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A LABORATORY STUDY OF THE MECHANICAL PROPERTIES
OF SAND/SULPHUR/BITUMEN MIXES

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A LABORATORY STUDY OF THE MECHANICAL PROPERTIES OF SAND/SULPHUR/BITUMEN MIXES

ABSTRACT
The mechanical properties of a sand/sulphur/bitumen mix comprising 80 per cent dune sand, 15 per cent sulphur and 5 per cent bitumen have been measured over a temperature range of 4-60°C and under stresses up to 900 kN/m². The fatigue properties and the tensile and flexural strength were found to be at least as good as high quality asphaltic concrete and the deformation properties, both static and dynamic, were found to be far superior. Deformation models were derived relating permanent strain to temperature, stress, pavement layer thickness, subgrade dynamic modulus and number of stress repetitions.

1 INTRODUCTION
The construction of road pavements in areas of dune sand usually requires the import of suitable aggregates from elsewhere. This is expensive and in many areas of the world it is becoming more so as aggregate resources become depleted and scarce. It should be more economical to stabilise the existing dune sand with bitumen but in the extreme climatic conditions of desert areas where road temperatures often exceed 60°C, sand/bitumen mixes are usually too weak to sustain vehicular traffic without excessive deformation and consequent failure.

The properties of sand/bitumen mixes can be considerably improved by the addition of sulphur. Sulphur is readily available in many parts of the world as a result of an oversupply from primary sources and because it is an unwanted byproduct of the petroleum, coal and natural gas industries where it is removed from fuels for environmental reasons. Indeed sulphur has been studied extensively for use in asphaltic concrete mixes where it can partially replace the more expensive bitumen and provide a cheaper and more deformation resistant mix (Haas et al 1980, Kandhal 1981).

Although there have also been some preliminary studies of the mechanical properties of sand/sulphur/bitumen (SSB) mixes, sufficient attention has not been given to the deformation and fatigue properties of such mixes under extreme loading and temperature conditions.

This paper describes a laboratory study of the mechanical properties of a candidate SSB mix.

The mix was tested both in the form of conventional cylindrical specimens and also as part of a model pavement which was designed to simulate better the stress conditions within a road. Emphasis was placed on the fatigue and deformation properties under dynamic loads over a wide temperature range but static properties were also measured. A complete characterisation of the mix was produced and mathematical models developed to describe the behaviour.

2 OBJECTIVES
The primary objectives of the study were:
1) To determine the following mechanical characteristics of a dune sand/sulphur/bitumen (SSB) mix over a range of temperatures and applied stresses.

![Relation between sulphur content and fatigue life for a sand/sulphur/bitumen mix](Burgess and Deme 1975)
3 MIX COMPOSITION

A number of laboratory studies of SSB mixes have been carried out in recent years. The primary purpose of the majority of these studies was to investigate the dependence of the Marshall properties (stability and flow) on the proportions of bitumen and sulphur in the mixes. Some of these studies are summarised in Table 1. Suitable compaction was usually achieved with two blows on one side of the Marshall specimens. Maximum stabilities ranged from 13–32 kN, depending on the type of sand, viscosity of the bitumen and the mixing sequence adopted. The optimum sulphur content i.e. the sulphur content corresponding to maximum stability, ranged from about 13 to 20 per cent and the optimum bitumen content from 4 to 6 per cent. Burgess and Deme (1975) investigated the fatigue behaviour of an SSB mix made using a medium-coarse sand and 150–180 penetration grade bitumen. The tests were carried out in the controlled stress mode using three point bending. The results are illustrated in Figure 1 where it can be seen that...
the optimum sulphur content is about 14 per cent for the conditions shown. The SSB mix was also found to be much less permeable than asphaltic concrete as illustrated in Figure 2.

Saylak et al (1975) reported that the stiffness of an SSB mix made with beach sand was approximately 2.5 times that of asphaltic concrete at high temperature (57°C) but slightly lower at low temperature (−6°C) as shown in Fig. 3. They also tested flexural specimens for fatigue by applying a half-wave sinusoidal loading of 100 cycles/min on the third point. All the tests were carried out at a constant temperature of 21°C. The results of these flexural fatigue tests on the SSB mixtures are shown in Fig. 4. The fatigue test results of Kallas and Puzinauskas (1972) and Irwin and Gallaway (1973) for asphaltic concrete, all of whom used a similar method of testing, are also shown for purposes of comparison. It may be seen from this figure that the fatigue behaviour of the SSB mixes is superior to that of asphaltic concrete.

