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## TITLE Design and performance of bituminous overlays

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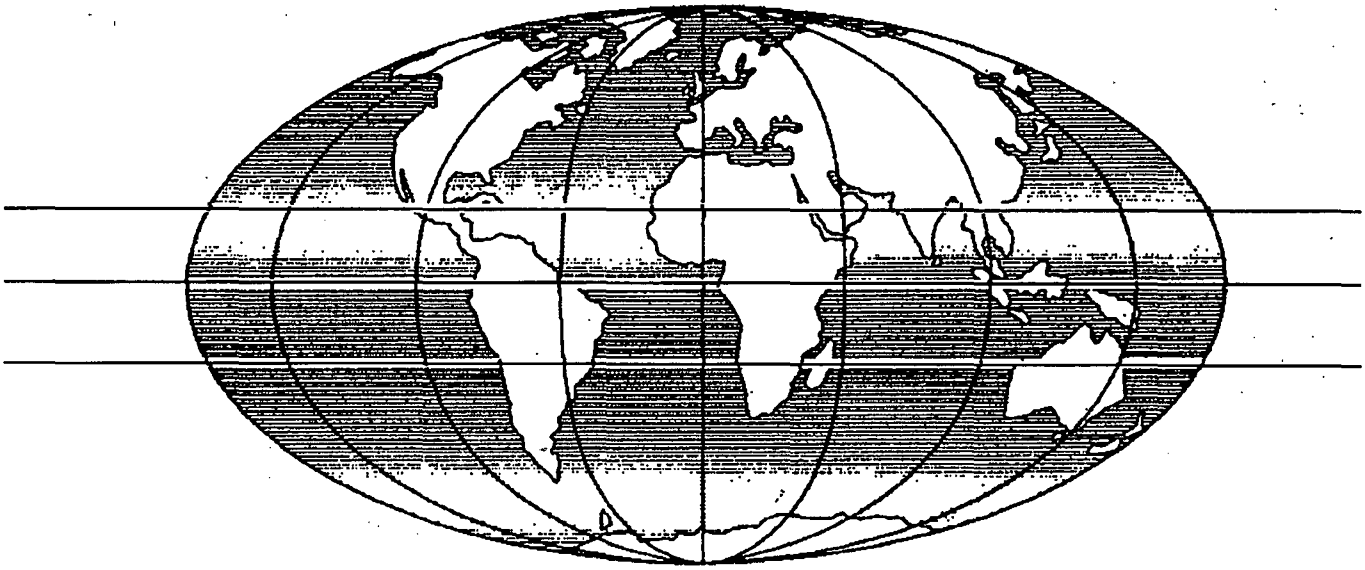

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# THE DESIGN AND PERFORMANCE OF BITUMINOUS OVERLAYS IN TROPICAL ENVIRONMENTS

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## ABSTRACT

This paper summarises the performance of 60 experimental overlays constructed on six sites in different climatic areas of Kenya. The overlays varied from 30 to 170 mm thickness on roads carrying up to 0.75 million standard axles per year. The majority of overlays were asphaltic concretes but the experiments included both hot rolled asphalts and dense bitumen macadams. The predominant form of deterioration was premature cracking which began at the top surface of the overlay and propagated downwards. The techniques of failure time analysis were used to identify the signficant variables on which the cracking depended. The cracking was always associated with age hardening of the bitumen, especially in the top few millimetres of the surfacing. No strong correlations could be established between cracking and deflection, radius of curvature, overlay thickness or traffic. The characteristics of overlays which have not cracked to date have shown how mixes can be designed for long life but the tolerances are likely to be too strict for normal production methods. Other techniques for improving performance are being tested and further analysis is being carried out to try and define the critical degree of ageing.

## 1. INTRODUCTION

Many of the paved roads in developing countries have, for sound economic reasons, been built on the 'stage construction' principle which requires that a road is strengthened periodically to match the growth in traffic. Consequently in many countries substantial programmes are now required to reconstruct or strengthen roads that have reached the end of their original design lives.

Authorities in most countries use deflection techniques for evaluating the structural condition of pavements and for designing the thicknesses of bituminous overlays but most of the available overlay design recommendations have been developed in countries with temperature climates. There is an urgent need to develop similar recommendations for use in countries with tropical climates.

This paper gives details of the construction and performance of a number of experimental overlays placed on a variety of road pavements in the Republic of Kenya between 1973 and 1977 as part of a cooperative study between the Kenya Ministry of Transport and Communications and the Overseas Unit of the Transport and Road Research Laboratory.(1)

## 2. THE EXPERIMENTS

The original objectives of the experiments were:-

(i) to compare the performance of overlays constructed using several different specifications for the premix,

(ii) to identify the primary factors on which the performance of the overlays depend,

(iii) to develop bituminous overlay thickness designs for use in tropical environments.

Different types and thicknesses of premixed bituminous materials were laid on various types of pavement in a range of climatic zones. Sites were located in the relatively cool and wet highlands, hot arid savannah and the hot and wet coastal strip. At each site a number of 100 metre long sections, separated by transitions, were overlaid with premixed materials to the specifications shown in Table 1.

The thicknesses of the overlays at each site were selected on the basis of available traffic loading data and the results of deflection measurements made before overlaying. The mean deflection for each section was calculated and an estimate of the overlay thickness required for a typical design life of eight years was obtained from the design curves developed in the United Kingdom.

At each site a 'design' thickness was chosen and each overlay material was laid on a section to this thickness. In addition an asphaltic concrete mix was also laid on three other sections to thicknesses of 25mm less than the design thickness and 25 and 50 mm more than the design thickness. The overlays were all between 30 and 170 mm thick.

## 3. CONSTRUCTION OF THE OVERLAYS

The characteristics of the existing roads have been described elsewhere.(1) The surface condition was measured in terms of cracking and rutting so that possible correlations with overlay performance could be identified and transient deflections were measured using the standard TRRL method(4) at five points in each wheelpath on each carriageway. A summary of these measurements is given in Table 2.

TABLE 1

Overlay materials(1)

| | | |
|---|---|---|
| Asphaltic concrete | A1 | MoTC 'new' specification, 20mm max. stone size. |
| | A2 | MoTC 'new' specification, 13mm max. stone size. |
| | A3 | MoTC 'old' specification, 20mm max. stone size. |
| | A4 | MoTC 'old' specification, 13mm max. stone size. |
| Hot rolled asphalt | H1 | BS 594 |
| | H2 | BS 594 but filler-binder ratio 1.7:1 |
| Dense bitumen macadam | DB | BS 1621 (site 1), BS 4987 (sites 2, 3, 4, 6) |
| Composite overlays | A5 | A2 wearing course)<br>)bitumen stabilised gravel base |
| | A6 | A4 wearing course) |

All the overlays, except for those on site 5, were constructed under normal contract conditions, whereas those on site 5 were constructed by direct labour. Details of the construction techniques employed have been presented elsewhere.(1)

The gradings of the asphaltic concrete mixes on site 1 were deficient in sand sized material. The bitumen contents for the asphaltic concretes and bitumen macadam basecourses were all within specification except for those on sites 2 and 5. On site 5 the range of bitumen contents was approximately twice as large as

