THE DEVELOPMENT OF STRUCTURAL DESIGN MODELS FOR FOAMED BITUMEN TREATED MATERIALS

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INTRODUCTION

The use of foamed bitumen treated materials in the construction of pavement layers is increasing both in South Africa and internationally. These materials are used as a method of cold treatment, and are particularly useful when used in conjunction with the Deep In Situ Recycling (DISR) technology. With the growing need to construct new roads for rural access in southern Africa and to rehabilitate existing roads, these materials are a viable option, because of the many advantages associated with their use, including:

- The ability to open the rehabilitated road to traffic immediately after construction, thereby eliminating the need to construct temporary detours and minimizing traffic disruption;
- Cheaper construction costs than standard methods of rehabilitation;
- Lower quality aggregates can be effectively used in pavement layers when treated with foamed bitumen, and
- Environmental savings through the reuse of natural materials.

Although foamed bitumen treated materials have been successfully used for a number of years, the structural adequacy of these materials has not been quantitatively proven. Recently, research has been performed to assess the structural performance of foamed bitumen materials.

The data used to develop the structural design models were obtained from both laboratory and Heavy Vehicle Simulator (HVS) testing. This paper discusses the development of these models. The paper begins with a discussion on the materials used to generate the data, then discusses the HVS and laboratory tests, and finally, presents the transfer functions. The models were developed from data on one material type and are most applicable to materials similar to this parent material. The models will be calibrated, modified and updated as more data become available.

MATERIALS

The material used in the laboratory testing was obtained from the HVS test site, after milling. The original pavement consisted of the surfacing (consisting of multiple seals), a cement stabilised ferricrete base layer, an untreated ferricrete subbase layer and a natural subgrade layer. The pavement was recycled with a Wirtgen type recycling machine to a nominal depth of 250 mm. The recycled material therefore contained the milled surfacing and ferricrete from the base and subbase layers. The grading of the milled material is shown in Figure 1. Although the grading conforms to that of a crushed stone material, based on other considerations, the untreated material is classified as a G7[1].

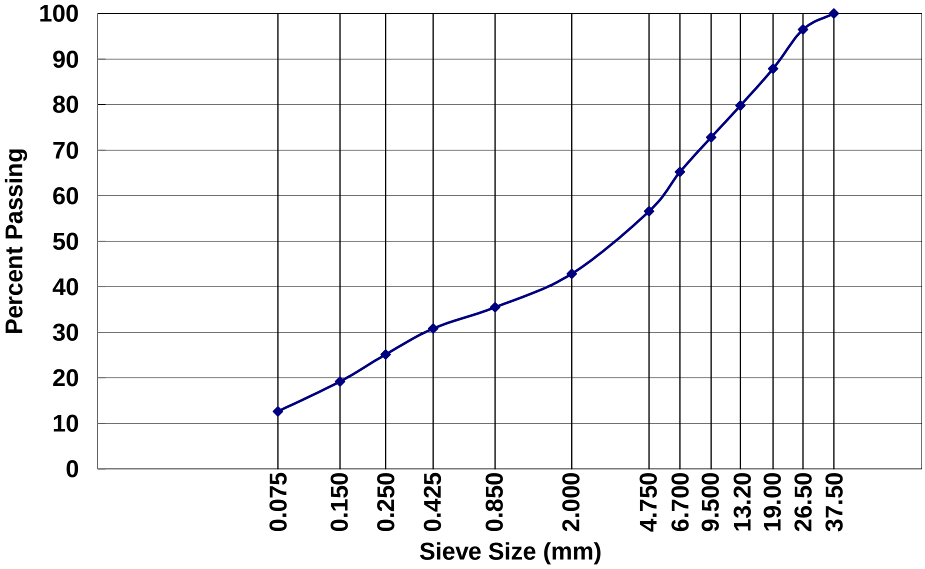


Figure 1. Milled Material Grading

The HVS test sections were constructed using DISR. The milled material was treated with 2 percent cement and 1.8 percent foamed bitumen. The material for the laboratory tests was treated in the laboratory over a range of cement and foamed bitumen contents.

HEAVY VEHICLE SIMULATOR TESTS

Two HVS sections were tested, 409A4/B4[2] and 411A4[3]. The HVS loads the pavement with dual wheels on a half axle. A 40 kN load is therefore assumed to transmit 20 kN through each tyre. This 40 kN HVS dual wheel load is equivalent to a standard axle load of 80 kN. Section 409A4/B4 was trafficked for 300 000 repetitions with an 80 kN dual wheel load (800 kPa tyre pressure), and thereafter with a 100 kN dual wheel load (850 kPa). Water was added for 8 000 repetitions at the end of the test. Section 411A4 was loaded for 950 000 repetitions with a 40 kN dual wheel load (620 kPa), and thereafter with an 80 kN dual wheel load (800 kPa). Water was added for 14 000 repetitions at the end of the test

Various instruments were used on the test sections, including multi-depth deflectometers (MDD). Two MDDs were installed on Section 409A4 and three on Section 411A4.

