KEYNOTE ADDRESS

ACHIEVEMENTS AND CHALLENGES IN ASPHALT PAVEMENT ENGINEERING

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Abstract. 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 quality 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.

Keywords. Design, Evaluation, Materials, Foundations, Theory.

INTRODUCTION

The review of this sequence of international conferences conducted by Witczak and Shook (1992) set out a record of real achievement and influence over the 30 year period since the first event at the University of Michigan, Arm Arbor, almost exactly 35 years ago. That first conference under the leadership of Professor Bill Housel was organised by a small but distinguished group of engineers, many of whose names have become part of the folk-lore of asphalt pavement engineering in the United States;

- Walter J Emmons, whose name lives on in the annual "best-paper" award of the Association of Asphalt Paving Technologists
- Fred Finn, veteran of the AASHO road test, the data from which partly inspired this first conference, and substantial contributor to research over many years
- Norman McLeod, the distinguished Canadian asphalt technologist
- John Griffith of the Asphalt Institute, which has strongly supported these conferences
- A C Benkelman, whose famous "Beam" became the work-horse of pavement evaluation over many years.

Witczak and Shook consulted the pavement engineering community to assess the impact of these conferences. The principal findings were:

- The written proceedings formed an invaluable reference source.
- Improvements to the state-of-the-art on theoretical modelling and materials characterisation formed the major achievement.
- Little impact had been made on construction,
- A moderate influence had been made on design but greater implementation required wider verification of research findings.

At the 1962 conference, "intellectual ferment" arose through the tension between the empirical and theoretical approaches to design but a paper of lasting significance by Gil Dormon of Shell (Dormon, 1962) was presented. This will form the starting point and basis for this lecture.

In 1967, perhaps recognising the problems of intellectual ferment, attempts were made to "Bridge the Gap" between theory and practice. By 1972, the ability to carry out theoretical analysis had been greatly enhanced through developments in computer technology but the "ferment" continued. At this conference attention started to be given to pavement evaluation and overlay design.

In an attempt to demonstrate that mechanistic design methods were complete and available, several substantial papers were solicited for the 1977 conference to describe such systems. Most of them were based on the general principles set out by Dormon in 1962. The potential for accelerated loading at full-scale was demonstrated at this conference through the work of the South Africans and progress on rehabilitation design was apparent.

By 1982, design methods were available in the form of computer programs but the problems of satisfactory rut depth prediction remained despite having been addressed at preceding conferences.

Use of the Falling Weight Deflectometer for structural evaluation of pavements was an important feature of the 1987 Conference and the impact of Personal Computers for pavement analysis became apparent.

Conscious of the ongoing criticism that the high quality research described at these international conferences was not being communicated to the design and construction community, the organisers of the 1992 Conference, under the leadership of the International Society for Asphalt Pavements, adopted the theme of "Paving-the-Gap" between research and practice. The title of the conference was changed and special sessions arranged to attract contractors and material suppliers. This approach has been continued here in Seattle.

In summing up the 1992 conference, Brown (1992) reported that real progress had been made through the availability of field and laboratory test equipment and analytical computer packages which allowed engineers to implement the results of research in user-friendly ways. Although there were few major "break-throughs" reported at this conference, improved communications across the "Gap" had been started and the potential for future progress was significant.

Another important review of developments in the mechanistic design of asphalt pavements was presented by Professor Carl Monismith when he delivered the first Transportation Research Board Distinguished Lecture at the annual meeting in Washington D.C. in 1992 (Monismith, 1992). As a significant contributor to all the "Ann Arbor" conferences since their inception 30 years earlier, Professor Monismith was in an excellent position to provide a perspective on what had been achieved in this field over that period. He pointed out that just a 1 % saving in the annual cost of asphalt paving in the U.S. would allow the $50m SHRP asphalt research programme to be paid for in just four months. He maintained that such savings could be made by implementation of the new technology which was available from research both under SHRP and the accumulation of knowledge from earlier investigations. Subsequent to the completion of SHRP, it has become clear that full implementation remains problematic but much technology in this field has been implemented in many countries and achieved significant improvements for the user and funder of asphalt pavements.

The main achievement of these conferences has been to focus on research which has contributed generally to the gradual move from empirical methods for design and material specification to those based on theoretical concepts and tests to measure mechanical properties. As interest in the maintenance of existing highway infrastructures has increased, the development of techniques for structural evaluation, and the design of rehabilitation, has become increasingly important.

To move from reliance on CBR curves, recipe specifications, "Black Magic" tests involving needles, rings and balls and the Benkelman beam, to computer based structural analysis, practical tests to measure mechanical properties of binders and asphalt mixtures and the use of the laser and the Falling Weight Deflectometer for pavement assessment represents real achievement.

Development of the South African Heavy Vehicle Simulators attracted World-wide interest in full-scale accelerated testing and provided a basis for verification of new designs and the utilisation of new materials. The dramatic increase in research based on the HVS philosophy, recently reviewed by Metcalf (1996), particularly in Australia, France and the USA, provides confidence that the verification of design concepts, identified in 1992 as a major barrier to the implementation of new technology, will be achieved over the next few years.

Despite real achievements, some of which have been noted above, many challenges and opportunities remain. A blend of innovation and steady attention to implementing what is known while communicating effectively between research and practice will bring real rewards in future.

This lecture will endeavour to focus on some of these challenges, point to some innovations and recognise the background achievement on which they are able to build.

FRAMEWORK FOR THE LECTURE

Fig. 1 is taken from the landmark paper by Dormon (1962) presented to the first international conference. It represents an asphalt pavement as a three layer structure of linear elastic materials subjected to a circular, uniformly distributed load. The two classical design criteria, compressive strain at the subgrade surface and tensile strain at the bottom of the asphalt layer, were derived from this paper. The tensile strain criterion was based on work done by Professor Peter Pell at Nottingham in conjunction with the Shell Laboratories, first reported in 1960 (Saal and Pell, 1960). It paralleled similar work by Professor Monismith at the University of California, Berkeley, published the following year (Monismith et al, 1961).

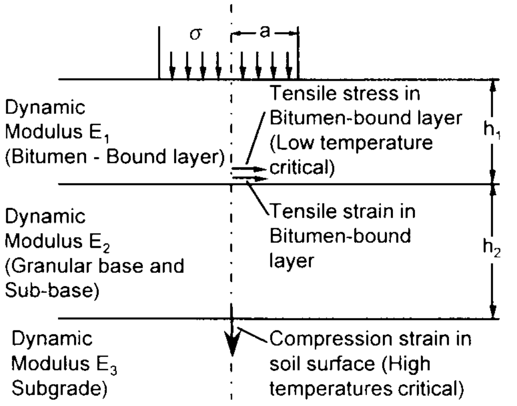


Figure 1. Pavement as a 3 layer elastic system with design criteria (after Dormon, 1962)

The remarkable feature of Fig. 1 is that it has remained the basis for mechanistic design (originally described as rational design) for asphalt pavements ever since. Fig. 2 shows a schematic based on the original Dormon figure which provides the framework for this lecture. The nine topics in this figure, some of which are intentionally linked, are used to highlight achievements and challenges in the design and evaluation of asphalt pavements, which, together with the key component parts of these subjects, might be referred to globally as "Asphalt Pavement Engineering".

STRUCTURAL DESIGN AND THEORETICAL ANALYSIS

Fig. 3 indicates the central part which theoretical analysis plays in the mechanistic design process. The achievements of the past have included incorporation of linear elastic theory and approximate techniques for dealing with the non-linear behaviour of pavement foundations within design methods. As computational power has developed, more realistic modelling of pavements has become possible. The finite element method has provided the basis for this, allowing, not only non-linear elastic models to be readily incorporated, e.g. the FENLAP program (Brunton and d'Almeida, 1992) but also visco-elastic and visco-elasto-plastic modelling, particularly for asphalt layers.

Chatti and Yun (1996) have developed the SAPSI-M program which represents the pavement as a series of horizontal elements (sub-layers) and a] lows moving wheel loads to be accommodated. Each layer is modelled as a linear visco-elastic material and the effects of vehicle speed can be computed. Good comparisons with field data have been reported as noted in Fig. 4.