TABLE 2

Summary of structural tests

| Site | Deflection before overlay $10^{-6}$m | Deflection after overlay $10^{-6}$m | Radius of curvature after overlay m | Modified structural number after overlay |
|---|---|---|---|---|
| 1 | 630 - 795 | 475 - 675 | - - | 4.1 - 4.9 |
| 2 | 795 - 1230 | 440 - 690 | 95 - 400 | 5.3 - 6.8 |
| 3 | 490 - 1110 | 320 - 540 | 124 - 487 | 5.2 - 6.8 |
| 4 | 680 - 970 | 330 - 690 | 70 - 233 | 4.5 - 5.7 |
| 5 | 255 - 755 | 175 - 505 | 87 - 357 | 3.5 - 5.8 |
| 6 | 400 - 735 | 330 - 540 | 78 - 230 | 4.0 - 5.0 |

allowed in the specifications, the mean value being 0.4 per cent high for the 13mm current mix and 0.5 per cent low for the old 13 mm mix. The 'current' 20 mm mix laid on sections 1, 2, 7, 8 and 10 on site 2 did not conform to the design mix. This resulted from the use of a high fines content sand, which had not been passed through the mixing plant drier, for determining the laboratory design mix. Despite established procedures the sand grading had been determined by dry sieving instead of by wet sieving. By chance, a similar proportion of fines was lost from the asphalt plant drier during the manufacturing process as was underestimated by dry sieving of the sand, so that analyses of the laid material gave the same aggregate gradings and bitumen contents as the design mix specification. The aggregate in the laid material has a lower surface area than the laboratory design mix and therefore the bitumen content is effectively too high. This provided an opportunity to study the performance of a bitumen-rich mix which should be susceptible to deformation under traffic but should have very good resistance to cracking.

On site 6, unavailability of suitable materials resulted in the dense bitumen macadams being very similar in grading to the '20 mm' asphaltic concretes, but they contained approximately 0.5 per cent less bitumen.

On sites 2 and 3 the bitumen content of the hot rolled asphalt was within specifications but the quantity of filler was high, giving a filler-bitumen ratio of about 1.7:1, the target being 1.3:1. On sites 4 and 6 the bitumen contents of the hot rolled asphalts were low being 5.8 instead of 6.3 per cent on site 4 and 5.1 instead of 5.9 per cent on site 6. However the filler quantities were also a little low giving filler-bitumen ratios of 1.2:1 and 1.0:1 respectively. There was no hot rolled asphalt on the other sites.

## 4. PERFORMANCE MONITORING

### 4.1 COMPACTION

In very few cases was the density of cores less than 97 per cent of the

Marshall design density which corresponded to air voids of between 3 and 5 per cent. However on sections 1-4 and 9-12 of site 5 the air voids were slightly higher with mean values in the range 5.5-7.5 per cent.

## 4.2 SURFACE CONDITION

Rutting in the bitumen rich mix on site 2 has been small, despite carrying heavy traffic, and has been negligible on all other overlays. The predominant mode of failure has been cracking. To measure cracking each carriageway of each section was sampled at ten points, five in each wheelpath. At each point a metre frame was placed on the road in such a way that it enclosed the maximum amount of cracking at the test point whilst keeping the test point within the frame. In effect this method allowed ten per cent of the carriageway to be sampled. Photographs were taken at each monitoring survey so that the progression of individual cracks could be followed.

All the cracking on every site was found to begin at the top surface and propagate downwards. Coring surveys were conducted to monitor changes in crack depth with time. The development of cracks to the full depths of the overlays has been very variable, both within sections and between different sites. Measurements indicated that only those cracks which were 0.25 mm or more in width were likely to be of significant depth during the early lives of the overlays. Cracking measurements referred to in this paper are therefore for cracks which are 0.25 mm or more in width. Care had to be taken with these measurements because it was found that the width of cracks could change between early morning and afternoon, when the maximum pavement temperature was reached. On site 5 crack widths decreased during this period by up to 60 per cent, the mean change being approximately 25 per cent.

An indication of the rate at which cracking progressed is given in Figure 1 where the cumulative percentage of the ten test points which had cracked is plotted against time for a selection of test sections. The width of some of the distributions is perhaps surprising since the sections are very uniform, having been constructed under well controlled conditions. The standard deviation of overlay thickness on any section was generally less than 5 mm and the standard deviation of deflection was less than 70 microns on most sections. The failure distribution for section 1, site 1, for example, indicates that 90 per cent of the test areas survived for 40 months, 50 per cent survived for 64 months and that 10 per cent lasted for 90 months. This example is by no means extreme. Some of the test sections shown in Figure 1 seem to display two patterns of failure whereby some of the test areas cracked early whilst others lasted a long time with none lasting intermediate times. It is probable that two separate failure mechanisms are operating.

The type of the cracking was variable even within sites. On site 5 the cracking appeared as block cracking resembling the common type of reflective cracking often found on roads with cemented bases. Investigations indicated that there were no discernible cracks in the base beneath the surface cracks. Shrinkage of the asphalt surfacing itself is the most likely cause. Similar cracks appeared on other sites but other types of cracking were also apparent. Transverse cracking was common as were cracks in random directions in the wheeltracks indicating that both thermal and traffic stresses were primary causes. No parabolic cracks were observed indicating that bonding between layers was good and this was confirmed by the integrity of cores.

Comparisons between wheelpaths indicated that there was no significant difference in wheelpath performance on any site. Wheelpaths are therefore not distinguished in the remainder of this paper.

### 4.3 AGE HARDENING OF THE BITUMEN

Samples of the overlays have been taken periodically to measure changes in the hardness of the bitumens over time using standard test methods(5) and indicate that with the exception of the bitumen rich mixes on site 2, the bitumen in all of the overlays hardened rapidly. Since the original penetration of the bitumens was variable the ratio of the penetration at any time to the original penetration has been used in the analysis. The initial value of this ratio at time zero is the penetration after the bitumen has been through the premix plant but before the mix was layed on the road. It was found that the penetration ratio decay function was exponential of the form

$$P(t) = A + (P_o - A) \exp(-t/L) \qquad (1)$$

where $P(t)$ is the penetration ratio at time t
$A$ is the asymptotic value
$L$ is the time constant of the decay
$P_o$ is the initial value of $P(t)$

Excluding the sections which did not age harden, the values of L ranged from 9 to 29 months with a mean value of 16 months. The values of A ranged from 16 to 70 per cent of the original penetration value with a mean of 38 per cent. The value of $P_o$ ranged from 49 to 89 per cent with a mean value of 68 per cent. The sections which did not age harden in the road had a $P_o$ value of 63 per cent.

The samples from which the above results were obtained are bulk samples from the top 50-70 mm of the overlays. Results obtained from the lower 50-70 mm of the thicker overlays indicated that in terms of penetration, the age hardening was only about ten per cent less. More detailed studies of the relationship between age hardening and depth were made by thinly slicing 150 mm diameter cores, extracting the bitumen from each slice and carrying out viscosity measurements using a torsional viscometer and a sliding plate viscometer. Some of the results are shown in Figure 3. The severe ageing of sections 1, 3 and 5 of site 5 is apparent and the comparatively low level of ageing on sections 2 and 8 of site 2. All of the overlays on site 5 performed poorly in terms of cracking whereas none of the three sections shown in the Figure for site 2 cracked at all.

