Performance models for deep in situ recycled, bitumen stabilised pavements under accelerated traffic

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ABSTRACT: This paper describes research to assess the use of foamed bitumen and bituminous emulsion treated materials with deep in situ recycling (DISR) technology. The paper discusses Heavy Vehicle Simulator (HVS) and laboratory test results on these materials. The results showed that the treated materials have higher resistance to permanent deformation than fatigue. The HVS sections failed after the addition of water, exhibiting erosion and pumping. The laboratory test results show that treating the material with bituminous binders and cement increases the permanent deformation resistance, and if enough binder is added, the flexibility of the material improves. The HVS data are used to develop preliminary structural design models for effective fatigue and permanent deformation, and to determine damage factors. The materials are more load sensitive in fatigue than permanent deformation.

1. INTRODUCTION

The use of foamed bitumen and bituminous emulsion treated materials in the construction of pavement layers is increasing both nationally 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 often be able to open the rehabilitated road to traffic soon after construction, thereby eliminating the need to construct temporary detours and minimizing traffic disruption.
- Cheaper construction costs than standard methods of rehabilitation [World Highways, 2001].
- Marginal aggregates can be effectively used in pavement layers when treated with foamed bitumen or bituminous emulsion.

Although foamed bitumen and bituminous emulsion treated materials are being successfully used in South Africa for a number of years, the structural adequacy of these materials has not been proven and no mechanistic-empirical structural design guidelines for their use are available. Research is currently underway to assess their use in the road-building industry. This research includes the following assessment techniques: laboratory testing, Heavy Vehicle Simulator (HVS) testing, and field trials. This work will create the knowledge base from which guideline documents and design methods can be developed. The main aspects that are being investigated include:

- The engineering properties, such as the bearing strength, permeability and erodibility, of the materials.
- The mechanical properties, such as the stiffness, shear strength and strain-at-break, of the materials.
- The material and pavement behaviour and performance under repeated loading.
- All aspects that impact on the above such as design, construction and maintenance.

This paper discusses results from HVS and laboratory testing on foamed bitumen and bituminous emulsion treated materials. The HVS test results are used to determine structural design and performance models for both fatigue and permanent deformation, for the particular materials tested, and load sensitivity and damage factors are estimated.

2. TEST SECTION MATERIALS AND CONSTRUCTION

The Heavy Vehicle Simulator (HVS) test sections were constructed on Road P243/1 between Vereeniging and Balfour in the Gauteng Province of South Africa. The original pavement consisted of the original surfacing made up of multiple seals, the cement stabilised ferricrete base layer, the untreated ferricrete subbase layer and the natural subgrade layer.

The original pavement was recycled with a Wirtgen recycling machine to a nominal depth of 250 mm. The recycled material contains the milled surfacing, cement stabilised ferricrete from the base layer and a small amount of the untreated ferricrete subbase layer. A large quantity of this milled material was retained for laboratory testing. The optimum moisture content of the milled material is 12.5 percent, and maximum dry density is 1970 kg/m^3. The gradation of the material is shown in Figure 1. The gradation of the milled material is similar to that of a crushed stone material [Long and Theyse, 2001].

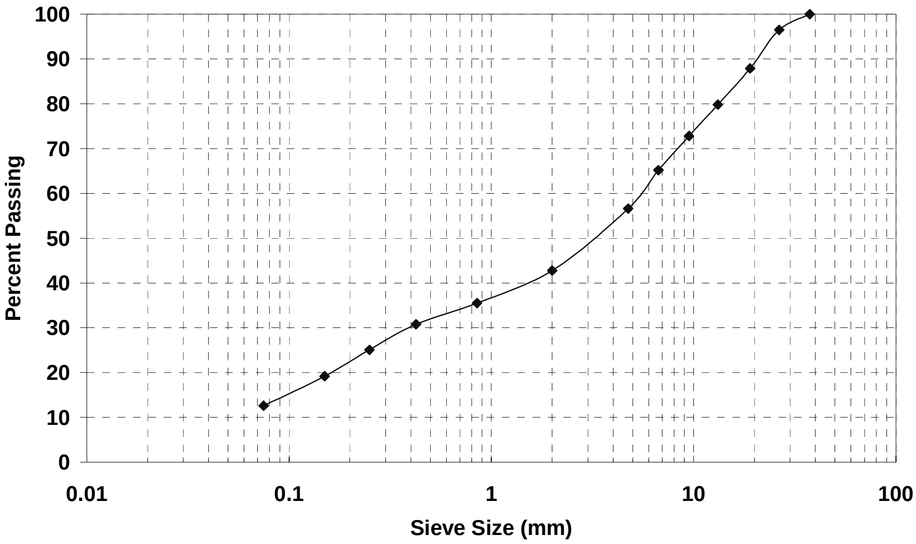


Figure 1. Gradation of Milled, Untreated Ferricrete

The majority of the road was rehabilitated by treating the recycled material with foamed bitumen, and a 100 metre section was recycled with bituminous emulsion. The foamed bitumen treated sections were treated with 1.8 percent residual bitumen (80/100 pen) and 2 percent cement. The bituminous emulsion was treated with 3 percent 60/40 anionic bituminous emulsion (1.8 percent residual binder) and 2 percent cement. A spring near the test sections resulted in high moisture contents, both before and after construction.

The design thicknesses of the rehabilitated pavements consist of 25 mm asphalt concrete surfacing, 250 mm of either foamed bitumen or bituminous emulsion treated ferricrete, 250 mm untreated ferricrete subbase and the natural subgrade.

3. HEAVY VEHICLE SIMULATOR (HVS) TESTING

Two HVS test sections were tested on each of the foamed bitumen and bituminous emulsion treated base pavements. The exact location of the test sections were selected from areas of fairly uniform falling weight deflectometer deflections. The foamed bitumen treated sections were designated 409A4/B4 and 411A4. The bituminous emulsion treated sections were designated 410A4/B4 and

412A4. The analyses of these test sections are discussed by Steyn [2001], Mancotywa [2001], and Long and Theyse [2002b].