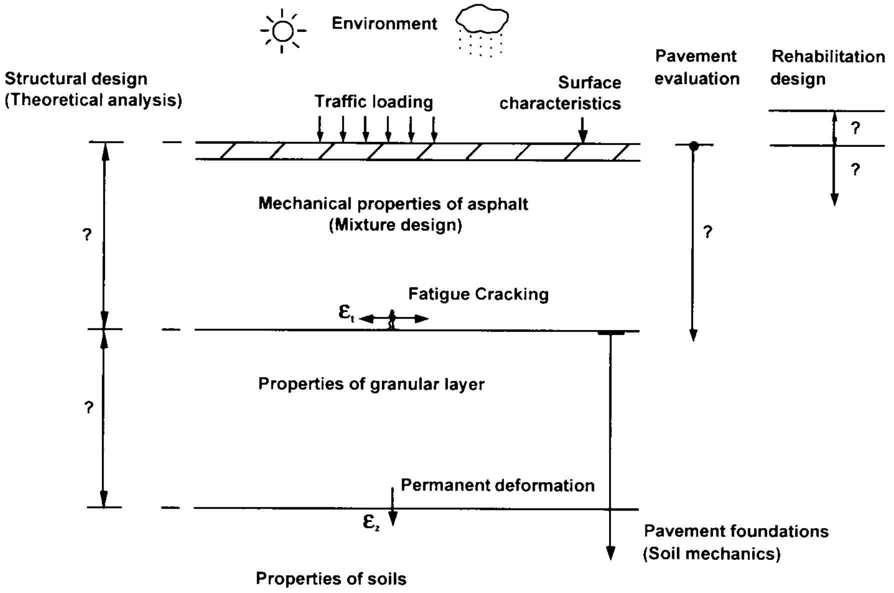


Figure 2. Topics covered by the lecture

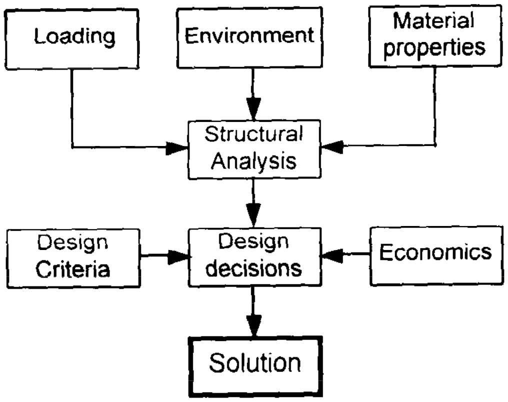


Figure 3. Simplified flow diagram for mechanistic (analytical) Pavement Design

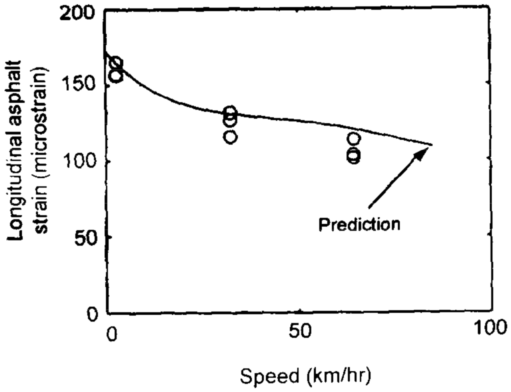


Figure 4. Comparison of calculated and measured strains at different speeds. (after Chatti and Yun,1996)

The VEROAD program developed by Hopman and reported by Nilsson et al (1996) uses 15 horizontal layers over an elastic half-space. Materials are characterised as linear visco-elastic for the shear response but linear elastic for volume change. Realistic transverse and longitudinal strain variations are predicted (Fig. 5).

The PACE program described by Rowe et al (1995) uses a conventional axi-symetric finite element configuration but models the materials as elasto-viscoplastic. Visco-elastic and elastic behaviour are treated as special cases of this generalisation, which is illustrated as a rheological model in Fig. 6. Realistic material response is obtained by overlaying several basic models in parallel and ensuring strain compatibility. In addition to predicting strain variations resulting from moving wheel loads, Rowe et al are able to compute contours of dissipated energy, which relates to fatigue cracking failure (Fig. 7) and rut profiles.

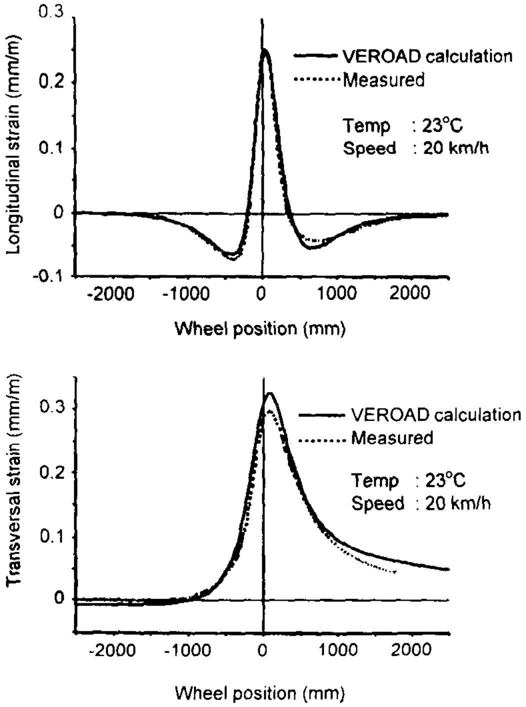


Fig 5. Comparison between measured and calculated strain (after Nilsson et al, 1996)

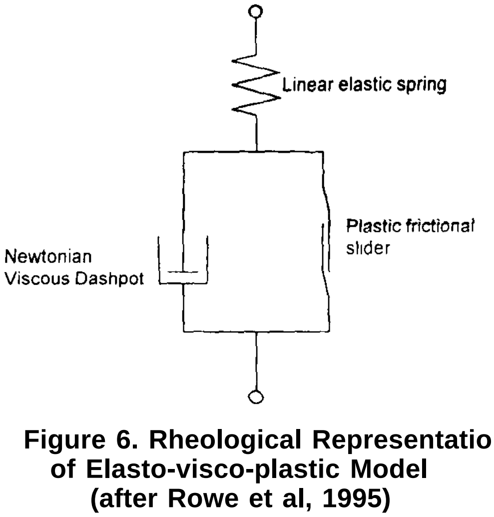


Figure 6. Rheological Representation of Elasto-visco-plastic Model (after Rowe et al, 1995)

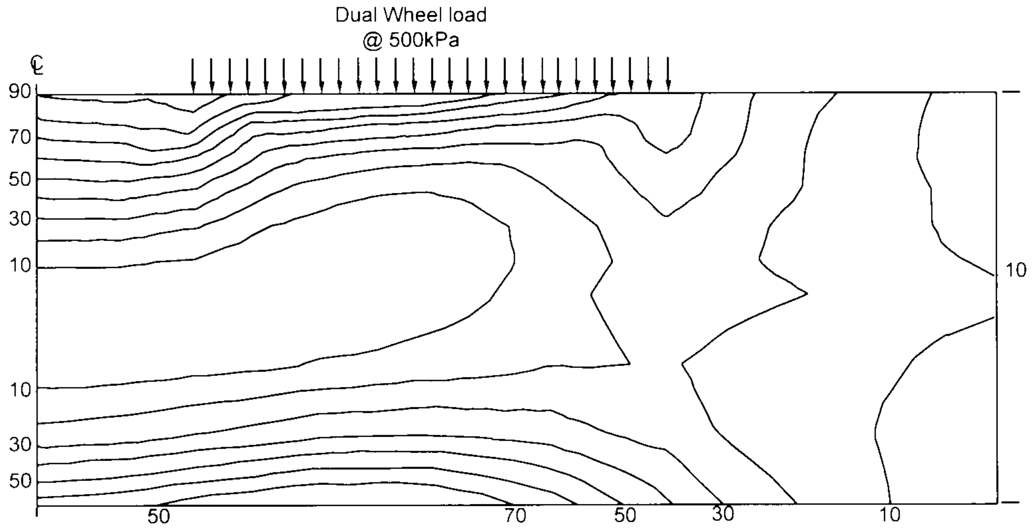


Figure 7. Contours of percentage fatigue damage in 200 mm dense bitumen macadam layer at 20°C (after Rowe and Brown, 1997)

The programs described above all require relatively detailed information to be specified for material characterisation. A simpler visco-elastic approach is described by Collop et al (1995) based on earlier work at the U.K. Transport Research Laboratory. Collop et al use the Burger rheological model to describe the bitumen characteristics and determine a parameter “q” originally introduced by the Shell researchers to relate mixture stiffness to binder stiffness. This can be defined by simple repeated load compression tests. Encouraging validation data is reported showing the accumulation of rutting from full-scale trials (Fig. 8).

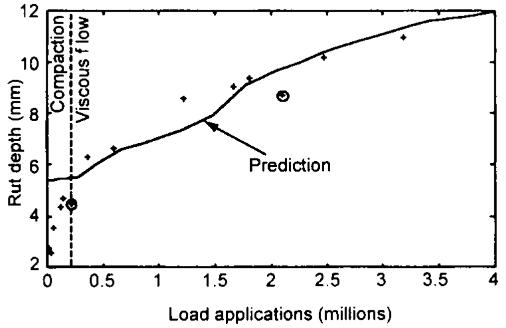


Figure 8. Predicted and Measured Rutting (after Collop et al, 1995)

For pavement design purposes, extensive use has been made of linear elastic theory applied to layered systems. The ready availability of programs to perform these analyses on PC's has brought the “feel” of mechanistic pavement design to large numbers of engineers. However, the limitations of this approach need to be recognised. For relatively thick asphalt construction, where the assumptions of linear elastic theory for a moving wheel load may be valid, satisfactory results can be obtained provided the stiffness of the asphalt layer is accurately specified. Where thin asphalt construction is being used and the non-linear characteristics of the granular layer(s) and soil dominate the response to wheel load, non-linear analysis is required.

As the detailed understanding of failure mechanisms improve from field observations and from accelerated loading experiments, more accurate analysis will be required to properly model the pavement. The tools are now available for this to be done in a practical way.

INFLUENCE OF THE ENVIRONMENT

The two environmental parameters which influence pavement performance are temperature and moisture.

Temperature conditions for a particular site have to be known to properly design an asphalt pavement or overlay. Predictive techniques such as the FHWA's Integrated Climatic Model (Lytton et al, 1990) may be used for this purpose.

Deacon et al (1994) have presented a comprehensive approach to accommodate temperature as a primary parameter in design of pavements and for the testing of asphalt mixtures. Their concept of Temperature Equivalency Factors (TEF) is used to convert the number of standard axles to an equivalent number at a standard reference temperature. The factors were quantified for nine climatic regions in the USA. Their approach allows design and laboratory materials testing to be carried out at standard temperatures with extensions to the field made possible via the TEF's.

This approach differs from that widely used in the past involving conversion factors for the average annual air temperature to define pavement design temperature and use of the actual number of standard axles in design calculations. As an example, for U.K. conditions, Brown et al (1985) devised factors of 1.47 and 1.92 applying to permanent deformation and fatigue design respectively.

The concept of a “Critical Temperature” for permanent deformation damage was also defined by Deacon et al (1994) as that temperature within 5°C of which the largest amount of permanent deformation develops in the field. This is recommended as the temperature for laboratory testing. Brown and Gibb (1996) had recommended that the test temperature should be selected so that the bitumen stiffness in the test matches that in the field. These concepts are compatible but would require that Deacon et al's Critical Temperature be modified to allow for different grades of binder.