### 4.4 DEFLECTION MEASUREMENTS

Transient deflection measurements were repeated periodically at the same test point locations as were used before overlaying. The mean deflections obtained for complete sections of twenty test points before and after overlaying have been used to obtain a relationship between deflections and overlay thickness:-

$$D_A = 36 + 0.818D_B - 0.0027D_B.H \qquad (2)$$

where $D_A$ = deflection after overlaying ($10^{-6}$m)
$D_B$ = deflection before overlaying ($10^{-6}$m)
$H$ = thickness of overlay (mm)

The correlation coefficient, R, for this regression was 0.96 and a comparison between the observed and predicted deflections after overlaying is shown in Figure 4. The dense bitumen macadam mixes laid on sites 2, 3 and 4 gave about 6 per cent less reduction in deflection than the denser mixes for which the equation applies. A summary of the deflection data is given in Table 2.

Measurements of the logitudinal radius of curvature were obtained using a modified Benkelman beam(1). A summary of these results is given in Table 2.

### 4.5 DYNAMIC MODULUS

It has become common practice to rely upon the nomograms derived by the Shell organisation(9) for the purpose of estimating the dynamic modulus of bituminous materials. However it is not known whether these methods are sufficiently accurate for mixes which have age hardened excessively.

Slabs were cut from some of the test sections and samples cut into beams for modulus testing. Some of the results are shown in Figure 5. There is some evidence that the samples which age hardened the most have moduli which are less temperature dependent. However the maximum penetration index was 1.0 with all the results lying in the range 0.0-1.0. The Shell method predicts the modulii to within a factor of two which is acceptable, but at the higher temperatures the parameters exceeded the range of the nomograms.

### 4.6 FATIGUE TESTING

A small selection of the overlays was sampled for fatigue testing to examine the effect of the age hardening in the body of the overlay on fatigue performance. Tests are being carried out in the controlled stress mode of loading using uniaxial fatigue testing equipment. Some preliminary results obtained from samples which did not age harden are shown in Figure 6 and compare favourably with similar mixes made in UK.(10)

## 5. PERFORMANCE OF THE OVERLAYS

### 5.1 FAILURE TIME ANALYSIS

The appearance of a crack in an area of pavement is an instantaneous failure which is amenable to analysis using the statistical techniques of failure time analysis in which the primary variable is the time to failure, T. Failure time analysis makes use of the survivor function of T which is defined as the probability that T is greater than or equal to a particular time, t. Analysing failure time data involves speculating that T belongs to a particular family of failure time distributions and then estimating the relevant parameters to exactly specify the distribution. The effect of independent variables is included by allowing parameters of the distribution to depend on a function of them. The most widely used distribution is the Weibull distribution which has a survivor function of the form

$$S(t) = \exp(-at^{b}) \text{ for } t > 0 \qquad (3)$$

where a and b are constants.

For the behaviour of the overlays the value of 'b' is expected to be greater than unity, increasing the risk of failure for the surviving areas of pavement as time passes. The shape of the distribution depends on 'b' and is normally independent of the regressor variables whereas the scale parameter 'a' is usually treated as a function of them. Various function forms are possible but one of the most suitable is

$$a(x) = \exp(x) \qquad (4)$$

where x is a linear combination of the independent variables. Thus the survivor function becomes

$$S(t|x) = \exp(-t^{b}.\exp(x)) \qquad (5)$$

The effect of making a distributional parameter a function of the regressor variables is that the resulting model specifies a separate distribution for each combination of these variables.

In this study the ten areas of each test section which were used to monitor cracking, deflection and rutting, are effectively independent since they are widely separated. The times at which each of the ten test areas cracked therefore defines the distribution of failure times for areas of overlay of about 4 square metres, each of these elements being characterised by the set of variable values unique to the section. Some of the measured cumulative distribution functions have been illustrated in Figure 1.

To characterise the performance of a test section, Weibull distributions were fitted to the observed distributions and the survivor functions calculated. Although the parameters 'a' and 'b' are all that are required for characterisation it is difficult to visualise the relative performance from these parameters. Instead the time at which the survival probabilities are 80 and 50 per cent have been calculated and are shown in Table 3. These times are the same as the times at which 20 and 50 per cent of the test areas on each section had cracked.

## TABLE 3

Observed survival times of test sections (months)

| SITE/ SECTION | MIX | THICKNESS | SURVIVAL TIMES | | | |
|---|---|---|---|---|---|---|
| | | | DIRECTION 1 | | DIRECTION 2 | |
| | | mm | 80% | 50% | 80% | 50% |
| 1/1 | A1 | 51 | 50 | 65 | 24 | 43 |
| 1/2 | A1 | 84 | 51 | 69 | 101 | 111 |
| 1/3 | A1 | 106 | 55 | 81 | 101 | 119 |
| 1/4 | A3 | 87 | 30 | 69 | 45 | 87 |
| 1/5 | A2 | 64 | 44 | 72 | 29 | 54 |
| 1/6 | DB | 96 | 21 | 26 | 7 | 19 |
| 1/7 | A1 | 54 | 21 | 37 | 31 | 52 |
| 2/1 | A1 | 70 | - | - | - | - |
| 2/2 | A1 | 110 | - | - | 59 | 136 |
| 2/3 | A2 | 114 | - | - | - | - |
| 2/4 | A3 | 102 | - | - | 48 | 87 |
| 2/5 | H2 | 100 | 10 | 112 | 0 | 9 |
| 2/6 | DB | 104 | 28 | 46 | 34 | 82 |
| 2/7 | A1 | 74 | 105 | 152 | - | - |
| 2/8 | A1 | 111 | - | - | - | - |
| 2/9 | A1 | 163 | - | - | 77 | 163 |
| 2/10 | A1 | 126 | - | - | - | - |
| 3/1 | A1 | 75 | 59 | 83 | 58 | 81 |
| 3/2 | A1 | 118 | 80 | - | 50 | 159 |
| 3/3 | A2 | 106 | - | - | 45 | 100 |
| 3/4 | A3 | 101 | - | - | 45 | - |
| 3/5 | A1 | 103 | 3 | 7 | 83 | - |
| 3/6 | DB | 102 | 34 | 82 | 43 | 61 |
| 3/7 | A1 | 108 | 16 | 38 | - | - |
| 3/8 | A1 | 168 | 35 | 71 | 45 | - |
| 3/9 | A1 | 131 | 32 | 50 | 71 | 94 |
| 3/10 | A1 | 74 | 35 | 66 | 60 | 83 |
| 4/2 | H1 | 101 | 61 | - | 71 | 88 |
| 4/3 | H1 | 104 | - | - | 80 | - |
| 4/4 | A3 | 100 | 19 | 74 | 24 | - |
| 4/5 | DB | 101 | 18 | 50 | 37 | 69 |
| 4/6 | A2 | 99 | - | - | - | - |
| 4/7 | A1 | 152 | 24 | - | - | - |
| 4/8 | A1 | 124 | 15 | 41 | 13 | 58 |
| 4/9 | A1 | 106 | 13 | 64 | 72 | - |
| 4/10 | A1 | 80 | 75 | - | 72 | - |
| 5/1 | A2 | 29 | 2 | 39 | 1 | 7 |
| 5/2 | A2 | 44 | 2 | 5 | 7 | 26 |
| 5/3 | A2 | 71 | 12 | 118 | 0 | 1 |
| 5/4 | A2 | 91 | 1 | 6 | 6 | 10 |
| 5/5 | A5 | 150 | 4 | 15 | 7 | 13 |
| 5/6 | A5 | 116 | 63 | 130 | 0 | 12 |
| 5/7 | A5 | 109 | 8 | 32 | 37 | 78 |
| 5/8 | A6 | 117 | 94 | - | 48 | 68 |
| 5/9 | A2 | 87 | 20 | 92 | 18 | 36 |
| 5/10 | A2 | 73 | 9 | 34 | 3 | 7 |
| 5/11 | A2 | 41 | 0 | 1 | 0 | 2 |
| 5/12 | A2 | 33 | 2 | 13 | 3 | 12 |
| 5/13 | A4 | 34 | 58 | 113 | 42 | 51 |
| 6/1 | DB | 47 | 79 | 102 | 65 | 97 |
| 6/2 | H1 | 49 | - | - | - | - |
| 6/3 | DB | 50 | 92 | 106 | 83 | 115 |
| 6/4 | A3 | 49 | 73 | 95 | 44 | 81 |
| 6/5 | A2 | 49 | 81 | 100 | - | - |
| 6/6 | A1 | 38 | 27 | 50 | 37 | 66 |
| 6/7 | A1 | 47 | 23 | 42 | 47 | 79 |
| 6/8 | A1 | 67 | 57 | 99 | 2 | 7 |
| 6/9 | A1 | 91 | 78 | 107 | 7 | 18 |
| 6/10 | A1 | 43 | 58 | 100 | 58 | 115 |

