Potgieter, D.E. Sadler and E.M. de Villiers

The three authors were involved with bitumen-rubber (B-R) binders and asphalts since its introduction into the Republic of South Africa (RSA) in the early 1980's. Recently they revisited most of these old projects to evaluate the performances of (B-R) asphalts over the last 20 years. This paper contains the result of this survey, it also details the B-R asphalt and binder properties at the time of manufacture. The outcome culminated in the present RSA specification for B-R binders and asphalts. Their specifications are also furnished in this paper. B-R products are normally at a disadvantage in that they are placed where the conventional asphalts have already failed and on top of this must now prevent the old asphalt's deficiencies from reflecting through the new surfacing again. B-R binder and asphalt performed this role admirably.

The crack dampening and waterproofing provided by the bitumen rubber stress absorbing membrane interlayers (SAMI's) and B-R asphalts, as well as the enhancement of structural capacity provided by the latter, were found to be far superior when compared with conventional binders and asphalts under similar conditions. For heavily trafficked and distressed roads B-R asphalts and SAMI provide the more economic overlay in the RSA.

09089 **Engineering Properties of Asphalt Concrete Mixtures Utilised in Thailand**
T. Ruenkrairergsa, S. Lekso and P. Silarom

The Department of Highways, Thailand, is considering improving its method of evaluating and designing flexible pavements from the conventional empirical method to the semianalytical method. Prior to doing so, the engineering properties of pavement materials of each layer need to be known. Since the engineering properties of Asphalt Concrete (AC) mixtures are the parameters of most concern in the pavement design process, these need to be considered in detail. Therefore, a research study into the engineering properties of AC mixtures used in Thailand was initiated. In this study, more than 300 Asphalt Concrete core samples were taken from more than 70 selected test sections around Thailand. The cores were tested by various laboratory-testing methods, such as the Indirect Tensile Strength test, the Resilient Modulus test and the Fatigue test to obtain the engineering properties of Asphalt Concrete in Thailand. The results indicate no major difference between Asphalt Concrete Mixtures used in different regions of Thailand. The average value of the Indirect Tensile Strength was found to be 1.08 MPa at 25°C. The Resilient Modulus was found to be quite high, the average values were found to be 2,468 / 4,410 / 7,794 / 13,183 MPa at 45 / 35 / 25 / 15°C, respectively, corresponding to nearly a twofold increase of the Resilient Moduli for every 10°C decrease in the testing temperatures. In addition to the laboratory tests, non-destructive testing of the test sections were performed using the Falling Weight Deflectometer (FWD) to obtain the backcalculated AC moduli. Subsequently, a comparison between the AC Resilient Moduli determined from laboratory testing and backcalculated AC moduli from FWD testing of selected road test sections was made. The AC Resilient Moduli determined in the laboratory are found to be higher than the AC moduli obtained from backcalculation by a factor of between 1.45 and 1.91. The differences were found to decrease with increasing temperature.

09090 **Using Field Measured Stresses and Strains to Quantify Flexible Pavement Responses to Loading**
A. Loulizi, I.L. Al-Qadi, G.W. Flintsch and T.E. Freeman

One of the 12 instrumented sections of the Virginia Smart Road was used to evaluate the effect of several loading parameters on the measured stresses at different layers and the measured horizontal transversal strain in the bottom of the hot-mix asphalt (HMA) layer. It was found that speed does not affect the measured vertical compressive stress in all layers, but does significantly affect the measured horizontal transversal strain under the HMA layer (190.5mm below the pavement surface). Strain was found to decrease by a factor of 2.7 when the speed increases from 8km/h to 72.4km/h at 25°C. Variation in tire inflation pressure from 551.6kPa to 724kPa was found not to affect the measured vertical compressive stress in all the layers and the measured horizontal transversal strain in the bottom of the HMA layer. Vertical stresses under the HMA layer were found to vary linearly with the applied tires' load at 25°C.

09091 **Estimation of the Plastic Strain in the Pavement Subgrade and the Pavement Functional Condition**
W. Zhang and P. Ullidtz

At the present time, most subgrade failure criteria use the permissible stress or strain at the top of the subgrade. The permissible stress or strain is related to the volume of traffic, and is mostly independent of soil type, moisture content and mechanical properties of the soil. Over the past six years, three test pavements in the Danish Road Testing Machine have been constructed and instrumented. Accelerated loading tests and freeze/thaw experiments were conducted. Based on the measured data, models to estimate the plastic strain in the subgrade and the pavement functional condition were established. In the models it is assumed that the plastic strain in the subgrade and the pavement functional condition are related to the number of load repetitions, resilient strain and stress. The parameters used in the models were obtained from the measured data using an incremental-recursive procedure. For both the measured plastic strain in the subgrade and the pavement profiles, reasonable predictions were produced with the models.