The work of Deacon et al (1994) was stimulated by the extensive programme of laboratory fatigue and permanent deformation testing conducted under SHRP contract A003A led by Professor Carl Monismith. The improved quality of materials data made possible through modem instrumentation and computer control of equipment combined with computer based analytical tools demonstrated how effective progress can be made in asphalt pavement engineering. Similar work had been conducted earlier for U.K. conditions by Brown et al (1984) but the work of Deacon et al demonstrates real progress at a detailed level. It represents an excellent example of how pavement analysis and design are intimately linked to asphalt material properties.

Design concepts for thermal cracking are well established and have been summarised by Monismith (1992). For the U.S., the performance grading of bitumens accommodates the requirements of low temperatures while Superpave levels 2 and 3 mixture design testing procedures are intended to provide the basis for predictive computations. However, recent modelling work as an extension of SHRP has indicated further research is required in this field.

The effects of air and water on deterioration of asphalt mixtures, known as “durability”, continues to present a challenge. Although oxidative aging of binders and water damage (stripping) in mixtures has been well researched, validation of laboratory testing procedures in the context of field performance remains problematic. This is principally because, by definition, long-term field monitoring associated with laboratory testing is needed. The other effect of water is in the influence it has on the mechanical properties of soils and granular materials, a subject dealt with under “Pavement Foundations” below.

The phenomenon of frost heave has been well studied but the problems presented by extended freezing of subgrades in northern climates would appear to merit further study. In these areas, it is a problem which tends to dominate pavement performance, not least because of the weakening effects caused by the Spring thaw.

TRAFFIC LOADING

Prediction of traffic volume for pavement design has always been an inexact science. However, the ability to model the effects of different wheel loads on pavement deterioration and to quantify dynamic effects has progressed. The current approach of converting traffic to an equivalent number of standard 80 or 100 kN axle loads using a fourth-power law is, at best, approximate and can only be justified in the context of the vagaries of estimating numbers of axle loads in various categories.

The interactions between surface profile and vehicle suspension systems have been satisfactorily modelled. The work of Dr David Cebon and his colleagues at the University of Cambridge is particularly noteworthy. Fig. 9 illustrates the “Quarter Car” model (Cebon, 1993) used to compute dynamic loads for single axle truck suspensions. In their “whole life pavement performance” methodology, Collop and Cebon (1997) use this to compute changes to dynamic loads as surface profiles deteriorate.

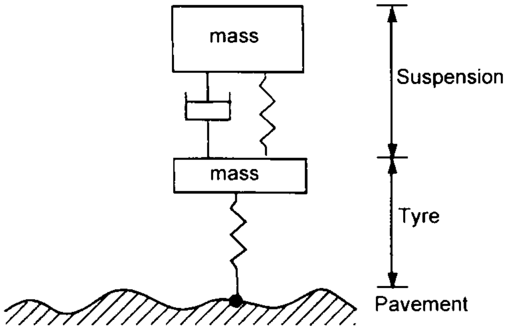


Figure 9. 'Quarter Car' vehicle model (after Cebon, 1993)

The use of Weigh-in-Motion systems has allowed improved data to be acquired for defining axle load spectra.

The various components now appear to be available for more comprehensive procedures to be evolved for defining traffic loading effects on pavements. Presenting this in a manner which will be of use for routine design is one of the challenges for pavement engineers.

PAVEMENT FOUNDATIONS

Fig. 2 shows that the pavement foundation is defined as the granular layer or layers placed over the subgrade. For pavements with asphalt bases, this implies the subgrade (cut or fill), probably a capping layer and the sub-base. For a pavement with a granular base and asphalt surfacing, the base could be considered as part of the foundation. The reason for considering all the unbound granular material with the soil is that both obey the principles of soil mechanics. These have not been consistently or effectively applied in pavement engineering given the extensive knowledge of soil mechanics which now exists. In the general field of geotechnical engineering, pavements have been rather left behind.

The, almost, universal parameter used to characterise soils for pavement design purposes is the California Bearing Ratio. This empirical index test was abandoned in California about 50 years ago but, following its adoption by the U.S. Corps of Engineers in World War II, it was gradually accepted World-wide as the appropriate test.

Given that the test is, at best, an indirect measurement of undrained shear strength and that pavement design requires a knowledge of soil resilience and its tendency to develop plastic strains under repeated loading, the tenacity exhibited by generations of highway engineers in regard to the CBR test is somewhat surprising. It is of interest to note the comments of various significant individuals in this regard. Jim Porter who, as Soils Engineer for the State of California, introduced the “Soil Bearing Test” in 1929 commented nine years later (Porter, 1938):

” .... the bearing values are not a direct measure of the supporting value of materials”

and subsequently (Porter, 1950):

” .... the results are influenced only to a minor degree by elastic deformation”.

Turnbull (1950) noted:

” .... the CBR is an index of shearing strength” and recognised that CBR design curves give a total thickness of pavement to prevent shear deformation in the soil.

In the U.K., despite continuous use of the CBR from 1949 to date, based on its relationship to shear strength and the influence of water content on both parameters, Croney 1977) noted that:

”The shear strength of soil is not of direct interest to the road engineer .... the soil should operate at stress levels within the elastic range .... The pavement engineer is, therefore, more concerned with the elastic modulus of soil and the behaviour under repeated loading”.

A detailed study of the CBR test by Hight and Stevens (1982) at Imperial College, reported in 1982 noted that the effective stress is unknown in the test and the drainage conditions are not controlled. They concluded that the test cannot distinguish between stiffness of soils at low strains, which is just what is of interest for pavement design. At Nottingham Loach (1987) reported the results of repeated load CBR tests on reconstituted soils of known effective stress and stress history. Typical results are shown in Fig. 10. The initial slopes of the load-penetration curves, whether in cycle 1 or subsequently, correlated with CBR but separate tests showed no correlation between CBR and resilient modulus.

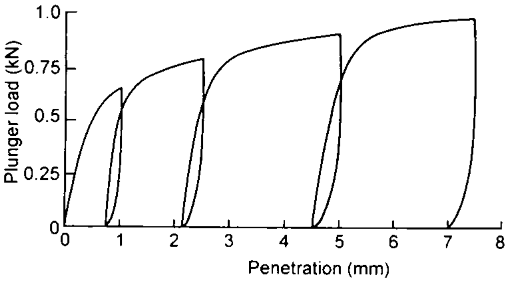


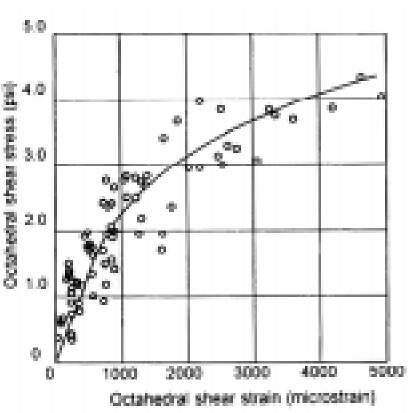
Figure 10. Repeated load CBR tests on reconstituted silty clay (after Loach, 1987)

One of the problems in this regard is the marked nonlinearity of stress-strain relationships for soils. This has been recognised since the alternative and more rational approach to soil characterisation began in the 1950's, also in California, under Professor Harry Seed. He and his colleagues followed the pioneering work of Francis Hveem, who applied a rational and logical approach to pavement design and materials testing, including introduction of the Stabilometer, which continues in use today, and the Resilometer. A modem variation of this latter equipment is known as the K-Mould (Semmelink and de Beer, 1995) in which lateral stress is mobilised by an elastic support system with a stiffness which can be set to simulate a range of insitu conditions.

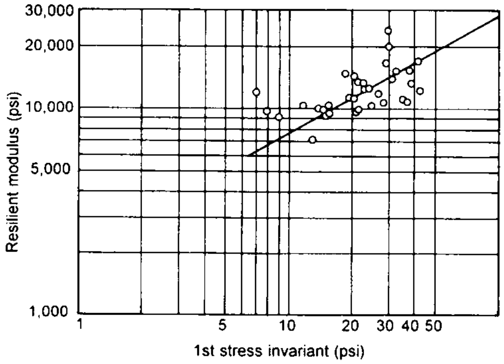
Today, quite extensive use is made of repeated load triaxial tests to determine the resilient characteristics of soils and compacted granular materials but few agencies include such tests as a formal requirement. It remains essentially a research tool despite the availability of simplified and relatively low cost equipment which utilises pneumatic loading systems.

The non-linearity of pavement foundations has been demonstrated both from insitu measurements of stress and strain, using field instrumentation, and through back-analysis of surface deflection bowls measured with the Falling Weight Deflectometer.

Fig. 11(a) shows the stress-strain relationship for a silty-clay, based on measurements from insitu instrumentation (Brown and Bush, 1972), while Fig. 1l(b) illustrates the well known stress-dependence of granular material determined from similar data in a crushed rock base (Brown and Pell, 1967).



(a) Shear stress - strain relationship for silty-clay (after Brown and Bush, 1972)



(b) Resilient modulus against 1st stress invariant for crushed rock (after Brown and Pell, 1967)

Figure 11. Non-linearity of soils and granular materials from insitu measurements

Recent FWD testing on a site in the U.K. was conducted as construction proceeded. Table 1 shows the back-analysed values of resilient moduli indicating how the granular capping and the subgrade mobilised higher stiffnesses when covered by the sub-base and base. This was caused by the consequent changes in stress level.

Table 1

Back analysed effective values of resilient modulus for road in cutting (after Brown, 1996,a)

Pavement layer	Effective Er (MPa)	
	Test on Capping	Test on road base
Road base	-	3200
Sub-base	-	240
Capping	90	200
Subgrade	70	200

These non-linear characteristics have also been extensively studied using repeated load triaxial facilities and various models proposed for use in pavement analysis. Some of these are quite sophisticated. For granular materials the use of stress dependent bulk and shear moduli provides a much sounder basis for analysis than the simple “K-θ” model in which the resilient modulus is expressed as a function of the mean normal stress and, usually, a fixed value of Poisson's ratio is adopted, typically 0.3. Fig. 12 demonstrates that both deviator stress and mean normal stress have an influence on resilient modulus for a typical crushed rock.