Notes. (1) - = failure not yet observed. (2) values above 110 months are extrapolated.

### 5.2 INDIVIDUAL SITES

Site 1. Although the particle size distribution of the asphaltic concretes on this site did not conform to the specifications, the general performance was not unusual. The DBM overlay performed poorly because of a poor bond between the two layers.

Sites 2 and 3. The two hot rolled asphalt overlays, generally performed badly but the behaviour was very unusual in that some areas cracked very early whereas others did not crack at all. One of the distributions is illustrated in Figure 1. These mixes derive their strength from the sand-filler bitumen matrix and because a softer bitumen than is recommended for UK conditions was used it was thought that a higher filler to binder ratio should be used to resist deformation under traffic at high pavement temperatures. Whilst negligible deformation has occurred a filler to binder ratio of approximately 1.7:1 in the mixes appears to have reduced their resistance to cracking. The variability of performance needs further investigation.

The excellent performance of sections 1, 2, 7, 8 and 10 of site 2 where the mix contained more bitumen than the Marshall design optimum is apparent. The comparatively poor performance of the DBM was probably a result of segregation which was observed during construction.

Site 4. The filler to binder ratio of the hot rolled asphalts were approximately 1.1:1 and the performance on this site was similar to that of the best asphaltic concretes.

Site 5. All the sections on this site performed badly with the exception of section 8 and one carriageway of sections 6 and 13. Some of the sections displayed a similar cracking pattern to the hot rolled asphalt section on site 2 where some areas cracked almost immediately whilst others lasted a long time. Two factors seem to have contributed to the development of cracks on this site namely the generally high level of voids in the mixes, especially on sections 1-4 and 9-12, and the greater variability of binder content. Higher voids not only reduces the tensile strength of a mix but also accelerates the age hardening of the bitumen.

Site 6. On this site the hot rolled asphalt with a filler binder ratio of 1.0 performed very well, no cracking occurring within ten years. The DBM performed well and the asphaltic concretes show similar performance to those on sites 1, 3 and 4 with high variability.

## 5.3 RIDING QUALITY

Despite the cracking, riding quality has remained acceptable for up to ten years. Little spalling of the cracks occurred and deterioration in riding quality only became significant on sections where the intensity of cracks exceeded 2.0 metres per square metre.

## 5.4 STATISTICAL ANALYSIS

A full statistical analysis was carried out as described above in which the scale parameter 'a' was expressed as a function of the independent regressor variables. The analysis was carried out for all sites together, subgroupings of sites which seemed to behaviour similarly, and finally for individual sites. The analysis was carried out in a stepwise manner using a standard statistical package to identify the statistically significant variables which influenced the failure time distributions. The variables included in the analysis were deflection and its standard deviation, overlay thickness, structural number and modified structural number, traffic, radius of curvature and its standard deviation, mix type, site dummy variable, the age hardening parameters, A, $P_o$ and L, filler binder ratio and bitumen content.

The age hardening variables are essentially secondary variables which in turn depend on mix properties and climatic variables. Eventually it will be necessary to consider this dependence in more detail to define critical values of the mix properties. Initially it is necessary to establish the importance of the age hardening and to define critical levels.

5.4.1 Traffic effects. On sites 2, 3, 4 and 5 traffic in one direction (Table 4) was between 3 and 4 times heavier than in the other. It might therefore be expected that the performance of the carriageways would reflect this difference.

TABLE 4

Traffic loading (millions of standard axles per year)

| Site | Direction 1 | Direction 2 |
|---|---|---|
| 1 | 0.101 | 0.052 |
| 2 | 0.197 | 0.685 |
| 3 | 0.206 | 0.624 |
| 4 | 0.175 | 0.552 |
| 5 | 0.200 | 0.590 |
| 6 | 0.019 | 0.017 |

On sites 2 and 5 the carriageways for direction 1 have performed slightly better than those for direction 2 but on site 3 the reverse is true and for site 4 there is no difference. Overall, on about 55 per cent of the sections there is no difference between carriageways, on 28 per cent the more lightly loaded direction has performed best and on the remaining 17 per cent the more heavily loaded direction has performed best. Any traffic effect is very weak and statistically not significant.

5.4.2 Thickness and deflection effects. The asphaltic concrete labelled AC1 in Table 3 was laid to several different thicknesses on most sites. Apart from a slight trend on site 1 there seems to be no relationship between overlay thickness and the time to cracking. Similar lack of correlations were observed between performance and deflection, both before and after overlaying, radius of curvature, structural number and modified structural number. Propagation of the cracks through the full depth of the overlays proceeded at the rate of about 25 mm per year, although this was very variable, hence the cracks took longer to propagate through the thicker overlays.

5.4.3 Age hardening effects. The age hardening variables were found to be very important. Sections which did not age harden either did not crack at all, or only cracked over a very small area. Age hardening is very sensitive to air voids(7) hence with the usual variability of voids within a test section it was expected that the age hardening variables would have a wide standard deviation. This was confirmed by the data and underlines the importance of a large data set.

5.4.4 Site effects. The site dummy variable was found to be statistically very significant indicating that some of the important factors affecting performance were site specific, relating either to variables which were not quantified e.g. drainage or to variables which were confounded with the site variable. Structural number fell into this latter category as did the air voids in the mix which were generally higher on site 5.

5.4.5 Other effects. The effect of filler-bitumen ratio for the hot rolled asphalts has been discussed above. A similar effect was statistically significant for the asphaltic concretes but the effect was small. In general the analysis was disappointing, reflecting the complexity of the phenomenon and the inherent variability associated with performance studies of bituminous materials.

## 6. DISCUSSION OF THE RESULTS

The outstanding features of the behaviour of the overlays has been the initiation of cracking from the surface on all sites, the overiding effects of the mix proportions and the almost total lack of correlation between performance and traffic loading, deflection radius of curvature, structural number, elastic modulus and so on. The cracking has generally occurred very early in the lives of even the thickest overlays. Similar behaviour has been observed elsewhere.(12)(13)(14)(15) In the study by Dauzats and Linder(12) it was shown that for overlayed pavements at least 87 per cent of the cracking began at the top surface and on new pavements, at least 35 per cent. These figures are minimum values because if a crack is observed to penetrate right through the bituminous surface it is not possible to know for certain whether it began at the top or bottom. The true figure for the percentage of cracks which begin at the top is therefore likely to be much higher. In South Africa various studies(14)(15) have shown that this type of cracking is very common and attempts have been made, with some success, to find correlations between the incidence of various patterns of cracking and over 40 explanatory variables. Similar cracks have been observed in the UK and the Netherlands.(13)(16) The experience of the Overseas Unit, TRRL has indicated that cracking of this form is by far the most common mode of failure in the tropics. Indeed traditional fatigue failure resulting from the horizontal tensile stress at the underside of the surface appears to be relatively uncommon, occurring on extremely underdesigned pavements where it can appear earlier than the type of cracking discussed here.