09092 **Instrumented Field Test on Light Expanded Clay Aggregate Used in Pavements**
I. Hoff, A. Watn, E. Oiseth and K.O. Amundsgard

Damages due to frost penetration into frost susceptible sub soil are a severe problem in the Nordic countries. Traditionally road construction materials like gravel and crushed rock have very low insulation capacity and quite thick layers are needed to avoid frost penetration. Light weight expanded clay aggregate (LWA) is a promising alternative because of its good insulation properties. To investigate the mechanical and thermal properties of the LWA-material in pavement structures a research project was initiated by a producer. The material has been studied in the laboratory by several tests including repeated load triaxial testing. A full scale laboratory test was also performed with a real pavement structure built in the laboratory and subjected to cyclic loading. These tests showed that the LWA-material behaves almost as traditional gravel or crushed rock material, provided that the stresses are small enough to avoid crushing of the grains. To validate the findings from the laboratory, a full scale test field was built just outside Trondheim. The test was constructed with 10 cm of asphalt and 30 cm crushed rock over 40 cm of LWA. The test field was instrumented with sensors for measuring horizontal and vertical stresses and deformations in the LWA-layer. In addition temperature sensors were installed in all layers of the structure. The test field was trafficked by heavy vehicles for two years, and in addition controlled loading with trucks, FWD and plate load tests was performed. In addition to the instrumented section a wedge-out section with gradually less material covering the LWA-material was constructed. At the weak end of this section only 4 cm of asphalt and 16 cm of crushed rock covered the LWA-material. Some rutting was observed initially after the field was constructed. This is believed to be caused by the use improper compaction equipment. The development of rutting stabilised after a few months except for the weakest part of the wedge-out section where a total of 80 mm of rutting accumulated after two years of service. The test field was excavated in August 2001 and the LWA-material was examined to check for crushing of grains. Some crushing was observed, but the crushing was not severe and is not considered to be a major problem.

09093 **The Design and Performance of Thin Surfacing Layers**
J. Carswell

Thin surfacing layers, originally developed in the 1980s, have grown dramatically in their application on the strategic highway networks. This paper reviews the design considerations of a range of thin surfacing systems within Europe and elsewhere and outlines the advantages over more traditional surface treatments. The scope for innovation is high and both wide grading ranges and different layer thicknesses have been successfully used. In particular, the role of the binder in thin layer applications is considered in some detail. The performance of a number of road contracts carried out under a range of climatic conditions is reported, including performance data from Sweden, United Kingdom and the United States. The road sites are still under assessment and all of them are performing satisfactorily. Given the wide application range for thin layer technologies, the paper also discusses the possible failure criteria for the various thin surfacing systems.

09094 **Skid Resistance Evolution of Different Wearing Course Techniques According to Traffic**
M. Gothie

This article presents how the skid resistance measurements carried out in France with the ADHERA device are grouped together in a computerized file named CARAT. This file allows specific studies to be carried out that show the relationship between skid resistance and various elements such as accumulated heavy goods vehicles traffic (AHGVT), the techniques used for wearing courses and their main characteristics. The AHGVT is divided into several different classes, according to quantity , and for 11 different techniques this article presents the evolution of skid resistance values under the effect of traffic and measured by the ADHERA device. The analysis that was carried out highlighted several wearing course techniques presenting and maintaining good skid resistance characteristics when exposed to traffic.

09095 **Relating Road Roughness to Human Discomfort and Health Impact**
C. A. Lenngren and J. Granlund

The International Roughness Index is the choice parameter of most road engineers for describing pavement surface roughness. It has been proven to satisfactorily explain phenomena such as pavement performance and pavement deterioration. However, vertical motion frequencies and amplitudes affecting humans the most are different from those used in the model. Humans are also affected by side motion, which is not accounted for at all. At a road test with instrumented vehicles it was found that the index did not indicate rough road sections being the most adverse for humans. From a previous study of performance based road maintenance it was also found that IRI was less suitable for this type of roads. A laser profiler commonly used for road surface surveying used for assessing the IRI was used for trying othe r measures of the roughness. Raw data were stored so that other models could be tried including horizontal acceleration. A comparison was then made to the instrumented vehicle test data. A discussion follows about vehicle simulation model versus generic measures for pavement management use. Finally, some suggestions are made for a ride quality index adjusted to human aspects.

09096 **Developments and Experience with the Testing of the Acoustic Performance of Asphalt Surfaces**
S. Phillips

Type approval for proprietary thin asphaltic surfacings has recently been introduced in the UK through the Highway Authorities Products Approval Scheme (HAPAS). This scheme includes a noise test that gives a noise classification for comparing different surfacings or even for the prediction of traffic noise. However, the Statistical Pass-by test used has only limited application when used alone and therefore additional test procedures were needed. One of these is the Close-

proximity (CPX) method test that measures the noise close to dedicated test tyres. The CPX method developed by the Transport Research Laboratory has the ability to enable the homogeneity of the noise of road surfacings to be determined arbitrarily along their length. When combined with other systems being developed for assessing acoustic properties indirectly, the current methods give a fuller description of road surface performance.