HVS Test Results

Back-calculated Elastic Stiffness

The elastic deflections measured in-depth with the MDDs were used to back-calculate the effective elastic stiffness values for the various pavement layers. The stiffnesses are back-calculated from the deflection caused by a 40 kN HVS dual wheel load. The stiffness values of the base layers are shown in Figure 2 for both test sections for all the MDDs. The scatter in the data is due to the scatter in the deflection data, which is, in turn, largely due to variability in the materials and construction. The back-calculation procedure is also sensitive to small changes in the measured deflections.

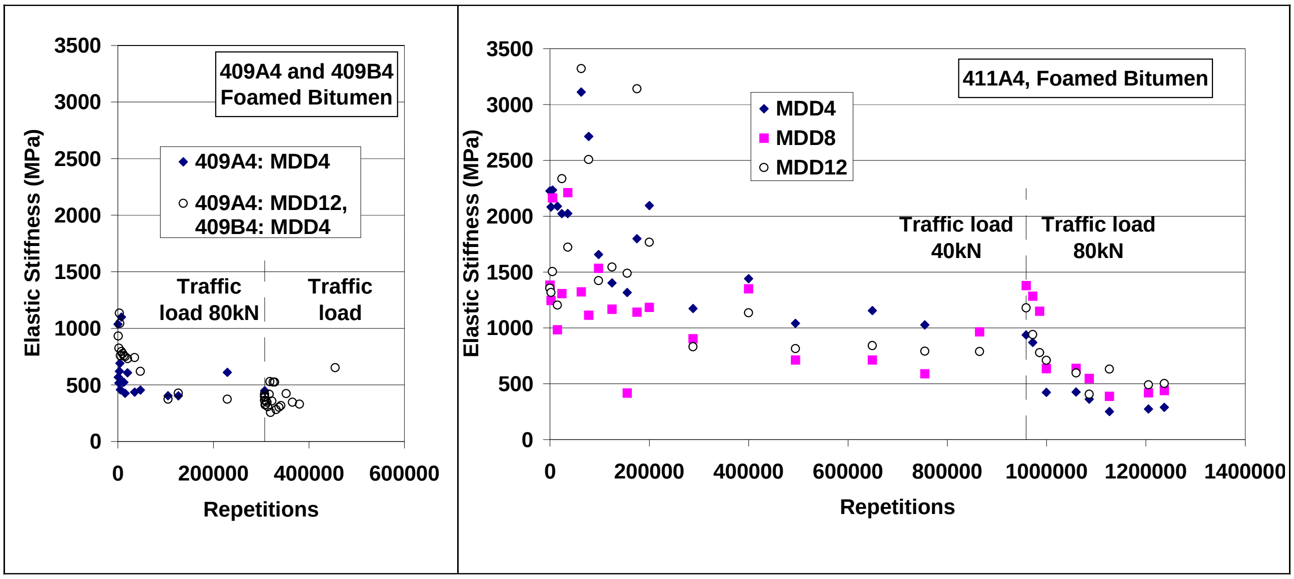


Figure 2. Back-calculated Base Layer Stiffnesses from MDD Measured Deflections

The initial stiffness of the materials is highly variable. For Section 409A4, the initial stiffness is between approximately 900 and 1100 MPa. Section 411A4 shows a large amount of variability, with an initial stiffness between 1250 and 3100 MPa. Because the initial stiffness is measured after 10 repetitions, the test section trafficked at the higher starting load had a lower initial stiffness, which demonstrates the rapid reduction in stiffness in the early stages of a test. This rapid reduction in stiffness is similar to the behaviour of cement treated materials[4].

As the test progressed, the elastic stiffness of the base layer reduced. This reduction was at a faster rate in the early stages of the test, and then decreased very gradually, seemingly to an asymptotic value. For Section 411A4 under the 40 kN load, the stiffness appeared to be decreasing gradually and had not reached a terminal value at the end of the test. When the load was increased to 80 kN, the stiffness decreased to approximately 250 to 550 MPa, with an average of approximately 400 MPa. The terminal value under the 80 kN load on Section 409A4 was approximately within the same range, and increasing the load to 100 kN did not result in a further decrease in the elastic stiffness. This indicates that, regardless of the load, the foamed bitumen treated material ultimately reaches the same equivalent granular state. From the trend in the data it seems reasonable to assume that, under the 40 kN load, the same equivalent granular state would have been reached. This material is very load sensitive in that the trafficking load determines the number of repetitions to reach the equivalent granular state. The time to reach this equivalent granular state is defined as the effective fatigue life.

