IS FLEXIBLE PAVEMENT DESIGN ON THE RIGHT ROAD?

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ABSTRACT

The principles underlying current mechanistic–empirical pavement design methods for fully flexible pavements have changed little in the past 30 years. They generally use linear elastic theory to determine the permissible strain at critical locations in the pavement structure to safeguard the road against excessive fatigue
and structural deformation. These criteria are calibrated using performance data from structures that experience has shown to perform well. In recent years, the traditional design concepts have been brought into question. The concept of long-life or perpetual pavements and the recognition of top-down cracking has initiated research that suggests that fatigue damage is not necessarily a cumulative damage mechanism and that rutting in many asphalt roads is confined to the surfacing. This paper, sponsored by the UK Highways Agency, examines the reasonableness of current design methodology and identifies shortcomings. Basic information on pavement behaviour of which we are more certain is identified and it is proposed that this should form a platform for the development of a new approach to pavement design, which offers a truer reflection of performance. The review suggests that threshold levels exist and that above these levels, a risk analysis approach to pavement design should be developed. This change in thinking will have far reaching implications for pavement research, design, condition assessment, construction and maintenance.

**Keywords:** Design of pavement, Fatigue cracking, Permanent deformation

**INTRODUCTION**

With modern pavement design methods, the road is designed by adjusting layer thicknesses and selecting materials so that the stress or strain, predicted using a pavement response model, at critical locations in the structure are reduced to permissible values to achieve a given design life. This results in a design curve in which the thickness of the structural layer increases with the design traffic. It is suggested that this method, based on controlling fatigue cracking and structural deformation and calibrated using processed data from experimental pavements, is a barrier to the development of a true understanding of pavement behaviour. The evidence used to develop the current design method could be interpreted in other ways.

The pavement structure does not lend itself to rigorous analytical study. At best analytical models can provide insight into the complex interaction of the many variables in play. Pavement performance involves the behaviour of very complex materials and systems, whose response under load cannot be characterised comprehensively in scientific terms. For example, asphalt is temperature dependent, and its deformation behaviour is non-linear in every sense of the word. In addition, physio-chemical changes result in its properties changing with time. One school of thought is to exploit the massive developments in modern computing power and modelling techniques to develop much more rigorous analytical approaches that take into account many of the factors that could not be dealt with previously. There is a belief that this all embracing approach, that nevertheless still retains traditional concepts, will produce a better design method. The development of complex
computing procedures to describe a complicated mechanical system may not be the best way forward. A simpler approach may be more applicable.

Whatever our level of understanding, a design method is required that needs to be based on the best interpretation of the information that is possible using the resources available in a manner compatible with our current level of knowledge. To do this we need to ask the questions: What are we certain about? What do we think we know and do we have the information to substantiate these beliefs? How can we use this information to develop a new approach to design?

The quest for solid information should focus on the behaviour of in-service roads rather than on the behaviour of materials and structures under idealised laboratory conditions. The areas of weakness in current methods need to be identified to enable a new interpretation to be made. This paper focuses primarily on information obtained in the UK to illustrate various points and outlines a possible new approach to pavement design. Whatever outcome is achieved, it will be far from perfect, but the objective is to produce a design methodology that represents a truer reflection of actual pavement behaviour compared to current methods.

MODERN DESIGN THEORY

Pavement design methods can be divided into three basic categories; namely, mechanistic, mechanistic-empirical and empirical. These methods can be defined as follows.

Mechanistic: A completely mechanistic approach method would be based on a fundamental understanding of the behaviour of materials in the road pavement. It will use analytical models of the physical processes that lead to pavement deterioration and these models would require input data on fundamental material properties, obtained from laboratory tests carried out under carefully controlled conditions. This goal has yet to be achieved and the design methods in regular use are either mechanistic-empirical or empirical.

Mechanistic-Empirical (M-E): M-E methods use empirical data obtained from in-service roads to calibrate analytically determined pavement design criteria. The philosophy is identical to that for designing any load bearing engineering structure. Generally a linear elastic pavement response model is used to calculate stresses and/or strains, induced by a wheel load, at locations in the pavement structure that are considered to be at greatest risk of deterioration. These calculated values are then compared with permissible values obtained from a back-calculation of structures that are known to perform well to achieve the required life. If the calculated responses exceed permissible values, the calculations are repeated after adjustments are made to either the thicknesses of the road layers or the properties of the constituent materials to determine suitable road structures.

