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Field Observations of Rutting and Their Practical Implications

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Observation of a series of full-scale road experiments in the United Kingdom indicates that, after an initial period of deformation, reflecting compaction, and moisture changes, permanent deformation and rutting can be related to ranges of cumulative equivalent standard axles of 82 kN (18 000 lb). Cracking of structural significance seldom occurs until ruts have developed to a depth of 10 mm (0.4 in). After the cracking occurs, deformation behavior is more difficult to predict; continuity of the relation of the cumulative equivalent standard axles is most likely on stronger pavements. The marked influence of temperature and subgrade strength on deformation is demonstrated by results from the AASHO Road Test in the United States and from road experiments in the United Kingdom. Essentially similar behavior was observed in both countries, and differences can be related to differences in climatic conditions. Accelerated pilot-scale testing under controlled conditions of wheel load and temperature in a circular road machine has quantified the contributions of these two factors to deformation behavior. The link demonstrated between this type of testing and actual road behavior indicates its potential for developing and validating predictive models of deformation behavior.

Road deterioration under the action of traffic takes two main visible forms: cracking of the road surface and deformation in the wheel paths along which the great majority of heavy vehicles pass. The appearance of either form is not necessarily accompanied immediately by the other. Cracking at the pavement surface is normally a fatigue phenomenon originating either in the surface itself or in a cement- or bituminous-bound base beneath. Cracking that originates in the surface is associated with underdesigned pavements having bituminous materials of the asphalt concrete type or thin rolled-asphalt surface layers. Once cracking has become general, rutting will occur because the lower layers of the pavement or the subgrade or both are consequently overstressed and because those elements of the road are weakened by the ingress of water. Prediction of road behavior after general cracking has taken place is difficult, and in many cases the onset of general cracking must be taken as the effective end of the life of the road without structural maintenance.

Rutting can develop over many years without cracking taking place, particularly if the rutting is associated with a fault in the surfacing laid on an otherwise structurally adequate pavement. When cracks finally occur, they tend to be confined to the wheel path and may or may not accelerate the development of rutting to an unacceptable failure condition.

Deterioration of the riding quality of a road will take place as a consequence of increasing rutting and, to a minor extent, as a direct consequence of cracking. Ultimately the pavement will require strengthening or resurfacing to prevent structural failure, to improve the riding quality, or to eliminate splash and spray resulting from ponding of water in pavement ruts. The development of rutting therefore plays a central role in determining the overall performance of pavements.

DEVELOPMENT OF RUTTING

In the United Kingdom, roads designed to carry moderate to heavy traffic are surfaced with bituminous material at least 75 mm (3 in) thick. The wearing course is of rolled asphalt. Pavement deterioration appears as rutting in the wheel paths and is followed by cracking of the asphalt as the road continues to deform, until, at failure, pavements are generally both cracked and deformed. The onset of critical conditions, which define the optimum time for extending pavement life by overlaying, is normally characterized by moderate rutting and little or no visible cracking. Thus in most British pavements deformation behavior is of prime importance; this is reflected in the present design recommendations for flexible pavements in the United Kingdom (1). The recommendations were developed from systematic observations of the surface behavior of a series of full-scale road experiments (2, 3). In these experiments different combinations of pavement materials were laid in a range of thicknesses on as uniform a subgrade as was practically possible. The performance of the experimental sections under normally mixed traffic was assessed primarily in terms of the development of deformation of the road in the wheel paths (3). The deformation was measured by precise optical leveling. The results are presented in terms of an equivalent rut under a 1.8-m (6-ft) straightedge so that comparisons can be made with results of other studies normally given in terms of rut depth.

Figure 1 shows a typical transverse road profile on the full-scale road experiment at Alconbury Hill (4). The greatest deformation is along the wheel paths of the lane carrying the greatest proportion of heavy vehicles (5). Deformation and rutting develop rapidly in the early life of the road. On roads that do not fail at this stage subsequent deterioration occurs at a slower rate, but progress to final failure is normally accompanied by a rapid increase in the rate of deformation and rutting. A typical history of rutting or deformation is shown in Figure 2. In addition to being influenced by the basic deformation behavior of the road layers, the form of the initial phase is also influenced both by the compacting effect of traffic on granular layers and by the moisture changes in the subgrade after the disturbance of the construction period.