09097 **Noise Reduction vs Wearing Properties**
J. Valtonen, I. Hyyppa and P. Sainio

One of the most promising way to protect citizens from noise is to lay low-noise asphalt on urban and sub-urban roads. Two test sections were laid in October 1999, but their wearing properties have not been satisfying. During the winter 1999-2000 the wearing properties of 17 different mixes were examined in the laboratory with PWR-equipment. The main result was, that SMA 5 was wearing more than twice as much as SMA 16. In the summer 2000 the low-noise SMA 5 was laid on four different roads near Helsinki. The ruts were measured in the spring 2001 to find out how much SMA 5 has worn compared to coarser pavements. These results show, that the ruts of SMA 5 were six times as deep as the ruts of SMA 11 and ten times as deep as the ruts of SMA 16. Noise measurements were done before and after the paving in the neighbourhood of the roads. When the speed limit was 50 km/h, the noise reduction was only 3 dB(A) both 10 and 30 m from the road, but when the speed limit was 80 km/h, the noise reduction was even 7 dB(A) even though only two of four lanes were paved with SMA 5. The opposite side of the road still had the old SMA 18-pavement. Also tyre-noise measurements have been carried out and one of the main result was, that after one winter the noise from a SMA 5 has increased significantly because of studded tyres.

09098 **Two-Layer Porous Pavements and Noise Reductions in Denmark**
H. Bendtsen and L.E. Larsen

Noise from the tire/road interaction is one of the two dominant sources to road traffic noise. The other source is engine noise. A research project was started in Denmark in 1999, with the purpose of developing noise reducing road surfaces for urban roads with speeds around 50 km/h. 3 test sections with two-layer fine grade porous drainage pavements and a reference section have been constructed on an urban road with 7000 vehicles per day. The pavements are cleaned twice a year by high-pressure water spraying and sucking. Some hypotheses on noise reduction, durability and traffic safety have been defined. A multi-disciplinary research group has established a comprehensive measurement program to test these hypotheses. This program includes acoustics (pass-by noise, road surface sound absorption, and noise inside vehicles), permeability, surface texture using laser, study of plane and thin sections from drill cores, friction, traffic safety, social surveys of annoyance and economic evaluation. The measurements are repeated every year, the goal is to continue in the whole lifetime of the pavements. The latest results on noise reduction, porosity and surface characteristics after 3 years of measurements are presented and discussed.

09099 **Development of Low-Noise Pavement Function-Recovery-Machine**
T. Abe and Y. Kishi

Research into ways to recover the higher drainage and noise- lowering function of porous low-noise asphalt was carried out. Tests in the laboratory indicated that the use of cavitation is very effective for this purpose. A recovery machine based on this was developed. The machine's water ejection system includes the utility of cavitation, induced by submerged high-speed water jets, held in place using a low pressure chamber, along with water jets in air. Field tests have been carried out on normal roads and on expressways and the machine has been confirmed to be very effective. This paper introduces the research into function-recovery technology of low-noise pavement and the machine consequently developed.

09100 **Asset Valuation Methodologies and Performance Measurement in Life-Cycle Analysis**
L.C. Falls and R.Haas

Pavement management systems, and now more broadly asset management systems, have been accepted and implemented by many agencies worldwide. Life cycle analysis is a key component of these systems at both the project and network level. However, the incorporation of asset value in life cycle analysis has received little attention. Rather, current and future costs are the prime elements. The time has come though where owners or operators of the assets, the latter particularly in the case of privatization, are starting to require the explicit incorporation of asset value in the life cycle analysis. In other words, the issue is what was the asset worth when built, today, and what is it estimated to be in future years under various alternative strategies and funding scenarios. This paper is based on a highway asset valuation and performance indicators study carried out for the Transportation Association of Canada. It describes the role of asset valuation in asset management, the available methodologies and their applicability and the direct incorporation and reporting of asset value in the life cycle analysis. As well, the paper describes the associated performance indicators related to the general, macro level, service quality to users, functional effectiveness and preservation effectiveness. Finally, the paper identifies the major issues and requirements involved in the proper application or use of asset valuation in life cycle analysis.

09101 **Preventive Maintenance Versus Reconstruction: Life Cycle Cost Analysis of Various Options**
T.V. Scholz, R.G. Hicks and J. Moulthrop

Life cycle cost analysis is increasingly being recognized by public agencies as an effective tool to assist in the selection of construction, maintenance, and rehabilitation treatments. The Federal Highway Administration has developed a life cycle cost analysis methodology that will likely become the standard in the industry in the USA. The methodology can be used to evaluate the life cycle costs strategies including preventative maintenance, rehabilitation, and reconstruction. For preventative maintenance treatments to be more widely accepted, they must not only extend the life of the existing pavement, but also be shown to be cost effective, i.e., lower life cycle cost than the alternates.