The term “equivalent granular state” is used to describe the loss in resilient modulus (stiffness) of the material and is comparable to granular materials only in the stiffness and not in the physical composition of the materials. The term does not imply that the material is in a loose condition consisting of individual particles. The reduction in stiffness results in: less protection for the underlying layers; possibly higher shear stresses within the layer relative to the shear strength of the material; and increased horizontal strains at the bottom of the asphalt layer, contributing to increased asphalt fatigue.

At different combinations of cement and foamed bitumen, the behaviour may not be the same as experienced in the HVS test sections, which have 2 percent cement and 1.8 percent foamed bitumen. However, without data for different combinations to suggest otherwise, it is reasonable to expect some similarities in the behaviour, in that a reduction in stiffness to an equivalent granular state under loading will be experienced. The time to reach an equivalent granular state is likely to be different for different combinations of cement and foamed bitumen.

Permanent Deformation

Surface permanent deformation was measured with the straight-edge, and the accumulation of in-depth permanent deformation was measured with the MDD. Figure 3 shows an example of the results from MDD8 on Section 411A4. The higher loads resulted in a higher rate of rutting. Once water was added to the section, the rutting increased dramatically. Although significant rutting was only experienced after the addition of water, known as moisture accelerated distress (MAD), there was still relatively little permanent deformation. The rut was formed by fines being pumped to the sides of the test section.

A considerable amount of the rut occurred in the layers underlying the foamed bitumen treated base under the higher wheel load. The difference between the deformation of MDDs at the top and bottom of the layer can be subtracted to obtain the deformation for that layer, as shown in Figure 3. This in-depth permanent deformation data for the base layer is used to develop the structural design models.

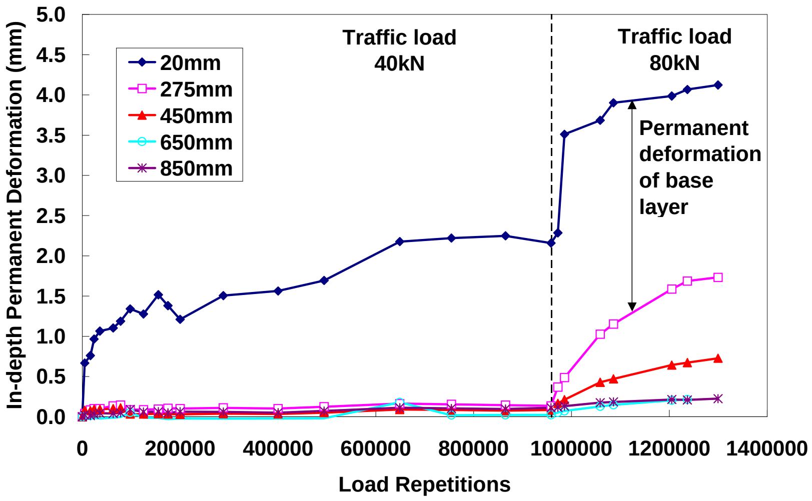
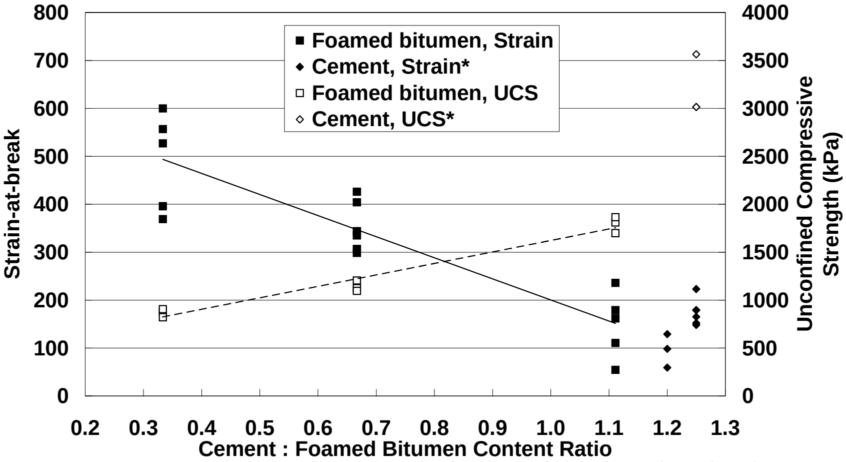