On the basis of the literature reviewed and some preliminary deformation tests under dynamic loading on mixes containing 13–18 per cent sulphur and 3–8 per cent bitumen, a candidate mix containing 80 per cent dune sand, 15 per cent sulphur and 5 per cent bitumen was chosen for the detailed investigations.

The dune sand used in this investigation was obtained from Ballykinler on the east coast of Northern Ireland. General soil classification tests were performed on this material including sieve analysis, specific gravity test, moisture content—density relationship and X-ray diffraction analysis. The results indicated that this material has a rounded shape and a grading typical of the dune sand found in desert areas, varying from medium to fine sand with a uniformity coefficient \( D_{90}/D_{10} \) of 1.9 and specific gravity of 2.614. Figure 5 shows the grading curve of this Ballykinler sand compared with the grading curve of a sample of Zabul dune sand obtained from the Lut Desert, Iran, and with the grading curves of two other desert dune sands reported in the literature. The X-ray diffraction analysis for the major elements of the Ballykinler sand revealed that it contained 84% silica, and 8% aluminium oxide.

The sulphur used throughout this investigation was an elemental sulphur of commercial grade of 99% purity in a powdered form. The bitumen used was Middle East crude based, of 70 penetration grade which is probably the most suitable for the type of sand used (Al-Salloum 1973).

To observe the effect of an inert filler on the properties of the sand bitumen mixes for comparison with the effect of sulphur, samples were also prepared using limestone dust as the filler. This mix contained the same percentage of bitumen, namely 5 per cent, but the optimum quantity of filler was obtained from a
Prior to mixing, the dune sand was kept at 160°C for 24 hours. The bitumen, sulphur, mixing bowl and blade were preheated to 145°C and then the sand and bitumen mixed for 3 minutes. The liquid sulphur was then added followed by another 30 seconds of mixing. The mixture was added to the preheated 150 mm diameter cylindrical mould in three layers, each layer being spaded with a trowel in a similar fashion to that described in BS 598 Part 3 for preparation of Marshall specimens. No further compaction was found to be necessary. After cooling, the specimens were extruded from the mould and the central 100 mm diameter of the sample cored out. This procedure helped to minimise any edge effects and guaranteed more uniform specimens. All the cylindrical specimens for deformation testing were 175 mm in length. The cylindrical specimens for tensile strength and fatigue testing were cored from the model pavement blocks and were either 102 or 204 mm in thickness.

The weight of the model pavement specimens precluded laboratory scale manufacture. These blocks were therefore made in two tonne batches at a quarry site using industrial equipment. Again the ‘regular’ mixing procedure was used in which the preheated sand and bitumen are first mixed and then the sulphur added. The mix was poured into moulds designed to produce 455 mm square blocks of 51, 102 and 204 mm thickness and then gently tamped. This batch procedure had the added advantage that variations in mix composition between specimens was minimised.

The other mixes used in the study, namely asphaltic concrete, dense bitumen macadam and the sand/limestone filler/bitumen (SLB) mix were prepared using standard techniques.

### TABLE 2
Composition of aggregate mixes

<table>
<thead>
<tr>
<th>Sieve size (mm)</th>
<th>Percentage by weight passing</th>
<th>Dense bitumen macadam</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Asphalitic concrete</td>
<td></td>
</tr>
<tr>
<td>28</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>20</td>
<td>88</td>
<td>88.1</td>
</tr>
<tr>
<td>14</td>
<td>76</td>
<td>72.2</td>
</tr>
<tr>
<td>6.3</td>
<td>58</td>
<td>52.2</td>
</tr>
<tr>
<td>3.35</td>
<td>45</td>
<td>41.2</td>
</tr>
<tr>
<td>1.18</td>
<td>31</td>
<td></td>
</tr>
<tr>
<td>0.425</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>0.3</td>
<td>11</td>
<td>9.0</td>
</tr>
<tr>
<td>0.075</td>
<td>6</td>
<td>5.0</td>
</tr>
<tr>
<td>Bitumen content</td>
<td>5%</td>
<td>4.3%</td>
</tr>
<tr>
<td>Bitumen grade</td>
<td>70 pen</td>
<td>200 pen</td>
</tr>
</tbody>
</table>