The 40 kN emulsion treated section (412A4) has stronger support than the other sections, and the 40 kN foamed bitumen treated section (411A4) had the weakest support. The 80 kN emulsion treated section (410A4/B4) has slightly stronger support than the 80 kN foamed bitumen treated section (409A4/B4).

3.1 Loading Sequence

The HVS testing consisted of two phases, which are detailed in Table 1. In Phase 1, after the application of the 80 load repetitions, the HVS was moved to create a new test section. This new 8 m test section consisted of 4 m of the previous test section, and 4 m of untrafficked pavement [Steyn, 2001]. During the wet testing water is continuously applied to the pavement surface during trafficking.

Table 1. HVS Test Section Loading Sequence

PHASE 1				
Test Sections	**Repetitions**	**Load (kN)**	**Tyre Pressure (kPa)**	**Comments**
409A4 (foamed bitumen)	307 224	80	800	
409B4 (foamed bitumen)	147 606	100	850	
	7 694	100	850	Water added
410A4 (bituminous emulsion)	295 617	80	800	
410B4 (bituminous emulsion)	171 500	100	850	
	13 907	100	850	Water added
PHASE 2				
Test Sections	**Repetitions**	**Load (kN)**	**Tyre Pressure (kPa)**	**Comments**
411A4 (foamed bitumen)	958 714	40	620	
	340 883	80	800	
	14 048	80	800	Water added
412A4 (bituminous emulsion)	957 714	40	620	
	346 969	80	800	
	17 610	80	800	Water added

3.2 Instrumentation

During an HVS test the elastic deflection, permanent deformation, temperature, and moisture conditions are measured and visual observations made at regular intervals. Various instrumentation was used including: multi-depth deflectometer (MDD), road surface deflectometer (RSD), falling weight deflectometer (FWD), laser profilometer, straight edge, thermocouples, and dynamic cone penetrometer (DCP). The MDDs were installed at the following depths in the pavement structure: 25 mm, 275 mm, 450 mm, 650 mm, and 850 mm. Two MDDs were installed in Sections 409A4 and 410A4, and three MDDs in Sections 411A4 and 412A4. For reference, the 8 m HVS test section is labelled every half a meter, from 0 to 16. The MDD number is a reference to the location on the test section, i.e., MDD4 is at point 4.

3.3 Results

The only results from the HVS tests discussed in this paper are those that either add insight into the test section behaviour, or are used to develop the structural design and performance models.

3.3.1 Surface Permanent Deformation

Surface rutting was measured with a straight edge. Figure 2 shows the straight edge measured average surface permanent deformation. The data in the early stages of a test is fairly variable. This is because of the coarseness of the measurement device, and in the small amounts of rutting experienced. The measurements below 2 mm of rutting are therefore fairly inaccurate.

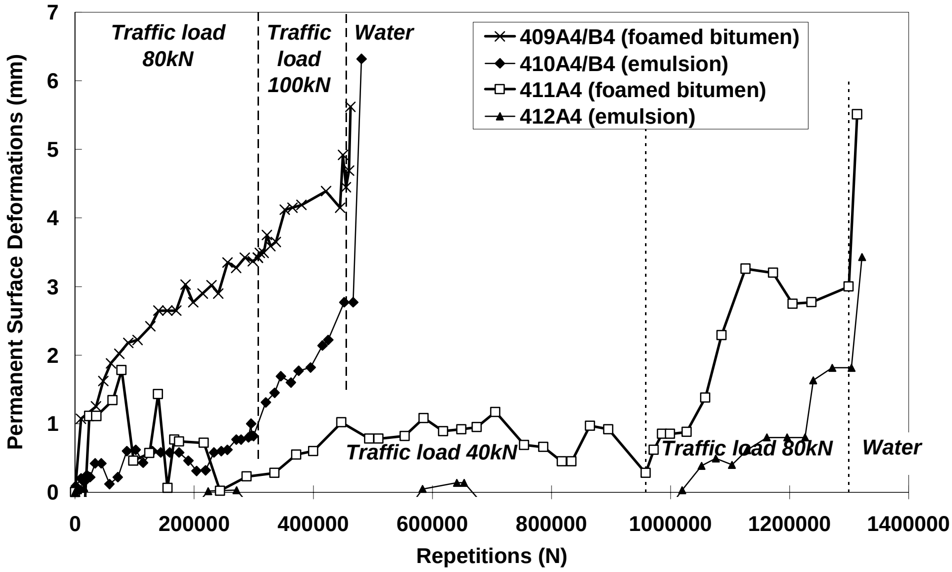


Figure 2. Surface Permanent Deformation

As expected, the higher loads resulted in more rutting. Once water is added to the section, the permanent deformation increases dramatically. This is known as moisture accelerated distress (MAD). Although the deformation increases with addition of water, there is relatively little permanent deformation.

The emulsion treated test sections seem to have performed better in terms of surface rutting compared to the foamed bitumen treated test sections. The improved performance on the 40 kN emulsion section is in some part due to the stronger support on this section.

3.3.2 In-depth Permanent Deformation

The accumulation of in-depth permanent deformation is measured with the MDD. Figure 3 shows an example from MDD8 on Section 411A4. The difference between the deformation at two MDD depths can be subtracted to obtain the deformation for that layer, as shown in Figure 3 for the foamed bitumen treated base layer. The use of the in-depth permanent deformation to develop structural design models is discussed further in Section 5.2.