No entirely satisfactory and complete explanation for the behaviour can be given at present because of the apparent complexity and sensitivity of the interrelationships between the explanatory variables, the problems of controlling these variables, even on well constructed experimental sites, and the difficulties associated with collecting sufficient data for statistically reliable relationships to be established. However the broad picture is reasonably well established.

The age hardening data shows that in hot climates the bitumen in a mix usually age hardens very rapidly throughout the layer and that the top few millimetres of the surfacing age hardens much more. Although it has not been possible to measure the tensile or fatigue properties of material from the top few millimetres of the overlays it is safe to assume that in such a highly degraded state the mix is very weak. The viscosity of bitumen recovered from the top few millimetres is far greater than the critical values established by Dickinson (17) for surface dressings. In such a situation there are various stress inducing mechanisms that could cause fracture of this surface skin. The pattern of the resultant cracking is dictated by the critical stress mechanism which happens to occur first. On some sites, especially those where absorptive aggregates have been used, shrinkage stresses are likely to dominate, giving rise to block cracking. On sites with stabilised bases extra movement of the surface in the vicinity of existing shrinkage cracks in the stabilised base can cause reflective cracking but propagating from the top surface downwards. In areas where temperature changes are sufficiently great, thermal stresses will cause cracking. Indeed, the commonly observed cracks around painted white lines are proof that thermal stresses can exceed the tensile strength of age hardened surfaces. Horizontal stresses caused by traffic loads, either the tensile stresses induced by the reverse surface curvature at the edge of the deflection bowl, or direct horizontal stresses caused by the rolling wheels, can be sufficient to cause cracking. Such stresses have been calculated by Gerrard and Wardle (18). Cracking caused by traffic will be concentrated in the wheelpaths and therefore resemble traditional fatigue cracking.

The cracking which arises primarily because the surface is very weak at the top can therefore depend on many different variables and can often masquerade as other types of cracking. This is why statistical analyses are often inconclusive and why engineers have often failed to appreciate the real reasons for premature cracking.

The conclusion is that if most of the age hardening can be prevented, bituminous overlays and premix surfaces in general, will perform much more satisfactorily. However the studies have so far not been able to show how the hardening of the bitumen affects the strength of the top of the surface and therefore it has not been possible to determine how much hardening can be tolerated in different situations. Furthermore it is expected that the propagation of the cracks is dependent on the properties of the premix just below the top surface. In some cases surface cracks have been observed to heal completely and in others it seems that the rate of change of hardening with depth is important.

From a practical point of view the first task is to reduce the age hardening as much as possible. There are four ways this can be done.

(i) suitable mix design using standard materials,

(ii) the use of additives to the mix,

(iii) suitable structural design or choice of pavement layers,

(iv) surface maintenance.

The relationship between mix properties and ageing has been studied extensively and the relationships between ageing, air voids in the mix, bitumen film thickness, temperature etc have been established.(6)(7)(19)(20) However although it is possible to design a mix, such as those used on sections 1, 2, 7, 8 and 10 of site 2, which will not age harden, crack or deform, the tolerances will be small and the mixes will be difficult to make consistently. Evidence from Kenya indicates that the tolerances are so critical that different mix specifications are needed, depending on the speed of the traffic. The use of additives has been discussed by Dickinson(17) and by Traxler and Shelby(20). No additives have been shown to be very effective but trials are continuing with hydrated lime filler which seems to be the most promising.

Since it seems to be the top few millimetres of the surface which are critical, the most effective method of reducing the problem of cracking may simply be to surface the overlays with a surface dressing, slurry seal or a combination of both. The rate of hardening of such surfaces is known to be much less than for premixes.(17) These techniques are being tried on an experimental basis in Kenya and Australia.

Finally maintenance techniques in which thin sprays of emulsion or bitumen rejuvenating agents may prove to be effective and are also being tried. Such techniques are not particularly attractive for developing countries because of the accepted difficulties often associated with road maintenance.

## 7. CONCLUSIONS

1. The overlays have been effective in providing a good riding quality and most have remained serviceable for up to ten years under heavy traffic (up to 6 million standard axles) despite cracking which appeared very early in the lives of many of the overlays.

2. Cracking has been the predominant form of deterioration, rutting and deformation have been negligible even on areas which required extensive repairs before overlaying. The pattern of the cracking has been very mixed and has included block, transverse, longitudinal, random and crocodile cracking, sometimes within the wheelpaths but often distributed over the entire carriageway.

3. The cracking has always begun at the top of the overlays and propagated downwards. Although this was originally thought to be unusual, subsequent studies have shown that this type of cracking is extremely common in the tropics. Crack propagation down through the overlays has been quite rapid, occurring within two years for overlays of 50 mm thickness.

4. Statistical analysis has shown that the occurrence of cracking is not well correlated with deflection, radius of curvature, overlay thickness or traffic.

5. The occurrence of cracking is highly correlated with age hardening of the bitumen. Ageing occurred throughout the depth of the overlays but was extremely severe in the top few millimetres.

6. An asphalt concrete mix which was rich in bitumen did not age harden significantly even after eight years of service. The sections laid with this mix did not crack or deform to any extent and any fine cracks which were observed tended to be full of bitumen. Unfortunately the mix tolerances necessary to reproduce this mix are too restrictive for normal production methods.

7. The hot rolled asphalt mixes which had a filler binder ratio close to unity performed very well. In view of the greater tolerances allowable with this type of mix, it should be considered for use in areas where suitable sand is available. The hot rolled asphalts which were stiffened by the addition of extra filler, cracked very early in their lives and therefore performed poorly.

8. The asphaltic concretes which were within the specifications, comprise the majority of the overlays. The distribution of times to cracking on nominally identical areas of overlay was very wide with the difference between the 10 and 90 percentiles often exceeding a factor of five. Variability of this magnitude is typical for pavement performance studies and underlines the importance of a large sample size.

9. The dense bitumen macadam basecourse mixes have not been as durable as the denser wearing course macadams or the asphaltic concretes.

10. The evidence suggests that if the ageing of the top few millimetres of the overlays could be reduced, the lives of all the overlays would be dramatically improved. Methods of doing this have been proposed.

