The Mechanistic Design and Evaluation of Unsealed & Chip-Sealed Pavements

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Briefing Paper

INTRODUCTION

Pavement Design is a process that has matured from experiential decisions by an engineer, through empirically-based procedures (which, in essence, sought to codify the engineer's experience) to modern analytical methods. The latest manifestation of these is the (US) AASHTO 2002 procedure which seeks to analytically compute the effects of most of the factors which can affect pavement performance. This procedure will allow design to be done to a level of detail not previously possible in a routinely available design method.

BACKGROUND

Despite its sophistication, the AASHTO 2002 approach shares the same essential features as for any other analytical approach. The features are illustrated, diagrammatically, in Figure 1. Firstly candidate materials must be selected, characterised by laboratory and/or in-situ tests and this characterisation used to compute the values of certain stresses or strains (or, conceivably, other mechanical parameter) at critical points within the pavement. These parameters, together with their locations, have previously been selected as design criteria on the basis of an assessment of the failure mechanisms that must be designed against. The values required for those parameters have been computed on the basis of the level of performance required. The actual and required values of the design criteria may then be compared and the design declared successful or not. If it is not successful an alternative design or alternative materials must be selected or remediation measures applied.

This approach is no different from that employed for any other structural engineering design - for example in a concrete cantilever beam the key design criterion is likely to be the limiting tensile extreme fibre stress which can be tolerated at the root of the cantilever, on its top surface, due to bending moment in the beam. Although the above description and Figure 1 show the design process where a pavement design and materials are found in order to provide a desired level of performance, it is equally possible to use the analytical approach to determine the life of a pavement for which materials and cross-section are already known.

THE NEED

Increasingly, we want to use non-standard (recycled, alternative and marginal) aggregates to build our low-volume unsealed or chip-sealed pavements and we want to be more efficient in our use of conventional materials. There have been many developments in the last 20 years or so in laboratory testing, computational methods, instrumented trials and full-scale experiments (like CAPTIF) but, to date, we haven't gone beyond empirical or chart-based methods. As a consequence, engineers don't have the flexibility of specific designs for individual roads and materials or the possibility of fairly comparing alternative designs or remediations and of localising the approach to the specific situation.

MECHANISTIC DESIGN

The overall aim of the workshop is to investigate the potential for truly mechanistic design/evaluation of low-volume road pavements. Mechanistic credentials are claimed by many of the available design methods (e.g. ARRB) but I contend that, while analysis has often been done to interpolate and extend the design approach, truly mechanistic methods (as laid out in Figure 1) do not exist for low-volume pavements.

Neither do I mean by the phrase “Mechanistic Design” merely that a numerical analysis is performed. A numerical computation is a tool which can be used or mis-used depending on the model of the pavement and of the component materials which make up the pavement. However, if a truly mechanistic method is to be used then a computational procedure, probably involving some numerical technique, would seem inevitable. Charts may be able to codify computations in some circumstances, but care must be taken that they remain graphical means of performing a computation (like a nomograph) and not a means of hiding empiricism.

For there to be a truly mechanistic approach the designer needs to be using relationships between the loading and the responses of the pavement which describe, in theoretical and numerical terms, rational cause-and-effect linkages. This needs to draw on an engineering description, in stress-strain terms, of the materials from which the pavement is to be constructed. It is unlikely that, in the immediate future, it will be possible to achieve this goal without various adjustment factors (“fudges” !) because we won’t understand all the conditions which contribute to the exact scaling of the relationships.

PROBLEMS TO OVERCOME

It will be evident from Figure 1 that the problems to be overcome in bringing together a truly mechanistic design / evaluation method for low-volume pavements are in four areas:

1) FAILURE - We need to know the myriad ways in which low-volume pavements could conceivably fail and then to identify a key mechanical measure for each (often a stress or a strain at some point in the pavement) which will act as an indication of the performance being achieved.
2) DESIGN CRITERIA - Each key mechanical measure has to be computable and its limiting value determined as that which relates directly to the minimum acceptable standard of pavement performance with which it is associated.
3) MATERIAL CHARACTERISATION - The validity of the computational technique rests, to a large extent, on the veracity of the constituent materials’ stress-strain relationships. This means that our measurement techniques need to be accurate and that we need to evaluate the correct parameters.
4) EXTERNAL INFLUENCES - Most low-volume pavement materials change their response to a greater or lesser extent when the load level, the moisture content, the temperature or the speed of loading change. Non-linearity with applied stress (or with ambient stress) is now generally incorporated into the more advanced material descriptions.
5) COMPUTATIONAL ANALYSIS - A computational technique which reproduces the in-situ stress-strain field is needed.

Each of these is now considered.

FAILURE

Before failure mechanisms can be discussed, it is necessary to define ‘failure’. Ultimate rupture/dislocation is rarely an issue, instead failure is usually defined as an unacceptable decrease in service provision to the pavement user. Sometimes a pavement’s integrity may also be an issue because failure of its integrity would lead to rapid decrease in serviceability or to unacceptable costs to reinstate.