### 5 FATIGUE TESTS

All fatigue tests on the cylindrical specimens were carried out in the axial controlled stress mode at a frequency of 10 Hz using a Mand machine. The initial tensile strains applied to the different specimens ranged from 45–220 microstrain. Three specimens were tested at each value of initial strain and the point of failure was defined either by a complete breakage of the specimen or by the point where the curve of the logarithm of initial strain versus the logarithm of the number of cycles of load showed a steep rise. In the latter case the point of failure was taken as the intersection of two
tangents to the curve and corresponds to the point at which a large decrease in stiffness occurs.

The initial tensile strains applied to the SSB specimens are plotted against the corresponding fatigue lives in Figure 6. All the specimens fractured completely, except for one specimen tested at an initial tensile strain of $43 \times 10^{-6}$. This test was discontinued after $10^6$ cycles of load application. Figure 6 shows that there is a linear relationship between the logarithm of the initial tensile strain and the logarithm of the number of cycles to failure, behaviour similar to that of more conventional mixes as confirmed by numerous research workers. The strain-fatigue life relationship was found to be

$$N = 2 \cdot 52.10^{-8}e_t^{-3.142} \quad (1)$$

where $N$ = the number of load repetitions to failure
$$e_t = \text{the initial tensile strain}$$

For comparison the results of the fatigue tests on the SLB mix and the asphaltic concrete are shown in Figure 7 together with some results obtained by Goddard, Powell and Applegate (1978) for a DBM mix using a similar method of test. The relationship obtained for the SLB mix was

$$N = 1 \cdot 67.10^{-12}e_t^{-4.10} \quad (2)$$

where $N$ and $e_t$ have been defined above. The Figure illustrates that the SSB mix is only slightly better than the SLB mix above an initial strain level of 50 microstrain but for practical purposes the differences are not important. The relationship for the asphaltic concrete was found to be

$$N = 1 \cdot 8.10^{-8}e_t^{-3.077} \quad (3)$$

which is also quite similar to the previous equations, differing significantly only at low values of initial strain where the equation has not been determined very precisely. By contrast the DBM tested by Goddard et al (1978) and containing only 2.7 per cent binder shows inferior fatigue behaviour. The dependence of fatigue behaviour on mix properties for conventional mixes is reasonably well understood and it is not the purpose of this paper to discuss this topic. The comparison merely illustrates that the behaviour of the SLB mix is as good as conventional mixes and that the presence of sulphur rather than an inert filler such as limestone seems to further enhance the fatigue performance although this effect is not strong. This is in broad agreement with the results of Hammond et al (1971) and Gallaway and Saylak (1974).

6 PERMANENT DEFORMATION
UNDER STATIC
LOAD-CREEP BEHAVIOUR

Twenty-seven cylindrical specimens of 100 mm diameter were tested under nine combinations of applied stress and temperature. The permanent axial deformation was recorded at different time intervals and analysed for the effect of applied stresses and temperatures. The applied stresses ranged from 300 to 900 KN/m$^2$ and the temperature from 4°C to 60°C.

To find a mathematical model to represent the static creep behaviour of the SSB mix, the least squares regression technique was used. It was found that there was a linear relationship between the logarithm of permanent strain and the logarithm of loading time at every
combination of stress and temperature. The values of slope and intercept of these lines are shown in Table 3, being dependent on the magnitude of the applied stress and the test temperature.