The development of rutting and deformation in those sections of the Alconbury Hill experiment (4) constructed with crushed-slag, wet-mixed bases is shown in Figure 3. In section D, the thinnest, which is grossly underdesigned for the intensity of commercial traffic, the initial phase leads straight to early failure. As thickness increases, the initial deformations and ruts decrease, and the rate of increase thereafter also decreases. In section C the onset of surface cracking (marked by an arrow) is followed by a rapid increase in rutting to failure; however, in section B, which has a thicker base, the development of rutting was unaffected by cracking, and a much longer life resulted. The behavior of section A, the strongest section, was similarly unaffected by cracking. The results are shown on a logarithmic scale in Figure 4. After about 500 000 equivalent standard axles of 82 kN (18 000 lb), the development of both rutting and deformation in the thicker sections can be related to a power index, at least up to the stage at which surface cracking occurs. The index is based on the equivalent standard axles to some power (in this case times 10^6). Data in Figure 5 from three sections of different thicknesses having lean concrete bases show a similar trend for both deformation and rutting. Sections with rolled-asphalt bases, although following the same pattern for rutting, appear to diverge from any simple power index relation when deformation is considered (Figure 6). Because cement-bound bases do not compact under traffic, the initial movement in pavements containing them was, as expected, smaller. The considerable compaction experienced by the sand subbase, equivalent to about 112 kg/m^3 (7 lb/ft^3) during the whole experiment, accounted for the large initial movements; these were about twice as great as observed elsewhere.

The pattern that emerges from the observation of a series of full-scale experiments is this: After the initial period, the deformation and rutting can be related in cumulative traffic by power index values between 0.2 and 0.5, at least up to the point at which surface cracking is evident. Values of 0.4 to 0.5 are most commonly observed; the lowest index values are normally associated with pavements having considerably thick bituminous bases. Cracking seldom occurs until ruts have developed to depths of at least 10 mm (0.4 in). After cracking, the relation is not necessarily predictable; the precracking trend may continue, or rutting and deformation may increase at a much faster rate. The stronger the pavement is the less is the likelihood that surface cracking is associated with the change in the trend.

INFLUENCE OF ENVIRONMENTAL FACTORS

Although the curves indicate systematic development of deformation and rutting, closer examination indicates the strong influence of seasonal factors. The limited accuracy of leveling measurements dictated the installation in the road of deformation gauges to measure those factors (6). Figure 7 shows the strongly seasonal cycle of movement superimposed on the deformation developing in a pavement with a rolled-asphalt base. In this section the bituminous layers and the clay subgrade contribute virtually all the significant measured deformation, and both pavement elements show the same pattern of seasonal movement. Figure 8 shows in greater detail the deformation behavior related to the temperature conditions within bituminous layers during the second year the road carried traffic. The maximum rate of deformation in both layers took place after the onset of high temperatures in the late spring when the water-table level in the subgrade was still high.

Seasonal changes in the strength of the clay subgrade are reflected in the annual cycle of wetting and expanding in winter and drying in summer. These changes are superimposed on an overall increase with time in subgrade deformation, which is also seasonal. The stresses transmitted to the subgrade are sufficient to bring about deformation within it under repeated loading only at high temperatures, when the bituminous pavement is at its weakest. The rate of deformation was highest in late spring and early summer when the subgrade was weak and lowest later in the year as drying occurred.

As expected, the rate of deformation in the bituminous

Figure 1. Typical mean transverse profile at four levels of traffic.

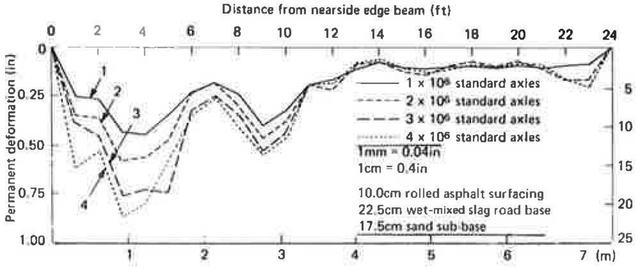


Figure 2. Typical development of rutting.