FAILURE MECHANISMS

OVERVIEW

Bearing in mind these comments structural failure modes for low-volume pavements can be grouped as follows:

a) Rutting

This may be in the aggregate, the subgrade or in both and may be due to compaction and/or shear deformation. In Table 1, which will be discussed soon, these form Mechanisms 2-6.

b) Excessive Resilience

Too great resilience in the pavement (see Mechanisms 1, 6 and 7) can lead to

i. fuel inefficiency,
ii. failure of other pavement layers which attract greater stress to themselves than would otherwise have been the case,
iii. pumping of fines, and
iv. difficulty in constructing higher layers.

c) Disruption

Localised movements can disrupt the pavement's serviceability and, if significant, even its integrity. These form Mechanisms 8-12 in Table 1. For sealed pavements, disruption of the surfacing is a particular problem (see Mechanisms 17 - 19).

d) Inadequate strength

Conceivably, a load could be applied to the pavement which exceeds the static strength of the system (e.g. like a geotechnical bearing capacity failure (punching)). However, this is seldom an issue in practice as failure due to one of the other mechanisms listed will almost inevitably have occurred first. For this reason these are not considered further.

Non-structural mechanical failure modes include all those which affect the loss of texture and surface wear. These are listed in Table 1 as Mechanisms 13-16 and 20-23 (shown shaded), but are not discussed further in this paper. However, the loosening of stones from the surface and their sideways displacement (Mechanism 14 - "Gravel Loss") can not be set aside so easily as it may be a major cause of rutting. However no fundamental model for this loss is in use and it must, therefore, be marked as 'requiring attention'.

DETAILS

Table 1 lists all of the failure mechanisms which have been identified. Some are climate or user-specific, others are general to all pavements. The 'Description' column seeks to group all the mechanisms under the headings of Resilience, Rutting, Roughness, Wear and Skid Resistance. The position of the number in Column 1 indicates each individual mechanism. The next two columns in the Table discuss the means by which:

a) the properties of the pavement's materials may be assessed at the design stage and, thus, the relevant pavement property assessed,

b) in-situ measurements of the relevant pavement property may be achieved (either as a quality control assessment or as a condition evaluation).

DESIGN CRITERIA

The column headed 'Design Criterion' seeks to identify the mechanical measure, and its position, which can / could be used as a means of quantifying the performance of the pavement in respect of the mechanism being considered. The penultimate column attempts to define the manner in which the value of the design criterion may be established. Sometimes it is relatively simple to define what measure is required as a criterion, but much more difficult to establish what is an appropriate value to set as a limit for design or evaluation purposes. In part this is because there has been little research to build up a body of evidence on the values that can be linked with failure. In principle, this should be obtained in the laboratory, but, in practice, there are many uncertainties surrounding the replication of the site conditions in the laboratory, so that we expect there to be some scaling factor, in many cases, between the limit conditions determined in the laboratory and those operative in the field.

Finally, the last column gives some notes of the problems and uncertainties that remain in implementing the mechanistic approach for the mechanism.

MATERIAL CHARACTERISATION

Returning to Figure 1, it will be seen that material evaluation is another important strand of any mechanistic design approach. This area is possibly the one most well covered by research. Mechanical characterisation, especially by the repeated load triaxial test, of a wide range of materials in a wide range of conditions has allowed the relevant properties of materials to be evaluated and to be incorporated into appropriate material models.

However, there are still many unknowns. For example, the effect of the rotating stress field caused by rolling wheels isn't well understood, though it is implicated as a major affect on the development of ruts. Even less is known about the means by which fines are liberated from a cohesive soil and the factors controlling their movement through the pores of an aggregate. Thus pumping cannot, at present, be linked to relevant material properties in a very causal manner. Some of these remaining deficiencies in understanding are listed in the last column of Table 1.

Even when an accepted test procedure is available, it is not a simple matter to obtain the correct value of the critical stresses, critical strains, moduli and susceptibility to permanent deformation, etc. from laboratory tests. To obtain the correct values would necessitate that we test the materials in the laboratory at the conditions of confining stress(es), moisture, loading time, etc. that pertain in the field. As the in-situ conditions vary from place to place, from time to time and from depth to depth, and because we may not be able to provide exactly replicate conditions in the laboratory, normally it is necessary to establish the way in which the property varies with variations in condition, then the relevant values may be deduced. Because there will be many adjustments to be made due to the application of each condition (and because of ignorance) the use of an overall adjustment factor (which is not explicitly defended) may be employed. This then becomes (in effect) a “fudge” factor.

COMPUTATIONAL ISSUES

MODEL

The third major element of a mechanistic design or evaluation is the computational model. There is no doubt that our ability to perform advanced non-linear computations has increased markedly in recent years. Nevertheless, the newer computational tools are seldom equipped with the material models required. The computationally simpler models may limit the modes of failure - or introduce artificial ones (artefacts). For example, they may compute tensile stresses in an aggregate or soil layer which are not credible in-situ. Or they may be designed with particular failure modes in view which, in practice are of little interest.