**TABLE 3**

Results of creep tests on the SSB mix

<table>
<thead>
<tr>
<th>Temperature °C</th>
<th>Stress KN/m²</th>
<th>Predicted from model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Measured values</td>
<td><strong>A(1)</strong></td>
</tr>
<tr>
<td>4</td>
<td>300</td>
<td>2.771</td>
</tr>
<tr>
<td>4</td>
<td>600</td>
<td>3.063</td>
</tr>
<tr>
<td>4</td>
<td>900</td>
<td>3.354</td>
</tr>
<tr>
<td>25</td>
<td>300</td>
<td>2.835</td>
</tr>
<tr>
<td>25</td>
<td>600</td>
<td>3.159</td>
</tr>
<tr>
<td>25</td>
<td>900</td>
<td>3.390</td>
</tr>
<tr>
<td>60</td>
<td>300</td>
<td>3.172</td>
</tr>
<tr>
<td>60</td>
<td>600</td>
<td>3.385</td>
</tr>
<tr>
<td>60</td>
<td>750</td>
<td>3.598</td>
</tr>
</tbody>
</table>

**NOTE:** 1) Equation 4

A general relationship defining the creep behaviour of the SSB mix was found of the following form:

$$e_p = 10^A \cdot t^B$$  \hspace{1cm} (4)

where $e_p$ is the permanent microstrain, 
$t$ is the loading time in seconds, 
$A$ and $B$ are constants depending on the applied stress, $\sigma$ kN/m², and test temperature, $\text{T} ^\circ \text{C}$, and are calculated from the following relationships:

$$A = 9 \cdot 714.1 \cdot 10^{-4} \cdot \sigma + 6 \cdot 0.161.10^{-3} \cdot \text{T} + 2 \cdot 456$$

$$B = 9 \cdot 014.10^{-5} \cdot \sigma - 5 \cdot 471.10^{-4} \cdot \text{T}$$

$$-1 \cdot 357.10^{-7} \cdot \sigma^2 + 0.117$$  \hspace{1cm} (5)

The equation for $A$ had an F value of 309 with 3,25 degrees of freedom and that for $B$ an F value of 127 with 5,25 degrees of freedom. An example of the data is shown in Figure 8 and plots of the predicted versus observed values of $A$ and $B$ are shown in Figure 9.

7 PERMANENT DEFORMATION UNDER DYNAMIC LOAD

The 100 mm diameter specimens were tested under different compressive sinusoidal stresses at temperatures of 4, 25 and 60ºC. The peak-to-peak amplitude of the sinusoidal stresses ranged from 300 to 900 kN/m².

An example of the results is shown in Figure 10 together with results for a DBM mix obtained...
by Snaith (1973). The relationship between the logarithm of the permanent deformation and the logarithm of the number of cycles of load was found to be linear for all stresses and temperatures. It can be seen from the Figure that not only is the 'intercept' for the SSB mix smaller than for the DBM under similar loading conditions but the slope of the line is also much less.

The permanent microstrain in the SSB mix, \( e_p \), occurring after \( N \) cycles of a dynamic stress of amplitude \( \sigma \) kN/m\(^2\) at a test temperature of \( T \) °C was found to be given by:

\[
e_p = 10^A \cdot N^B
\]  

(6)

where \( A \) is given by

\[
A = 1 \cdot 208 + 8 \cdot 488.10^{-4} \cdot \sigma \\
+ 1 \cdot 277.10^{-2} \cdot T
\]

(7)

with an \( F \) value of 146 and 6.25 degrees of freedom and \( B \) is given by

\[
B = 0 \cdot 2128 - 1 \cdot 726.10^{-4} \cdot \sigma \\
+ 3 \cdot 635.10^{-4} \cdot T + 9 \cdot 419.10^{-8} \cdot \sigma^2
\]

(8)

with an \( F \) value of 88 and 5.25 degrees of freedom. The actual and predicted values of \( A \) and \( B \) are shown in Table 4 and in Figure 11.