This paper presents:
1) an identification of preventative maintenance treatments and their benefits;
2) a description of the life cycle cost analysis process utilized in this study; and
3) comparative results that evaluate the life cycle cost for pavements that receive preventative maintenance treatments applied early on in the life of the pavement compared with those that receive only major rehabilitation/reconstruction strategies.

	The findings indicate that preventative maintenance at early stages in a pavements life is cost effective in all of the scenarios studied. However, the reader should be aware that the estimated lives and costs used in this study are based on presently available information and engineering judgment. Deviations from these values could affect the final conclusions.
09102	**Life Cycle Cost Analysis Gives the Possibility to Pay for the Value of the Pavement** *A. Huvstig* Performance requirements on road surfaces are sometimes being used as an alternative to materials specifications for achieving pavement quality. Pavement performance affects user costs, safety costs, environmental costs, etc. Life cycle analyses and new deterioration models make it possible to put a value on the performance of a pavement both today and in the future, which in turn means being able to set a monetary value on the performance of a pavement handed over by a contractor.This paper describes a method for assigning a value to specific surface characteristics. This enables the client to pay for a performance characteristic rather than contractor costs.Life cycle cost analysis (LCC/WLC) and PMS models are based on specific economic models used to calculate a net present value (NPV). A normally used simplification is the net present cost model (NPC). There are some major flaws in these simplifications, which cause unnecessary costs for the maintenance. This paper also describes the background of the economic models, and recommends a better way to use economic models as basic input in LCC/WLC models and PMS models.
09103	**Environmental Improvement of Binder Content and Aggregate Gradation Determination** *M. Jegsen, A. Kargo and E. Nielsen* One of the threats to both working and external environment in analysing asphalt material has been the use of hazardous solvents for determining the aggregate gradation, the binder content and the recovery of binder. The objective of this paper is to provide the technical basis for a large reduction of solvents used through introducing a binder content by ignition method, AM-1. The paper verifies and documents through round robin testing that quality control of binder content and aggregate gradation with this technique has the same (or perhaps slightly improved) precision compared to the "traditional" solvent based methods for the benefit of the environment. It is estimated that this new method fully implemented will reduce the amount of solvents used in asphalt laboratories in Denmark by 90%.
09104	**Characterization of Asphalt Odors and Emissions** *C. Lange and M. Stroup-Gardiner* A total of nine asphalts were selected from five regions of the United States. These asphalts were evaluated using a gas chromatograph; compounds were separated into six odor volatile organic compound (VOC) groups. Changes in these odor VOC groups were evaluated after the addition of one of two commercially available odor reducers used at one of two concentrations (1:5,000 and 1:12,000). Results indicate oxygen reactions are a major contributor to the formation of odor VOCs and that odor reducers appear to act as anti-oxidants. Mass loss, measured every minute over a 90-minute period can be related to the formation of odor VOCs. This frequent measurement of mass loss is better correlated with odor VOCs than the industry standard rolling thin film oven. Concurrent opacity measurements are also correlated with odor VOCs. The addition of odor reducers reduces both mass loss and opacity.
09105	**Noise Reduction with Porous Asphalt Costs and Perceived Effect** *L.E. Larsen and H. Bendtsen* Three test sections of two-layer porous asphalt and a reference section of dense asphalt concrete were laid on Oster Sogade in Copenhagen in 1999. An extensive measurement program including noise, surface characteristics and traffic safety is part of the project, which also includes a before-after questionnaire survey on noise annoyance among those living along the road. Two-layer porous asphalt pavements are more expensive than ordinary dense pavements, but comparisons done as part of the project of the cost of porous asphalt, noise barriers and sound insulation shows the asphalt to be economically attractive where there is a need for reduction of the traffic noise. The questionnaire survey shows that the reduction in decibel is matched by a reduction in annoyance both in and outside the homes of those living along the road.
09106	**Porous Asphalt and Traffic Safety** *P. Greibe* The behaviour of porous asphalt is different from that of dense asphalt concrete. The open structure of porous asphalt reduces traffic noise, drains water from the road surface and reduces the thermal conductivity. These differences can have an effect on road safety. This article presents a literature review on porous asphalt and safety and furthermore summarises the preliminary results from a Danish pilot study using porous asphalt on an urban road.
09107	**Austrian Experiences with Winter Maintenance on Porous Asphalt** *J. Litzka* The paper deals with the specific requirements for winter maintenance on sections with porous asphalt and the experiences in Austria with some additional informations from neighbouring countries. After extensive use of porous asphalt on motorways in Austria until the early nineties the application of this type of surface course has been reduced significantly. Besides other problems like clogging, durability and difficulties with local repairs the main reason for this change is the difficulty of winter maintenance on porous asphalt connected with increased risk for the highway operator. This is of special importance for the Austrian climatic situation with rather cold winters and a large numer of freeze-thaw cycles.
09108	**Over Ten Years Experience with Porous Road Surface** *C.J. Padmos* The use of porous road surface is attractive because the emission of rolling noise is less compared with situations where Dense Asphalt Concrete is used. This means that provisions for noise abatement can be lower and cheaper. In general the road users are very satisfied with porous road surfaces. They are not interested in the lower noise production, but in the fact that under wet conditions they have less problems with plash and spray. Only in the case that a road will be constructed near living areas de people living nearby insist on the use of quiet road surfaces with the highest reductions. Is the use the use of porous asphalt so advantageous as it seems? What about the other properties of porous asphalt, does they remain on the same good values? After ten years it is good to make up the balance and to formulate the wishes

for improvements.