The computationally more advanced models (e.g. Finite Element Methods) are, however, not without their own problems. Apart from the issues of their need to incorporate appropriate material models, the also may not be discretised to the detail required in critical areas. For, example, cracking response in chip-seals may be almost impossible to replicate.

CONDITIONS FOR ANALYSIS

Then the choice of the appropriate material condition must be considered. Given that the materials which comprise the pavement are often very sensitive with respect to moisture and or temperature, the analysis must be performed at the ‘correct’ value of theses conditions. As the condition will almost certainly change during the life of the pavement this is no simple matter and computations may be required at different conditions.

DAMAGE ACCUMULATION

This raises a further issue which has hardly been researched at all - damage accumulation and load equivalency. Damage to a pavement is built up incrementally under each trafficking pulse, but the non-linearity of the stress-strain behaviour of the component materials in most layers of a low-volume pavement suggests that calculation of accumulating damage due to spectra of different load levels, differing temperatures and differing moisture conditions will not be straight-forward.

LOAD EQUIVALENCY

Equivalency between traffic load level and number of passages of an axle loaded at a standard level is commonly expressed by the 'fourth power law'. Several researchers have observed that this 'law' doesn't hold for low-volume roads reflecting either that damage doesn't follow such an equivalency pattern and/or that the power term is not 4 for these pavements. An appendix to these notes shows how equivalency should be formulated if pavement damage follows the form of some common types of material response models. It will be seen that the equivalency is not independent of the non-linearity of response of the material and varies over the life of the loading.

ENVIRONMENTAL LOADING

Finally, the loading by the environment should not be ignored. Frost-heave and soil swelling are mentioned in Table 1 as specific distress modes caused by temperature and moisture respectively (Mechanisms 11 and 12). To these mechanisms should be added cracking of a seal coat due to tension induced by temperature effects, perhaps exacerbated by bitumen embrittlement due to uV aging and/or oxidation. These mechanisms need a separate analytical approach.

A PRACTICAL APPROACH

Reviewing Table 1 in the light of the foregoing, it seems that a reasonable approach is available for overall pavement resilience and pavement rutting (Mechanisms 1, 2 and 4). Mechanisms 3, 7, 8, 9, 11 and 12 can be avoided by simple strategies (given in Table 1). The remaining mechanisms listed concern rutting (5 and 6), corrugations (10) and the seal (17, 18 and 19) and need addressing.

Although a reasonable approach is available for Mechanisms 1, 2 and 4, the computational requirements and the conditions at which analyses should be performed are less certain. For a sealed pavement the moisture conditions are likely to be in some kind of dynamic equilibrium with the surroundings, so could be estimated from suction tests and ground water table information. Such research as there is on this topic is rather incomplete. But our knowledge of in-situ moisture conditions is likely to improve as the results of current and recent in-situ studies are disseminated. However, the complexities increase markedly for an unsealed pavement where evaporation, generating high suctions, and rainfall events, cancelling the suction, must be allowed for. It is not practical to perform any computational assessment of the consequences of this, so empiricism will, doubtless, continue to control our assessments in this application.

Regarding computation for Mechanisms 1, 2 and 4, it is highly desirable that non-linear stiffnesses be modelled and a resilient analysis performed. Thus a linear computational method, like ELSYM or CIRCLY, may provide a basic assessment technique, but a non-linear model like NON-CIRL or a FE method like ABAQUS is preferred.

For Mechanisms 5 and 6 (rutting as a consequence of interactions with the underlying layer) our appreciation of the mechanisms is so incomplete that mechanistic analysis of them is practically impossible. It seems that the interplay of the resilient and plastic strains in both the aggregate and in the subgrade changes the stress field in the system to such an extent that permanent deformation either can, or can't, take place in a manner that might have been expected. Without a clearer understanding of the mechanism, little is possible here. It is hoped that, by meeting the requirements to prevent in-layer rutting (Mechanisms 2 and 4), these more complex ones will automatically be addressed - although this cannot be certain.

Corrugations and gravel loss, similarly, resist simple analysis (Mechanisms 10 & 12).

Current approaches for the performance of the seal (Mechanisms 17, 18 and 19) appear to be the use of established mixes which experience shows are adequate. Again, a full understanding of the modes of failure is not available so experience may be the only way forward, at present.

CONCLUSIONS

This paper has sought to outline the means by which low-volume road pavements can fail, the means by which we may analyse them so as to assess the likelihood of failure and the knowledge of the condition of the pavement which is required for this to be successful. It has indicated that some of the more complex rutting mechanisms, corrugations and seal cracking are all resistant to current analysis. Also, failure propensity, in whatever manner, is usually sensitive to moisture and (perhaps) other environmental factors - factors which cannot be well described.

THE WORKSHOP

The overall aim of the workshop is to investigate the potential for truly mechanistic methods of analysis to be applied to the design and evaluation of low-volume road pavements. My hope is that we will be able to discuss in more detail the items discussed in the preceding pages so that we can go away having

1) agreed a basic framework for linking an engineering understanding of aggregate and soil layers to a mechanistic explanation of the pavement as a basis for design and for pavement evaluation,
2) defined the issues which need to be solved in order for such a fundamental and scientific understanding of the pavement to be implementable in day-to-day practice, and
3) laid out pointers as to how solutions to these might be achieved.