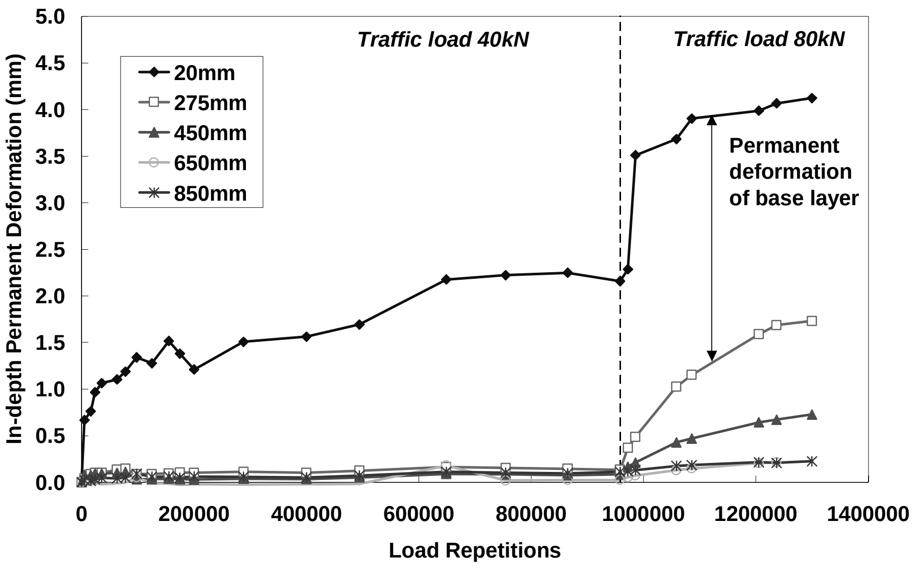


Figure 3. In-depth Permanent Deformation for MDD8, Section 411A4

3.3.3 Elastic Deflections

The elastic surface deflections measured with the RSD are shown in Figure 4. A fairly wide range of deflections is measured along the test section. The values shown in Figure 4 are the averages for the data measured along the centreline. As an example of the variation across a test section, all the RSD data points are shown in Figure 5 for Section 411A4. The data points from the first four meters of the test section (points 0 to 8) are shown in the solid diamonds, and for the second four meters (point 8 to 16) as open squares. The average is shown for the longitudinal centreline. It is clear that the first portion of the test section had higher deflections, therefore lower stiffness than the second part. This variation in deflections across the test sections explained the differences in the measurements obtained from MDDs on the same test section.

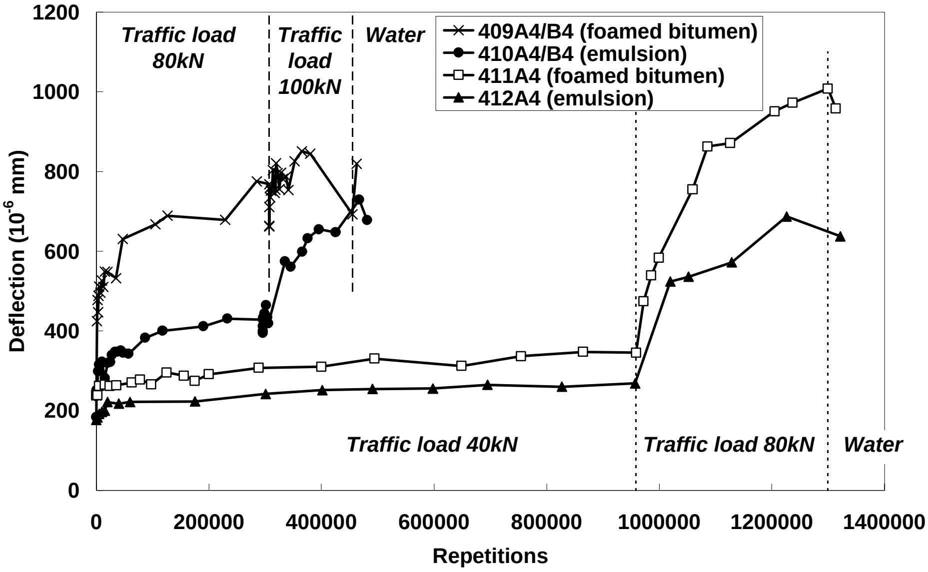


Figure 4. Elastic Surface Deflections Measured with the RSD

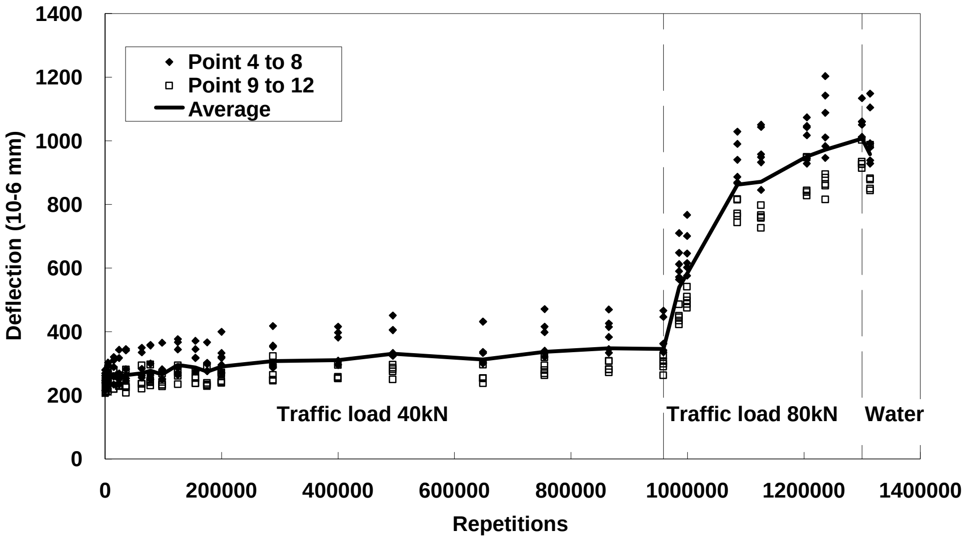


Figure 5. Elastic Surface Deflections on Section 411A4

Higher deflections were experienced for the tests run at the higher loads, as expected. The increase in traffic loading resulted in a fairly large increase in the deflections for the foamed bitumen treated sections, but did not result in such a significant increase in the bituminous emulsion treated section. The deflections were higher for the foamed bitumen treated sections than for the emulsion treated sections. This is partly due to the improved support conditions on the emulsion treated sections.

After water is added to the test sections, the deflections appeared to decrease, which is unexpected. The deflections were influenced by the extent of the cracking on the test section and the amount of cracking increased dramatically after water was added.

3.3.4 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. Regardless of the trafficking load, the stiffnesses are back-calculated from the deflection caused by a 40 kN wheel load. The stiffness values of the base layers are shown in Figure 6 for the four test sections. The data for all the MDDs on each test section are shown to demonstrate the variability in stiffness experienced along the test sections. Similar variability was experienced in the deflection data. The scatter in the data is due to the scatter in the deflection data, and the back calculation procedure. Despite the variability, trends are still clearly observable.