09109 **Pavement Performance During Thaw Weakening**
V.C. Janoo and L. Barna

Freeze-thaw tests were conducted on full-scale test sections in the Frost Effects Research Facility at the Cold Regions Research and Engineering Laboratory. During the thaw period, the test sections were subjected to a single wheel load of 133 kN. FWD tests during the thaw period showed that the maximum base reduction factor was 67%, and the thaw-weakening period was approximately two weeks. For the subgrade the maximum reduction factor was 56%, and the thaw-weakening period was about three weeks. The critical strains in the base were 300- 500% larger then pre-freeze strains. In the subgrade the critical strain reached over 1000% its pre-freeze values. Permanent deformations at the end of thaw in the base and subgrade were 12 and 55 mm, respectively. The total deformation of the base and subgrade when compared to the surface rut depth was 7 mm. The reduction factors for the base and subgrade were 64% and 3-6%, respectively.

09110 **The Model Mobile Load Simulator as a Tool for Evaluating Asphalt Performance Under Wet Trafficking**
A. de F. Smit, L. Walubita, K. Jenkins and F. Hugo

Model Mobile Load Simulator (MMLS3) tests have proven capable of evaluating the moisture susceptibility and relative performance of asphalt mixes through the use of accelerated pavement testing (APT) techniques. A number of case studies using the MMLS3 are presented. Wet MMLS3 trafficking has been conducted under varying temperature conditions (ambient up to 50 °C). Non-destructive stiffness measurements with seismic devices were performed intermittently during MMLS3 testing to monitor changes in the asphalt stiffness. It was found that stiffness loss, micro-cracking, and stripping is evident when the mix is susceptible to water damage. Indirect tensile strength and fatigue performance in laboratory testing were used as a measure of the distress due to the microfracturing and water damage. It has been found that the fatigue life expectancy of asphaltic materials susceptible to moisture damage was significantly reduced by wet MMLS3 trafficking. Overall, the MMLS3, used in conjunction with forensic testing, appears to be a valuable tool for supplementing full-scale APT devices for evaluating distress due to wet axle trafficking. It offers the potential for evaluating surrogate tests for quick detection of susceptibility to damage due to wet trafficking.

09111 **The Effects of Freeze - Thaw Periods on a Test Pavement in the Danish Road Testing Machine**
W. Zhang and R.A. Macdonald

Accelerated load testing (ALT) by dual wheel loading at load levels from 40 kN to 60 kN were performed on the second test pavement, RTM2, constructed and instrumented in the Danish Road Testing Machine between 1995 and 1997. To accelerate the deterioration and failure of RTM2, and the rehabilitated RTM3 test pavement, further freeze-thaw experiments were conducted during 1998 and 1999. The experiments consisted of accelerated load testing at 60 kN applied load during the thaw periods of three freeze-thaw cycles. During these freeze-thaw cycles, the temperatures in the pavement layers were monitored during the thaw periods, and the porewater suctions in the Subgrade, the pavement material responses and the pavement profiles were measured regularly. This paper introduces the RTM2 and RTM3 test pavements and the experimental procedures employed during these freeze-thaw periods. Models for estimating the plastic strains at the top of the Subgrade, the permanent deformation of the Subgrade and the pavement functional deterioration, which were developed during accelerated load testing of the RTM2 and RTM3 test pavements at constant +25°C conditions, are presented. Conclusions are drawn from the three freeze-thaw experiments.

09112 **The Fourth Power Law and Thin Surfaced Flexible Pavements**
D. Alabaster, J. de Pont and B. Steven

Recent surveys of New Zealand's Heavily Vehicle industry have indicated a desire to move to higher allowable axle weights. A series of accelerated dynamic loading tests have been conducted at the Canterbury Accelerated Pavement Testing Indoor Facility (CAPTIF) to investigate the proposed changes. The first test examined the appropriateness of using the 4th Power Law, developed on structural asphaltic concrete pavements, to determine increases in pavement wear on the thin surfaced flexible pavements widely used in Australasia. The experiment found power relationships between 3 and 9 for the conventional 4th Power law model. A proposed new twopart power model, the 'compaction-wear' model, more accurately reflected the performance of the pavement. The exponent values for the compaction component were between 1 and 3.4, and 1.8 and 3 for the wear component. This model has significant implications, which are not predicted with the 4th Power Law, for roading authorities considering increases in mass limits for heavy vehicles.

