Effect of traffic loading and binder ageing on the structural deterioration of bituminous pavements

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SYNOPSIS: This paper aims to study the structural weakening mechanisms of bituminous pavement layers and the effect of traffic loading and binder ageing on the structural deterioration of the pavement. The results of a detailed investigation of in-service motorway pavements are presented. In the investigation, four pavement sites of various age and traffic conditions were examined. Cores were taken from the nearside and offside lanes, and samples were cut from the roadbase of the cores and tested in the laboratory under fatigue loading. The widely held concept of roadbase fatigue cracking was closely examined.

1. INTRODUCTION

In the United Kingdom and many other countries, structural design of bituminous pavements has become common practice, in which some design criteria are applied. One of the criteria widely adopted is the fatigue cracking criterion, which implies that fatigue of the bituminous pavement materials under the repetitive action of traffic loading is one of the major mechanisms of structural weakening of the pavement. Since the fatigue is controlled by tensile strain which reaches maximum at the underside of the bituminous roadbase of a pavement under traffic loading, it is assumed that fatigue cracking would eventually initiate at the underside of the roadbase and propagates upwards till it reaches the surface. Therefore the maximum tensile strain induced by a standard loading has generally been accepted as a factor controlling the service life of a pavement. Such a fatigue weakening mechanism has been adopted in many of the pavement design methods, such as the Shell method [1], the Transport and Road Research Laboratory (TRRL) method [2], and the University of Nottingham method [3].

For a pavement structure containing a bituminous surfacing and a bituminous roadbase, this understanding of fatigue weakening means that the roadbase would suffer more fatigue damage than the surfacing, and the more heavily trafficked lane (the nearside lane) would suffer more cracking than the less trafficked lane (the offside lane). However, this has not been evidenced in field investigations of pavements. Goddard [4] investigated a number of bituminous pavements in the UK, with estimated residual life varying from 0 to more than 50 million standard axle (msa) loads, and observed that in some cases surface cracking existed with no associated roadbase cracking, whilst roadbase cracking was always accompanied by surface cracking.

On the other hand, it is well known that bituminous binders harden with time. However, the effect of binder hardening on the structural deterioration and fatigue life of pavement materials has not been well studied. Generally, binder hardening increases the stiffness of the material but reduces its ductility and resistance to cracking. These two effects are offsetting as far as fatigue cracking is concerned, because an increased stiffness leads to a lower level of tensile strain induced by traffic loading and thus less fatigue damage. Goddard [4,5] found in field investigations that, although in some cases harder binder existed where cracking occurred, binder hardening did not necessarily lead to cracking.

Because of the importance of fatigue cracking in the design of new pavement and the design of strengthening measures for existing pavement, a better understanding of the weakening mechanism and the effect of traffic loading and binder hardening to the structural deterioration and the fatigue life of bituminous pavements is needed. Towards this purpose a detailed investigation of in-service bituminous pavements in the UK was conducted, involving Falling Weight Deflectometer (FWD) tests,

Heavy vehicles and roads: technology, safety and policy. Thomas Telford, London, 1992.

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core-cutting from the pavement, foundation stiffness measurement, laboratory fatigue testing of samples of the roadbase layers, material composition and recovered binder hardness analysis, and theoretical life calculation. This paper presents some of the results of the investigation and discusses some of the findings.

2. FIELD INVESTIGATION AND LABORATORY TESTS

Four sites of in-service motorway pavements were investigated. The relevant details are given in Table 1. The typical structure of the pavement is shown in Fig. 1.

Table 1   Details of pavements investigated

Site No.	Age (Years)	Traffic (msa)	Thickness# (mm)	Roadbase type	E_f* (MPa)
1	11	22	230	RA	195
2	19	66	300	DBM	103
3	23	71	310	DBM	247
4	21	57	300	DBM	188

#: for bituminous layers
*: stiffness of foundation (subbase and subgrade combined)
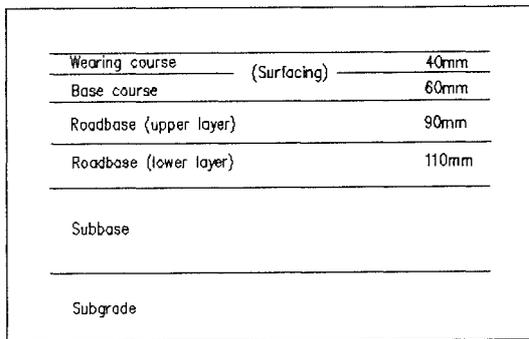

Fig. 1   A typical structure of bituminous pavement

At each site 10 cores of 450mm diameter were cut through the bituminous layers to the granular subbase, 5 on the nearside lane (slow lane) and 5 on the offside lane (fast lane), as shown in Fig. 2. The slow lane cores were located along the wheel track where maximum traffic loading would have been cumulated, and the fast lane cores were located along the lane centre where minimum traffic loading cumulated. Such an arrangement of coring was to enable a comparison between the cores to establish the effect of traffic loading on the structural deterioration.