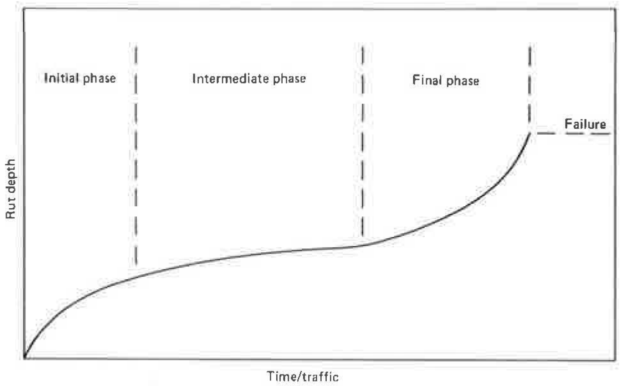
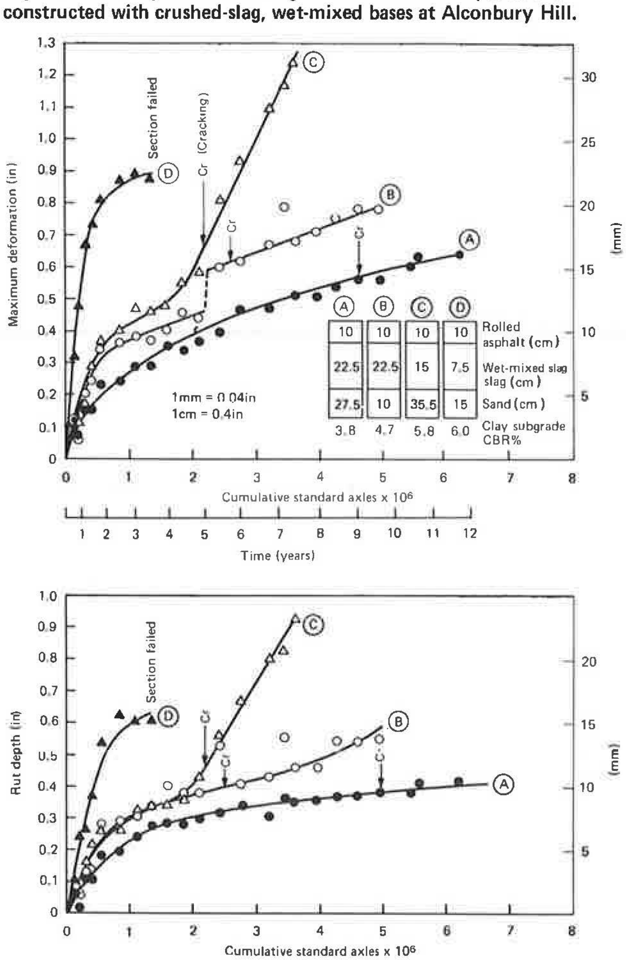


Figure 3. Development of rutting and deformation in pavement constructed with crushed-slag, wet-mixed bases at Alconbury Hill.



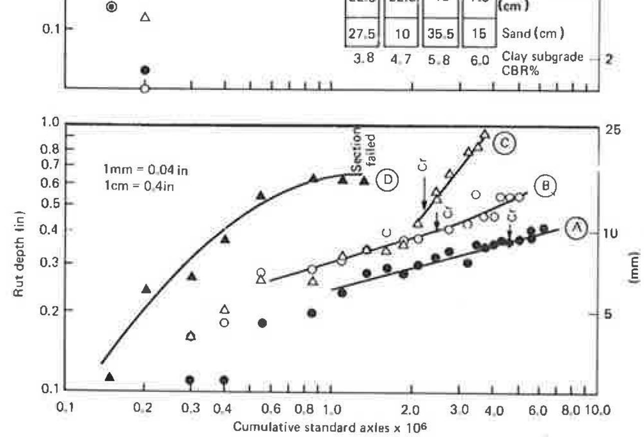
layers was closely related to the high temperatures of the late spring and summer. The apparent recovery from deformation in winter is harder to explain and may possibly be a consequence of the nonuniform distribution of heavy wheel loads across the wheel-path zone. Pavements with crushed-stone bases showed the same pattern of deformation behavior and the same seasonal dependence (7).

Extensive information on rutting behavior in the United States was obtained during the AASHO Road Test (8). Accelerated trafficking tests were made during a 2-year period under climatic conditions that produced frost penetration of the subgrade for periods of about 2 months each winter. These conditions are much more severe than are encountered in the United Kingdom, where frost penetrates below formation level on major roads every 15 years or so. (The effect of one such year is shown in Figures 3, 4, and 5 at about 2.2 million standard axles.)