Empirical: There are a range of empirical methods. At one extreme, an empirical method may be based solely on engineering experience, in which case, it
may have evolved over time with regular reviews as more experience is accumulated. At the other extreme, an empirical method may be the result of the systematic collection of condition data over a period of time and a statistical correlation of design variables with this performance information.

**DESIGN ASSUMPTIONS**

M-E design methods involve many assumptions. The more important considered in this paper are:

- Fatigue cracking and structural deformation are the primary modes of structural deterioration assumed by all modern analytical pavement design methods;
- The difference between laboratory performance and in-service performance can be bridged by a simple transfer function for each mode of deterioration;
- The limited empirical performance data available, and more importantly its interpretation, are adequate to calibrate these transfer functions;
- Miner’s hypothesis is used to sum incremental damage for each wheel until pavement life is consumed.

**Structural Deterioration**

The empirical performance data used to calibrate the UK design method, described in the Transport Research Laboratory (TRL) Report LR1132 (1) were obtained from the long-term monitoring of TRL experimental pavements that were built into the primary road network.

The individual trial sections had carried up to 20 million equivalent 80 kN standard axles (msa) of traffic. Only sections with less than 185 mm of asphalt had reached a failure condition and therefore the lives of the thicker experimental pavements were predicted by the extrapolation of performance trends. At the time LR1132 (1) was produced, the extrapolations were based on the work of Lister (2) who defined the latest intervention point when a strengthening overlay could still be applied by taking advantage of the remaining strength of the pavement to provide a further 20 years of life. At the time this intervention point was known as the onset of the critical condition and it was associated with rutting in the wheel path of 10 mm or the occurrence of cracking in the wheel path. Although these criteria were based on extensive comparisons between the surface condition and the structural integrity of relatively thin, lightly-trafficked constructions built predominately in the 1950s and 60s, they were assumed to be valid for the full range of pavement construction. Lister (2,3) demonstrated that roads gradually weakened with cumulative traffic and that the remaining life of the road, to the onset of the critical condition, which could be determined from knowledge of the cumulative traffic the road had carried and by measurement of the deflection of the pavement under a standard wheel load. If this
condition was exceeded, pavement deterioration was expected to accelerate in an unpredictable manner.

The development of the rut depth under traffic loading of the TRL experimental pavements was monitored annually and this information was extrapolated to determine the amount of traffic required to produce a 10 mm rut depth.

The predicted pavement lives, used to calibrate the fatigue and structural deformation criteria are illustrated in Figure 1.

![Figure 1: Performance data from TRL experimental pavements (Powell et al, 1984)](image)

The experimental pavements provided no evidence of classical fatigue cracking. When LR1132 was formulated, both the design criteria for structural deformation and fatigue cracking were calibrated using the data shown in this Figure. For the fatigue criterion, this was a conservative stance in which it was deemed that future roads should not be built at a greater risk of fatigue cracking than those built in the past. The level of risk implicit in the trial pavements was unknown and could have been zero.

In the mid-1990s, a major review of UK pavement design and performance was undertaken (4) to obtain feedback on the design methodology for roads that had now carried traffic well in excess of that carried by the experimental pavements. This revealed that the relationship between pavement deflection and life, which was
developed for relatively thin roads in the early 1970s (2, 3), was not valid for thicker modern pavements. More importantly it also showed that:

Ruts that appeared at the surface of pavements, with at least 180 mm of asphalt on a sound foundation, originated in the top 100 mm or so of asphalt (4, 5).

Extensive investigations found no evidence of fatigue cracking in either the experimental pavements or in any other roads investigated (5, 6, 7). The majority, if not all, of the cracks in fully flexible pavements initiated at the surface and propagated downwards.

The above observations were subject to the proviso that roads needed to be well constructed using good materials and construction practice. A sound foundation was considered to be equivalent to 225 mm of unbound granular material on a subgrade with a CBR of 5%. Experience suggests that that premature pavement failure generally result from defects build into the pavement at construction and this may account for much of the apparent observed random nature of pavement performance.

The re-interpretation of the rutting data from the experimental pavements carried out in the review (4) is shown in Figure 2.

![Figure 2: Rut rate as a function of asphalt thickness (after Nunn et al, 1997)](image)

High speed road monitor surveys (8) and measurements from individual schemes (4, 5) demonstrated that the plateau in the rate of rutting for UK pavements thicker than about 180 mm was universally true.

The results presented above suggested that pavement deterioration via a fatigue mechanism is not as serious as the consensus view suggests. Fatigue was not
an issue for thick fully flexible pavements and the evidence indicated that, the limited number of pavements examined with less than 180 mm of asphalt failed by structural deformation. The data also demonstrated that structural deformation was governed by a threshold level of stress in the subgrade.