Figure 3. In-depth Permanent Deformation for MDD8, Section 411A4

LABORATORY TESTING

Several laboratory tests were performed on the material milled from the HVS site and treated in the laboratory, including: indirect tensile strength test (ITS), unconfined compressive strength test (UCS), flexural beam test, and static and dynamic triaxial tests. The foamed bitumen contents used were 0, 1.8, 3, and 5 percent with cement contents of 0, 1 and 2 percent. Not all tests were run at all combinations of cement and foamed bitumen contents. The specimen preparation, laboratory tests and test results are discussed by Long and Theyse[1], and Robroch[5].

The laboratory testing results showed that, by treating the materials with foamed bitumen and cement, their properties were improved. The addition of cement significantly contributes to the permanent deformation resistance, and the addition of foamed bitumen significantly contributes to the flexibility of the material. This is demonstrated in Figure 4 where the strain-at-break values from the flexural beam tests are plotted on the left hand side vertical axis, as a function of the ratio of the cement to foamed bitumen contents. The strain-at-break values give an indication of the flexibility and, therefore, the fatigue resistance of the materials. The unconfined compressive strength (UCS) values are plotted on the right hand side vertical axis. The UCS values give an indication of the compressive strength, and therefore the permanent deformation resistance of the materials. Included in the figure are data for the same milled material treated with 1 and 2 percent cement and no foamed bitumen, plotted at arbitrary ratios of 1.2 and 1.25, respectively[1].



* Cement treated with 2 percent cement and no foamed bitumen. Values plotted at an arbitrary ratio of 1.25 for 2 percent cement and 1.2 for 1 percent cement.

Figure 4. Strength and Flexibility of Foamed Bitumen Treated Materials

Figure 4 clearly shows how the flexibility of the material decreases with an increase in the cement to foamed bitumen content ratio, whereas the compressive strength increases. The addition of foamed bitumen contributes significantly to the fatigue resistance of the mix, although, if not enough foamed bitumen is added, these benefits are significantly reduced. Some minimum compressive and flexural strength is needed in the material and this is best provided by the addition of cement. The exact proportions of cement and foamed bitumen that should be included in a mix depend on the specific project, and the required balance of flexibility to compressive and flexural strengths.

Permanent Deformation in the Dynamic Triaxial Test

Dynamic triaxial tests were performed to assess the permanent deformation behaviour and structural capacity of the mix. The tests were performed at two relative densities and saturation levels and run at two confining stresses (80 and 140 kPa) and three stress ratios (0.20, 0.55 and 0.90). Relative density and stress ratio are defined in Equations (1) and (2)[6].

$$\mathrm{RD} = \frac{\text{dry density}}{\mathrm{ARD} \cdot \text{density of water}} \qquad (1)$$

$$\mathrm{SR} = \frac{\sigma_1^a - \sigma_3^a}{\sigma_1^m - \sigma_3^a} = \frac{\sigma_1^a - \sigma_3^a}{\sigma_3^a\left(\tan^2\left(45^\circ + \frac{\phi}{2}\right) - 1\right) + 2C\tan\left(45^\circ + \frac{\phi}{2}\right)} \qquad (2)$$

In the equations, RD is the relative density, ARD is the apparent relative density or specific gravity, SR is the stress ratio, $\sigma^a{}_1$ and $\sigma^m{}_1$ are the applied and maximum allowable major principal stresses, $\sigma^a{}_3$ is the applied minor principal stress, C is the cohesion and ϕ is the friction angle.

A regression model is fit to the permanent deformation accumulation curve of each specimen tested in the dynamic triaxial test. The form of the model and the data fits are discussed by Long[1,8]. These regression models were used to calculate the structural capacity (load repetitions) to a specific plastic strain (PS) as a function of the relative density (RD), stress ratio (SR) and the ratio of the cement to foamed bitumen contents (cem/bit), the form of which is shown in Equation (3). The letters a to e are regression coefficients.

$$\log\ N = a + b \cdot RD + c \cdot PS + d \cdot SR + e \cdot (cem/bit) \qquad (3)$$

The model shown in Equation (3) was combined with the HVS permanent deformation results to develop a field calibrated permanent deformation design model.