In the AASHO Road Test the maximum rutting rate in pavements with granular bases occurred during and immediately after the thaw; considerable movement continued through spring and summer. In the United Kingdom, where subgrades are in a relatively stronger condition in the early spring, movement begins only when temperatures rise in the late spring. In the AASHO Road Test pavements with bituminous bases deformed more slowly in the early spring when those layers at low temperatures were stiff enough to protect the greatly weakened road foundation. In the United Kingdom temperature is also the dominant factor for roads with bituminous bases and, as we have seen, the maximum rate of deformation takes place in the late spring and early summer in pavements built with both bituminous and crushed-stone bases.

The rutting behavior of cement-bound bases in the AASHO Road Test is broadly typical of their behavior as observed in the United Kingdom. Rutting is less for a pavement of a given thickness than for other base types; that is, in pavements that have cemented bases

Figure 4. Logarithmic presentation of data shown in Figure 3.



sufficiently thick to remain substantially uncracked, rutting is confined to the bituminous surfacing alone. When the base breaks up, rutting behavior is similar to that of pavements with granular bases.

DEVELOPMENT OF RUTTING UNDER CONTROLLED CONDITIONS

The importance of temperature in determining the development of rutting under traffic load has been demonstrated. Although both size and distribution of wheel loads and temperatures are measured on full-scale road experiments, the damage potential of various wheel loads under different temperature conditions cannot be distinguished. The distinction is being examined in a circular road machine at the Transport and Road Research Laboratory, where we are repeatedly testing experimental pavements with different combinations of wheel loads and surfacing temperatures. Details of the experimental technique used and method of analysis of results obtained are given in another report (7).

Figure 9 shows the development of rutting in a pavement with a crushed-stone base trafficked while mean surfacing temperatures were 25, 35, and 45°C (77, 95, and 113°F); each mean temperature represents testing

Figure 5. Development of rutting and deformation in pavement constructed with lean concrete bases at Alconbury Hill.

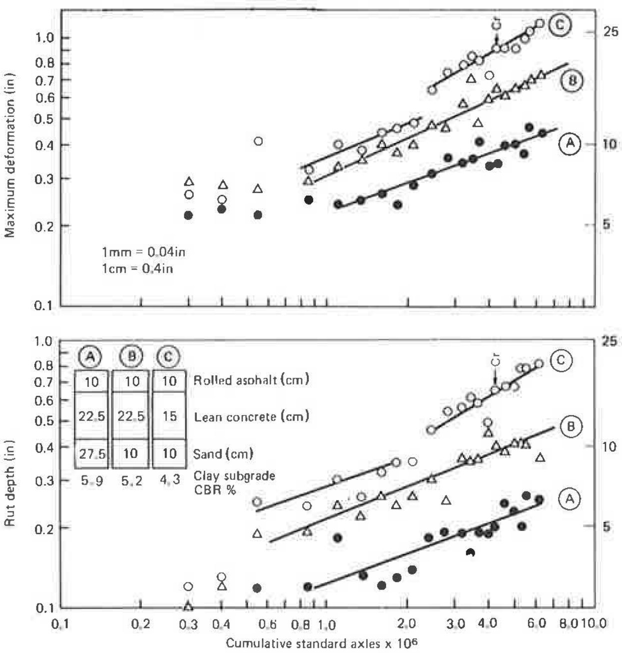


Figure 6. Development of rutting and deformation in pavement constructed with rolled-asphalt bases at Alconbury Hill.

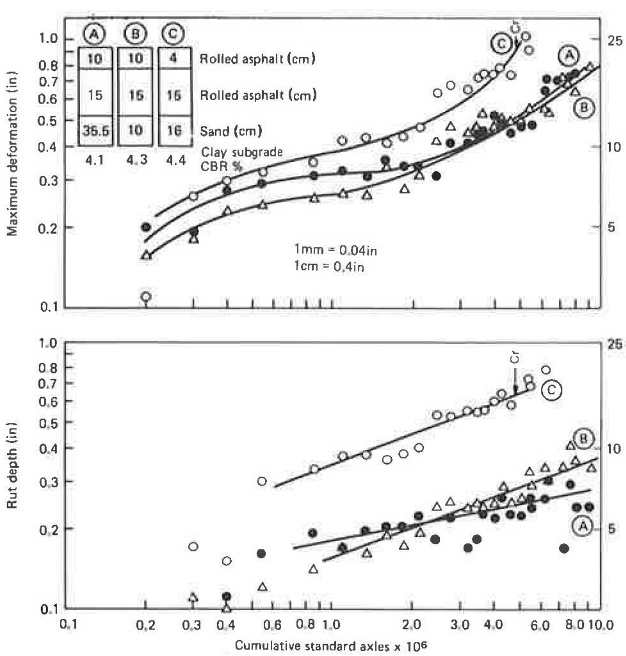


Figure 7. Development of deformation in pavement constructed with rolled-asphalt base at Conington Lodge.