### Table 4

<table>
<thead>
<tr>
<th>Temperature °C</th>
<th>Stress kN/m(^2)</th>
<th>Measured values</th>
<th>Predicted from model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>( A^{(1)} )</td>
<td>( B^{(1)} )</td>
</tr>
<tr>
<td>4</td>
<td>300</td>
<td>1.604</td>
<td>0.1638</td>
</tr>
<tr>
<td>4</td>
<td>600</td>
<td>1.780</td>
<td>0.1475</td>
</tr>
<tr>
<td>4</td>
<td>900</td>
<td>1.956</td>
<td>0.1384</td>
</tr>
<tr>
<td>25</td>
<td>300</td>
<td>1.780</td>
<td>0.1792</td>
</tr>
<tr>
<td>25</td>
<td>600</td>
<td>2.017</td>
<td>0.1556</td>
</tr>
<tr>
<td>25</td>
<td>900</td>
<td>2.257</td>
<td>0.1404</td>
</tr>
<tr>
<td>60</td>
<td>300</td>
<td>2.071</td>
<td>0.1975</td>
</tr>
<tr>
<td>60</td>
<td>575</td>
<td>2.534</td>
<td>0.1638</td>
</tr>
<tr>
<td>60</td>
<td>705</td>
<td>2.680</td>
<td>0.1558</td>
</tr>
</tbody>
</table>

NOTE: \( ^{(1)} \) Equation 6

**Fig. 10.** Comparison of permanent strains in DBM and SSB under different dynamic vertical stress

**Fig. 11.** Predicted versus observed model parameters (dynamic deformation)
A mathematical model was also derived for the creep stiffness of the SSB mix after 10^6 cycles of load defined as follows:

\[
S_{\text{dynamic creep}} = \frac{\sigma}{(\text{final}-\text{initial permanent strain})}
\]

The equation was

\[
\log(S_{\text{dynamic creep}}) = 2 \cdot 819 + 0.896 \cdot \sigma - 1.343 \cdot 10^{-2} \cdot T \\
- 2.098 \cdot 10^{-5} \cdot T^2 - 0.434 \cdot \sigma^2
\]

with the applied stress, \(\sigma\), and \(S\) being in MN/m^2. The \(F\) value for this equation was 301 with 5, 25 degrees of freedom.

8 COMPARISON OF STATIC AND DYNAMIC CREEP BEHAVIOUR

The equivalent static stress is defined as that constant stress which produces the same permanent strain as a given dynamic stress when applied for the same total loading time, the loading time for sinusoidal compressive loading being defined as

\[
t = \frac{N}{2} \cdot f
\]

where \(N\) is the number of load cycles and \(f\) is the frequency. The ratio of the equivalent static stress to the peak-to-peak value of the dynamic stress (twice the amplitude) was found to have a mean value of 54.3 per cent with a standard deviation of 3.2 per cent. The value was independent of temperature and stress level.

9 PERMANENT DEFORMATION OF THE MODEL PAVEMENT

The model pavement blocks, each consisting of a two-layer combination of the SSB mix and simulated subgrade consisting of a rubber mat were tested at a number of combinations of parameters, i.e. test temperature, applied stress and subgrade modulus. Dynamic vertical stresses of the same magnitude as used in previous tests were applied at the centre of the block. This sinusoidal vertical stress was kept constant throughout the test and the permanent deformations at the centre of the block and at different radial distances from the centre were recorded. These values were analysed for the effect of different test parameters on the permanent deformation.

The Generalised Linear Interactive Modelling (GLIM) program was used to analyse the data and a number of different mathematical models were fitted to the results with varying degrees of success. It was again found that there is a linear logarithmic relationship between the permanent deformation and the number of stress applications at each combination of independent variables.

Both the slope and the intercept of the linear logarithmic relationships were found to depend on the applied stress \(\sigma\) kN/m^2, block thickness \(h\) mm, test temperature \(T\) °C and the dynamic modulus of the subgrade \(E\) kN/m^2. First of all the set of data for each test was analysed on its own to obtain the slope and intercept values. Attempts were then made to relate these parameters to the independent variables. The best models were again of the form

\[
P = A \cdot N^B
\]

where \(P\) is the permanent deformation at the centre of the block (mm)

\[
\log A \text{ is the 'intercept' of } \log P \text{ versus } \log N \text{ and is a measure of the initial deformation occurring in the early stages of loading}
\]

\(B\) is the slope

Both \(A\) and \(B\) are functions of \(\sigma\), \(T\), \(h\) and \(E\) as follows:

\[
B = -3.397 \cdot 10^{-3} + 5.617 \cdot 10^{-5} \cdot \sigma + 7.62 \cdot 10^{-4} \cdot T \\
- 5.574 \cdot 10^{-3} \cdot h + 3.833 \cdot 10^{-7} \cdot E \\
+ 2.766 \cdot 10^{-7} \cdot h \cdot \sigma + 3.79 \cdot 10^{-9} \cdot h \cdot E
\]