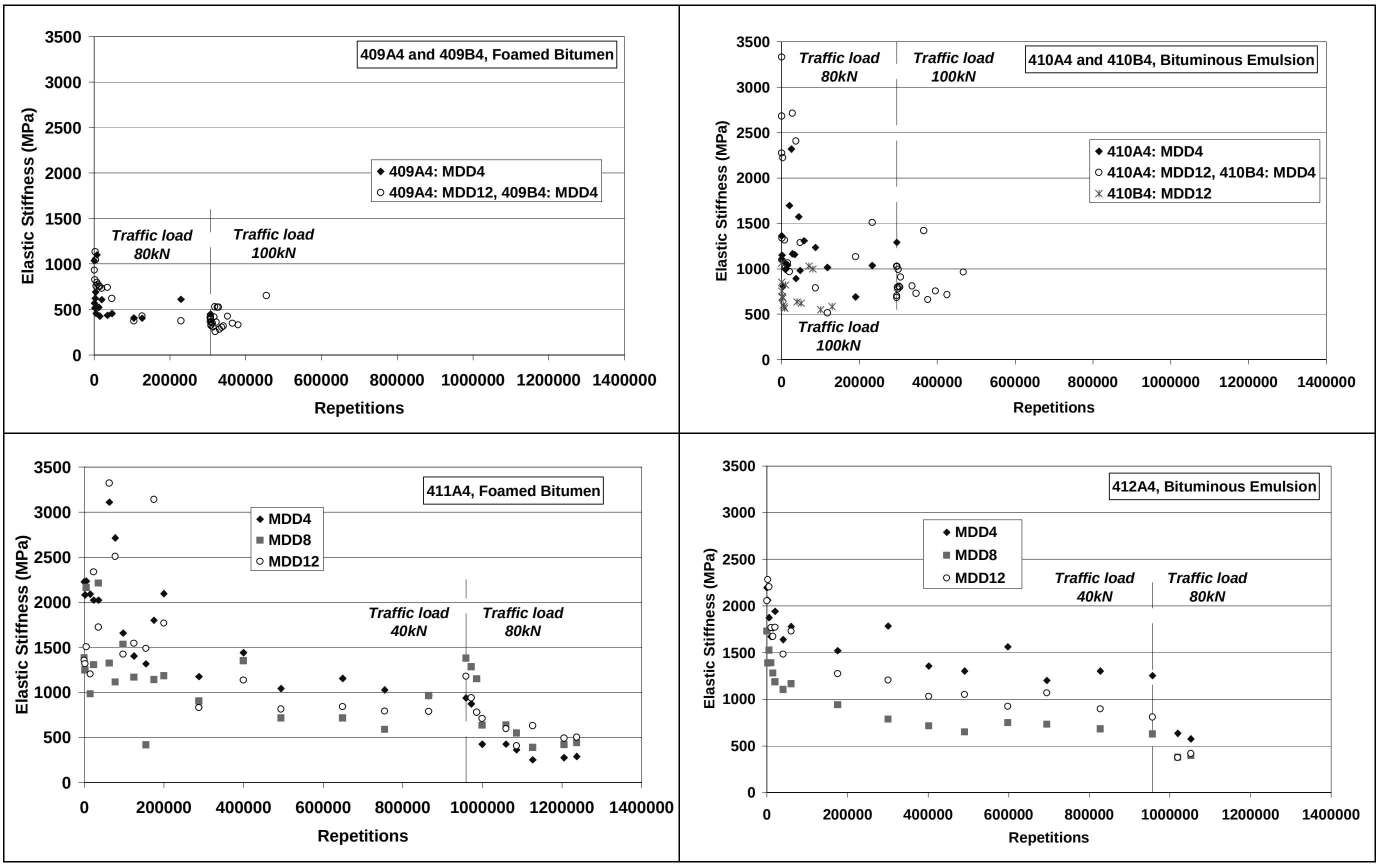


Figure 6. Back-calculated Base Layer Stiffnesses from MDD Measured Deflections

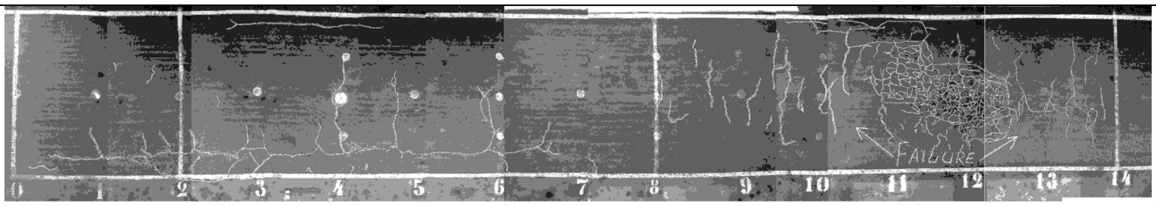
The initial stiffness of the materials was highly variable. For Section 409A4, the initial stiffness was between approximately 900 and 1100 MPa. Section 411A4 showed a large amount of variability, with an initial stiffness between 1250 and 3100 MPa. The initial stiffness of the bituminous emulsion treated material ranged between 1100 and 2650 MPa for Section 410A4, 850 and 1050 MPa for Section 410B4, and 1400 and 2300 MPa for Section 412A4. Because the initial stiffness was measured after 10 repetitions, the test sections trafficked with the higher starting load had a lower initial stiffness, which demonstrates the rapid reduction in stiffness in the early stages of a test.

As the test progresses, the elastic stiffness of the base layer reduced. This reduction was at a faster rate in the early stages of the test, and then flattened off, seemingly to an asymptotic value termed the equivalent granular state. When the load was increased, the stiffness reduced further. For Sections 411A4 and 412A4 under 40 kN loads, the stiffnesses appeared to be decreasing gradually and have not reached a terminal value. When the load was increased to 80 kN, the stiffnesses decreased to approximately 250 to 550 MPa for the foamed bitumen treated base and 400 to 600 MPa for the bituminous emulsion treated base. Representative values for the equivalent granular state are 400 and 500 MPa for the foamed bitumen and bituminous emulsion treated base layers. The terminal values under the 80 kN loads on Sections 409A4 and 410A4 were within approximately the same range as the corresponding 40 kN sections, and increasing the load to 100 kN did not result in further decreases in the elastic stiffnesses. This indicates that, regardless of the load, the treated materials ultimately reach an equivalent granular state. It seems reasonable, from the trend in the data, to assume that under the 40 kN loads the same equivalent granular states would have been reached. The term “equivalent granular state” is used to describe the loss in stiffness of the materials 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.