09113 **Asphaltic Plug Joint Characterization and Performance Evaluation**
M.N. Partl, S. Hean and L. Poulikakos

This paper presents the initial results of research on polymer-modified asphaltic plug joints (APJ) on bridges and an overview on the practical aspects and scientific background of the new Swiss guidelines, which were released by the Swiss Federal Roads Office (ASTRA) and developed in close coordination with the German road authorities. It focuses on recent EMPA research for laboratory and field characterization of the APJ materials as well as on the evaluation of the relevant mechanical characteristics for the APJ system such as adhesion, permanent deformation and low temperature cracking. In addition, results from a construction monitoring and long-term field performance research project on eighteen plug joints on bridges are presented. Further development of accelerated full-scale laboratory tests at EMPA are also discussed. The experience with the new Swiss guidelines and the research results show, that the performance of polymer-modified asphalt plug joints can be improved significantly if materials are selected and handled professionally and construction is carried out by well trained teams. It was found that tests and requirements are suited to detect and eliminate inadequate materials and systems, thus reducing the risk of damage and encouraging the development and improvement of those joints. It was also found that accelerated full-scale laboratory testing might be of assistance in this respect.

09114 **Crack Geometry Analysis in Asphalt Samples Obtained from a Heavy Vehicle Simulator Test Site**
P. Offrell, J.Harvey and C. Scheffy

The purpose of the study was to compare vertical crack propagation in samples obtained from a HVS test site and to know whether cracks propagate through all the asphalt layers, and if not, how deeply they penetrate. Furthermore, the purpose was also to investigate any correlation between compaction grades and crack appearance as well as the effect of bonding

between asphalt concrete layers. An enhanced technique of marking and recording hairline cracks in the surface is described. The results show no significant correlation between airvoid content and crack initiation. However, the results do indicate a correlation between crack density and air-void content. It seems as if the lack of bonding between the two AC layers has to some extent prevented the crack from propagating down into the lower AC layer. The crack patterns are similar in the different layers, and indicate that the cracks have initiated somewhere close to the bottom surface of the upper asphalt concrete layer. The enhanced method of marking cracks using UV-light has proven very useful.

09115 **Evaluation of Asphalt Pavement Analyzer as a Tool to Predict Rutting**
A.Cooley and P.S. Kandhal

A standardized laboratory test to predict the rutting potential of an HMA that is accelerated,relative-ly inexpensive, and able to be used during quality control/quality assurance (QC/QA) testing would be of great benefit. Currently the most common type of standardized laboratory test of this nature is a loaded wheel tester (LWT). The objective of this study was to evaluate the Asphalt Pavement Analyzer (APA), the most common LWT in the U.S., to determine its suitability as a general method of predicting the rut potential of HMA mixes. Ten HMA mixtures of known field performance were selected for testing by the APA. Various APA testing parameters were used in a full factorial experiment. The combination of testing parameters which provided APA rut depths closest to and highly correlated with the actual field rut depths, were recommended to fine tune the APA testing protocol.

09116 **Results of Accelerated Tests on Flexible Pavements in Brazil Using the UFRGS-DAER Simulator**
F.P. Goncalves, J.A.P. Ceratti and R.M.Rodrigues

Full-scale accelerated tests with traffic simulators have been used to improve methodologies for pavement design. To evaluate the performance of conventional and polymer modified asphalt mixtures a study is being conducted on a full-scale test facility at the Federal University of the Rio Grande do Sul. A linear traffic simulator has been used to carry out accelerated tests on six test sections of flexible pavements in asphalt concrete. The most important variables for asphalt mixtures performance evaluation in field are: evolution of surface cracking, rutting in wheel tracks, deflections, horizontal tensile strains in the bottom of the asphalt layer, measured with electrical resistance strain gauges, and vertical stress measured with total pressure cells in different locations of the pavement structure. This paper presents an evaluation of the several stages that composes the experimental part proposed. Special emphasis is given to results involving residual horizontal stress developed on the granular base layer during the compaction process.

09117 **Finite Element Simulation of Rutting on Superpave Pavements**
M. Hossain and Z. Wu

Rutting is a major distress on asphalt pavements. This paper presents a threedimensional (3-D) nonlinear finite element (FE) model to simulate the initiation and propagation of rutting damage on the Superpave test sections at the Kansas Accelerated Testing Laboratory (KATL). A creep model and a Drucker-Prager model was chosen to characterize the permanent deformation characteristics of the Superpave mixtures and the aggregate base and subgrade materials, respectively. The 3-D FE model was built in several steps. First, a two-dimension (2-D) linear-elastic FE model was constructed. Then, the proposed non-linear material models were incorporated into the 2-D model and finally, into a 3-D model. However, the 3-D simulation was deemed to be very time consuming to implement, and a 2-D model was chosen for full simulation. The rutting simulation using the 2-D FE model was done up to 10,000 repetitions of the K-ATL tandem axle load. The predicted rut depths checked reasonably well with the measured values.