Before removing the cores, FWD tests were conducted on top of them to measure the equivalent foundation stiffness (Table 1). The measurement is

+ ⊕: Positions of FWD tests before coring
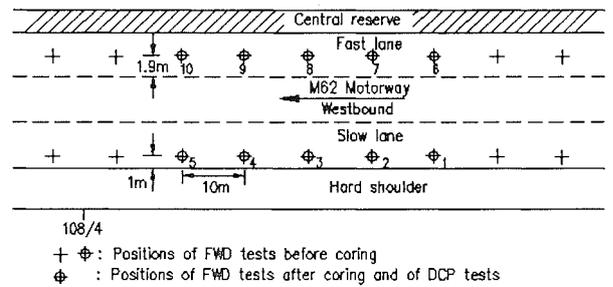⊕ : Positions of FWD tests after coring and of DCP tests

Fig. 2   Pattern of coring on a pavement (M62 Motorway)

discussed in detail by Goddard [4]. The cores were then taken out and close inspection of the structural integrity of the cores and core pits were undertaken.

Samples of 75mm square by 225mm long were cut from the roadbase layers of the cores, with 8 samples being obtained from each core (Fig. 3). The samples were tested in the laboratory under fatigue loading. The fatigue tests were of controlled stress mode of uniaxial tension-compression at 25Hz and 25°C. The stiffness (E) and fatigue life (N_f) of the samples were obtained. The stiffness values are an measure of the present load spreading property of the material whilst the fatigue life gives an indication of the durability of the material to future traffic action. The laboratory fatigue life is not equal to the actual life of the pavement material, nevertheless it can be expected to reflect any significant influence of traffic loading or material composition on the fatigue life of the pavement. A typical diagram of the fatigue test results of samples from one site is shown in Fig. 4, and the mean values of stiffness (E) and fatigue life corresponding to initial strain of 100×10^{-6} (N100) for each pavement site are listed in Table 2, where V(E) is the coefficient of variation of stiffness values and $E_{85\%}$ and $N100_{90\%}$ are respectively the 85% probability stiffness value and 90% confidence fatigue life value.
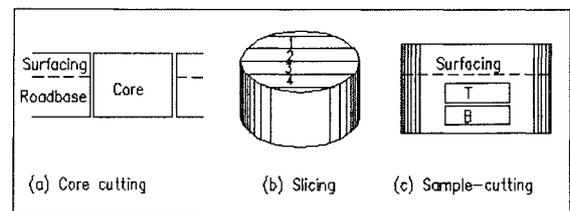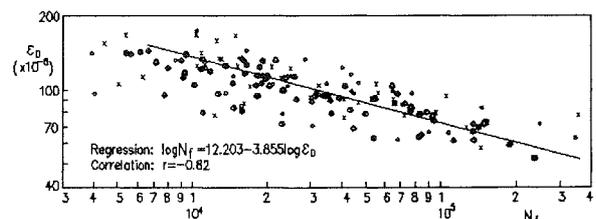

Fig. 3   Schematic diagram of sample-cutting

Regression: $logN_f = 12.203 - 3.855 log\varepsilon_0$
Correlation: r=-0.82

Fig. 4   Fatigue test results of samples from one site

Table 2 Stiffness and fatigue life of roadbase samples

Site No.	E (GPa)	V(E) (%)	$E_{85\%}$ (GPa)	N100	$N100_{90\%}$
1	5.13	19	4.11	31100	27600
2	5.44	47	2.77	740	470
3	6.74	40	3.93	700	540
4	7.44	46	3.86	3670	2850

3. ANALYSIS OF TEST RESULTS

3.1 Examination of roadbase fatigue cracking and effect of traffic loading

The slow and fast lane roadbase samples are compared in Table 3 for each pavement site, in terms of stiffness and laboratory fatigue life. On the whole, the fast lane samples were not in a clearly better condition than the slow lane samples, and the difference in stiffness and fatigue life was generally not statistically significant.

Table 3 Comparison between slow and fast lane roadbase samples

Sites No.	Stiffness E (GPa) SL	FL	Fatigue life N100 SL	FL
1	5.41	4.83	26000	38000
2	5.32	5.92	890	600
3	8.25	6.19	520	810
4	4.23	10.2	5300	1900

This was supported by the visual condition of the samples. Generally, samples from the two lanes of each site did not appear to be noticeably different in structural integrity, and the fast lane samples were not visually stronger. Whilst the two lanes had obviously carried quite different traffic loading, this did not significantly affect the structural condition of the roadbase layers.