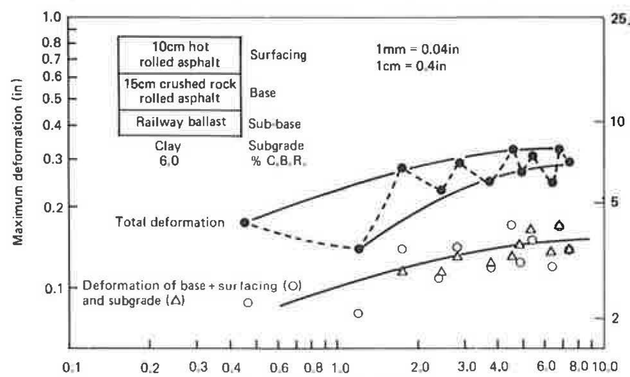


Figure 8. Relation of development of deformation in rolled-asphalt pavement and its subgrade to temperature.

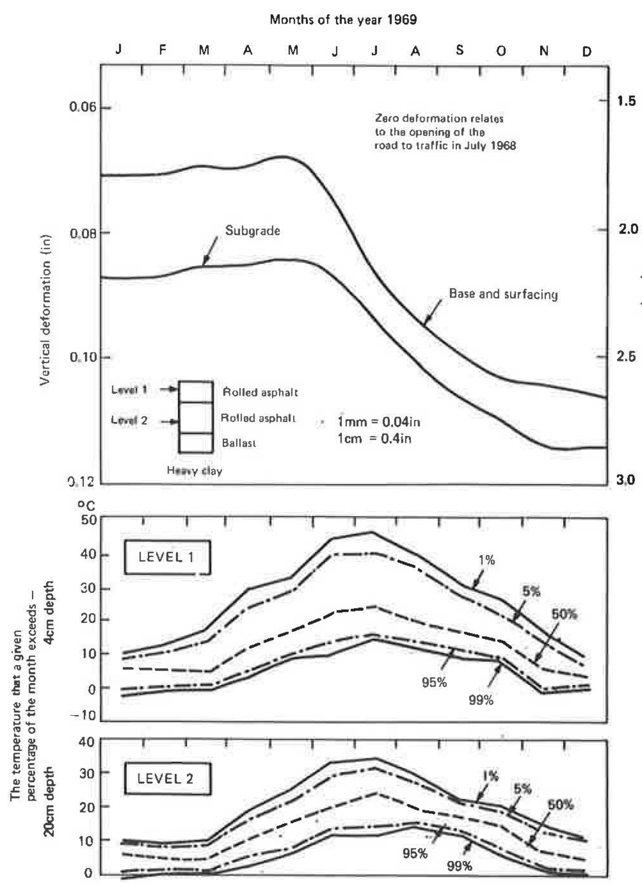


Figure 9. Development of rutting under controlled wheel loads and temperature.