**FATIGUE AND STRUCTURAL DETERIORATION**

**Fatigue**

Fatigue cracking is considered to occur as a result of the asphalt layers flexing under a wheel load. This flexing induces a high tensile strain at the underside of the base layer. Although this strain is well below the level that would cause failure by a single loading, it is implied from experience of laboratory studies that many load repetitions will result in crack initiation. The crack will then propagate to the surface.

Performance data from the well constructed experimental roads did not provide evidence of a bottom-up fatigue mechanism and the data implied that the road would need to be very thin before traffic induced bottom-up cracking might occur. Figure 3 shows the tensile strain predicted by a 40 kN wheel load at the underside of the 180 mm thickness asphalt resting on 225 mm of granular subbase and a subgrade with a California Bearing Capacity (CBR) of 5% as a function of pavement temperature.

Figure 3 shows that very high tensile strains are induced and that laboratory data together with conventional fatigue theory would suggest that pavements as thin as this would have a relatively short fatigue life, especially at elevated pavement temperatures. The failure to observe fatigue in these pavements suggests that there is a fundamental difference between fatigue phenomenon observed in simple laboratory tests and the complex conditions in roads in service.

Encouraging research from the USA suggests that a threshold condition exists for fatigue (9, 10) and/or that there is a critical state condition below which fatigue damage is healable (11). However, evidence from the performance of UK roads (4) suggests that the threshold condition is much lower than work in the USA suggests.

On the other hand, load associated cracking will be affected by the ageing characteristics of the asphalt. Age hardening will progressively reduce the tolerance of the asphalt to withstand load-induced tensile strains and eventually cracking will occur, especially in thin pavements. It could be conjectured that this is something waiting to happen when the asphalt hardens sufficiently. In thicker pavements (4), it can be shown that any reduction in cracking resistance caused by age hardening is more than offset by the reduction in the load induced tensile strain that results from stiffer asphalt. As a result, age hardening will reduce any risk of bottom up cracking in thick pavements.
Structural Deformation

There is now abundant evidence to support that rutting is confined to the top 100 mm of a well constructed pavement (4, 5, 12, 13). The evidence suggests a threshold condition governs whether or not subgrade deformation occurs. The questions that need to be answered are - What level of protection, in terms of layer thicknesses and material properties, is required to prevent subgrade deformation?, and - How is structural deformation affected by the type and nature of the subgrade?

![Tensile strain induced at the underside a 180 mm thick asphalt pavement layer](image)

**Figure 3: Tensile strain induced at the underside a 180 mm thick asphalt pavement layer**

A NEW APPROACH TO PAVEMENT DESIGN

The above information suggests that the basic building block for a new approach to design would hinge on the identification of a pavement threshold strength which would be the transition point above which structural damage will not accrue or accrue at a very much reduced rate.

The identification of threshold conditions will revolutionise the way that we think about pavement design, construction and maintenance. Potentially pavements could be constructed thinner than they are today, but the quality of the materials and construction will be paramount. More effort will need to be placed on these aspects.
but the potential savings for the environment and the economy will provide the incentive for these changes.

A truer understanding of the pavement’s performance will result in better and less maintenance. There will be less maintenance because roads will be constructed with fewer faults and the condition assessment and maintenance will focus more closely on the defects in the pavement.

The highway research community has been wedded to traditional design concepts for several decades and any change in the status quo will require convincing evidence.

A possible way forward would be to identify threshold conditions for structural deformation and load associated cracking under idealised conditions in Accelerated Pavement Test (APT) facilities. Threshold conditions are likely to be governed by many factors. For example the threshold for structural deformation is likely to be influenced by the type and nature of the subgrade.

The approach to design would be to first establish threshold design thicknesses for well constructed pavements under idealised conditions. These would be the basic pavement design thicknesses that are capable of carrying traffic without structural deformation and fatigue cracking. Pavements constructed to this basic threshold thickness would carry a risk of early failure that could initiate from built-in any defects or unexpected loading or environmental conditions. A pavement constructed to the basic threshold thickness would incur excessive risk. To reduce this risk, some structural redundancy (safety factor) would need to be introduced and the level of structural redundancy would need to be related to the strategic, economic and political importance of the road. This will require developing a methodology to determine relationships between structural redundancy and risk. The increase in safety factor with the importance of the road will result in a progressive increase in pavement thickness above the threshold conditions up to a certain limit.