The \(F\) value for the equation was 136 with 7, 25 degrees of freedom. Full details of the statistical analysis used in the derivation of the model is given by Khodaii (1985)

\[
A = 0.6403 + 6.692.10^{-5} \cdot \sigma + 1.602.10^{-3} \cdot T \\
- 5.635.10^{-4} \cdot h - 2.638.10^{-9} \cdot E
\]
10 PREDICTION OF RUT DEPTH USING THE CREEP DATA

The method of Hills, Brien and Van de Loo (1974) for rut depth prediction was used to predict the final permanent deformation at the centre of a block specimen under dynamic load. This method is based on the assumption that the permanent deformation of bituminous mixes is a function of the viscous or non-elastic component of the bitumen stiffness \( S_{\text{bit,visc}} \).

The reduction, \( \Delta H \), in the thickness of the top bituminous layer is calculated from the following equation:

\[
\Delta H = \frac{Z \sigma_0 H_0}{(S_{\text{mix creep}})}
\]  

(12)

where \( Z \) is a dimensionless factor, \( \sigma_0 \) is the surface contact stress, \( H_0 \) is the thickness of this layer of modulus \( E \), and \( (S_{\text{mix creep}}) \) is the stiffness of the mix as derived from creep data.

Hills et al (1974) used elastic layer analysis to calculate numerical values of \( Z \) as a function of \( a/H_0 \), \( a \) being the radius of the applied load, and their results are shown in Figure 14. The upper curve is for ratios \( E_2/E_1 \) greater than \( 10^4 \) and applies to the situation in a tracking machine where the bituminous layer rests on a steel...
base-plate. The lower curve is for the ratio \( E_2/E_1 \) equal to about 0.1 corresponding to the case of the laboratory test track where the bituminous layer is laid on a base-course of compacted sand.

The lower of the two curves in Figure 14 was used to obtain the values of \( Z \) corresponding to the three values of \( a/H_0 \) for the block thicknesses of 51 mm, 102 mm, and 204 mm. The predicted permanent strains were compared with those measured on the block specimens with a high subgrade modulus of 200 mN/m² representing dense compacted sand.

The predicted permanent strain after \( 10^6 \) cycles of stress application, at the centre of the block specimen, is plotted against the measured value in Figure 15. The mean and the 95% confidence intervals are also shown. It can be seen that the method of Hills et al (1974) overestimates the permanent strain by a constant amount over the range. The percentage error is therefore small at the higher values of strain.

11 TENSILE STRENGTH

Various methods have been used in the past to measure the tensile strength of building materials, the most popular being the direct tension test, the beam or modulus of rupture test, the cylinder splitting or Brazilian test and the double punch test described by Fang and Chen (1971) and Jimenez (1977). The relative advantages and disadvantages of each method have been reviewed by Khodaii (1985). In this study the double punch test was used. The test is carried out by using two steel discs (punches) centred on both flat ends of a cylindrical specimen. A vertical load is applied until the specimen reaches failure. The tensile strength of the specimen is calculated from the maximum load by a simple equation based on the theory of plasticity as follows

\[
f_T = \frac{P}{\pi (c r_1 h - r_2^2)}
\]

where \( f_T \) is the tensile strength, \( P \) is the load at failure, \( r_1 \) is the radius of the specimen, \( r_2 \) is the radius of the punch, \( h \) is the height of the specimen, and \( c \) is a constant (1.2 for bound aggregate material).