STRUCTURAL DESIGN TRANSFER FUNCTIONS

The philosophy used to develop the structural design procedure is founded on examining the material behaviour and distress mechanisms in the pavement from the laboratory and HVS tests. This behaviour is then related to engineering parameters determined from mechanistic analyses of the pavement structure. Transfer functions are developed relating the observed distress to the engineering parameters. The process involves interpolating and extrapolating the available data to obtain a general procedure applicable to a wider range of pavement types and foamed bitumen layers. The interpolating, extrapolating and the development of the transfer functions rely heavily on engineering judgement. This is the same philosophy used to develop the South African Mechanistic-Empirical Design Method (SAMDM)[4] and is used in TRH4[7].

The two major forms of distress on the HVS test sections are permanent deformation and effective fatigue. Structural design and performance models were determined for both modes of distress[8].

The transfer functions determine the structural capacity to reach the terminal distress state. The terminal distress conditions assumed are 20 mm of rutting or shear failure in the critical layer or fatigue cracking on the surface of the pavement[4]. The extent of the distress depends on the road category. Five percent of the total design section length is allowed to have failed at the end of the structural design life of the pavement for Road category A, whereas road categories B, C and D allow 10, 20 and 50 percent[4].

Effective Fatigue of Foamed Bitumen Treated Materials

The effective fatigue transfer function was determined from the elastic stiffness data in Figure 2 and is the number of load repetitions to reach the equivalent granular state. For the 40 kN load case, a straight line was fitted to the gradually decreasing stiffness data for each MDD, and extrapolated to determine the number of repetitions to a stiffness of 400 MPa, indicative of the equivalent granular state. A straight line fit gives a conservative estimate. The effective fatigue lives for the 40 and 80 kN load cases are shown in Table 1.

Table 1. Effective Fatigue Life of Foamed Bitumen Treated Base

Load Case	Effective Fatigue Life
40 kN	2 000 000 1 560 000 2 200 000
80 kN	20 000 75 000

These data give the effective fatigue life as a function of the high and low wheel loads, and a straight line can be fit to the data to determine the effective fatigue life at any wheel load. Such a model is only applicable to the specific materials, pavement structure and environmental conditions of the HVS test sections. For a general pavement design procedure it is necessary to adapt such a model to estimate the effective fatigue life using an engineering parameter determined from a mechanistic pavement analysis.

Mechanistic Pavement Analysis for Effective Fatigue

In the SAMDM and TRH4, the pavement structures are usually modelled using multi-layer linear elastic theory[4,7]. The engineering parameter typically used for the effective fatigue life is the ratio of the tensile strain at the bottom of the pavement layer to the maximum tensile strain that the material can sustain at crack initiation, called the strain ratio[4,7]. Mechanistic analyses were performed to determine the induced tensile strain at the bottom of the pavement layer. The induced tensile strain values were obtained for each MDD from each HVS test section. The stiffness values used in the analyses were the initial stiffnesses and the layer thicknesses were determined from the test pit data[2,3]. The maximum tensile strain is determined from the strain-at-break from a laboratory flexural beam test[1,5].

The average laboratory strain-at-break (ε_b) value for the 2 percent cement and 1.8 percent foamed bitumen combination and the induced tensile strains (ε) from the mechanistic pavement analyses, were used to calculate the strain ratio ($\varepsilon/\varepsilon_b$)[1]. These data were then used to revise the effective fatigue function developed from the HVS data, with the strain ratio replacing the wheel load.

This transfer function was adapted to account for the different reliability levels of the different traffic categories. The transfer function is shown in Equation (4) and in Figure 5. The R^2 of the transfer function regression fit is 0.79.

$$N_F = 10^{\left[A - 0.708\left(\frac{\varepsilon}{\varepsilon_b}\right)\right]} \qquad (4)$$

In Equation (4), N_F is the effective fatigue life, A is 6.339 for Category A roads, 6.499 (Category B), 6.579 (Category C), and 6.619 (Category D), $\varepsilon/\varepsilon_b$ is the strain ratio, ε is the induced tensile strain at the bottom of the layer, and ε_b is the strain-at-break.

This transfer function is developed from the HVS test sections, for a base layer with 2 percent cement and 1.8 percent foamed bitumen. There are no HVS data available to check this effective fatigue function for different combinations of cement and foamed bitumen contents or using a different material. Until data are available to modify the transfer function, the effect of different foamed bitumen and cement contents are only accounted for in the strain-at-break value. Using the transfer function shown in Figure 5, if a higher strain-at-break is determined from a mix tested with an increased foamed bitumen content the strain ratio is reduced and consequently a longer effective fatigue life is obtained.