09118 **Performance Prediction with the MMLS3 at Westrack**
A.E. Martin,T. Ahmed, D.C. Little, F. Hugo, P. Poolman and M.Mikhail

The one-third scale Model Mobile Load Simulator (MMLS3) was used to traffic five pavement sections (including one replicate) at WesTrack to establish and validate its ability to reliably predict rutting performance under full-scale trafficking. Researchers found similar performance rankings and conducted statistical analyses for field and laboratory results to compare performance under both loading conditions of three coarse-graded sections that showed poor performance and one fine-graded section with good performance. A standard rut depth (RD) analysis method and MMLS3 testing conditions were suggested to determine a RD for (1) comparison with acceptable performance criteria or (2) use with a theoretical rutting ratio based on stress analyses to predict performance under full-scale trafficking. A quantitative comparative analysis based on the assumption that rutting is dependent on the pavement structure and loading and environmental conditions was conducted to successfully validate the hypothesis required in the performance prediction methodology.

09119 **The Implications of Dynamic Loading and Tyre Type on the UK Road Network**
D.B. Merrill, D. Blackman and V. Ramdas

DIVINE, an international project sponsored by OECD, has highlighted the need to consider the interdependence of components of the road system (heavy goods vehicles, tyres, pavement construction, traffic levels etc.) when optimising the economics of road infrastructure. EC COST Action 334 examined more closely the effects of wide-single and dual tyres on pavement wear. This paper describes work carried out by TRL as part of the UK Highways Agency research programme, to interpret the outcomes of these two studies with respect to traffic and pavement conditions in the UK. The work described in this paper focuses on three principal areas: the effect of dual and single tyres; the influence of dynamic loading on pavement wear; and a whole life cost assessment of the significance of these effects. The effect of dual and single tyres was investigated using instrumented pavements in TRL's Pavement Test Facility. In an accelerated trafficking trial the relative rates of rut formation were measured. Contact stress distributions under six types of tyre were measured and compared with the observed responses and deformations in the test pavements. In a complimentary investigation, the influence of dynamic loading on pavement wear is being examined on a number of test sites on UK roads. The road profile and deflection of these sites was surveyed over a period of time. Any deterioration was correlated to the dynamic load profile recorded by a specially instrumented heavy goods vehicle. Using results from these studies a whole life cost analysis will be carried out to evaluate the financial implications of these factors on road maintenance.

09120 **HVS - Testing of Icelandic Low Volume Road Structures**
T. Ingason, L.G. Wiman and H. Haraldsson

Two typical Icelandic road structures were tested in the Heavy Vehicle Simulator facilities at VTI in Sweden. The aim of

