Fatigue of bituminous materials in flexible pavements

by

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Dr K. R. Peattie (Esso Petroleum Co. Ltd) wrote that in §§ 51 and 52 Dr Pell discussed surface deflexion in relation to strain in the various layers of a flexible pavement and hence in relation to possible fatigue failure of the bitumen-bound material. He had very rightly pointed out that although surface deflexion had been shown to be related to overall pavement performance it was not directly related to fatigue cracking.

84. Dr Peattie had examined⁴³ the validity of using surface deflexion as a performance criterion for flexible pavements in the light of a fundamental analysis⁴⁴ of such pavements based on the theory of elasticity. In this analysis it was considered that the two critical factors affecting the performance of flexible pavements were the vertical stress at the top of the sub-grade and the horizontal tensile strain at the bottom of the bitumen-bound layer. The latter factor was introduced in order to take into account fatigue in this material.

85. The values of the vertical stress in the sub-grade and the horizontal strain at the bottom of the top layer were calculated for a number of three-layer structures, all subjected to the same loading. The surface deflexions were also calculated and compared with the other two factors.

86. Fig. 19 showed that a reasonable degree of correlation existed between surface deflexion and the ratio of the actual stress in the sub-grade to that permissible for the soil.

87. In Fig. 20 the values of the horizontal tensile strain at the bottom of the top layer were plotted against the corresponding surface deflexions. There was little general correlation between these two quantities. If the comparison was limited to those structures in which the ratio of the modulus of the base, E_2 , to that of the sub-grade E_3 lay between 2 and 5 (shown by filled circles in Fig. 20) a better correlation was obtained between strain and deflexion.

88. It might be concluded that surface deflexion gave an indication of pavement performance insofar as this was related to sub-grade stress. It was, however, likely to be of limited value as a means of assessing the probability of failure of the bitumen layer by fatigue.

89. The method of preparing Fig. 16 in Dr Pell's paper was not entirely clear. The diagram in Fig. 16 gave E_1 as 500 000 lb/sq. in. and E_3 as 12 500 lb/sq. in. and stated that the value of E_2 varied. Presumably E_1 and E_3 therefore remained constant in all the calculations, in which case both K_1 and K_2 varied simultaneously. But the abscissa in Fig. 16 was designated 'Ratio $K_2 = E_2/E_3$ '. It would appear that a designation of ' E_2 ', with an appropriate change of scale, might possibly be used in Fig. 16. A similar situation existed in Fig. 18 where the various lines were designated by values of K_2 , although here also E_2 was the primary variable. In both these figures a value of K_2 in excess of 40 meant that E_2 was greater than 500 000 lb/sq. in. and hence K_1 was less than unity.

90. Dr Pell stated that Figs 17 and 18 appeared to indicate an optimum base thickness of 8 in. This was true only so far as the tensile strain conditions in the

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FIG. 20: HORIZONTAL TENSILE STRAIN AT BASE OF TOP LAYER AS A FUNCTION OF SURFACE DEFLECTION

FIG. 19: ACTUAL STRESS/PERMISSIBLE STRESS IN SUBGRADE AS A FUNCTION OF SURFACE DEFLECTION

bitumen-bound layers were concerned. It was certainly not the optimum thickness so far as reducing the stress transmitted to the subgrade was concerned. Fig. 12 showed that increasing the base thickness above 8 in. produced further reductions in this stress, which was the more critical one as far as pavement performance was concerned. Having made a choice of layer materials and thicknesses to give a satisfactory value of vertical stress in the sub-grade, it was, of course, necessary to ensure that none of the bitumen-bound layers had an excessive tensile strain developed in it, but it was probably not necessary to adjust the base thickness further so as to develop the same value of tensile strain in both the wearing course and the base. It was felt that to refer to the particular value of base thickness which produced this equality of strain as the 'optimum thickness' could be misleading.

91. An example might be taken from Figs 12 and 17(a). If it was assumed that 20 lb/sq. in. was a reasonable sub-grade stress, this could be obtained with a bitumen-bound base 9 in. thick or a granular base 21 in. thick (using the curves for $h_1 = 5$ in. in Fig. 12). From Fig. 17 it would be seen that the pavement with the bitumen-bound base had strains of 70 and 55×10^{-6} developed at the bottom of the wearing course and base respectively. The corresponding strains for the pavement with the granular base were 180 and 70×10^{-6} . This example showed the striking effect of using a bituminous base not only in the economy resulting from the considerably reduced base thickness but also in the decrease in tensile strains developed in the bitumen-bound materials.