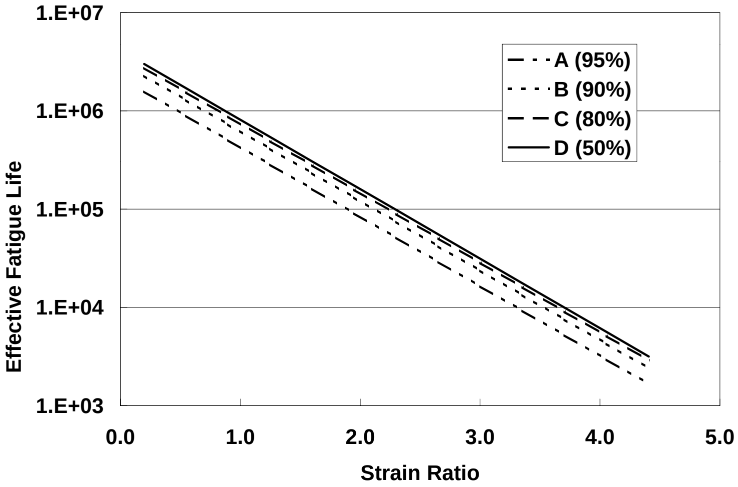


Figure 5. Effective Fatigue Life Transfer Function

The end of the effective fatigue life is not a terminal distress. The pavement is not likely to have failed and will continue to support loading in the equivalent granular state. The SAMDM procedure should be followed to analyse the phases of the pavement life[4].

Permanent Deformation of Foamed Bitumen Treated Materials

Once the foamed bitumen layer has reached the equivalent granular state, the permanent deformation of the layer becomes the critical distress.

The structural design model for permanent deformation of the foamed bitumen treated material was developed from the in-depth permanent deformation of the base layer measured by the MDDs on the HVS test sections and the permanent deformation response measured in the laboratory with the dynamic triaxial test. The laboratory model was calibrated with the HVS model.

In-depth MDD HVS Permanent Deformation Data

The first step in developing a structural design model was to fit a regression model to the MDD permanent deformation data for the base layer, an example of which is shown in Figure 3. The model determines the permanent deformation after a selected number of load repetitions. Justification for the selection of this model is discussed by Theyse[6] and the model fits are discussed by Long[8].

Because of the variation in MDD data along a test section, the model is fitted to each MDD from both test sections, rather than averaging the data. To determine the permanent deformation for the treated base layer only, the deformation of the MDD module at 275 mm is subtracted from the deformation of the top MDD module (25 mm). Only the data from the first loading sequence for each test section were used in these analyses. The data for the second sequence of loading have a load history, which is difficult to incorporate correctly.

Using the regression model from the MDD data it is possible to determine a simple equation to predict the repetitions to a certain level of permanent deformation (or plastic strain) for a given wheel load. The model is formulated in terms of plastic strain to allow for the use of different layer thicknesses. The plastic strain is the ratio of the permanent deformation to the initial layer thickness, as a percentage.

The model is calibrated by determining the permanent deformation (in terms of plastic strain) for a series of repetitions generated using the MDD regression model. This gives a range of data for each wheel load and MDD. These data, for all the MDDs, are then used to fit a model, shown in Equation (5), where N_{PD} is the structural capacity, PS is the plastic strain (%), WL is the wheel load (kN), and a, b, and c are regression coefficients.

$$\log N_{PD} = a + b \cdot PS + c \cdot WL \qquad (5)$$

This model is only applicable to the specific pavement structure and material properties at the HVS test site, and is not useful for general design and analyses purposes. For this, it is necessary to have a transfer function that estimates the structural capacity of any pavement structure with a foamed bitumen treated layer. This should account for the different material properties of the treated layer and layer thicknesses from pavement to pavement. This is typically done by estimating material properties from laboratory or field testing, or from recommended values, and then analysing the pavement to determine a mechanistic parameter that is related to the structural capacity.

A mechanistic parameter which has been recommended for granular materials is the stress ratio, defined in Equation (2)[6]. The stress ratio is the inverse of the factor of safety, used in the SAMDM for granular materials. As recommended in the SAMDM, a tensile principal stress is set equal to zero and the magnitude of the minor principal stress is added to the major principal stress so the deviator stress is the same magnitude[4]. Theoretically, a stress ratio greater than one indicates a shear stress failure. It was decided to develop the permanent deformation transfer function as a function of the stress ratio. This entails determining the critical (maximum) stress ratio in the foamed bitumen treated layer and using this parameter in the place of the wheel load in Equation (5).