	the project was to compare these two structures and to compare them with Swedish and Finnish structures tested with the HVS. Most of the public road system in Iceland is low volume roads (traffic less than 300 AADT on 79 % of the roads), but goods transport is growing and the heavy traffic is increasing. The structures tested were composed of Icelandic aggregates, transported to Sweden. One with unbound base course, and the other with bituminous bound base course, both had thin surface dressing on top. All results indicated more bearing capacity of the structure with bituminous base course. Propagation of rutting was greater than expected and twofold of rutting measured in a Swedish low volume road structure. It should though be considered that the base layer material used, did not fulfil specifications for grain size distribution and the bituminous base course did not get enough time to harden before the test started. Results from theoretical calculations (3D FEM) compare reasonably with results of response measurements. The data collected during these tests will be stored in a common Finnish-Swedish database.
09121	**Numerical Validation of Pavement Performance at the Louisiana Accelerated Loading Facility (ALF)** *B. Huang, L.N. Mohammad, M. Rasoulian, F.L. Roberts and H. Qin* This paper presents the numerical simulation results of the Louisiana Accelerated Loading Facility test pavements. Three asphalt pavement test lanes: one with conventional hot-mix asphalt mixtures, one with crumbrubber modified (CRM) wearing course, and one with CRM asphalt base, were tested using the ALF. These test lanes were numerically simulated through a three-diminensional finite element analysis using the commercial finite element software, ABAQUS. Fundamental engineering properties of the conventional and the crumb-rubber modified asphalt mixtures were studied. A Drucker-Prager based viscoplastic constitutive model was used to characterize the asphalt concrete. Elastoplastic constitutive models were employed for other paving materials. Dynamic traffic load was applied during the finite element analyses. Pavement distress of rutting was predicted using the stress and strain obtained from numerical simulation and field collected data. These predictions were compared with the ALF test results.
09122	**Authors Index** An aplhabetical listing of authors.
09123	**Conference Introduction** - Foreword - Conference Committees / Sponsors - Daily guide to scientific sessions - Conference Summary - Distribution of participants by country
09124	**Conference Opening Addresses** Opening Welcome Address - Thomas Egebo, Permanent Secretary of the Danish Ministry of Transport - Mads Lebech, Mayor of Frederiksberg Municipality - Henning Christiansen, Director General, the Road Directorate, Ministry of Transport - S F Brown, University of Nottingham, Chairman ISAP Board
09125	**Conference Keynote Address - Analytical Tools for Design of Flexible Pavements** *Per Ullidtz* This paper falls into two parts. In the first, the widely used analytical-empirical method of pavement design and evaluation is discussed and in the second two simulation models are presented. There are important differences between the assumptions on which the theoretical models are based, and the reality of pavement materials and structures, and these differences are important both for the determination of input values (elastic parameters) and for the calculation of pavement response. Linear elastic theory often results in incorrect moduli, when used for backcalculation of layer moduli from deflection testing, and in questionable stresses and strains, when used for forward calculation. Including non-linear materials characteristics may improve the theoretical model, but no theoretical model has yet been conclusively verified with experimental data. The empirical relationships used to predict pavement deterioration from critical stresses or strains, are equally problematic. In the second part of the paper two theoretical models are presented. The first model simulates the deterioration of a section of pavement over time using an incremental-recursive process. The model is stochastic and considers the spatial variation of pavement materials, layer thickness and traffic loads as well as seasonal variations. The second model deals with the forces on, and the displacements of, the individual grains in a particulate medium. This model does not rely on empirical relationships to predict permanent deformation or failure, but models this in the same process as forces and displacements. The input to this model includes the grain size distribution, the shape of the grains and the degree of compaction, parameters that are similar to those used for specification of materials and quality control. It is concluded that an interaction between development of theoretical models and experimental verification is needed to improve the understanding and predictability of the complex process of pavement deterioration.
09126	**Plenary Session I - U.S. Perspective on Design and Construction of Perpetual Asphalt Pavements** *David E. Newcomb* The construction of long-lasting hot mix asphalt pavements has been practiced for a number of decades in the United States. Full-depth (asphalt courses used for all layers above subgrade) and deepstrength (asphalt surface and asphalt base over a minimal aggregate base above subgrade) pavements were originally designed for 20-year life expectancies. One of the primary advantages to these designs was that the total pavement sections were thinner when compared to conventional designs of asphalt over thick aggregate bases. As these full-depth and deep-strength pavements performed beyond their design lives, many only required surface restoration such as a thin overlays or mill and overlay. This practice of replacing only the surface offers a number of rehabilitation advantages in terms of speed of construction (user delay costs) and construction costs. The challenge for today is to obtain a longer surface life on a long-lasting asphalt support structure. Recent efforts in materials selection, mixture design, performance testing and pavement design offer a methodology which may be employed to obtain very long term performance from asphalt pavement structures (greater than 50 years) while periodically (approximately every 20 years) replacing the surface (top 25 to 100 mm) of the

	pavement. This concept has been proposed for use in Europe and it is rapidly gaining acceptance in the U.S. The common theme in these approaches is to combine a rut resistant, impermeable and wear resistant top structural layer with a rut resistant and durable intermediate layer and a fatigue resistant and durable base layer. This paper presents the ongoing efforts to develop methods for Perpetual Pavements in the United States. The pavement is designed to avoid bottom-up fatigue cracking by providing a total asphalt thickness that keeps the tensile strain at the bottom of the layer below a critical level and/or the use of a slightly asphalt-rich bottom layer. Rutting resistance in the intermediate layer can be obtained through the use a large-stone mixture or a dense-graded Superpave mixture. The surface course is comprised of a premium asphalt mixture which may be either a stone matrix asphalt (SMA) or a high-quality Superpave mixture. For areas where the use of an open-graded friction course (OGFC) is desired, this feature can be incorporated and viewed as a renewable surface.
09127	**Plenary Session II - Overheads From the Plenum Session on Perpetual Pavements** *Brian Ferne* Mr Ferne's presentation slides.
09128	**Plenary Session III - Overheads From the Plenum Session on Noise** *Ronny Klaeboe* Mr Klaeboe's presentation slides.
09129	**Plenary Session IIII - Overheads From the Plenum Session on Noise** *Hans Bendtsen* Mr Bendtsen's presentation slides.
09130	**Reports on Plenum Sessions** *Jorgen Christensen, Johann Litzka, Christian Busch* Report on the Plenum Session on Perpetual Pavements by J. Christensen. Report on the Plenum Session on Noise by J. Litzka. Report on the Plenum Session on AASHTO 2002 by C. Busch.
09131	**Open-Forum: New Contractual Relationships as a Driver of Innovations. Dissemination of Knowledge.** *Mikael Thau, Joe P. Mahoney and David E. Newcomb* Panel discussion and audience comments/questions about the topics addressed.
09132	**Closing of Conference** *S F Brown* Parting reflections from Stephen F. Brown, Chairman ISAP Board.
09133	**Exhibitors** A listing of 9th Conference Exhibitors and their contact details.
09134	**Participants** A listing of 9th Conference Participants and their contact details.