Mr J. F. Blott (Consultant in Petroleum Technology, formerly Shell Research Ltd, Thornton Research Centre) thought that the passage in § 16: 'the fact that the CBR method of design ignores the load-spreading properties of the upper layers of the pavement structure . . .' might be misleading.

93. The CBR method embodied practical experience of the behaviour of many different road structures and, in principle, had to take into account all properties which determined performance, including fatigue and perhaps other factors not yet appreciated. A mathematical analysis of hypothetical structures indicated by the CBR method had been used¹⁶ to derive values of stress which might be permitted to reach subgrades of different CBR values, and these calculated values were assumed to be valid, although approximate. An appropriate statement on the limitations of the CBR method was, in fact, given by the Author in § 15, *viz.* ' . . . this method of design does not take into account the different load-spreading properties of these materials'.

94. Mr Blott suggested therefore that the Author probably intended to make the point in § 16 that the CBR method ignored *differences* in load-spreading properties of the upper layers of the pavement structure and not that it ignored the fact that these layers had load-spreading properties.

Mr G. M. Dormon and Mr J. F. Hills (Shell International Petroleum Company Ltd) wrote that while the fracture of bituminous materials in flexible pavements by fatigue deserved careful investigation, the extent to which it was critical for design purposes should not be over-estimated. In this connexion the conclusion referred to in § 9, regarding the significance of fatigue in the asphalt in the A.A.S.H.O. road test, was not substantiated, but merely the opinion of some contributors. A detailed analysis of the results, using elastic theory,¹⁹ provided substantial support for the contrary conclusion, that the primary cause of deterioration was excessive stress on the sub-grade soil, and that the cracking of the asphalt was only secondary. Further analysis confirmed that the pavement deterioration was not directly related to the maximum tensile strain calculated as being developed in the asphalt layer.

96. It had also been shown¹⁹ that for designs with thick asphalt layers the critical strain for design purposes was the vertical compressive strain at the surface of the sub-grade soil, and that there was then no necessity for precise knowledge of the fatigue behaviour of the asphalt layer.

97. In § 57, Dr Pell mentioned the use of elastic theory applied to a three-layer model analysed to find the interfacial stresses on the vertical axis of the load. He commented that whilst, theoretically, these stresses would give a maximum principal strain on the axis, considerable tensile strains were also likely to occur in the top layer under the edge of the loaded area, because of the presence of shear stresses there. Whilst such shear stresses should not be forgotten, some experimental work⁴⁵ recently done suggested that it was likely that these were not critical. A fatigue test was carried out with a loaded wheel rolling over a slab of bitumen mix, which was mounted on a slightly resilient base so that the loading and strain conditions simulated the situation in a road. After a large number of loadings, fatigue cracks appeared on the underside of the slab. For the conditions of this test, therefore, the critical strain was the tensile one at the bottom of the slab, and not that at the edge of the loaded wheel on the surface of the slab.

98. With regard to the method of making measurements in the field, associates of the writers' firm in Germany, *Deutsche Shell*, had developed techniques for measuring tensile strains within the asphalt layer and at the surface or the interface. Measurements in a road structure had shown that the strain in the transverse direction was indeed normally greater than in the longitudinal direction. The strains measured were also in acceptable quantitative agreement with calculations made using elastic theory.

99. In several numerical examples, the Author suggested that there was an optimum thickness of bitumen-bound base, namely 8 in. This was misleading, because the criterion of equal maximum tensile strain in each layer, on which this conclusion was based, was not necessarily related in any way to an optimum thickness. Furthermore, experience had shown that the mode of failure for 'black base' construction, with an overall asphalt thickness considerably less than the 13 in. used as an example, was more likely to be excessive deformation than cracking, fatigue or otherwise.

100. The Author suggested a value of 1×10^{-4} (or lower for base-type mixes) as the maximum permissible strain which should be allowed to develop in the asphalt layer. It was considered that this value might be too conservative when applied to practical loading conditions if, as indicated in the Paper, it was associated with soil, temperature, and loading conditions liable to give rise to the maximum tensile strain ever occurring in the asphalt layer. In an attempt to apply laboratory fatigue criteria to practice in a realistic manner, the contributors had made calculations assuming:

- (a) that Miner's Law might be used to integrate the effect of typical climatic variations;
- (b) that some allowance for crack propagation, as well as initiation, might be made by using a 50% reduction in the initial stiffness modulus as the fatigue criterion in a constant strain test;
- (c) that Miner's Law might be used to integrate the effect of typical traffic loading distributions.