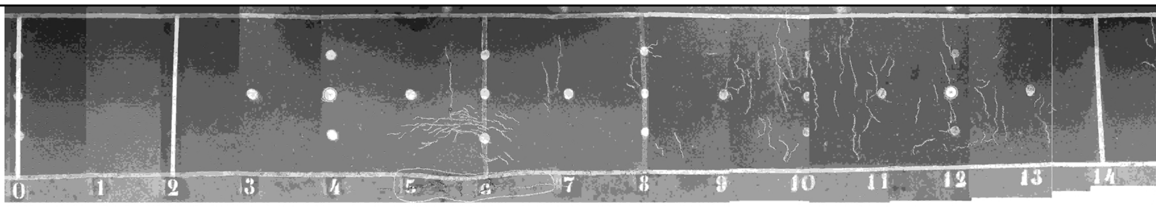
The materials are very load sensitive in that the trafficking load determined the number of repetitions to reach the equivalent granular state. This number of repetitions is termed the effective fatigue life. These elastic stiffness data are used to determine structural design models for effective fatigue in Section 5.1.

3.3.5 Visual Observations

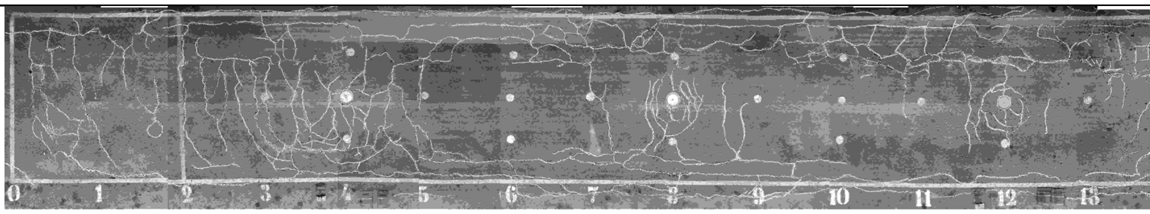
The cracking of the test sections is monitored visually and recorded on camera. The test sections showed very good performance, with very little visible cracking before the addition of water and rut depths of less than 7 mm. In general, when the sections were trafficked with the addition of water, the distress accumulated rapidly, with severe cracking being experienced. The permanent deformation also increased more rapidly. This is known as moisture accelerated distress (MAD). The tests were stopped when continuous trafficking on the disintegrating surface had the potential to damage the HVS. Photographs of the completed test sections are shown in Figure 7.



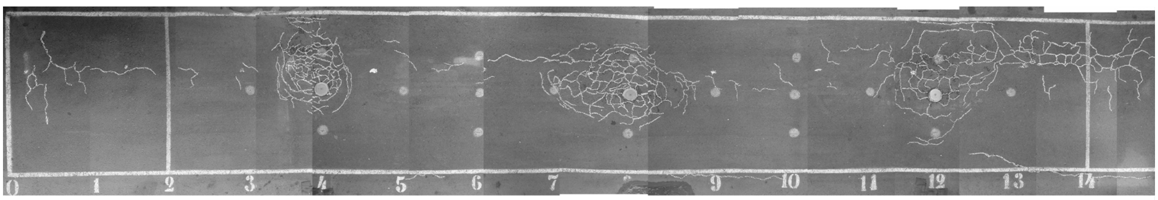
Section 409B4



Section 410B4



Section 411A4



Section 412A4

Figure 7. Crack Patterns on HVS Test Sections

Sections 409A4 and 410A4 had no cracking at the end of the 80kN tests. The HVS was subsequently moved, and cracking appeared on the sections before the addition of water. On Section 410A4 (bituminous emulsion), prior to the wet testing, it was noticed that the fines from the base had been pushed to the sides of the test section, causing small “humps”. Similar behaviour was experienced on Section 409A4 (foamed bitumen) after the addition of water, and on both sections pumping was experienced, with the fines coming through the cracks.

Section 411A4 also had very few cracks before the addition of water. The water resulted in MAD and pumping was also experienced. A test pit across the test section indicated the movement of fines from the trafficking area to the sides of the test section between the base layer and the asphalt surfacing. This showed that the loading reduced the bond between the surfacing and the base, and created fines. High tire inflation and water pressures forced the fines to move away from the loaded area.

On all the test sections, the distress from cracking was more critical than from permanent deformation.

4. LABORATORY TESTING

To supplement the HVS testing, a laboratory testing program was conducted. Four treatments on the milled ferricrete were tested to determine the tensile, compressive and shear strength, flexibility, and permanent deformation resistance.

4.1 Materials

The materials tested in the laboratory testing program included an untreated, milled ferricrete and the same material treated with three treatment options. The ferricrete was obtained from the HVS site after milling, and therefore included some of the original asphalt surfacing and ferricrete from the cement stabilised base and the untreated subbase. This material was treated with cement only, cement and foamed bitumen, and, cement and bituminous emulsion. Various combinations of cement and either foamed bitumen or bituminous emulsion were used, the specific details of which are given for each test. All treatments and specimen preparations were performed in the laboratory.

4.2 Laboratory Tests and Results

Several laboratory tests were run, including: indirect tensile strength test (ITS), unconfined compressive strength (UCS), flexural beam fatigue test, and, static and dynamic triaxial tests. The ITS test results are not presented in this paper. All the laboratory tests are discussed by Liebenberg [2002], Long and Theyse [2002a] and Robroch [2002].

4.2.1 Compressive Strength and Flexibility

The compressive strength of the treated materials was determined with the unconfined compressive strength test for a range of foamed bitumen, emulsion and cement contents. The flexibility of the treated materials was determined with the flexural beam fatigue test. In this test, a constant displacement rate is applied and the strain-at-break is measured, which is equal to the strain at the point of crack initiation. The test is discussed in more detail by Long and Theyse [2002a].