11. A relationship between reduction in deflection and overlay thickness has been derived.

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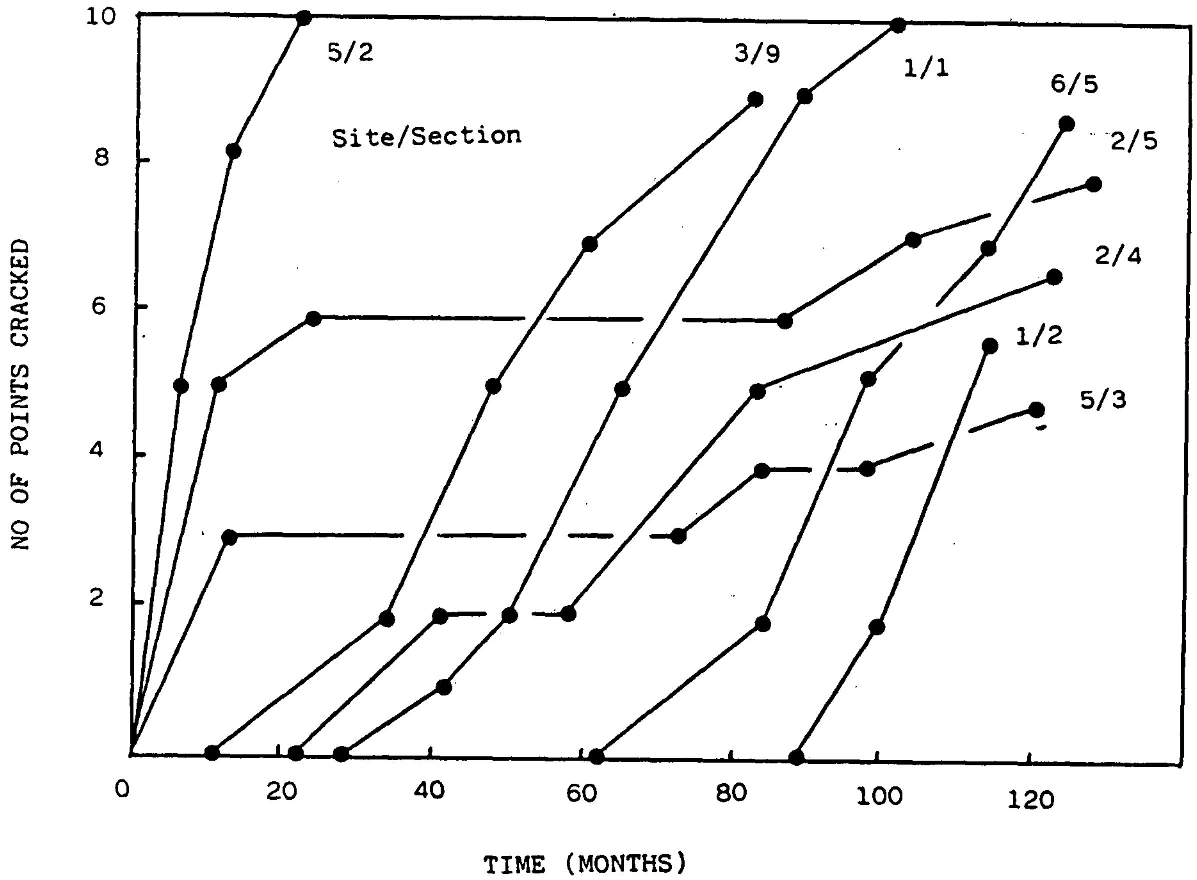