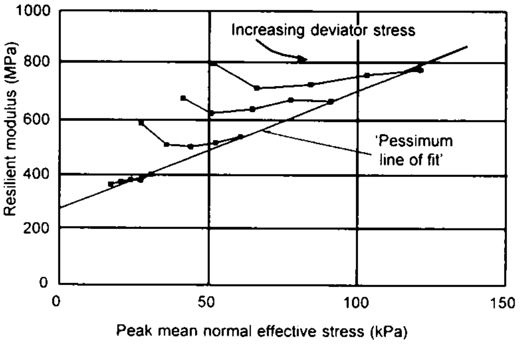


Figure 12. Resilient modulus for crushed dolomitic limestone as a function of applied stresses (after Dawson et al, 1993)

For fine grained soils, emphasis has been placed on the relationship between resilient modulus and deviator stress following the early work done by Seed et al (1962). However, when the effective stress state of the soil is taken into account, sometimes expressed in terms of soil suction, it is apparent that this parameter too has a major effect. For saturated silty-clay, Brown et al (1987) suggested the following model based on a series of good quality laboratory tests:

$$G_r = \frac{q_r}{C}\left[\frac{p_0'}{q_r}\right]^m \qquad (1)$$

where G_r = Resilient shear modulus
q_r = Repeated deviator stress
p_o' = Mean normal effective stress
C, m = Constants for the particular soil.

For partially saturated soils with degrees of saturation in excess of 85%, the same equation was valid with p_o' being replaced by the soil suction.

The shortcoming of this model is that unrealistically high values of resilient modulus are predicted at low stresses. To avoid this, and to make use of expertise developed in another field, pavement engineers should consider use of the strain dependent stiffness models adopted in earthquake engineering and for other small strain geotechnical problems. Fig. 13 shows a set of curves in which the shear modulus (G) is normalised with respect to the maximum value (G_o), which occurs at very low strains. The actual relationship between G/G_o and cyclic shear strain is shown to depend on the plasticity characteristics of the soil (Roblee et al, 1994, Vucetic and Dobry, 1991, Sun et al, 1988). Viggiani and Atkinson (1995) have presented a procedure to estimate G_o from Plasticity Index, effective stress and overconsolidation ratio for the soil.

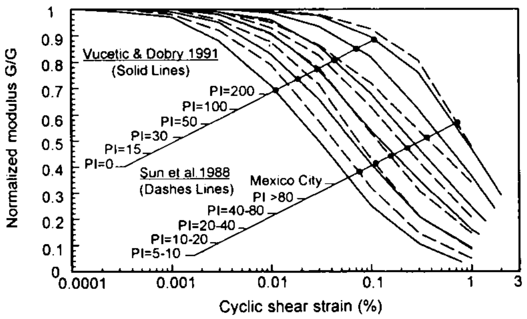


Figure 13. Relationship between normalised shear modulus and Cyclic Shear Strain (after Roblee et al, 1994)

The tradition in pavement engineering has been to think in terms of stress-dependent rather than strain-dependent resilient moduli. This possibly derives from the idea that subgrades are subjected to a controlled stress environment. Some simple linear elastic calculations on two layer systems following the principles established by Monismith and Deacon (1969) in relation to asphalt fatigue indicate that this is not the case.

The simple structures are shown in Fig. 14(a). A thick and thin asphalt layer placed directly on soils of varying stiffness was used. The effect of reducing the soil stiffness by 25% in each case led to calculation of the Mode Factor, M, where:

$$M = \frac{|A| - |B|}{|A| + |B|}$$

in which |A| = % change in shear stress
|B| = % change in shear strain

for the 25% change in soil stiffness.

Pure controlled stress conditions are given by M = -1 while M = +1 corresponds to pure controlled strain.

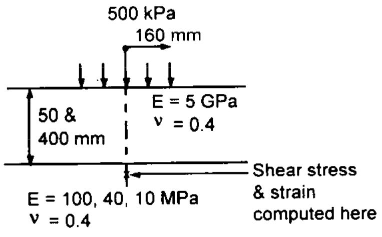
Figs. 14 (b) and (c) show the results. For the thin structures M is close to zero, indicating conditions midway between the two extremes. However, for the thick structure, which is closer to a real situation, $M \approx 0.5$ showing controlled strain conditions to be more appropriate than controlled stress.

For practical use, the following model for resilient modulus was developed by Dawson and Gomes Correia (1996) based on analysis of laboratory data and recognising the need for realistic values at low stress (or strain):

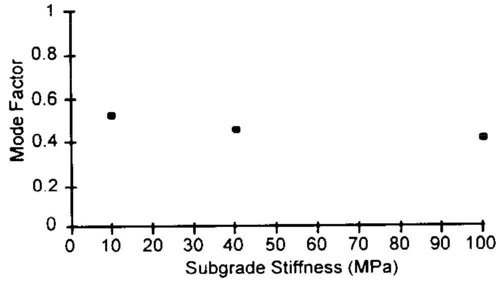
$$E_r = 49{,}200 + 950\, p_o' - 370\, q_r - 2{,}400\, w_p \qquad (3)$$

in which E_r p_o' and q_r are in kPa and w_p is the Plastic Limit expressed as a percentage. For compacted, partially saturated clays, p_o' could be replaced by the soil suction. Fig. 15 shows that this model compares reasonably well with actual measurements over a practical range of resilient modulus.

At the 1992 Conference, Brown and Dawson (1992) outlined a two stage approach to pavement design in which the first stage involved design of the foundation to carry construction traffic. In the second stage, the foundation was represented as an equivalent elastic half-space characterised by an effective foundation stiffness modulus (E_f). This is a parameter which can readily be determined from some form of dynamic plate loading test on site or can be computed using elastic analysis. Design of the asphalt layer can be based on a two layer system with the lower layer representing the foundation and characterised by E_r. The problem in applying these concepts is to ensure that non-linear effects are taken into account. In practice, this means that E_f will increase when the asphalt layer is constructed. This is well demonstrated by the data in Table 2 taken from field testing with an FWD, during construction. It shows how E_f increases from 30 MPa for the exposed subgrade to 90 MPa for the composite, including 300 mm of general capping and 150 mm of crushed rock sub-base.



(a) Simplified structures



(b) Subgrade Mode Factor: Stiff Structure

(c) Subgrade Mode Factor: Soft Structure

Figure 14. Computed Mode Factors for Subgrades in idealised pavements

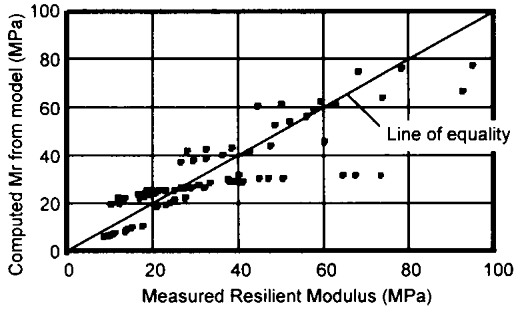


Figure 15. Computed verses measured values of resilient modulus for clays (after Dawson and Correia, 1996)

Table 2

Equivalent foundation stiffness values for road on embankment (after Brown, 1996,a)

Test on:	Equiv. found. stiffness (MPa)
Subgrade	30
Capping	50
Sub-base	90

The mechanistic design of pavement foundations still presents analytical problems, not least because of the high stresses relative to failure conditions to which the granular layer is subjected when loaded by construction traffic. The design criterion is clearly rutting and a limit of 40 mm has been suggested in work conducted at Nottingham (Dawson et al, 1993). Thom et al (1993) have outlined a novel design method which includes several approximations but attempts to deal both with the rutting problem and with the resilience of the foundation. This latter is of importance for satisfactory compaction of the asphalt layer as well as for its long-term performance.

The Wedge model shown in Fig. 16 is proposed as an approximate method for dealing with rutting (Thom et al, 1993). In this, the granular layer is characterised by its angle of shearing resistance (ϕ') while an allowable deviator stress on the subgrade is determined from laboratory testing based on limiting the plastic strain accumulated in 1000 cycles to 0.6%. An alternative approach is to determine the "threshold stress" for the soil. This is defined as the maximum repeated deviator stress which results in negligible accumulation of plastic strain. Fig. 17 shows how it relates to soil suction for three different clays (Loach, 1987). However, this parameter is not easy to define for some soils, so a maximum allowable plastic strain of, say, 0.6% is an alternative approach.

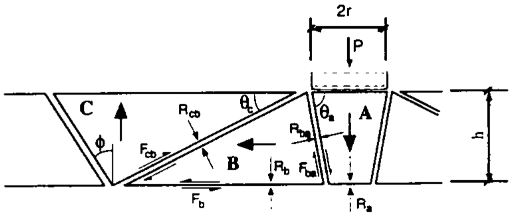


Figure 16. Proposed 'wedge model' for calculating rutting in pavement foundations (after Thom et al, 1993)

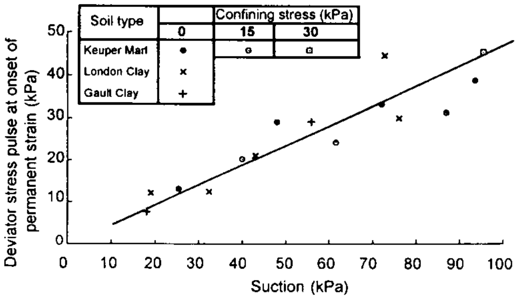


Figure 17. Threshold deviator stress as a function of suction for three clays (after Loach, 1987)

As more accurate modelling of pavements becomes widely used with the advent of faster computers and high quality "user-friendly" programs, the non-linear characteristics of soils and granular materials will be routinely accommodated. However, this depends on reliable models being used and field conditions, particularly the effective stress state, being properly defined. Further field observations of moisture conditions beneath pavements are badly needed to assist with this process.