The effect of traffic loading and roadbase fatigue cracking are further examined by comparing the upper and lower roadbase layer samples (Table 4). According to current understanding of fatigue weakening mechanism, the lower part of the roadbase suffers more fatigue damage due to higher levels of tensile strain induced by traffic, and the lower samples should in a weaker condition and have shorter fatigue life after the pavements had been so many years in service. But as shown in Table 4, samples from the two layers did not have a consistent and significant difference in stiffness and

laboratory fatigue life. This was also supported by the visual condition of the samples.

Table 4 Comparison between upper and lower roadbase layer samples

Sites No.	Stiffness E (GPa) Upper	Lower	Fatigue life N100 Upper	Lower
1	5.35	5.09	29000	34000
2	5.08	5.09	510	1010
3	6.82	8.08	660	390
4	7.04	7.86	3300	4400

In fact, although the pavements had been in service for 11 to 23 years, none of the site provided evidence of any cracking in the roadbase. The surfacing layers of the pavement at one site were extensively cracked, but the roadbase there was still intact without any sign of cracking and the roadbase samples obtained still looked strong.

It therefore appears that, at least for these four pavements investigated, which all had relatively thick bituminous construction (230-310mm) and relatively strong foundation (equivalent stiffness > 100MPa), the current understanding of roadbase fatigue weakening is questionable, and traffic loading is not necessarily the major factor for the structural weakening of the roadbase.

3.2 Effect of binder hardening and material composition

Material composition and recovered binder hardness were analysed for a total number of 40 samples from the four sites after fatigue testing and multi-variable regression analyses were carried out for them between the laboratory fatigue life and the material composition factors and recovered binder hardness. The volume binder content (VB), void content (VA), and recovered binder penetration at 25°C (Pen) were best correlated to the laboratory fatigue life, and the following relationship for N100, the fatigue life corresponding to an initial strain level of 100×10^{-6}, was obtained:

$$N100 = 7.94 \times 10^{-5} (VB)^{5.77} (VA)^{-0.079} (Pen)^{1.30}$$

The correlation coefficient of the equation is 0.95, i.e. 91% of the variation in the fatigue life can be accounted for by the three factors. Individually, the binder content, void content, and binder penetration can each account for 87%, 66%, and 53% of the total variation of the fatigue life.

Clearly, binder content is the most influential

factor to the fatigue life of the roadbase samples, this is in line with the fatigue performance of new bituminous materials which is also most closely related to binder content. According to Goddard [6], the fatigue life of new DBM material is

$$N100G = 7.616x10^{-4} (VB)^{3.99} (VMA)^{3.167}$$
$$= 7.616x10^{-4} (VB)^{7.16} + 7.616x10^{-4} (VB)^{3.99} (VA)^{3.167}$$

As far as the percentage of the residual fatigue life in the total fatigue life is concerned, the follow equation is used:

$$RP = N100/N100G$$

where RP is the percentage, N100 is the residual fatigue life of the roadbase samples obtained from laboratory tests, and N100G is the total fatigue life of the roadbase materials calculated using Goddard's equation.

A multivariable regression analysis between the residual fatigue life percentage (RP) and other factors was carried out and void content (VA) and recovered binder penetration value (Pen) were found to be most influential to the percentage. Based on the 40 samples with composition data, the following regression equation was obtained:

$$log(RP) = -0.149 - 0.389(VA)^{1/2} + 1.27log(Pen)$$

The relationship accounts for 77% of the total variation of the RP data. Individually, VA and Pen account for 66% and 46% of the variation respectively.

It is clear that the fatigue life of the bituminous materials decreases with time after laying down. The decrease is related more to environmental effects than to the cumulative action of traffic loading. For the four motorway roadbases investigated, it appears that higher void content and faster binder hardening would lead to faster decrease of fatigue life. Since the decrease in fatigue life was not mainly caused by traffic loading, the residual fatigue life of the roadbase samples is not a direct indicator of the capacity of the pavement in carrying further traffic volume.

3.3 Structural deterioration of the surfacing layers

Of the four motorway sites investigated, only one showed extensive surface cracking: a longitudinal crack appeared along the wheeltrack on the slow lane, and frequent transverse cracks at about 1-4m spacing on the middle lane, whist the fast lane was
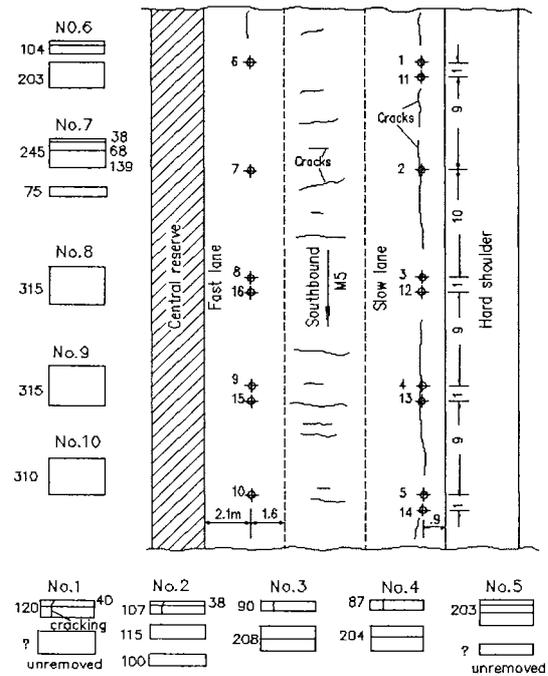