Figure 8 illustrates the compressive strength and flexibility results as a function of the ratio of the cement to the residual bituminous binder content. The data for the cement treated materials are shown at arbitrary ratio values of 1.8 for the 1 percent cement data and 1.9 for the 2 percent cement data.

At the lower binder contents (high cement to bitumen content ratio), the bituminous emulsion and foamed bitumen treated materials had similar strain-at-break values as the material treated with cement only. However, at the higher binder contents (low cement to bitumen content ratio), the strain-at-break value increased. Therefore, for this range of binder contents, increasing the binder content increased the flexibility of the material, and increasing the cement content decreased the flexibility of the material.

On the contrary, increasing the cement content increased the compressive strength, but decreased the flexibility of the material. The cement content and bituminous binder content need to be carefully selected to optimise the performance of the material in terms of the compressive strength and flexibility.

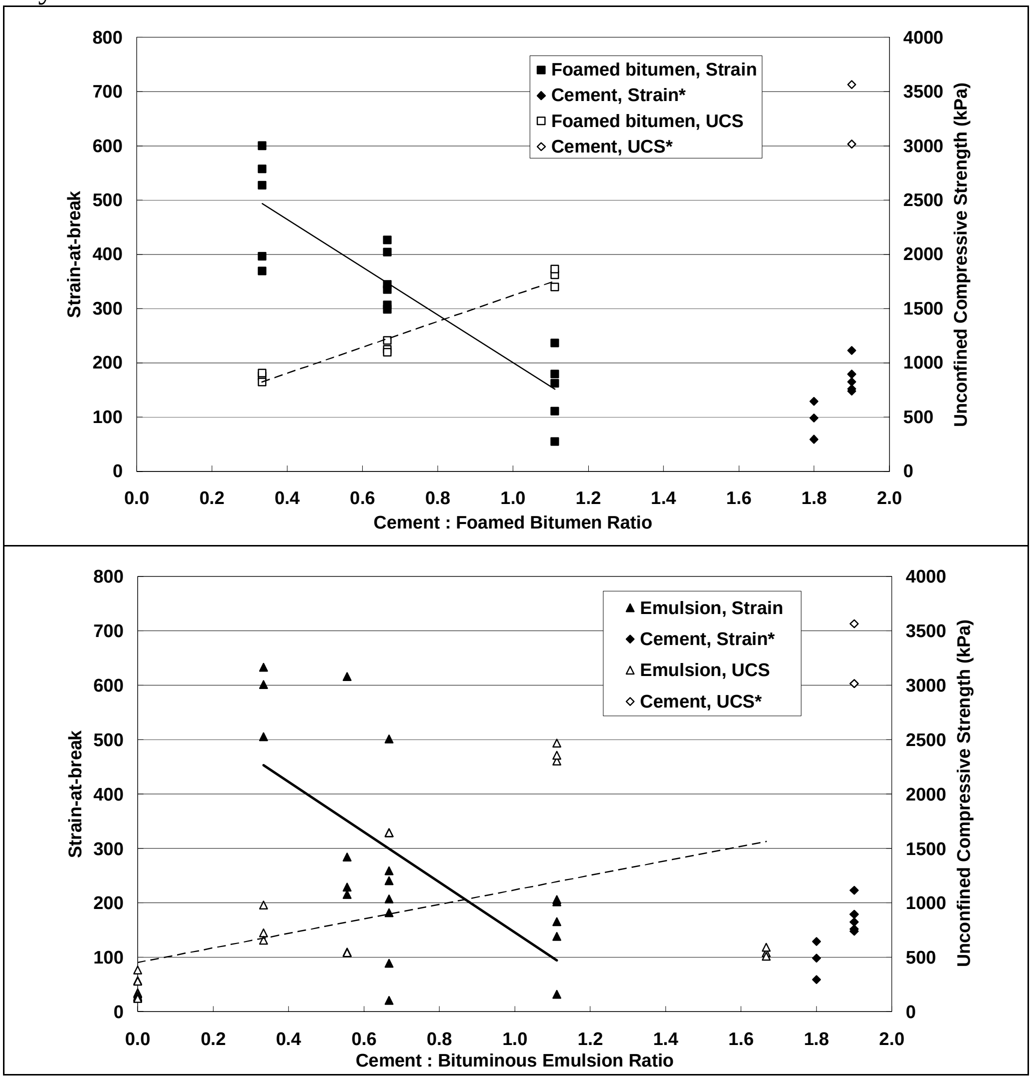


Figure 8. Compressive Strength and Flexibility of the Treated Materials

4.2.2 Shear Strength

The shear strength, in terms of the friction angle and cohesion, is determined using the static triaxial test. The tests were run at two densities and two saturation levels for the following materials:

- Untreated ferricrete
- Cement treated ferricrete (2.0 percent cement)
- Foamed bitumen treated ferricrete (2.0 percent cement with 1.8 percent residual binder, and 1 percent cement with 3.0 percent residual binder)
- Bituminous emulsion treated ferricrete (2.0 percent cement with 1.8 or 3.0 percent residual binder)

The results of the static triaxial tests are shown in Figure 9 for all the materials and all four combinations of density and saturation. Although the results are variable, on the whole, the untreated ferricrete had the lowest cohesion, but a friction angle in the same range as the treated materials. The cohesion of the bituminous emulsion treated material was larger than for the foamed bitumen treated material at the same cement and residual binder contents, and slightly larger than the cement treated material. The friction angles of the bituminous binder treated materials were in the same range, as were the cement treated material values. The friction angles of the cement treated materials were insensitive to the relative density and saturation levels. Increasing the residual binder and decreasing the cement contents of the foamed bitumen treated material reduced the cohesion and, in general, decreased the friction angle. The results are shown for the low and high values of relative density and saturation. The actual values are not necessarily the same for all the materials, which accounts for some of the variability in the results.