Such an approach would, eventually, allow performance-design not just performance-related design (just as the strength of steel and concrete are used as direct inputs to the analysis of a bridge deck). Ideally we'd like to take measures of soil and aggregate strength and stiffness, from laboratory or field testing, using them to calculate stresses and strains in the pavement and so predicting whether failure/distress will occur.

It would be a bonus if we could also extend this approach to chip-seals, too.

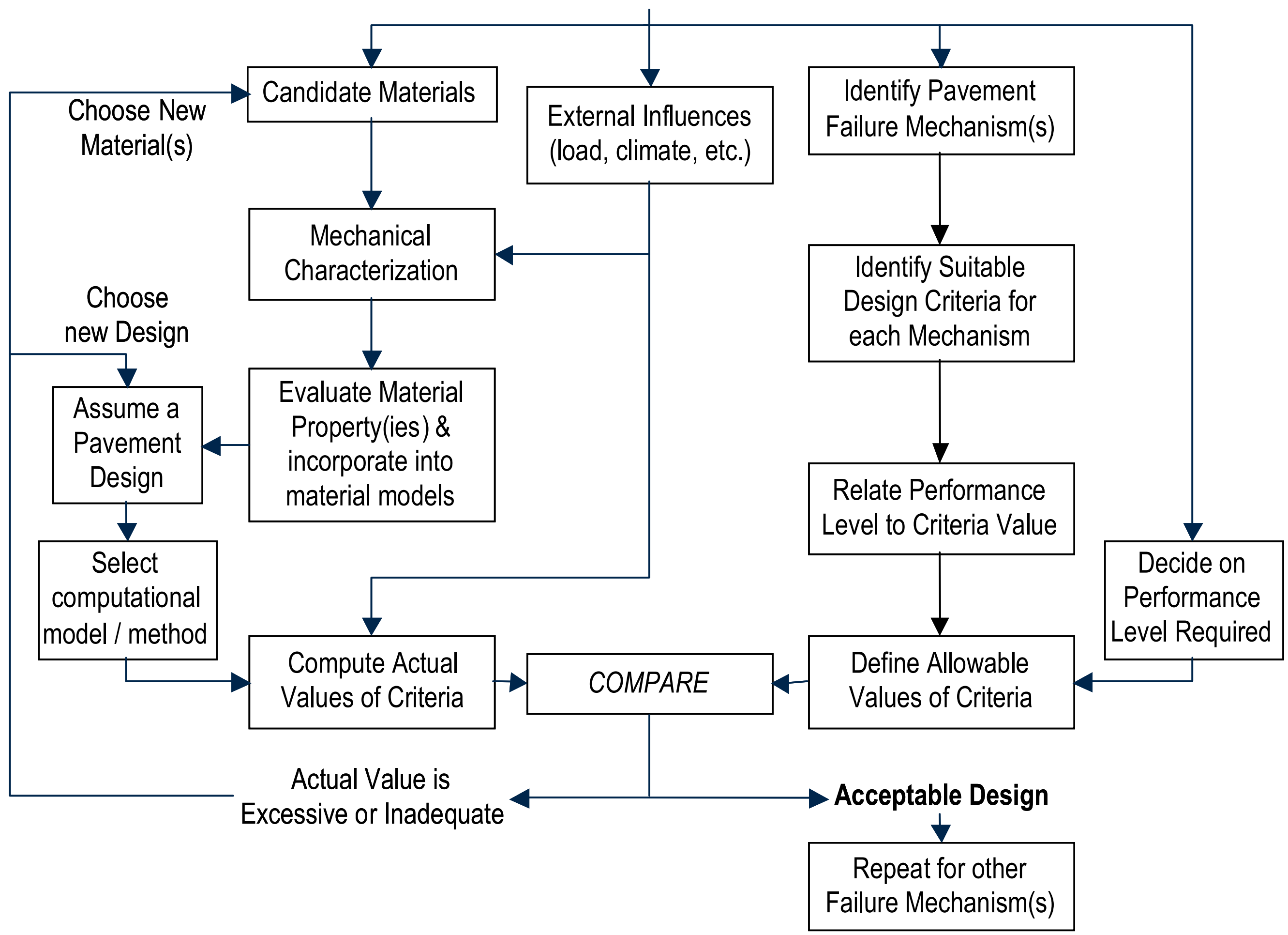

Figure 1 Procedural Flow Chart for Analytical Pavement Design

Table 1 Failure Mechanisms in Thinly Surfaced and Unsealed Pavements (page 1)