Pending these developments, it is appropriate to consider the importance of non-linearity for pavement design calculations of the type presently undertaken. Sensitivity analyses reported by Dawson and Plaistow (1996) are helpful in this context. They analysed 14 pavement structures with asphalt layers between 50 and 250 mm in thickness and granular layers between 300 and 700 mm. Non-linear models were used for the granular layer and the subgrade was modelled with a series of sublayers for which the stiffness increased with depth. The asphalt stiffness varied from 2 to 8 GPa. Computations were performed with the finite element program FENLAP (Brunton and d'Almeida, 1992). The results showed that the tensile strain at the bottom of the asphalt layer only changed by 2% for a change in subgrade stiffness from 40 to 90 MPa at formation level. However, changes to the non-linear parameters for the granular layer, representing a practical range, caused the tensile strain to change by 70%. Clearly, the resilience of the support directly beneath the asphalt layer needs to be accurately quantified for fatigue cracking design calculations.

Similar computations by Dawson and Plaistow (1996) showed the importance of the resilient characteristics of the granular layer in the context of permanent deformation developing both in this layer and in the subgrade under construction traffic. Some linear elastic calculations by the Author have indicated that the pavement foundation characteristics have much less influence on the potential for permanent deformation developing in the asphalt layer except when that layer is relatively thin.

From the above discussion it may be concluded that more effort should be devoted to correctly modelling and specifying granular materials for pavement design purposes while subgrade characteristics are relatively less important.

By contrast, when dealing with pavement evaluation, proper characterisation of the subgrade is vital. This is because the magnitude of surface deflection at all radial positions relative to the load is strongly influenced by subgrade stiffness. Fig. 18 taken from a contribution to the 6th Conference (Brown et al, 1987) shows the large influence which the subgrade has on surface deflection in a typical pavement situation. It is for this reason that proper non-linear characterisation of the subgrade is needed for successful back-analysis computations. Such models should reflect the influence of changes in both the effective stress and the deviator stress with depth and, if finite elements are used, with radial position too. A back-analysis program FEAD has been developed to perform these calculations (Brunton and d'Almeida, 1992).

There are many other aspects of pavement foundations which are of importance. Reference may be made to Brown (1996,a) for a review of soil mechanics aspects. The opportunities for correctly modelling partially saturated soils (e.g. Wheeler and Karube, 1995) have improved as a result of research in recent years and this opens up opportunities in pavement engineering which need to be exploited.

Concepts of drainage and permeability, of stabilisation and the use of geosynthetics are all of importance and require further research to fully realise their potential. The concepts illustrated by Fig. 19 indicate how an improved pavement foundation might be conceived. The ideas involved are:

(a) An open-graded drainage blanket connected to a side drain to remove water ingress from the subgrade or through pavement "leakage".
(b) A geosynthetic separator to minimise contamination of the drainage layer.

(c) A high quality dense crushed rock sub-base reinforced by a geogrid to mobilise high stiffness and good rutting resistance.

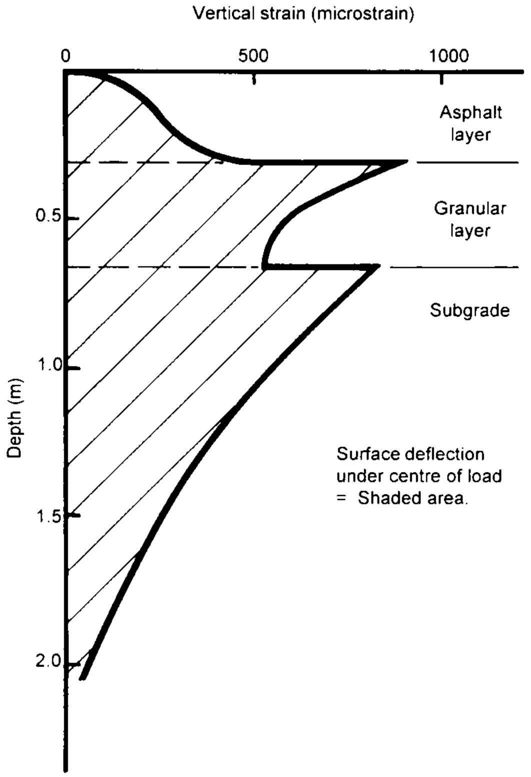


Figure 18. Typical variation of vertical resilient strain through pavement structure below centre of single standard wheel load

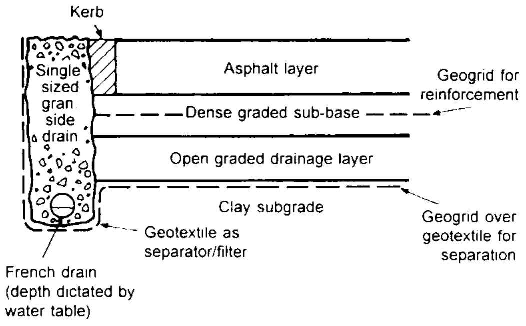


Figure 19. Cross-section showing idealised pavement foundation

There are other ways of achieving some of these ends but the principles of good drainage, trafficability by construction traffic and long-term stiffness of support are considered desirable principles.

PERMANENT DEFORMATION

Rutting remains a major failure mechanism and recent research led by SHRP has concentrated on dealing with this through improved asphalt mixture technology. Analytical techniques to predict rutting are improving, as noted in the Section on structural design and theoretical analysis which reviews the increasing use of visco-elastic analysis. The work of Deacon et al (1995) shows how advanced laboratory testing using the Superpave Shear Tester (SST) combined with theoretical analysis can produce design guidance for rutting in the asphalt layer. They showed that the rut depth (in mm) is approximately 2.5 times the maximum shear strain (in per cent) measured in the constant height SST test. While this is useful, it still requires an expensive test facility but the principle could probably be exploited using simpler facilities of the type discussed in the next Section.

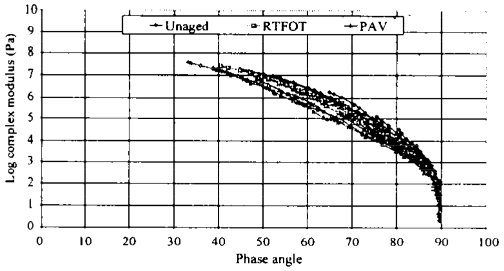
While this concentration on analysis and related testing of the asphalt layer is entirely appropriate for heavy duty pavements, for those with thin asphalt layers, significant contributions to rutting may come from the pavement foundation. This can be minimised by adopting the procedures outlined in the preceding Section in relation to soils and granular materials. For the subgrade, imposed stress levels need to be below the threshold or similar value. For the granular layer in a completed structure, the same principle applies. For such material the ratio of shear to normal stress should be kept below 70% of static failure (Brown, 1996,a). Consequently, specification and measurement of shear strength for granular materials should be encouraged.

These approaches to the rutting problem indicate that the concept of limiting the vertical subgrade strain at formation level through an elastic analysis is outdated. Brown and Brunton (1984) reviewed the use of this semi-empirical criterion. While they improved its application to allow for varying rut resistance of different asphalt mixtures, they made it clear that the parameter is only an indicator of the potential for critical rutting to develop as a consequence of permanent deformations developing in all layers. A common misconception is that the subgrade strain criterion only refers to permanent deformation in the subgrade. The relationships between allowable strain and numbers of standard wheel loads were developed from linear elastic back-analysis of structures with known performance in relation to rutting. The parameter is not, therefore, fundamentally based and cannot be expected to provide reliable design guidance for pavements with characteristics that differ significantly from those used in the back-analysis.

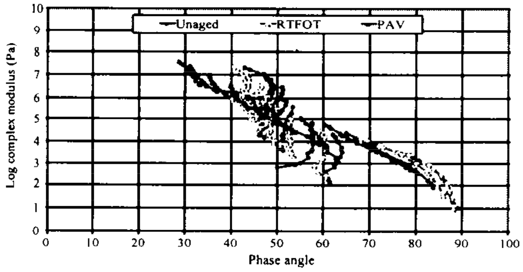
For heavy duty pavements, the stress levels in the lower layers are unlikely to cause significant rutting and, hence, concentration on limiting permanent strains in the asphalt surfacing is an entirely appropriate approach. Equally, to minimise maintenance operations, preservation of a sound foundation is highly desirable so that rehabilitation can be limited to a quick resurfacing operation.

PROPERTIES OF ASPHALT MIXTURES

This is a field in which there have been major advances stimulated by SHRP. These are well known and will not be reviewed in detail here. The ability to test asphalt binders to determine relevant mechanical properties and the implementation of specifications based on such tests represents a major positive achievement. The old empirical “Black Magic” tests such as “Penetration” and “Softening Point” have served a useful purpose but they are not relevant to the needs of an industry increasingly looking at modified binders and specifying mechanical properties. In this context, Fig. 20 shows the kind of interesting data which can be obtained from a Dynamic Shear Rheometer demonstrating the very different characteristics of an EVA modified bitumen compared with the standard product (Airey, 1997).