Designs made on this basis resulted in structures comparable to existing roads in the United Kingdom which had behaved satisfactorily.

101. Thus, whilst research had led to a certain understanding of fatigue, and had shown the relative importance of many of the variables, it was considered that some caution should be exercised when attempting to relate the results of laboratory tests to the performance of the road structure. In particular, it would not be possible to predict the fatigue life of road structures with great accuracy until more was known about crack propagation in bituminous mixes. Such knowledge might also throw some light on the mechanism of the fatigue process itself, which was more gradual than the use of terms such as 'crack initiation' implied.

The Author wished to thank the contributors to the discussion for drawing attention to several important points.

103. Mr Blott's comments regarding the C.B.R. method were quite relevant and the correct statement was made in § 15 regarding the differences in load spreading properties of the upper layers.

104. Dr Peattie's information on the lack of correlation between surface transient deflexions and horizontal strain at the bottom of the bitumen-bound layer was welcome as it supported the contention that it was necessary to measure accurately the actual strains occurring in the road in order to investigate fatigue. In this connexion it was interesting to learn from Messrs Dormon and Hills of the measurements of tensile strain made in Germany which agreed reasonably with the proposed theoretical analysis.

105. The experimental work with a loaded rolling wheel,⁴⁵ mentioned by Messrs Dormon and Hills, led to the formation of fatigue cracks on the underside of the bituminous slab, and this was indeed in line with theory which gave maximum principal strain at this point. However, cracks resulting from additional high tensile strains occurring within the layer due to shear stresses under the edge of the load, referred to in § 57, would probably propagate to the bottom of the layer and hence be difficult to distinguish from those initiating in the area of theoretical maximum principal strain.

106. Dr Peattie raised a point regarding Figs 16 and 18. The ratio K_2 could be replaced by E_2 , the stiffness of base, if so desired. The Author chose to use the parameter K_2 for convenience for, as stated in the Paper, the purpose of the theoretical analysis was to investigate trends rather than obtain absolute values.

107. Both Dr Peattie and Messrs Dormon and Hills found the term 'optimum thickness' misleading and the Author agreed that this was possibly so if viewed in the larger context of overall pavement design. However, it was emphasized that the Paper was concerned solely with the fatigue factor which was only one aspect to be considered when deciding on a suitable base thickness. Whether this optimum thickness of base was critical on a fatigue basis depended on the strain/life relationship of the base material, and, as stated in § 69, little information was available on the behaviour of this type of mix.

108. In the two years which had elapsed since the Paper was written the Author had carried out fatigue tests both on wearing course⁴⁶ and base course mixes and if it was assumed that a bituminous road base was constructed from rolled asphalt base-course mix, and the results applied to the example quoted by Dr Peattie in § 91, the following facts emerged. By replacing a granular base 21 in. thick by a 9-in. thick bituminous base the strains in the wearing course were reduced by a factor of 2.6, which would indicate a fatigue life increased approximately 300 times. The bituminous base had a tensile strain less than the wearing course, but the much shorter fatigue life of this type of mix would reduce the overall improvement in life to approximately 10 times. Thus it could be seen that while the improvement was still considerable it was not as great as at first appeared.

109. Messrs Dormon and Hills consider that the suggested value of maximum strain of 1×10^{-4} might be too conservative, but the results of fatigue tests on a 60% crushed rock base course mix having a binder content of 6% gave a mean life of only 2×10^5 applications of load at this strain. This value of fatigue life compared with a life of over 10^6 applications of load for a sandsheet type of mix as shown in Fig. 7.

110. The more refined approach, suggested by Messrs Dormon and Hills, which took into account cumulative damage and crack propagation, was certainly very attractive but it should perhaps be treated with caution until it had been demonstrated that Miner's Law did in fact apply to the types of mixes used in practice and over the relevant ranges of stress, strain and temperature. Also more quantitative information was needed on crack propagation and how this affected not only the laboratory fatigue life but also the consequent reduction in stiffness of the bituminous layers which in itself would probably reduce the actual service life of the pavement.

111. It was not considered that at the time of writing fatigue was the major cause of cracking in flexible pavements in Great Britain, but clearly any rational method of design must incorporate strength considerations and, by the very nature of the problem, fatigue strength was one of the factors which should be taken into account.

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