No	Description	Measuring Relevant Properties a priori	Measuring Property in-situ†	Design Criterion	Setting Appropriate Criterion Value	Problems & Uncertainties
1	*Excess resilience of pavement* (see also Mechanisms 6 and 7) causes excess fuel consumption & tyre wear; also makes compaction of subsequent layers difficult during construction. ♦ due to soft granular material ♦ inherently ♦ as a consequence of pumping of subgrade into base course (see Mechanism 7) ♦ due to soft subgrade ♦ **due to combination of subgrade & granular material resilience** individually the layers may be satisfactory, but not in combination. Although the layers individually, or in combination, may cause the problem and any solution must be applied to a layer, it's the surface response which causes the problem and where the criterion must be defined. So this is treated as only one failure mechanism.	Granular materials and subgrade soils may be tested for resilient modulus in the lab in (for example) the repeated load triaxial apparatus. To predict surface deflection, these values need to be put into a resilient pavement analysis (layered elastic (LE) or Finite Element (FE)). For softening of granular layers, see Mechanism 7	FWD or other plate test	Surface **deflection** OR Surface deflection **curvature**	Based on fuel efficiency requirements (e.g. 5% fuel efficiency loss = 1mm deflection - Jamieson study, OPUS, NZ)	Uncertain about criterion which is best. Performance depends on resilient modulus of layers which are v. sensitive to moisture and load level
2	*Excess rutting* causes excess fuel consumption, tyre wear, loss of steering, water collection on subgrade leading to softening, water collection on surface leading to trafficking difficulties (e.g. spray / aqua-planing). ♦ from within granular layer ♦ **due to granular material shear**	Use layered elastic or FE analyses with resilient data as Mech. 1 to compute stresses. We have to assume stress conditions in-situ to obtain answer	Only possible once rut has appeared	Repeated load triaxial tests thence determining **shakedown stress limit** value.	Stress chosen to keep permanent deformation development in stabilising (non-accumulating) zone of behaviour.	a) Need a predictive tool for in-situ assessment. DCP is a v. indirect method. b) Computed stresses sensitive to assumptions of at-rest stress state.
3	♦ **due to compaction by traffic loading**	Avoid by proper compaction	In-situ density tests	% of **Max. d.d.**	Empirical or % of solid density	Not many
4	♦ from within subgrade layer ♦ **due to subgrade shear**	As Mechanism 2.	Only possible once rut has appeared	Repeated load triaxial tests thence determining **shakedown stress limit** value or q/s_u ratio at top of subgrade.	Stress chosen to keep permanent deformation development in stabilising ('Shaken-down") or slowly accumulating zone of behaviour. e.g. $q/s_u<(1+\pi/2)$	a) Need a predictive tool for in-situ assessment. DCP is a v. indirect method. b) Computed stresses sensitive to assumptions of at-rest stress state.

Table 1 Failure Mechanisms in Thinly Surfaced and Unsealed Pavements (page 2)

No	Description	Measuring Relevant Properties a priori	Measuring Property in-situ†	Design Criterion	Setting Appropriate Criterion Value	Problems & Uncertainties
5	♦ combined action of subgrade and granular layer(s) ♦ **due to** complex **stress interaction** effects ○ ***when subgrade is entirely resilient*** *in behaviour, even weak aggregates may give acceptable base courses with respect to rutting*	Need resilient properties of subgrade and granular layers e.g. by repeated load triaxial tests. Then need FE or LE resilient analysis to estimate in-situ stresses. Granular layer permanent deformation information (as in 2 above) as a function of stress system then needed.	Subgrade resilience by FWD. Granular response would need exhumation	?? max q/p in granular layer (c.f. threshold value?) ? Also need to ensure threshold not reached in subgrade	As Mechanisms 2 & 4	Mechanism very poorly understood, so approach in some doubt and analysis, criteria and tests may be inappropriate.
6	○ ***when subgrade is too resilient*** *in behaviour, overlying base courses may suffer rutting due to excessive flexure.*	Need resilient properties of subgrade and granular layers e.g. by repeated load triaxial tests, then need FE or LE resilient analysis. Not known what is needed to assess granular response to flexure.	FWD to give resilient properties. Unknown what would assess flexure response of granular material.	Minimum subgrade stiffness (simplistic as it doesn't allow for granular layer thickness / properties)	Not known	Mechanism very poorly understood, so approach in considerable doubt. Analysis, criteria and tests may be inappro-priate. Would need information on susceptibility of granular materials to flexure.
7	♦ **locally causing pumping of subgrade into base course** and thus, indirectly, causing rutting. As this affects pavement integrity and cannot be remedied without complete excavation, it is considered important to avoid.	Plasticity testing and grain size analysis to define susceptibility of subgrade. Could perform repeated load triaxial tests at different contamination levels.	Impossible	Empirical guidelines on suscept-ibility	None. Use an appropriate geosynthetic to remove problem.	Hardly any work done on analysing the stress or strain issues which drive this.