(a) Unmodified bitumen



(b) Bitumen with 7% EVA

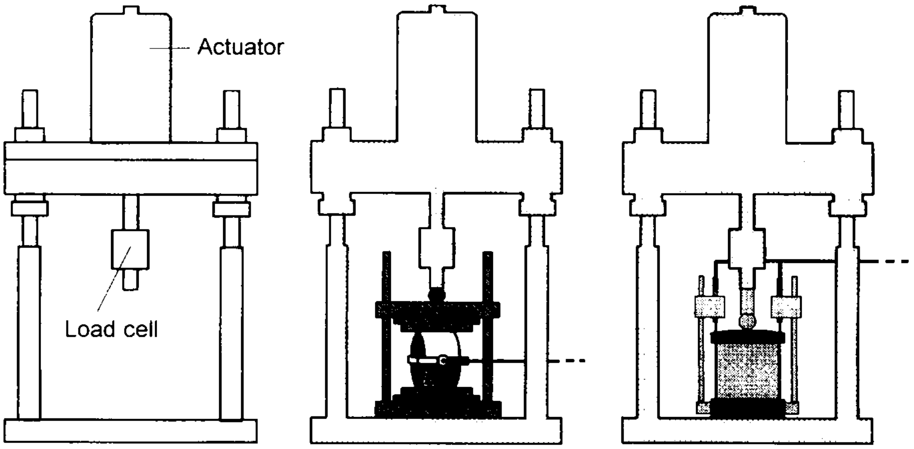
Figure 20. Black diagrams for 701100 Venezuelan bitumen (after Airey 1997)

In the U.S., the Superpave procedures resulting from SHRP have left a gap between Levels 1 and 2 which needs to be filled pending the results of continuing long-term research. The need for a simple test or tests to measure key mechanical properties as an adjunct to the Level 1 volumetric mixture design is essential. Such a test system needs to be economic and practical so that a wide range of laboratories on both sides of the industry can perform the necessary tests. This procedure is being successfully introduced in Europe and in Australia. Its adoption in the U.S. could lead to Superpave “Level 1.5” (Brown, 1996,b) which would greatly enhance present practice. General guidance on this matter has been published recently (NAPA, 1997) concentrating on tests to deal with rutting.

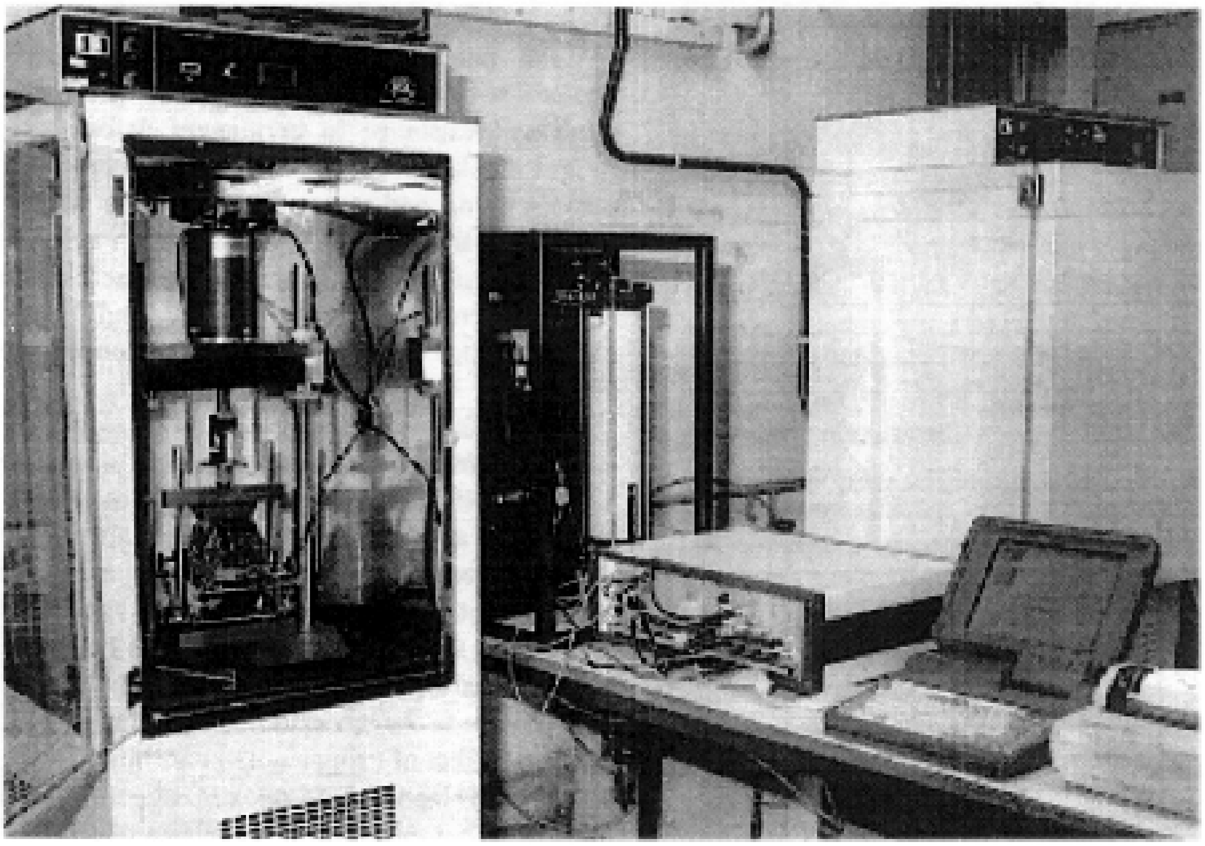
At Nottingham, a suite of tests linked to mixture design and accompanied by a set of experimental protocols was developed in a joint project involving academia, oil companies, contractors and Government (Brown et al, 1996). The results are presently being adopted by the British Standards Institution and are the subject of discussion in connection with European Standards. Trial contracts in the U.K. (Nunn, 1996) have allowed contractors to use these procedures to develop their own improved mixtures with enhanced mechanical properties relative to current practice. This is giving confidence to the highway authorities as they seek to introduce specifications based on measured mechanical properties and allows the contractors to use their expertise to meet these specifications.

The pneumatically operated Nottingham Asphalt Tester (NAT) (Fig. 21) is used to measure stiffness modulus, resistance to permanent deformation and to fatigue cracking. Procedures derived from SHRP are set out for aging and water damage. The whole package represents an excellent example of “Paving the Gap” between research and practice. Its implementation has depended crucially on the low cost and “user-friendly” characteristics of the test apparatus (Cooper and Brown, 1989).

For permanent deformation, the original Repeated Load Uniaxial Test has been adapted to allow confining stress to be applied using an internal partial vacuum with the specimen surrounded by a rubber membrane. This arrangement is shown in Fig. 22 and allows more appropriate testing of mixtures such as Porous Asphalt to be conducted without much increase in equipment cost and little change to the laboratory procedures. Fig. 23 shows the huge effect of using a small confining stress (20 kPa) on the development of permanent strain in a Porous Asphalt with unmodified binder. Use of an SBS modifier produced significantly better performance with unconfined specimens but no enhancement when the 20 kPa confining stress was used. These results pose a question about the appropriate degree of confinement to be used when carrying out laboratory tests on pavement “elements”. Clearly some confinement occurs insitu and the laboratory test needs to reproduce this realistically for the results to be valid. Brown and Gibb (1996) demonstrated, for continuously graded mixtures, that confined specimens may exaggerate the role of the aggregate structure relative to performance in the pavement.



(a) The test frame and subsystems



(b) The test facility

Figure 21. The Nottingham Asphalt Tester

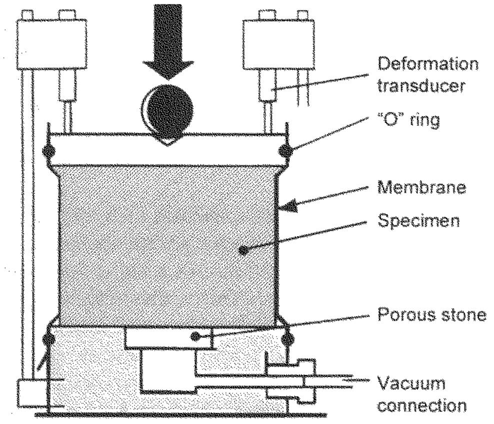
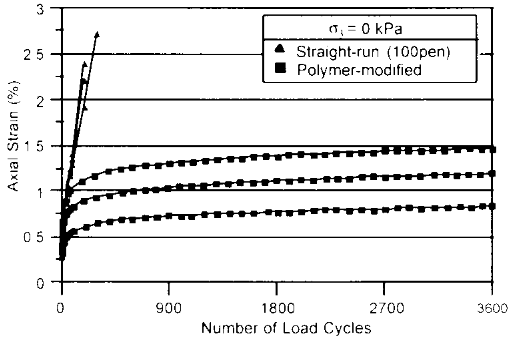
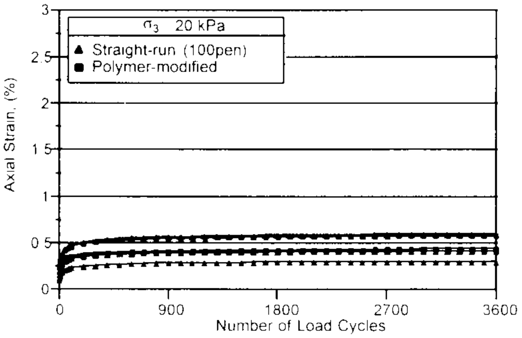


Figure 22. Confined RLA Test Arrangement for NAT



(a) Unconfined



(b) 20 kPa confining stress

Figure 23. Permanent deformation of Porous Asphalt at 40°C

The future challenge here is to calibrate the results from this test to field performance, to explore how it compares with the SST and investigate how data from the test may be reliably used in predictive computations for rut depth. This is the subject of ongoing research.

The increasing use of wheel tracking apparatus in various countries represents a pragmatic approach to testing for rutting potential. It also allows, in some cases, an immersed specimen to be tested, thus dealing with the problem of water damage which is of great concern in some locations. Wheel tracking, however, does not allow any fundamental property of the mixture to be measured and there are concerns about scale effects since loaded areas are usually small in relation to aggregate size and much smaller than the situation on site.

The full-scale accelerated loading work, which is currently gathering data for validation of mixture design and predictive methods, will contribute significantly to knowledge and to the confidence with which laboratory test methods can be used. Notable amongst these efforts are those at WesTrack, Nevada (Nevada Automotive Test Center et al, 1996), Richmond, California (Noakes et al, 1996) and at the FHWA Turner-Fairbanks Center near Washington, D.C. (Bonaquist and Mogaver, 1997).