Risk, although it is a difficult area to deal with, should not be ignored. The following risks may need to be considered:
 Higher than expected traffic growth;
 Allowance for increase in axle load and axle configuration;
 Changes in tyre technology (new generations of wide-base singles);
 Pavement construction and material tolerances;
 Climate change;
 Durability issues.

The traditional design approach may be suitable for lightly trafficked pavements that are below the threshold thickness.

**IMPLICATIONS**

The implications for pavement design and construction will include:
The development of a new design methodology with a basic threshold design and any additional thickness being determined by risk assessment. More emphasis on placement of materials to avoid built-in defects. Quality of construction will be paramount. Redefine the functional roles of the various layers. In addition to other functions, the total thickness of the asphalt layers above the threshold thickness will be for risk mitigation. Improved reliability in pavement design and maintenance based on a truer understanding of the deterioration processes.

For research, the primary thrust would be to identify threshold levels and how the threshold levels change as a function of the various design inputs, such as, soil characteristics, pavement temperature and asphalt properties. Laboratory studies on deterioration mechanisms would need to be refocused. Perhaps the largest impact would be on the design and interpretation of experiments carried out in APT facilities. In APT facilities, pavement deterioration is accelerated by using one or more of the following:

- Applying more loads in a shorter time;
- Reducing the thickness of the structure to accelerate deterioration;
- Increasing the wheel load;
- Applying adverse environmental conditions (for example, increasing the temperature, raising the water table, freeze/thaw effects, etc).

If pavement behaviour is governed by threshold effects, then APT results obtained by accelerating deterioration by reducing the thickness of the test pavement, increasing the wheel load or increasing the temperature are unlikely to relate to the structural performance of full-scale pavements. In taking these measures to accelerate pavement performance it is likely that the performance evaluation is being carried out on a sub-threshold pavement. It would therefore be very difficult, if not impossible, to relate the APT results of a sub-threshold pavement to the in-service behaviour of a full-scale pavement with a construction above the threshold level. It is possible that this is the reason for the difficulties in relating APT data to full-scale pavement trials on the road network. The European Commission COST Action 347 (14) recognised that developing robust transfer functions to relate APT performance to in-service performance was a challenge for research.

An important change will occur on how damage by heavy traffic is perceived. The fourth power damage law and dynamic effects of suspension systems will need to be revised. Higher tyre contact stresses will cause more surface rutting (which can be countered by appropriate mixture design) and higher loads are likely to increase the pavement threshold thickness for that particular load.
CONCLUDING REMARKS

The behaviour of pavement materials under the complex loading conditions experienced in the pavement is extremely complex and this complexity is compounded by material properties changing over time by the environment and traffic loading. This is recognised implicitly by the limited success of researchers, after several decades of endeavour, in developing good mechanistic models for any pavement deterioration mechanism.

The main message of this paper is that we should now stand back from this problem and based on the information we know, ask ourselves the question:

Can we do better and begin to develop a pavement design method that is a truer reflection of how pavements perform?

To do this we must ask ourselves the questions:
What are we certain about?
What do we think we know and do we have the information to substantiate these beliefs?
How can we best use this information to develop a new approach to design?

Performance data from well constructed UK roads suggests that structural rutting will only occur if a threshold condition is exceeded. A similar argument can be put forward about classical fatigue cracking. This form of cracking was not detected in the thinnest TRL experimental pavements. Furthermore, the introduction of the long-life pavement concept has caused views about pavement cracking to shift. Longitudinal cracks in the wheel path, which were once cited as fatigue, are now generally accepted to be the result of a top-down cracking phenomenon. Also the explanation of lack of fatigue in pavements above a certain strength is being attributed in the USA to either a fatigue endurance limit or a critical state condition below which all fatigue damage is healable if this condition is not exceeded. Performance data from in-service roads in the UK suggests that the threshold strain level for fatigue is much higher than indicated by laboratory investigations. This implies that there is a fundamental difference between fatigue phenomenon observed under idealised conditions in simple laboratory tests and the complex conditions in roads in service.

The existence of threshold conditions will have far reaching implications for pavement research, design and maintenance. For example:

Interpretation of pavement performance and design of experiments in accelerating pavement testing facilities will need to be revised. It will not be valid to infer pavement behaviour under realistic in-service conditions from the results of accelerating performance by applying heavier loads, testing thinner structures or testing under adverse environmental conditions.

An important change will occur on how damage by heavy traffic is perceived.
New approaches to pavement design, condition assessment and maintenance will need to be formulated.

Testing pavements under controlled conditions in an accelerated pavement test facility offers the best means of demonstrating threshold levels for pavement deterioration.

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REFERENCES