Traditionally in SAMDM[4], granular materials are evaluated in the middle of the layer, between the tyres. However, this was not found to be the critical location for foamed bitumen treated layers. It is therefore recommended that the stress ratio is evaluated at all four locations illustrated in 0. The largest of the four values should be used in the further analyses.

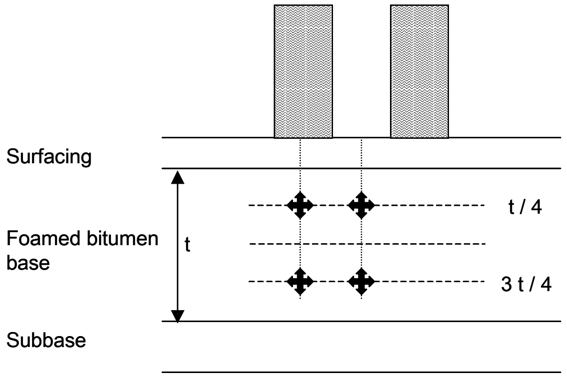


Figure 6. Recommended Locations to Calculate the Stress Ratio

The increase in permanent deformation in the HVS test sections is at a much more gradual rate than the reduction in stiffness. Much of the permanent deformation occurs once the foamed bitumen layer has reached the equivalent granular state. For this reason the stress ratios were determined using the initial back-calculated stiffnesses for all layers other than the foamed bitumen treated layer, for which the equivalent granular state value of 400 MPa was used.

To determine the stress ratios of the HVS test sections, multi-layer linear elastic analyses were performed for all the MDDs on each test section. The values calculated for each test section showed little variation. For the 40 kN section, 411A4, the average stress ratio was 0.21 and for the 80 kN section, 409A4, the average stress ratio was 0.33. These stress ratios are used to replace the wheel load variable in Equation (5).

Calibration of Laboratory Transfer Function with HVS Transfer Function

The permanent deformation model from the dynamic triaxial tests (Equation (3)) is a function of the plastic strain, stress ratio, relative density and the cement to bitumen content ratio. The HVS transfer function (Equation (5) with the stress ratio replacing the wheel load) is for the specific combination of 1.8 percent foamed bitumen and 2 percent cement of the foamed bitumen layer in the HVS test sections. The HVS model also does not directly account for the relative density, although it has an influence on the cohesion and friction angle values in the calculation of the stress ratio. To determine a transfer function that directly accounts for the relative density and is applicable to other cement and foamed bitumen contents, the laboratory model (Equation (3)) was calibrated with the HVS model. Using both models the structural capacities were calculated using: a range of plastic strains; the stress ratios calculated for the HVS pavements; a relative density of 0.73, which is the estimated relative density of the HVS test sections; and, the cement to bitumen content ratio of 1.111. These results are shown as the solid diamonds in Figure 7, in which the results from the laboratory and HVS models are compared.

The laboratory model predicts a larger structural capacity than the HVS model, but the trends in the data are the same. The laboratory test was performed on new material that had not experienced damage. The loads were relatively small so the specimen was not significantly damaged during the test. Therefore, it is reasonable to expect that the structural capacity estimated using the laboratory model would be greater than for the HVS model. The boundary conditions of the HVS test are similar to those of a pavement in the field, and it is therefore likely that the HVS results are closer to field results than the laboratory results. It is therefore reasonable to shift the laboratory model predictions to be in closer agreement with the HVS model predictions.

By calibrating the laboratory and HVS permanent deformation transfer functions as described above, a general transfer function to determine the structural capacity of all types of pavement structures with a foamed bitumen treated layer with any combination of foamed bitumen and cement was developed. This transfer function is given in Equation (6) and illustrated in Figure 8 for an assumed plastic strain of 9 percent. The R^2 of the original laboratory model from which Equation (6) was calibrated was 0.81, and only the statistically significant variables were included in the model.

$$N_{PD} = \frac{1}{30} \cdot 10^{\left[-B + 11.938 \cdot RD + 0.0726 \cdot PS - 1.628 \cdot SR + 0.691 \left(cem / bit\right)\right]} \qquad (6)$$

In Equation (6), N_{PD} is the structural capacity (load repetitions), RD is the relative density (proportion), PS is the plastic strain (percent), SR is stress ratio (proportion), defined in Equation (2), and cem/bit is the ratio of bitumen and cement contents (percent). B is 2.047 for Category A roads, 1.951 (Category B), 1.816 (Category C), and 1.625 (Category D).