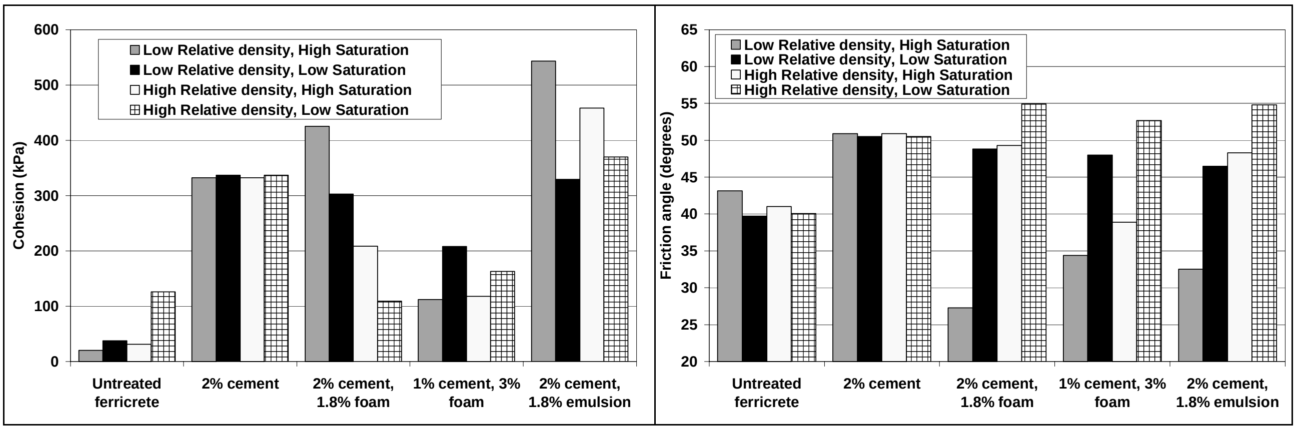


Figure 9. Cohesion and Friction Angle from Static Triaxial Tests

The cohesion and friction angle results were used to determine the maximum allowable deviator stress that the materials can withstand. These results are shown in Figure 10 for an assumed confining stress of 100 kPa. This value is within the range tested. For almost all the cases, the maximum deviator stress is considerably larger for the treated materials than the untreated materials, and larger for the bituminous emulsion and cement treated materials than the foamed bitumen treated material. Increasing and decreasing the residual binder and cement contents, respectively reduces the maximum allowable deviator stress of the foamed bitumen treated material, effectively indicating a reduction in the static strength and a reduction in the permanent deformation resistance.

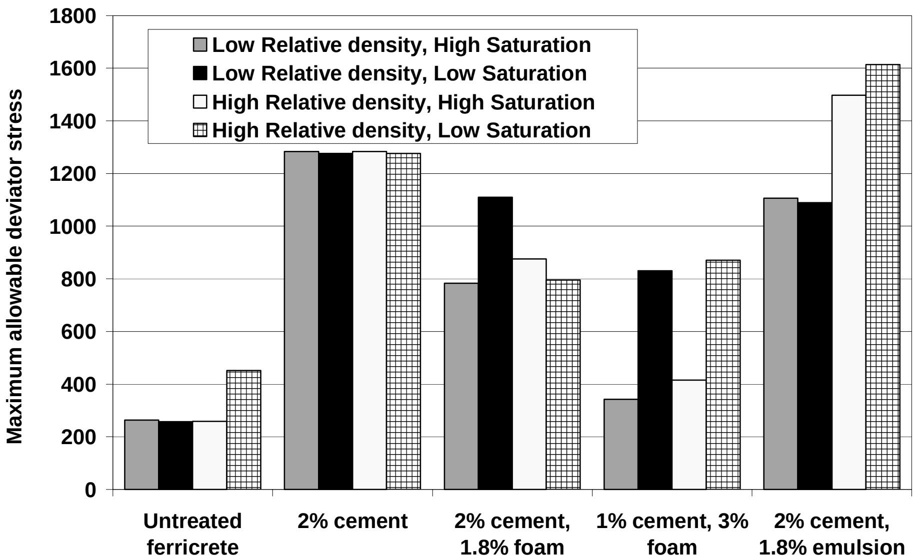


Figure 10. Maximum Allowable Deviator Stress

4.2.3 Elastic Stiffness (Resilient Modulus)

The dynamic triaxial test is used to determine both the resilient modulus and the permanent deformation response of the materials. The dynamic triaxial tests were performed at two densities and saturation levels, and three stress ratios.

The resilient modulus was measured on each specimen. Regression models were fit to the data as a function of the relative density, saturation, confining stress and stress ratio. The regression model for the untreated material had a reasonable fit and was sensitive to all four input variables. For the treated materials, the models did not show a good fit [Long and Theyse, 2002a]. This is partly due to the large variability in the test data, but also indicated that by treating the materials the sensitivity to the relative density and saturation was reduced. Because of the poor fits, it is recommended that the stiffnesses of the treated materials be selected from the averages shown in Table 2.

Table 2. Resilient Modulus

	Untreated	Cement Treated	Bituminous Emulsion Treated	Foamed Bitumen Treated	
		2 % cement	2 % cement 1.8 % binder	2 % cement 1.8 % binder	1 % cement 3.0 % binder
Average	665	2194	2039	1657	1154
Standard Deviation	237	473	450	419	470
Coefficient of Variation	0.36	0.22	0.22	0.25	0.41

The stiffness of the untreated material increased with cement and/or bituminous binder treatment. The cement treated material had the highest stiffness, and the addition of a bituminous binder reduced the stiffness. The stiffness of the bituminous emulsion treated material was higher than the foamed bitumen treated material. The addition of binder and reduction in the cement content reduces the stiffness of the foamed bitumen treated material.

The resilient modulus values from the dynamic triaxial tests were in the same range as the initial resilient modulus values back-calculated for the base layers of the HVS test sections (see Figure 6).