While practical tests are needed to help today's engineers and to improve quality control and quality assurance, research to understand fundamental mechanisms should continue. Fresh ideas using idealised models, both theoretical and physical, and treating the problem at the micro-level will generate new insights; in due course. The philosophy of the work initiated at Cambridge under David Cebon and extended to Nottingham under Andrew Collop is outlined in Fig. 24 for permanent deformation. Following detailed study of binder properties over a wide range of conditions by Cheung (1995) a Deformation Map was produced as shown in Fig. 25 drawing on concepts used in polymer engineering and elsewhere. This Map identifies zones in which the bitumen will exhibit different characteristics and obey different models. Recognising that the aggregate in a mixture is almost rigid, it follows that the binder film must be subjected to a wide range of strain conditions.

Fig. 24 shows how understanding of real asphalt mixtures can be approached in stages from binder alone to simple idealised mixtures with large and with small particles using two and three-dimensional conditions.

Proposals for similar work have been made by Professor Monismith and his colleagues at Berkeley. Typical mixtures can be modelled to understand their micromechanical behaviour using finite element simulations based on use of image processing methods. Development of a macro constitutive law can be facilitated by studies on idealised mixtures.

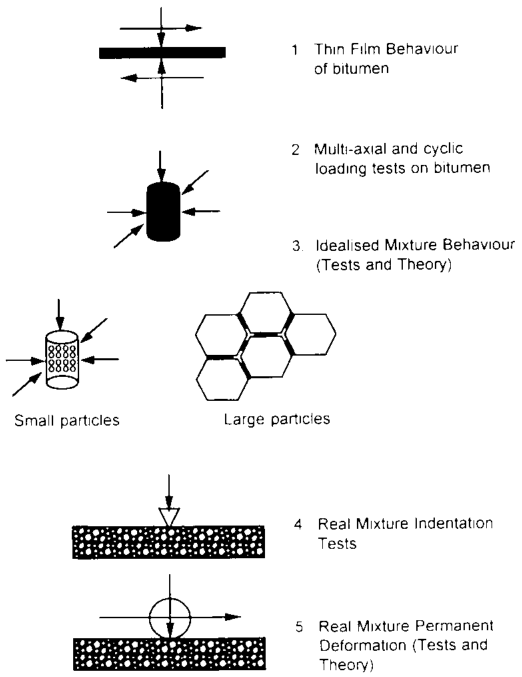


Figure 24. Sequential approach to fundamental understanding of permanent deformation in asphalt mixtures

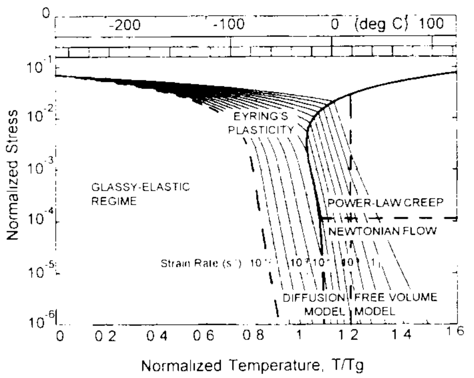


Figure 25. A Stress/ temperature deformation mechanism map for bitumen (after Chan, 1995) ***(T_g = Glass transition temperature)***

One of the significant opportunities presented by the SHRP asphalt programme was to take a fresh look at dissipated energy concepts in fatigue. This idea was first reported in 1972 but improved test facilities allowed more accurate data to be collected in the 1990's. Professor Monismith and his team (Tayebali et al, 1995) concluded that dissipated energy was an equally valid criterion for predicting fatigue life to crack initiation compared with tensile strain. They also pointed out that fatigue performance of asphalt mixtures must be considered in the context of the pavement because of the interactions between layer thickness and stiffness and the influence of the supporting layers. When using tensile strain as the criterion, elastic analysis of the pavement is adequate but dissipated energy calculations require visco-elastic theory.

Rowe et al (1995) have shown that such calculations can be performed and that, for some pavements, maximum dissipated energy occurs at the surface rather than at the bottom of the asphalt layer. This is illustrated in Fig. 7 (Rowe and Brown, 1997).

For heavy duty pavements, field observations agree with this concept (Nunn, 1997) since cracking is usually seen to initiate at the surface. However, there may be other reasons for this, since the asphalt surface is subject to more aging and can contain various crack initiators which take the form of roller cracks and surface texture provision.

The need to properly model this form of fatigue cracking is a future challenge. Matsuno and Nishizawa (1992) reported progress on this subject at the last Conference. They argued that aging prevents healing of surface cracks and demonstrated that the phenomenon depended on high temperature conditions and that it was inhibited by shadows cast from over-bridges.

In view of the continuing difficulties of predicting fatigue cracking, partly caused by the differences in circumstance between the laboratory and the field, the concept of insitu stiffness deterioration deserves more prominence and this is discussed in the next Section.

There have been encouraging recent developments in asphalt technology for surfacing, notably in Europe. The lead came from France, where the partnership arrangements between the highway authorities and the contractors has been effective in stimulating innovation. This has been backed by a framework of comprehensive test methods which have been in use for many years (Bonnot, 1986).

The “thin” and “ultrathin” wearing courses pioneered by French contractors have been based on the requirement for a non-structural surface which provides good skid resistance, low noise and which is waterproof, durable and rut resistant. A related development involving some of the same principles is the widespread use of Stone Mastic Asphalt (SMA) since it offers the characteristics noted above but in a structural layer. These principles were set out by Molenaar and Liljedahl (1992) at the previous Conference.

It is significant that while the SHRP was concentrating on conventional dense graded asphaltic concrete mixtures in the U.S., developments elsewhere were concerned with novel gradings and the exploitation of modified binders and fibres, principally through the development of SMA and Porous Asphalt (PA). The common feature of these two mixture types is the coarse aggregate structure which is filled, but not overfilled, with mortar for SMA and left open for drainage in PA.

EVALUATION AND REHABILITATION

The growth in detailed pavement evaluation work has been the most significant development of recent years. Since the majority of pavement expenditure in the developed World is on maintenance rather than new construction, it is in this field that most of the future challenges and opportunities for improved engineering will occur.

While there are achievements to report, there are also major future requirements, particularly for equipment to facilitate improved gathering of relevant data and for improved solutions to particular design problems such as that posed by reflection cracking.

The structural evaluation of pavements and design of rehabilitation form part of the overall management requirement for a pavement network and should be seen in that context. High speed, laser-based systems are now routinely used to gather data on riding quality, skid resistance and rutting. This can identify sections for more detailed study and this is where structural evaluation techniques have been most successfully applied.

In the context of this Conference, for which the use of mechanistic methods is a central theme, as is the need to “Pave-the-Gap” between theory and practice, structural evaluation techniques present a good example of real achievement.

In the design of a new road, there are many unknowns. Many of these are quantifiable when the same mechanistic design principles are applied to the evaluation and rehabilitation of an existing road. These include traffic characteristics, the pavement structure, the subgrade, which will have reached an equilibrium condition, and mechanical properties of materials which can be sampled and tested.

The Falling Weight Deflectometer (FWD) has become the standard equipment for structural evaluation testing because of the accuracy with which it can measure the deflected shape of a loaded pavement at appropriate rates of loading. The use of elastic theory to back-analyse deflection bowls allows such theory to be matched to the reality of the site. This then forms the basis for confident use to be made of the figures in assessing residual life and designing the overlay or partial reconstruction as appropriate.

Table 3 illustrates that various field testing, laboratory testing and analytical concepts can be combined to good practical effect for the evaluation and rehabilitation design of a section of highway or other paved area. Many of these techniques have been in use for some time but are not always combined to focus on this problem. The Dynamic Cone Penetrometer (DCP) has been extensively used for pavements with thin surfacings but it is extremely useful for heavy duty pavements when operated down a core hole after extraction of the core. Fig. 26 shows how the data can be used to assess thicknesses for the unbound layers below. Ground Penetrating Radar is also extensively used for layer thickness evaluation and has the advantage of being non-destructive. The merit of coring is not simply to determine bound layer thicknesses but also to obtain samples for laboratory testing which can very usefully augment and complement FWD data.

Use of the Nottingham Asphalt Tester (NAT) allows stiffness modulus at various temperatures to be measured. This assists with temperature corrections needed in the interpretation of effective stiffnesses back-analysed from FWD data. It also allows rutting potential of the various asphalt layers to be assessed and relative fatigue strengths to be measured. Hence, the NAT is seen to have applications beyond those associated with mixture design. Similarly, the Dynamic Shear Rheometer (DSR) can provide valuable information on the mechanical characteristics of binders recovered from field cores. Such matters as excess hardening, the presence of modifiers and temperature susceptibility all provide useful information when assessing the present pavement condition and predicting future performance.

In this connection, the calculation of residual life based on rutting can use the principles set out in the Section on theoretical analysis with visco-elastic parameters determined from the NAT tests. For fatigue life assessment, there are always uncertainties and the increased incidence of surface crack initiation for thick pavements throws into question the traditional approach based on cracking from the bottom.

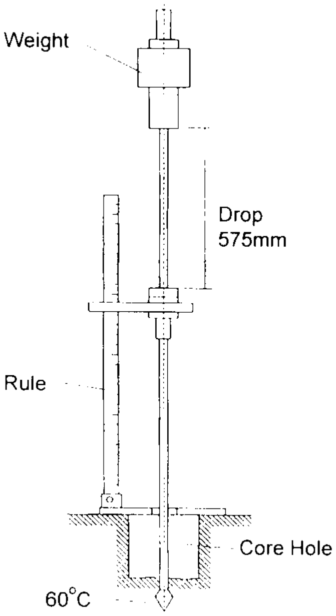
The “effective stiffness” of the asphalt layer determined from back-analysis will generally be less than the “as-built” stiffness because of accumulated damage. It is this effective stiffness which is of prime importance rather than the extent of cracking which may have brought it about. Nunn (1997) reports at this Conference that heavy duty pavements observed in the U.K. show no sign of fatigue damage to the base and, in fact, increased stiffnesses are reported. Evaluation of a major U.K. motorway with a 330 mm asphalt layer and subjected to 50 million standard axles supports this view (SWK Pavement Eng., 1996). The stiffness reduction concept is, however, considered valid for thinner structures.