Table 1 Failure Mechanisms in Thinly Surfaced and Unsealed Pavements (page 3)

No	*Description*	*Measuring Relevant Properties a priori*	*Measuring Property in-situ†*	*Design Criterion*	*Setting Appropriate Criterion Value*	*Problems & Uncertainties*
8	*Excess longitudinal roughness* causes user discomfort and, in extreme cases, vehicle damage; also liable to be damage-enhancing as loading due to vehicle becomes more uneven as vehicle moves along pavement (due to bouncing). ♦ **uneven-ness** probably due to uneven rutting	Impossible	Roughness meter or similar	IRI value	Depends on user desirability	Very indirectly related to structural properties. Try to avoid by limiting rutting (Mechanisms 2-6 above).
9	♦ **potholing** probably due to vehicle bounce over irregularities on pavement	Impossible?	Roughness measure or semi-objective counting method	IRI or maximum count value	Depends on user desirability	Very indirectly related to structural properties. Try to avoid by limiting rutting (Mechanisms 2-6 above) and by choice of grain size distribution/plasticity of base which resists their formation
10	♦ **corrugations** caused by vehicle suspension effects ("wheel-hop"). May be exacerbated by 'snatching' on corners.	Impossible	Roughness meter or similar	IRI value	Depends on user desirability	Very indirectly related to structural properties. Try to avoid by choice of grain size distribution/ plasticity of base which resists their formation
11	♦ heave / shrinkage ♦ **due to frost action on susceptible subgrades or granular materials**	Frost heave tests in laboratory	Surface observations	Limit on laboratory heave value to remove or limit problem	Unavoidable in subgrade, so include frost break or thick (insulating) aggregate blanket. In aggregate, typically set very small value (e.g. <12mm) in low-frost areas where economic to avoid; otherwise select a value based on experience of acceptable heave.	Absence of good heat flow and icing models prevents laboratory and in-situ response being causally linked. N.B. Design thickness of thick blankets in high frost areas will not be on the basis of structural performance.

Table 1 Failure Mechanisms in Thinly Surfaced and Unsealed Pavements (page 4)

No	Description	Measuring Relevant Properties a priori	Measuring Property in-situ†	Design Criterion	Setting Appropriate Criterion Value	Problems & Uncertainties
12	♦ **due to moisture-sensitive volume change of subgrade or granular materials**	Soil swell tests in laboratory	Surface observations	Limit on laboratory expansive-ness test (ASTM D-4829 / 4546 or Pot. vol. change test (Lambe))	Unavoidable in subgrade, so include moisture barriers or treat soil to remove problem. Construction materials are limited to non-swell materials	Absence of good moisture diffusion/flow models prevents laboratory and in-situ response being causally linked
13	*Surface wear* may cause impermeable surface to be lost or compromised, thereby letting in water which will cause failure of other layers as effective stress is reduced; also causes roughness as wear is seldom even along pavement. ♦ **dust loss** loses material and generates a health or amenity hazard	Plasticity testing, grain size analysis and moisture content of surfacing measured	Measure dust emitted by visual or collection methods	Visual opacity and/or health limits	User requirements (may vary depending on speed of road)	Poor understanding of connection between dust generated and material properties which would control it (? I think)
14	♦ stone displacement ('**gravel loss**') loses coarse material or displaces material to margins	Plasticity testing, grain size analysis and moisture content of surfacing measured	Only possible after loss by brush collection	Slow rate of loss	Based on regrading/ regravelling maintenance costs which will be prevented	Poor understanding of connection between stone loss and material properties which would control it (? I think)
15	♦ stone abrasion / attrition ♦ **due to tyre action** This relates to stone breakage and wear on unsealed roads. Not to be confused with polishing (see Mechanism 20 below).	Stone hardness, grain size analysis, durability testing	?	Slow rate of loss	Based on regrading/ regravelling maintenance costs which will be prevented	Empirical data relates stone characteristics to frictional properties, not to wearing away of stone
16	♦ **due to studded tyre action**	Stone hardness, Nordic Ball Mill assessment	?	Slow rate of loss	Based on regrading/ regravelling maintenance costs which will be prevented	? I'm unfamiliar with this
17	♦ seal breakage ♦ **due to traffic-induced flexure**	?	measure cracks once formed	crack length per m^2.	no cracks is ideal but this is impractical	How is damage related to loading?
18	♦ **due to environmentally-induced shrinkage**	?	measure cracks once formed	crack length per m^2.	no cracks is ideal but this is impractical	How is damage related to loading?

Table 1 Failure Mechanisms in Thinly Surfaced and Unsealed Pavements (page 5)

No	Description	Measuring Relevant Properties a priori	Measuring Property in-situ†	Design Criterion	Setting Appropriate Criterion Value	Problems & Uncertainties
19	♦ **due to shoving / tearing / shearing**	?	Observation post failure?	?	?	Aim is usually to avoid altogether. Relationship between loading and failure not quantified
20	*Inadequate Surface condition* causes poor skid-resistance in dry and/or wet weather ♦ sealed surface too smooth ♦ **due to aggregate texture loss**	Stone hardness, PSV	Only possible on sealed road after damage. Use SCRIM, braked wheel, etc.	sideways force coefficient (e.g.)	Based on desirable behaviour of vehicles in skid tests	Relationship between stone characteristics and pavement performance empirically understood but not fundamentally.
21	♦ **due to excess bitumen rising to surface**	Air voids in asphalt mix, ?? for chip seals	Air voids in cores for asphalt mixes. ?? for chip seals	?	?	Approach is to avoid in asphalt mixes which seems a reasonable approach. Voids can't be measured in chip seals so estimation inevitable.
22	♦ unsealed surface too slippery ♦ **due to excess fines on surface** (wet weather)	Plasticity testing and grain size analysis of surfacing measured	? impossible?	?	?	Many! General approach is to try to avoid entirely, but low plasticity/low fines requirement conflicts with needs to avoid Mechanisms 13, 14 & 23
23	♦ **due to loose gravel on surface**	See Mechanism 14	Brush collection of loose stones	Low occurence	?	Relationship between degree of skidding and amount of loose stones not well understood (? I think)

Notes to Table 1
† Measured in the pavement post-construction for quality assurance purposes or in-service to assess need for remediation and/or cause of failure.