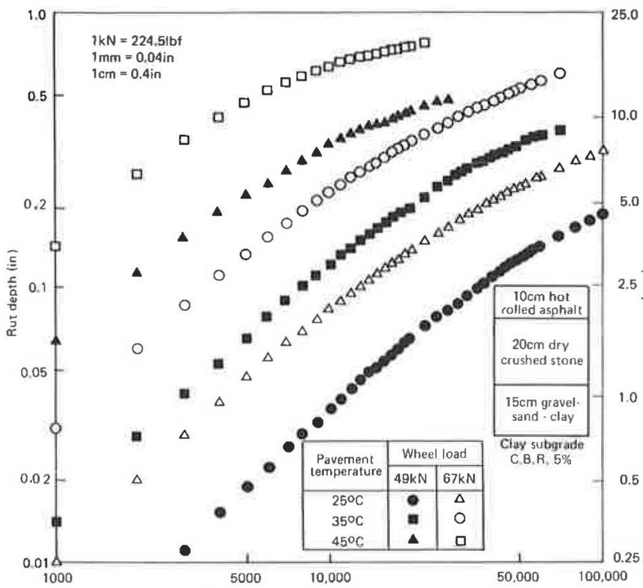
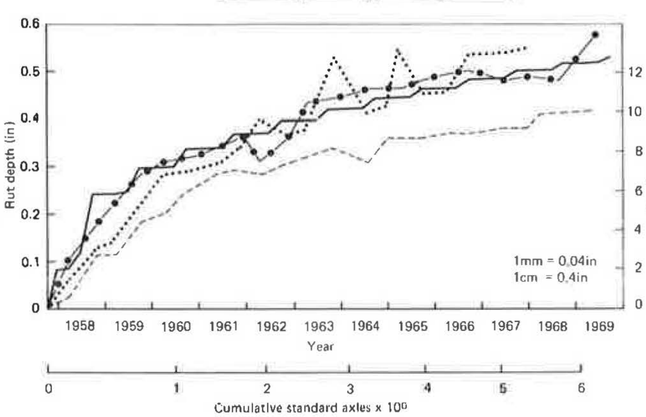


Figure 10. Comparison of development of rutting in granular-based pavement occurring under actual traffic and predicted from road-machine test results.

	Road machine	Full-scale road experiment		
	Controlled test pavement	Similar strength pavement	Similar strength pavement	Stronger pavement
Surface	10cm Hot rolled asphalt			
Base	20cm crushed stone	22.5cm Wet-mixed slag	15cm Wet-mixed slag	22.5cm Wet-mixed slag
Sub-base	15cm gravel-sand-clay	10cm sand	35cm sand	27.5cm sand
Clay subgrade	6% C.B.R.	4.7% C.B.R.	5.8% C.B.R.	3.8% C.B.R.
Key	Predicted	Measured	Measured	Measured



under a series of cooling cycles starting 5°C (41°F) above the mean and finishing 5°C below it. The marked influence of temperature and wheel load on the rate of surface rutting is shown; during the first 10 000 repetitions of load at 45°C, mean rates were about 10 times those at 25°C. The relatively small change in the size of wheel load from 49 to 67 kN (11 000 to 15 000 lb) resulted in a doubling of the rate, indicating the great importance of wheel-load size in the development of ruts.

The model describing rutting behavior under constant wheel-load and temperature conditions developed from these tests was used to predict the relation that could be expected between rutting and load repetitions in the test pavement when subjected to the wide spectra of wheel loads and surfacing temperatures of an actual road. Results using load and temperature data obtained at the Alconbury Hill experiment (4) were used to compute the development of rutting that could be expected under those conditions during the 12-year life of the experiment. In the computations, the increments of rut were assumed to be additive; that is, the additional depth of rut produced by the application of a particular combination of wheel load and temperature was a function only of that wheel load and temperature and of the rut depth at the time of its application.

The marked seasonal variations predicted are shown on linear scales in Figure 10; nearly all the predicted rutting developed in the three warmest months of each year (June, July, and August). Figure 10 also shows the development of rutting at the Alconbury Hill site on three experimental pavements built with granular bases. Although none is identical with the pavement tested in the road machine, good agreement was obtained with the two that can be considered to be similar in strength. The third pavement, which was definitely stronger, rutted less.

The results also indicate the great importance of large wheel loads in combination with high temperatures in the development of rutting. Out of a total rut of 14.2 mm (0.56 in) developed in 12 years of traffic, 2.54 mm (0.1 in) was contributed by the 0.003 percent of wheel loads greater than 82 kN (18 000 lb) that traversed the road when surfacing temperatures were higher than 30°C (86°F), that is, in a period corresponding to only about 4.5 percent of a normal year.