Table 3

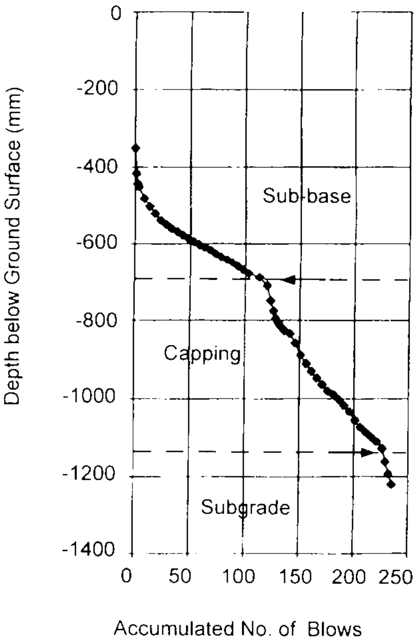
Procedures for pavement evaluation and rehabilitation design

Field testing	FWD Survey	Deflection profile Data for back-analysis
	Coring	Bound layer thickness Specimens for lab. testing
	Dynamic Core Penetrometer down core holes	Unbound layer thicknesses Foundation properties
	Ground Radar Survey	Layer thicknesses Large voids
Laboratory testing	Dynamic Shear Rheometer	Recovered binder properties
	Nottingham Asphalt Tester	Mechanical properties of asphalt layers
Analysis and Design	Back-analysis	Effective stiffnesses of layers
	Forward analysis	Residual fatigue life Rutting potential
	Rehabilitation	Overlay options and/or partial reconstruction

Unfortunately, FWD surveys tend only to be conducted when pavements are likely to be in need of some rehabilitation. If more data could be accumulated on the effective stiffness changes taking place from the time the pavement is first built, through regular FWD testing, then relevant models could be developed to assist with computations. The increased use of accelerated loading devices can assist with this process, as demonstrated by Jameson et al (1992) using the Australian Accelerated Loading Facility (ALF). Fig. 27 taken from their paper shows data with considerable variability but a trend for decreasing stiffness as cracking developed.



(a) Apparatus



(b) Results

Figure 26. Use of Dynamic Cone Penetrometer to identify layer thicknesses

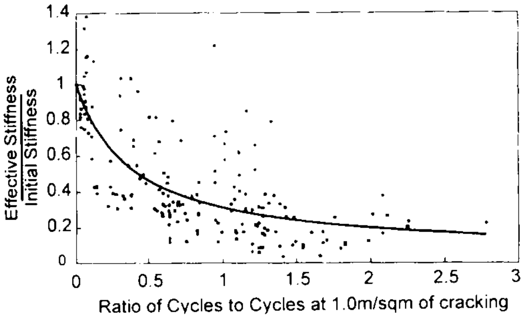


Figure 27. Relationship between effective stiffness and crack development (after Jameson et al, 1992)

It is, however, important to recognise that cyclic environmental effects on pavements are not accelerated in these trials. Consequently, properly planned programmes of FWD testing on “in-service” roads are also needed.

Collop and Cebon (1996) report a theoretical approach to prediction of stiffness deterioration. Fig. 28 shows how they related it to cumulative fatigue damage for some of the Australian ALF trials.

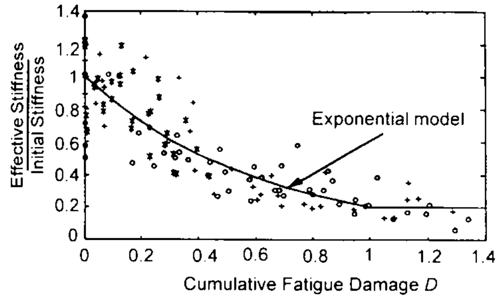
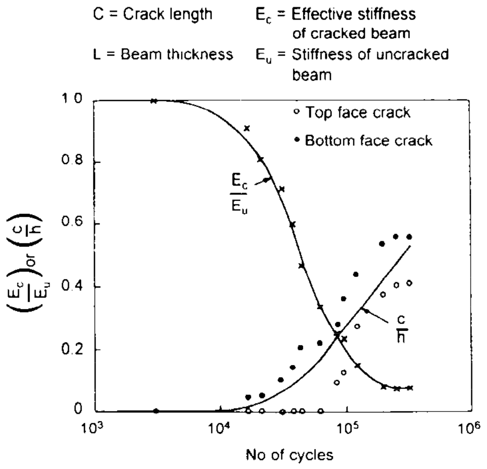
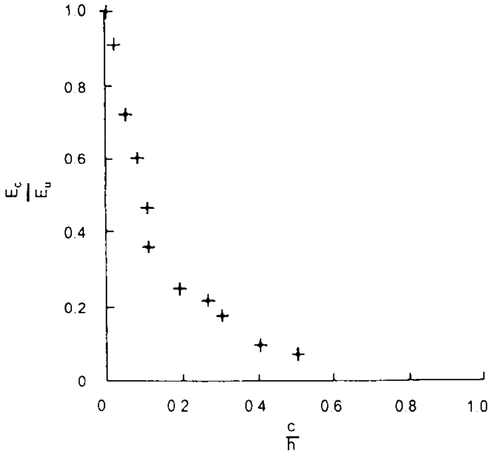


Figure 28. Reduction in effective stiffness of asphalt layer: theory compared with data from ALF trials (after Collop and Cebon, 1996)

Laboratory testing of asphalt beams by Tam (1987) generated the data shown in Fig. 29 which relates the decrease in effective stiffness of the beam to the growth in crack length. His results showed that a 50% reduction in stiffness can be expected for a crack which is 15% of the layer thickness. He also demonstrated, using controlled deformation testing, that a residual stiffness of less than 1 GPa may be expected for a fully cracked section. This would be consistent with an unbound granular material of good quality and supports the concept of downgrading cracked layers of bound material to a stiffness of 500 MPa for rehabilitation design when they are overlayed.



(a) Influence of number of cycles



(b) Influence of crack growth

Figure 29. Relationship between crack growth and reduction in effective stiffness of asphalt beam in four-point bending (after Tam, 1987)

The major future challenge in this field is to develop a moving deflectometer which does not require lane closure but which can measure deflection bowls to an accuracy comparable with that of the FWD, i.e. to a few microns. Complete non-destructive evaluation is always going to produce less information for the engineer to conduct forensic studies of an existing pavement than intrusive methods. However, the pressures to keep traffic moving on very busy major highways are real and a challenge. Night time lane closures are already the norm in many countries. It should, however, be recognised that even the most cosmetic of rehabilitation treatments will need a lane closure. For such treatments to be cost effective, they need to be based on the best design information and this, presently, requires an earlier lane closure for realistic site investigation.

The particular problem of reflection cracking through overlays placed over pavements with well defined discontinuities, such as concrete slab joints remains a subject of research study and field trials. The RILEM Conferences in recent years have focussed on this problem and useful theoretical work, notably by Scarpas et al (1996), has provided an improved basis for design. His work has also allowed reinforcement to be incorporated in a finite element analysis that is helpful for dealing with reinforced asphalt, one of the treatments used for reflection cracking.

The concept of precracking cement treated layers is being implemented and good examples of this have been reported by Shahid and Thom (1996) and were used on the main runways for the new Kuala Lumpur International Airport in Malaysia as part of an innovative pavement design. This used a granular sub-base, a cement treated base (precracked into 3 m square sections), an open textured bitumen macadam and a two course asphalt concrete surfacing incorporating modified binders.

The concept of “Smart Pavements” is receiving attention in the U.K. Investigations are underway to identify appropriate low cost instrumentation which can, preferably, be retrofitted into pavements to monitor key parameters. These include critical stresses and strains, temperature, permanent deformation and moisture. If successful, computer based systems would allow remote monitoring of pavement performance. This would certainly be helpful for research and, with appropriate development, could be part of routine pavement management.

CONCLUDING DISCUSSION

The principal future challenges which have been identified in this lecture are:

1. Capitalise on the opportunities for theoretical modelling made possible by innovative ideas and powerful computers.

2. Replace old ideas such as the CBR concept and the subgrade strain criterion for rutting.

3. Improve fundamental understanding of asphalt mixtures including durability.

4. Develop the concept of effective stiffness deterioration to deal with fatigue cracking in pavement design.

5. Provide theoretical understanding and practical solutions to reflection cracking.

6. implement simple test methods to measure mechanical properties of asphalt mixtures, i.e. Superpave Level 1.5.

7. Upgrade the design and construction significance of granular layers.

8. Improve non-linear resilient modelling for foundations.

9. Incorporate the principles of soil mechanics more effectively into pavement engineering including new thinking on partially saturated soils.

10. Make good use of the data from accelerated testing facilities and field observations.

11. Develop the Smart Roads concept to measure key parameters routinely.

12. Recognise the different characteristics of heavy duty and low volume pavements.

13. Present the results of research in a manner which can be readily used in practice.

This lecture has endeavoured to present a combination of achievements and future challenges and opportunities in the field of asphalt pavement engineering. Inevitably there are areas which have not been discussed, notably the need for highway engineering to become more sustainable through imaginative recycling and the use of secondary aggregates. In addition, the need to reduce energy consumption and address alleged health issues is pointing to the need for improved cold-mix technology.

Progress will depend on continuing research, particularly in pursuit of innovation and by taking advantage of the I.T. revolution. It will also require that existing knowledge is implemented in practice by Paving-the-Gap.

Both these sets of activities present challenges and require that able people are involved. The pavement industry internationally is vast and still relatively backward technically, so there are plenty of opportunities. The realisation of these will require that both the public and the private sector recognise the need for research and development to be properly funded. It also requires that both sides of the industry display a willingness to introduce new ideas to practice.

The subject must be properly featured at an advanced level in University courses and in continuing professional development programmes. This will create an educational cohort of asphalt pavement engineers available to respond to the challenges of the future, some of which have been identified in this lecture.

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