APPENDIX

POWER LAW EQUIVALENCY

A power law damage equivalency approach, such as that used in the "4th Power Law", says that damage due to a certain number of loadings at a high magnitude is equivalent to a greater number of loadings but at a lower magnitude. This is expressed as:

$$\frac{N_2}{N_1} = \left(\frac{P_1}{P_2}\right)^f \qquad [1$$

where f is the power term (conventionally taking the value of 4), N is the number of loadings applied, P is the magnitude of the load applied and the subscripts 1 and 2 indicate the actual and equivalenced conditions. So, according to Equation 1, damage is proportional to NP^f, i.e. it is linear with number of applications but not with load level. More generally we need an equation of the form:

$$\frac{N_2}{N_1} = E(P_1, P_2) \qquad [2$$

where E( ) indicates the load equivalency function and takes the value of 1 at the reference conditions and decreases as P_2 increases above P_1.

♦ FOR THE LINEAR CASE IN N

Let us assume that for a certain material or pavement:

$$\varepsilon_{damage} = AN/E() \qquad [3$$

where ε_{damage} = some damage strain, A is the material constant and N is the number of cycles of the applied load. So, initially $N = N_1$ and E( ) = 1, such that:

$$\varepsilon_1 = AN_1 \qquad [4$$

Now increasing the number of load applications to N_2, remaining at load level P_1, gives:

$$\varepsilon_2 = AN_2 = A\,xN_1 \qquad [5$$

where $x = N_2/N_1$.

However, on the basis of Equation 2 the damage would have remained unchanged if, at the same time as the number of cycles of loading is increased from N_1 to N_2, the load level is dropped from P_1 to P_2.

$$\varepsilon_1 = AN_1 = AN_2/E() = AxN_1/E() \qquad [6$$

Thus E( ) = 1/x. Hence damage is defined as follows (Table 1):

Table 1 Damage at two numbers of applications and two loading magnitudes

Axle Load	Number of Load Applications Original = N_1	New (increased) = N_2
Original = P_1	$\varepsilon_1 = A\,N_1$	$\varepsilon_2 = A\,x\,N_1$
New (decreased)= P_2		$\varepsilon_1 = A\,x\,N_1 / E()$

So, by comparing the upper left and bottom right entries in the table:

$$\frac{xN_1}{N_1} = x = E(P_1, P_2) \qquad [7$$

and Equation 1 is a satisfactory solution to Equation 7. Of course, many others could be invented which satisfy the mathematical requirements, but Equation 1 has been generally adopted because it more readiy fits observed performance than other relationships.

Thus Equation 3 may, more generally be written as follows for a value of $N = N_2$ and a corresponding value of load magnitude $P = P_2$:

$$\varepsilon_{damage} = A\left(\frac{P}{P_1}\right)^f \left(\frac{N}{N_1}\right) N_1 \qquad [8$$

♦ FOR THE SIMPLE PARABOLIC CASE IN N

Now let us assume that for a certain material or pavement:

$$\varepsilon_{damage} = An^B / E(\,) \qquad [9$$

where B is a second material constant. Following the same logic as before:

$$\varepsilon_1 = AN_1^B \qquad [10$$

and:

$$\varepsilon_2 = AN_2^B = Ax^B N_1^B \qquad [11$$

If a reduced load is applied (a new value of P_2) in order to ensure that the damage doesn't change, then:

$$\varepsilon_1 = AN_1^B = Ax^B N_1^B / E(\,) \qquad [12$$

so that:

$$x^B = E(P_1, P_2) \qquad [13$$

and Equation 1 is NOT a satisfactory solution to Equation 13. If the form of Equation 1 is to be maintained, it is necessary to take the Bth root of each side, generating an equation of the form:

$$\frac{N_2}{N_1} = \left(\frac{P_1}{P_2}\right)^{\frac{f}{B}} \qquad [14$$

Thus a "power law" equivalency factor is possible, but that the factor is NOT independent of the material parameters. Ideally we would wish that the relationship between load application number and magnitude was independent of material constants, but this cannot be so for non-linear response because damage superposition is not valid.