IMPLICATIONS FOR STRUCTURAL DESIGN OF PAVEMENTS

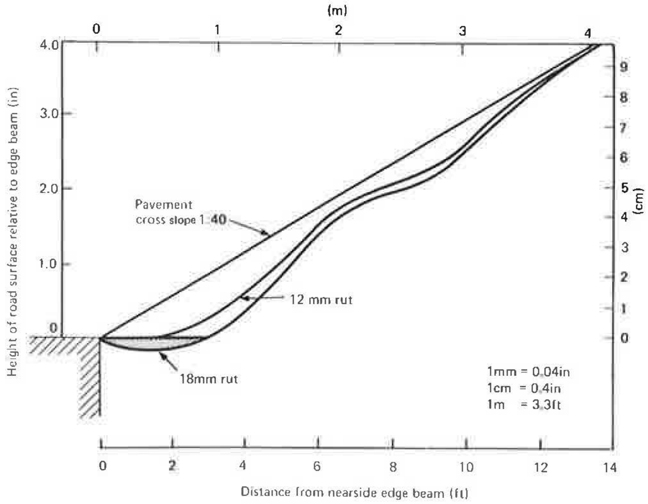
Structural methods of pavement design based on an understanding of the stress-strain behavior of pavements and subgrades are being developed worldwide. Such methods are essential to enable road designers to respond to changing technical and economic circumstances.

Essential to such methods are procedures for predicting the deformation behavior of roads from mathematical models and from experimental data on the dynamic and long-term behavior of pavement materials and soils. However, the laboratory test regimes that are practically possible do not simulate real road conditions at all closely, and the behavior of the materials themselves is complex.

Test methods and computation techniques must therefore represent a considerable degree of simplification and compromise with reality, and a link is required between the predictive procedures and the road. The link is needed for both the development and the validation of the procedures. Information from full-scale experiments on real roads cannot be used because of their mixed loading and temperature conditions.

Figure 10 suggests that the testing of pilot-scale pavements under controlled conditions of wheel loading and temperature can be used to predict the deformation of real roads. This form of testing, therefore, has potential both for developing and validating prediction procedures under simplified conditions of constant wheel load and temperature and for providing the essential extension of the validation process to the road itself.

Figure 11. Typical transverse pavement profiles superimposed on 1:40 cross slope.



PRACTICAL IMPLICATIONS OF RUTTING

In well-designed, well-constructed roads in the United Kingdom, ruts as deep as 10 mm (0.4 in) are unlikely to be associated with cracking of structural significance. Measurements of the change of deflection with time and traffic indicate that at that stage the pavement has retained most of its overall structural strength (10) but that the development of cracking and the loss of structural strength once this critical condition is reached are less predictable. For preventive road strengthening by overlaying, United Kingdom recommendations use deflection criteria that should ensure that the rutting not exceed 12.5 mm (0.5 in) in depth and that structural cracking be confined to isolated instances (11). The equivalent value of present serviceability index is estimated to be between 3.1 and 3.3.

In the absence of strengthening measures, the road will deteriorate to failure. The criterion of pavement failure generally accepted in the United Kingdom is rutting to a depth of 18 to 19 mm (0.75 to 0.8 in) under a 1.8-m (6-ft) straightedge. At this stage rutting normally increases rapidly; water ponded in the ruts penetrates the road structure through surface cracks; and the condition of the pavement requires reconstruction of at least the base and surfacing.

PONDING OF WATER

When rutting becomes deep enough to allow ponding of water, the safety of the road user is adversely affected. Visibility in wet weather is reduced by increased splash and spray. Skid resistance in the wheel paths is reduced and aquaplaning is also a danger. In the United Kingdom in 1971, 25 000 injury accidents on wet roads were attributable to reduced skid resistance, to impaired visibility from splash and spray, and to glare at night (12).

The standard cross slope or cross fall on new construction in the United Kingdom is 1:40, or 2.5 percent. Figure 11 shows two typical transverse profiles having rut depths of 12.5 and 18 mm (0.5 and 0.75 in) superimposed on this cross fall; the shape of the ruts is distorted by the scales adopted. The potential extra hazards associated with ponding occur when ruts deeper than about 12.5 mm (0.5 in) are present, and at a failure condition the ruts may retain about 3.75 mm (0.15 in) of water. In practice rut profiles seldom follow exactly the smooth profiles shown in the figure, and actual variations will inevitably cause localized areas of ponding at depths shallower than 12.5 mm (0.5 in). Rutting confined to the surface, because of its relative thinness, may also cause ponding at depths much shallower than 12.5 mm (0.5 in). The timing of overlay placement recommended in the United Kingdom should virtually prevent ponding in most situations and greatly limit it in the remainder.