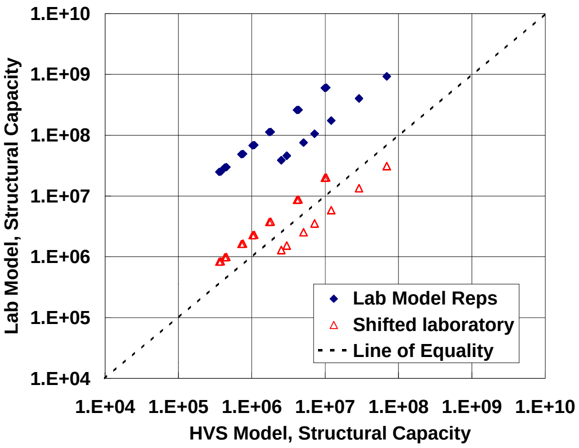


Figure 7. Comparison of Laboratory and Permanent Deformation HVS Transfer Functions

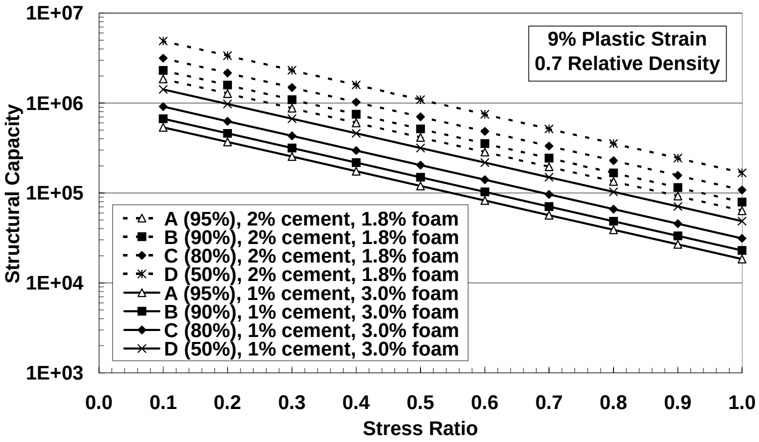


Figure 8. Permanent Deformation Transfer Function

CONCLUSIONS AND RECOMMENDATIONS

This paper described the development of structural design models for foamed bitumen treated materials for incorporation into the SAMDM. The models were developed for effective fatigue and permanent deformation from HVS data and calibrated and expanded to a wider range of pavement and material conditions using laboratory data.

The laboratory tests showed that foamed bitumen improves the flexibility and therefore the fatigue resistance of the material, with higher foamed bitumen contents showing higher flexibility. However, with the addition of cement, a minimum amount of foamed bitumen is necessary to affect the flexibility. The cement improves the compressive strength and therefore the permanent deformation resistance of the material. The optimum balance between the cement and foamed bitumen contents depends on the desired material properties.

Preliminary structural performance models for the foamed bitumen treated material were determined from the HVS data, both for permanent deformation and for effective fatigue. The models determine the number of load repetitions to the selected failure criteria as a function of the wheel load. Using the laboratory data and mechanistic pavement analyses, these models were converted to determine the structural capacity or effective fatigue life as a function of an engineering parameter determined from mechanistic pavement analyses. The stress ratio was used for permanent deformation and the strain ratio was used for effective fatigue.

The effective fatigue transfer function predicts the expected pavement life to reach an equivalent granular state. On the HVS test sections, regardless of the load, an equivalent granular state was reached at approximately 400 MPa. The transfer function determines the effective fatigue life, which is the pavement life to reach the equivalent granular state. The equivalent granular state does not imply the pavement has reached a terminal failure condition, rather that the end of this phase of the pavement life has been achieved.

The permanent deformation transfer function was determined from dynamic triaxial tests over a range of relative densities and stress ratios to various levels of plastic strain for two combinations of foamed bitumen and cement. This model was calibrated with the permanent deformation response observed on the HVS site.

The HVS test sections include a foamed bitumen treated milled ferricrete with 2 percent cement and 1.8 percent foamed bitumen. A wider range of foamed bitumen and cement contents were tested in various laboratory tests. The structural design models (transfer functions) were developed from these available data and are therefore most applicable to situations with similar cement and foamed bitumen contents and materials similar to the filled ferricrete. The models will be calibrated, modified and updated as more data become available. Gathering more data for different materials has been identified as a key research priority.

ACKNOWLEDGEMENTS

The laboratory and HVS testing used to develop the structural design models were funded by the Gauteng Provincial Government, Department of Public Transport, Roads and Works. The development of the design models was funded by SABITA, and managed on their behalf by the Asphalt Academy.

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I got my Ph.D. in Civil Engineering from the University of California at Berkeley in 2001. My dissertation work focussed on modelling rutting of asphalt pavements.

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