Fig. 5 Surface condition and coring at one site
(Layer thickness in mm, other dimensions in m)

crack free at the site although further up a short longitudinal crack appeared in the lane (Fig.5). However, coring revealed that these cracks were all confined to the surfacing, the roadbase was still intact without any sign of cracking. No rutting was found in the site.

The bond between the surfacing and the roadbase at this site was generally very poor. As shown in Fig.5, debonding at the surfacing roadbase interface occurred in 4 out of the 5 slow lane cores and one out of the 5 fast lane cores. There appeared to be a close association of such debonding (between the surfacing and the roadbase) and surface cracking: for the slow lane cores, all the debonded had surface cracking while the non-debonded no surface cracking; for the fast lane cores, only in core No.6 such debonding was found, and surface cracking existed in the immediate vicinity.

On the other hand, debonding between the roadbase layers did not appear to be related with surface cracking: two cores out of ten at the site had debondings in the roadbase but not at the surfacing roadbase interface did not have any surface cracking. This was confirmed by the situation of another site where debonding between the two roadbase layers were found in 5 of the 10 cores, but no surface cracking was found in any of the cores. At the other two sites, there was no debonding at the surfacing roadbase interface and no surface cracking was observed.

The close association of surface cracking with

poor bond at the surfacing roadbase interface is considered to indicate that the poor bond at the interface was likely to have contributed to the surface cracking. This is probably because the reduced constraint of roadbase to the surfacing, due to the poor bond, allows a concentration effect of low temperature contraction of the surfacing material and the effect of horizontal traffic loading.

Nunn [7] has found that surface cracking is related to binder hardening which reduces the yield strain of the bituminous material. Although his findings were from investigations of composite pavements, it is considered to be also applicable to bituminous pavements. The surface cracking was likely to have formed during winter. At low temperature the bituminous materials become harder with lower breaking strain, which reduces the crack resistance of the materials [8].

So it appears that traffic loading is not the only factor for surface cracking, binder hardening with age may be a more important factor, and poor bond at surfacing roadbase interface or between the surfacing layers is conducive to surface cracking.

4. CONCLUDING REMARKS

Field investigations of in-service bituminous pavements have given little evidence for the widely held concept of roadbase fatigue cracking. Surface cracks were often observed where the roadbase layers were still intact without any sign of cracking.

For a bituminous pavement of high standard such as motorways, it is suggested that the bituminous surfacing and roadbase are structurally supportive to each other, and any structural defect in one of them would reduce its support to the other and therefore result in a faster deterioration. However, the surfacing and the roadbase do not necessarily deteriorate in structural conditions at the same rate. Subjected to the direct action of wheel load and environmental effects such as severe temperature conditions, the surfacing is likely to deteriorate faster than the roadbase which, protected by the surfacing, is much less prone to loss of structural integrity. The vertical and horizontal forces due to traffic has been distributed by the surfacing and are therefore less intensive in the roadbase, and the temperature condition there is much less severe. Although the tensile strain caused by traffic in the pavement is likely to be the maximum at the roadbase, for the current design and materials the level of strain caused is still relatively low and fatigue damage is not critical. Generally, the roadbase can be expected to remain structurally

intact and perform well after a considerable period in service.

This understanding of the structural weakening of bituminous pavement indicates that, in normal circumstances, the roadbase should be retained in any structural strengthening schemes and an overlay should be adopted instead of a reconstruction, unless there is clear evidence that the roadbase has lost its structural integrity. Poor bond between the roadbase layers is not severely damaging to the structural condition of the pavement and therefore is not a reason for digging out the roadbase.

However, the overlay should be applied in time, i.e. it should not be delayed till the surfacing has significantly lost its integrity. In the application of an overlay, effort should be made to ensure a satisfactory bond between the overlay and the existing layers.

Since fatigue cracking is unlikely to be a major mechanism for the structural weakening of the roadbase, a closer examination of some aspects of the current practice of pavement design and condition assessment is needed. Traffic volume and age are related but are different. The current design method is mainly based on the total traffic volume expected for the pavement during the design life, however, age in years should be paid more attention. On the other hand, material properties at low temperatures in relation to cracking, needs further investigation.

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