CONCLUSIONS

1. Flexible roads in the United Kingdom deteriorate primarily by rutting in the wheel paths. The development of rutting in relation to cumulative traffic can be characterized by a power index, at least up to the stage when cracking appears in the road surface at rut depths greater than 10 mm (0.4 in).
2. Development of rutting in the pavement layers and the subgrade is related primarily to the effect of high road temperatures, which increase the deformability of bituminous pavement layers and reduce their load-spreading ability.
3. Pilot-scale tests carried out with a circular road machine have quantified the effects of wheel loading and temperature on the development of rutting in a pavement with a granular road base. The results have been used to predict successfully the development of rutting in broadly similar pavements in a road experiment subject to a known mix of wheel loading and pavement temperatures. The results indicate the potential of pilot-scale testing in the development and validation of structural methods of road design.
4. Recommendations for structural strengthening in the United Kingdom are designed to ensure that ruts in pavements do not exceed 12.5 mm (0.5 in), at which safety problems associated with ponding of water in ruts are largely eliminated.

ACKNOWLEDGMENTS

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Viscoelastic Deformations in a Two-Layered Paving System Predicted From Laboratory Creep Results

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A new viscoelastic method developed to calculate deformations in a two-layered flexible pavement system subjected to both single and repeated moving loads is described. On the basis of laboratory creep experiments the rheologic behavior of all asphalt-bound materials can be represented in viscoelastic equations by a simple analytical expression for creep compliance. The mathematical analysis is performed by (a) calculating the viscoelastic deformations (vertical, transverse, and longitudinal strains) around the moving load and (b) predicting the repeated load effect, considering the effects of velocity and waiting time between two consecutive loads. The theory is applied to the asphalt pavement design for a steel slab bridge on an Italian motorway. Calculated deformations are compared with actual deformations, measured by means of strain gauges incorporated into the asphalt layers. Temperature for tests and calculations was 40°C (104°F). Both the theoretical predictions and the experimental results show that recovery is considerably delayed for the vertical and the transverse elongational deformations only. No delay was observed for the longitudinal deformation. The contribution of delayed viscoelastic deformations to total deformations was found to be relevant under some actual traffic conditions.

Elastic methods in pavement design can be used to predict the fatigue behavior of flexible pavements and generally to determine maximum deformation from the passage of a single load. These methods provide no useful information regarding the onset of permanent deformation that may be largely due to viscoelastic effects associated with the deformation from repeated loads. However, adequate methods for calculating viscoelastic deformations in layered systems are not currently available.

Some authors have provided interesting solutions to viscoelastic problems (1, 2), and even for multilayered systems (3), but these consider repeated application of static loads. This simplification may lead to a substantial underestimation of deformability in the lowest layer of a paving system, since the diffusion of stresses gives rise to an effective load time that increases with depth if the load moves on a viscoelastic system. Experimental results (4) confirm that load time relates to the load velocity and to the depth of the point under examination. For this reason viscoelastic models dealing with repeated application of a static load underestimate the deformation at greater depths. Therefore, a theoretical method was developed for predicting the viscoelastic behavior of a two-layered system subjected to repeated moving loads (5).

A two-layered, incompressible asphalt pavement system subjected to a sequence of moving loads is examined. On the basis of laboratory experiments (6), asphalt-bound materials can be characterized rheologically in terms of Equation 1, where J(t) is the viscoelastic creep compliance function.

$$J(t) = \alpha_1 J_1 \tau_o^{\alpha_1} \gamma(\alpha_1, t/\tau_o) \qquad (1)$$

When a single or only a few load passages are being considered, Equation 1 reduces to the simpler formula

$$J(t) = J_1 t^{\alpha_1} \qquad (2)$$

for short time periods, generally <10 s ($t \ll \tau_o$).

In Equation 1 $\gamma(\alpha_1, t/\tau_o)$ is the incomplete gamma function of α_1 and t/τ_o:

$$\gamma(\alpha_1, t/\tau_o) = \int_0^{t/\tau_o} u^{\alpha_1 - 1} e^{-u} du \qquad (3)$$

Equation 2 takes slope α_1 as a straight line on a log-log plot. We assume that characteristics of the subgrade can also be described by Equations 1 or 2, provided we choose suitable values for the parameters. We observed, also, that putting $\alpha = 0$ in Equation 2 gives us the elastic behavior.

Creep tests carried out in the laboratory on a large class of asphalt concretes show that the order of magnitude of τ_o is nearly 1 000 to 10 000 s at a temperature of 20°C (68°F) and nearly 10 to 100 s at a temperature of 40°C (104°F).