A simple way of overcoming this limitation would be to replace Equation 9 with a similar but critically different equation:

$$\varepsilon_{damage} = A\left(n / E(\,) \right)^B \qquad [15$$

then a solution as in Equation 1 is possible - i.e. there is now a material-independent equivalency relationship between load and number of applications, but at the price of a somewhat more complex definition of damage. If this formulation is adopted the generalised relationship is:

$$\varepsilon_{damage} = A\left(\frac{P}{P_1}\right)^{fB} \left(\frac{N}{N_1}\right)^B N_1^B \qquad [16$$

on the same basis as Equation 8.

♦ FOR THE LOGARITHMIC CASE IN N

Now let us assume that for a certain material or pavement:

$$\varepsilon_{damage} = {}^{\text{A}\log n}\!\Big/_{\text{E}(\,)} \qquad [17$$

As before:

$$\varepsilon_1 = \text{A}\log \text{N}_1 \qquad [18$$

and by equivalency with a new *N* and *P*:

$$\varepsilon_1 = \frac{\text{A}\log \text{N}_2}{\text{E}(\,)} = \frac{\text{A}\log x\text{N}_1}{\text{E}(\,)} = \frac{\text{A}}{\text{E}(\,)}(\log x + \log \text{N}_1) \qquad [19$$

so that, comparing Equations 18 and 19:

$$\text{E}(\,).\log \text{N}_1 = \log x + \log \text{N}_1 \qquad [20$$

Hence:

$$x = \frac{\text{N}_2}{\text{N}_1} = \text{N}_1^{\,\text{E}(\text{P}_1,\text{P}_2)-1} \qquad [21$$

Note that there is no way that a power law relationship between *P* and *N* can be established as N_1 appears on both sides. Equations which would give relationships somewhat similar to Equation 1 are:

$$x = \frac{\text{N}_2}{\text{N}_1} = \text{N}_1^{\,(\text{P}_1/\text{P}_2)^f-1} \quad \text{or} \quad x = \frac{\text{N}_2}{\text{N}_1} = \text{N}_1^{\,f((\text{P}_1/\text{P}_2)-1)} \qquad [22$$

Figure 1 shows these relationships plotted against Equation 1 for $N_1 = 1000$ load applications and f chosen as 4 for Equation 1 and as the value needed for Equations 22a and 22b to ensure that all the relationships evaluate identically at P_2=60kN.

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If the formulation of Equation 22a is adopted for equivalency, the generalised relationship is:

$$\varepsilon_{damage} = \text{A}\log\left[\frac{1}{\text{N}_1^{\,(\text{P}_1/\text{P}_2)^f-1}}.\frac{N}{\text{N}_1}.\text{N}_1\right] = \text{A}\left[\log \text{N}_1^{\,2-(\text{P}_1/P)^f} + \log\frac{N}{\text{N}_1}\right] \qquad [23$$

on the same basis as Equations 8 and 16. A similar equation may be developed for Equation 22b:

$$\varepsilon_{damage} = \text{A}\left[\log \text{N}_1^{\,f+1+f(\text{P}_1/P)} + \log\frac{N}{\text{N}_1}\right] \qquad [24$$

♦ FOR THE ASSYMPTOTIC CASE IN N

Now let us assume that for a certain material or pavement:

$$\varepsilon_{damage} = \frac{\text{A}}{\text{E}(\,)}\left(1 - \text{B}^{-\text{C}n}\right) \qquad [25$$

As before:

$$\varepsilon_1 = \text{A}\left(1 - \text{B}^{-\text{CN}_1}\right) = \frac{\text{A}}{\text{E}(\,)}\left(1 - \text{B}^{-\text{C}x\text{N}_1}\right) \qquad [26$$

thus:

$$\text{B}^{-\text{CxN}_1} = \text{E}(\,)\text{B}^{-\text{CN}_1} - \text{E}(\,) + 1 \qquad [27$$

Hence:

$$-\text{CxN}_1\log \text{B} = \log\left(\text{E}(\,)\text{B}^{-\text{CN}_1} - \text{E}(\,) + 1\right) \qquad [28$$

And

$$x = \frac{N_2}{N_1} = \frac{-\log\left(E(\,)B^{-CN_1} - E(\,) + 1\right)}{CN_1 \log B} \qquad [29$$

So that:

$$\varepsilon_{damage} = A \frac{-C\left(N/N_1\right) N_1^{\,2} \log B}{\log\left(E(P,P_1)B^{-CN_1} - E(P,P_1) + 1\right)} \qquad [30$$

Note that the form of x now depends on B, C and N_1 (see Equation 29). If certain combinations of C and B are used (those which dictate a long time until the assymptotic condition is reached) the E( ) can be selected to be as in the right hand side of Equation 1 with f=4 when it will deliver the same equivalency as Equation 1. However, with values of C and B which dictate a more rapid approach to the assymptote, no simple relationship of the form $(P/P_1)^f$ can be made to replicate, even approximately, the shape of the earlier functions plotted in Figure 1. Indeed, typically it is found that a small increase in axle load at a low load is equivalent to a much larger change in number of load applications than if the same increase in loading were to be applied at a higher load condition (see Figure A1)

In each of the above cases we would, ideally, wish that the relationship between load application number and magnitude was independent of material constants, but this cannot be so for non-linear response because damage superposition is not valid.

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