FIGURE 1 CUMULATIVE DISTRIBUTION OF CRACKED TEST AREAS

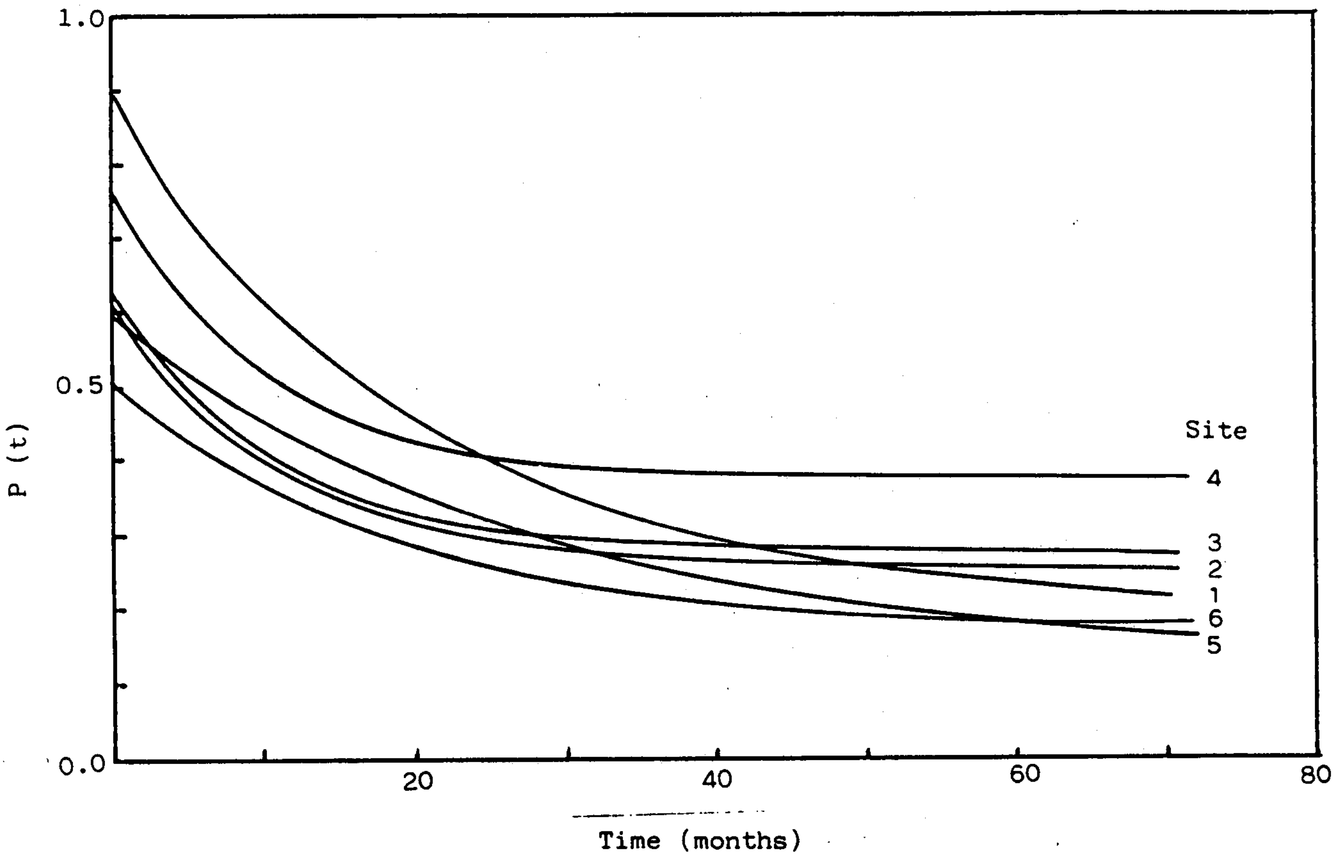

Figure 2   Change in penetration ratio with time

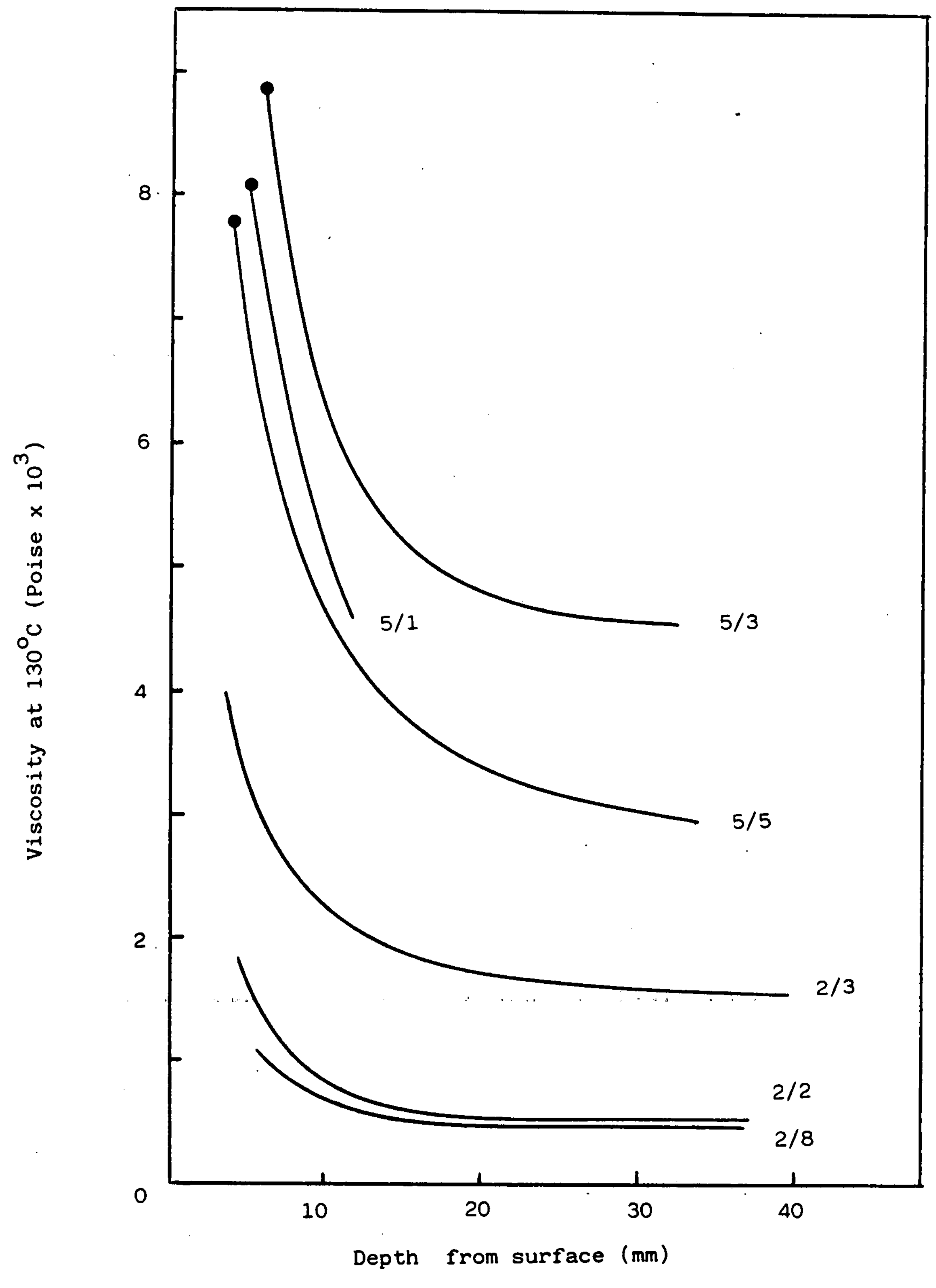

Figure 3 Viscosity of recovered bitumen with depth

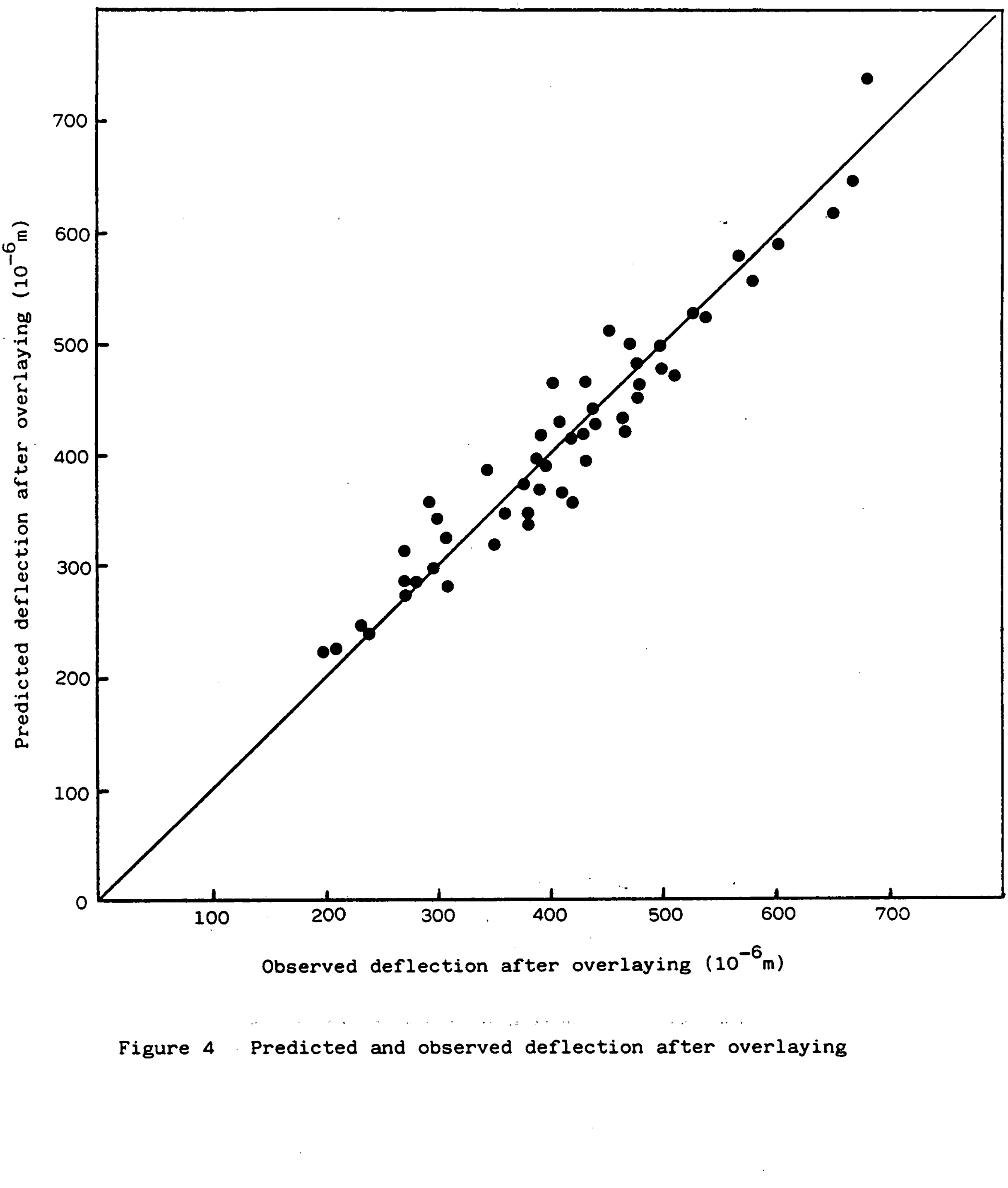