In these tests both the height and diameter of the specimens were 102 mm and the radius of the punch 25 mm. The rate of loading was set at 1.25 mm per minute. Tests were carried out on the SSB mix, asphaltic concrete and DBM, at temperatures of 4°C, 25°C and 60°C. The results are shown in Figure 16. The SSB mix has a higher tensile strength than both the AC

![Fig. 15. Comparison of measured and predicted permanent strain](image)

![Fig. 16. Tensile strength of the SSB mix, asphaltic concrete and dense bitumen macadam at different temperatures](image)
12 FLEXURAL STRENGTH

The flexural strengths of beam specimens of the SSB and the SLB mix were tested according to ASTM method D-1635-63 using simply supported beams with third point loading at a deformation rate of 1.2 mm/min. The beam specimens were cut from the 455 mm square slabs manufactured for the model pavement tests. After cutting, the beams were 51 mm square by 200 mm long. Test temperatures were again 4°C, 25°C and 60°C. The results are shown in Figure 17. The flexural strength of the SSB mix is approximately 7 or 8 times greater than that of the SLB mix. The relationship between the tensile and flexural strengths is shown in Figure 18 the relationship between the two being

\[ f_T = 0.042 f_F^{1.23} \]  \hspace{1cm} (14)

13 SUMMARY AND CONCLUSIONS

This study was concerned with the feasibility of using dune sand as a paving material in hot desert areas by stabilising with bitumen and sulphur. A laboratory testing programme to determine the mechanical properties of a candidate sand/sulphur/bitumen mix has been completed. The sand used was uniformly graded with an average particle size of 0.3 mm and a uniformity coefficient of 1.9, quartz being the major constituent mineral. The sulphur content by weight was 15 per cent and the bitumen content 5 per cent, a combination which has been shown to have characteristics close to the optimum.

In addition to standard tests on cylindrical and beam specimens, a model pavement was designed and tested to determine the permanent deformation behaviour of the mix under simulated road conditions.

The temperature range of the tests was 4–60°C and loading stresses up to 900 kN/m² peak to peak were used. The principal results are as follows:

1) In the controlled stress mode of fatigue testing using uniaxial tensile stresses the relationship between strain and fatigue life was found to be of the same form as for conventional mixes (equation 1). The performance of the SSB mix was at least as good as that of high quality asphaltic concrete.
The relationship between the logarithm of axial permanent strain under a constant static stress and the logarithm of the duration of loading was found to be linear for all combinations of stress and temperature. A suitable model was derived relating the coefficients of the relationship to temperature and applied stress (equations 4 and 5).

The relationship between the logarithm of axial permanent strain under a dynamic sinusoidal compressive stress and the logarithm of the number of stress cycles was also found to be linear for all combinations of stress and temperature. A mathematical model was derived relating the coefficients of the relationship to temperature and applied stress (equations 6, 7 and 8).

A comparison of static and dynamic deformation behaviour showed that a static stress of 54.3 per cent of the peak-to-peak dynamic stress produces the same deformation for the same total loading time.

The deformation behaviour of the model pavement followed the same mathematical form as that of the cylindrical specimens namely

\[ P_d = A \cdot N^B \]

where \( P_d \) is the permanent deformation, \( N \) is the number of load cycles and \( A \) and \( B \) are constants. In this equation \( A \) and \( B \) are functions of temperature, stress level, pavement layer thickness and subgrade dynamic modulus. The values are estimated from equations 10 and 11.

The deformation behaviour of the model pavement could also be predicted reasonably accurately from the creep characteristics obtained in a standard laboratory creep test, the theoretical method overestimating the actual deformation by about 17 per cent at a total measured strain of 5 per cent.

The tensile strength of the SSB mix was found to be twice as high as that of asphaltic concrete at 4°C but the difference decreased with temperature such that the SSB was only slightly stronger at 60°C.

The relationship between flexural and tensile strength was found to be of the form

\[ \text{Tensile strength} = k \cdot (\text{Flexural strength})^m \]

where \( k \) and \( m \) are constants.

The mechanical properties of the SSB mix were always at least as good as those of high quality asphaltic concrete and even at high temperatures the deformation behaviour was far superior. It was not possible to determine the long term effect of environmental factors in these studies but previous work has shown that SSB mixes have extremely low permeability. It would therefore be expected that age hardening and degradation of the bitumen would be considerably less than for conventional asphaltic concrete mixes. The long term effect of severe environmental conditions on the sulphur and the sulphur/bitumen combination is not known but evidence from studies of sulphur extended asphalt indicates that this may not be a serious problem. If this can be confirmed by means of a full scale trial, SSB mixes should perform exceptionally well in hot desert areas.

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15 REFERENCES


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