Figure 4 Predicted and observed deflection after overlaying

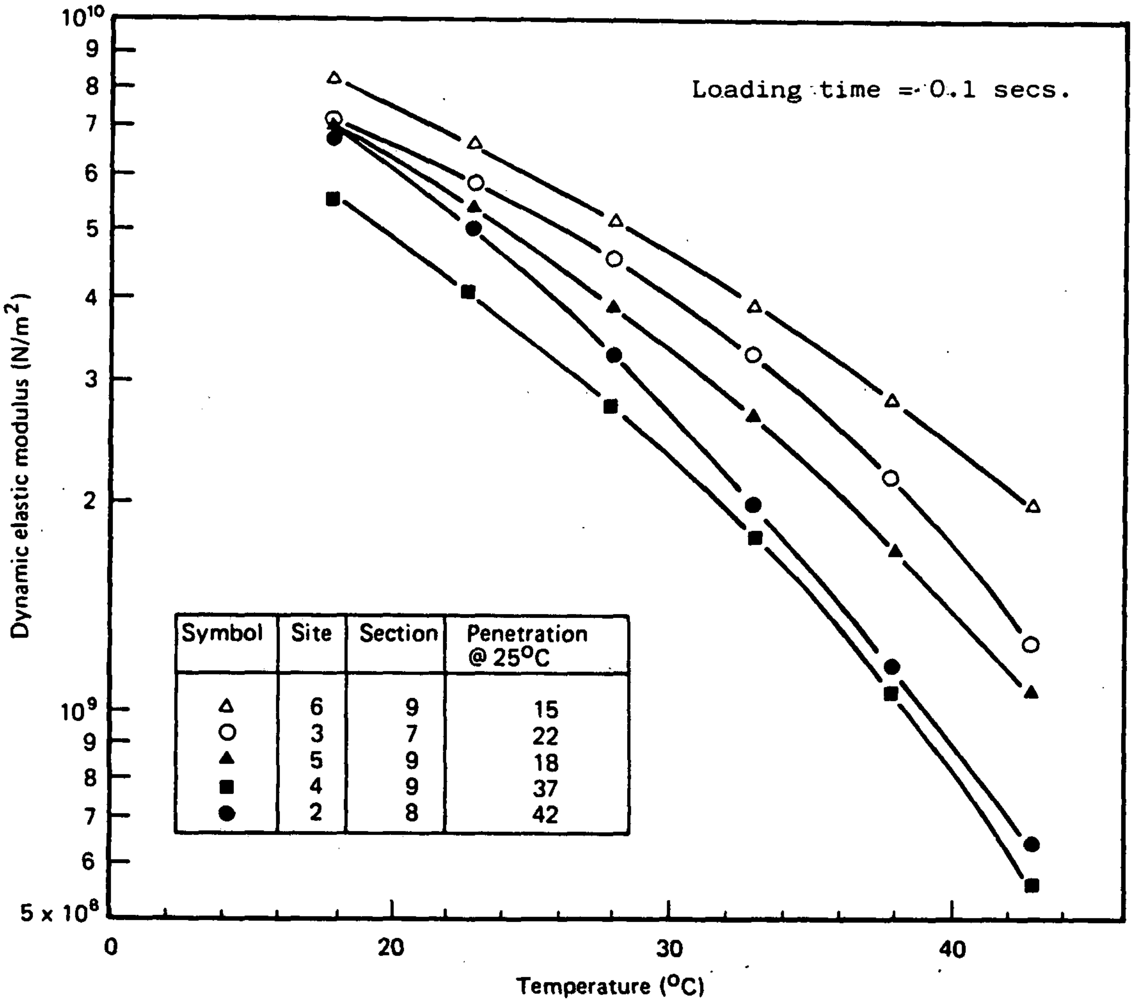

Fig. 5 Dynamic modulus of asphaltic concrete samples

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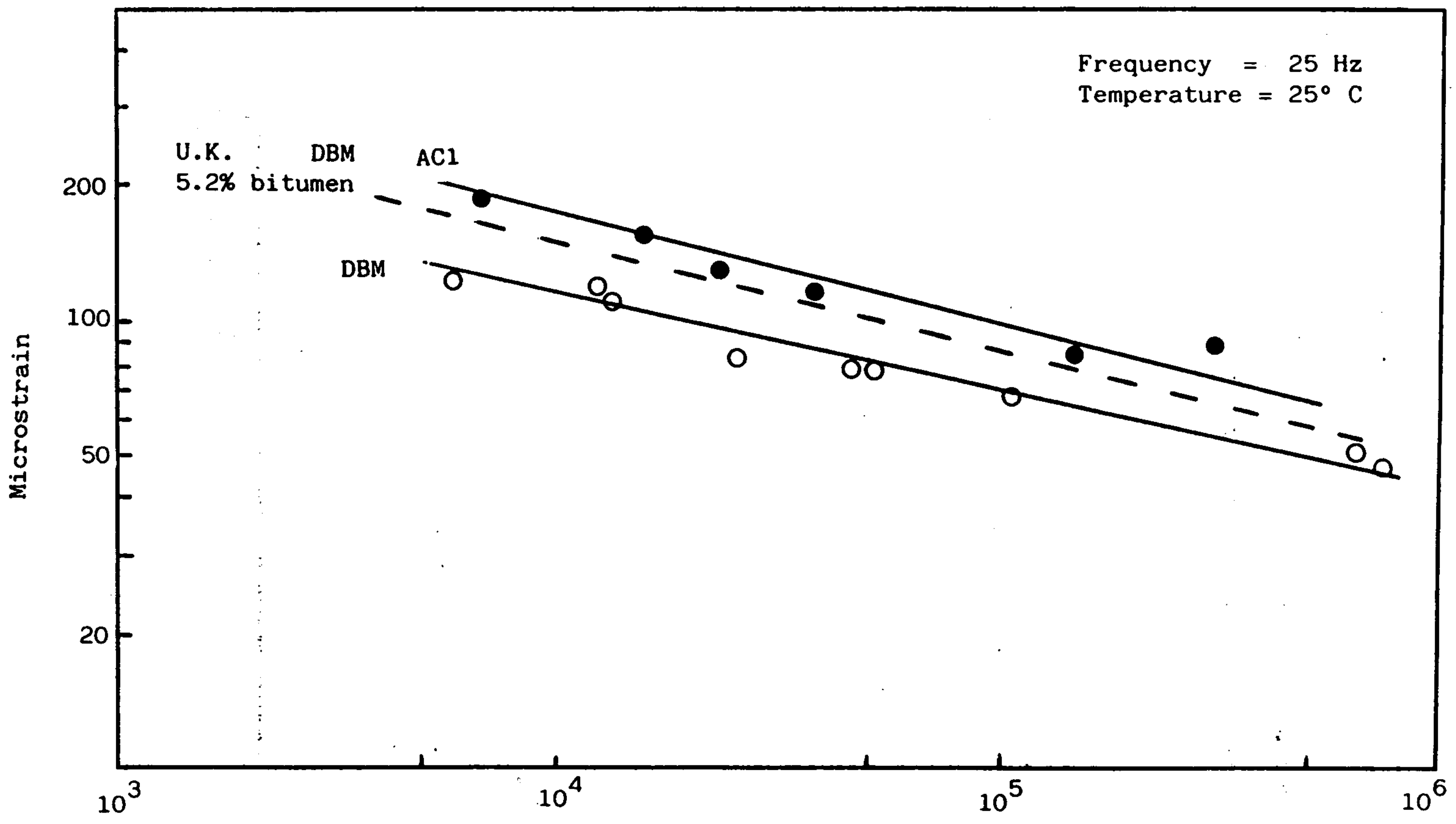

Figure 6 Fatigue life of overlays