4.2.4 Permanent Deformation

Dynamic triaxial tests were also performed to assess the permanent deformation behaviour of the untreated and treated materials. A model, of the form shown in Equation (1) was fit to all the reasonable data for each specimen. For the data fitted, the model fits were reasonable.

$$PD = mN + \frac{cN}{\left[1 + \left(\frac{cN}{a}\right)^{b}\right]^{\frac{1}{b}}} \qquad (1)$$

where PD = permanent deformation (mm)
m, a, b, c = regression coefficients
N = load repetitions

The regression models were used to calculate the repetitions to a specific plastic strain (PS). These values were used with the relative density (RD), degree of saturation (S) and stress ratio (SR) to develop a regression model for each material to predict the structural capacity, the form of which is shown in Equation (2). The term (cem/bit) is only valid for the foamed bitumen treated materials, and represents the ratio of the cement to foamed bitumen contents. The letters a to f represent the regression coefficients.

$$\log N = a + b \cdot RD + c \cdot S + d \cdot PS + e \cdot SR + \left(f \cdot (cem/bit)\right) \qquad (2)$$

The stress ratio is a measure of the ratio of the applied shear stress and the measured shear stress, as shown in Equation (3).

$$SR = \frac{\sigma_1^a - \sigma_3^a}{\sigma_1^m - \sigma_3^a} = \frac{\sigma_1^a - \sigma_3^a}{\sigma_3^a\left(\tan^2\left(45° + \frac{\phi}{2}\right) - 1\right) + 2C\tan\left(45° + \frac{\phi}{2}\right)} \qquad (3)$$

where $\sigma^a{}_1$ = applied major principal stress
$\sigma^m{}_1$ = maximum allowable major principal stress
$\sigma^a{}_3$ = applied minor principal stress
C = cohesion
ϕ = friction angle

Figure 11 shows a plot of the structural capacity (laboratory load repetitions) regression models for the materials. The data is shown for an assumed plastic strain of 10 percent, a relative density of 70 percent and a saturation level of 75 percent, these values are all within the range of laboratory data.

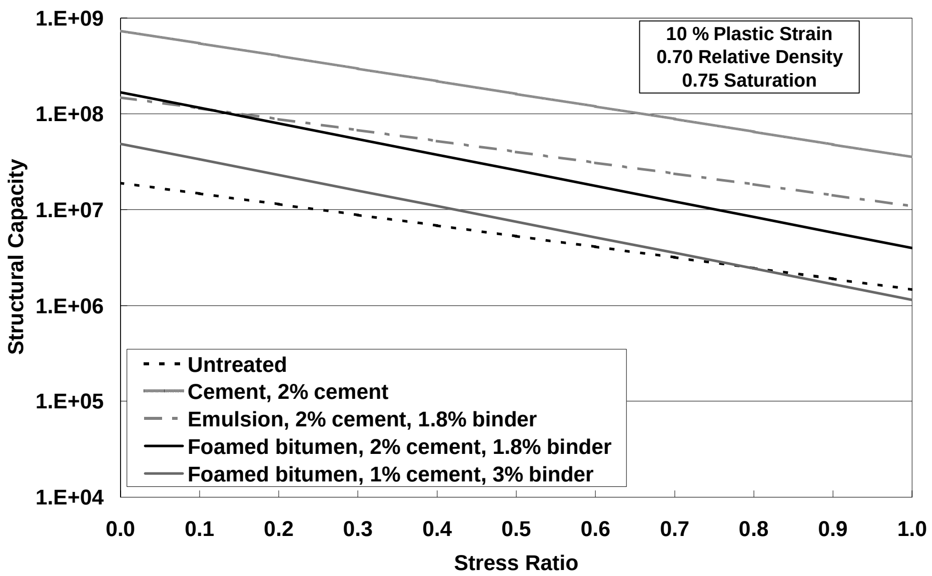


Figure 11. Bearing Capacity from Laboratory Permanent Deformation Tests

The cement treated material had the highest bearing capacity, followed by the materials treated with bituminous binders, and the untreated material had the lowest bearing capacity. The emulsion treated material performed better than the foamed bitumen treated materials. The increase in the foamed bitumen binder content and associated decrease in the cement content reduced the permanent deformation resistance of the material.

4.3 Discussion

The laboratory testing results showed that by treating the materials the structural capacity was improved. The material treated with 2 percent cement had a higher resilient modulus, increased bearing capacity and approximately the same flexibility as the foamed bitumen and bituminous emulsion treated materials containing 2 percent cement and 1.8 percent residual binder. At the higher residual binder content, 3.0 percent, the flexibility of the bituminous binder treated materials was greater than the cement treated material. The addition of the bituminous binder only increased the flexibility when sufficient bituminous binder was added.

Varying the cement and residual binder content of the foamed bitumen materials showed that the flexibility improved, whereas the bearing capacity decreased, at the higher binder content and lower cement content. Similar results are expected with the bituminous emulsion treated materials, for which no data are available.

Fatigue of the HVS test sections was the dominant distress, with little permanent deformation. By increasing the bituminous binder content and reducing the cement content the material will have a greater effective fatigue life, which is expected to provide longer pavement lives, without causing excessive permanent deformation.

The HVS test sections failed rapidly with the addition of water, therefore durability of the treated materials is an important issue. Testing is currently underway to determine the durability, in terms of permeability and erodibility of these materials. These results will evaluate the benefits of bituminous binder treatment for all weather conditions.

5. STRUCTURAL DESIGN AND PERFORMANCE MODELS

From the HVS and laboratory data it was possible to determine preliminary structural design and performance models for use in mechanistic-empirical pavement design. The two major forms of distress on the HVS test sections were effective fatigue and permanent deformation. Structural design and performance models were determined for both modes of distress.

5.1 Fatigue

The back-calculated stiffnesses from the in-depth MDD data discussed in Section 3.3.4 were used to determine a preliminary structural design model for fatigue of the foamed bitumen and bituminous emulsion treated materials.

From the stiffness data in Figure 6 it was noticed that the trend could be separated into three phases; the first initial rapid decrease in stiffness, a gradual decrease in stiffness, and finally, a constant stiffness indicative of the equivalent granular state. Not all the test sections had all three phases, particularly at the higher loads where the equivalent granular state was rapidly achieved. Attempts to fit a single curve to describe the reduction in stiffness due to trafficking were unsuccessful for the foamed bitumen treated sections. The beginning of the effective granular state was defined as the effective fatigue life.

For the foamed bitumen treated sections the effective fatigue life was determined from Figure 6 for the 80 kN load case. 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. These results are shown in Figure 12. A straight line fit gives a conservative estimate of the repetitions to the equivalent granular state.

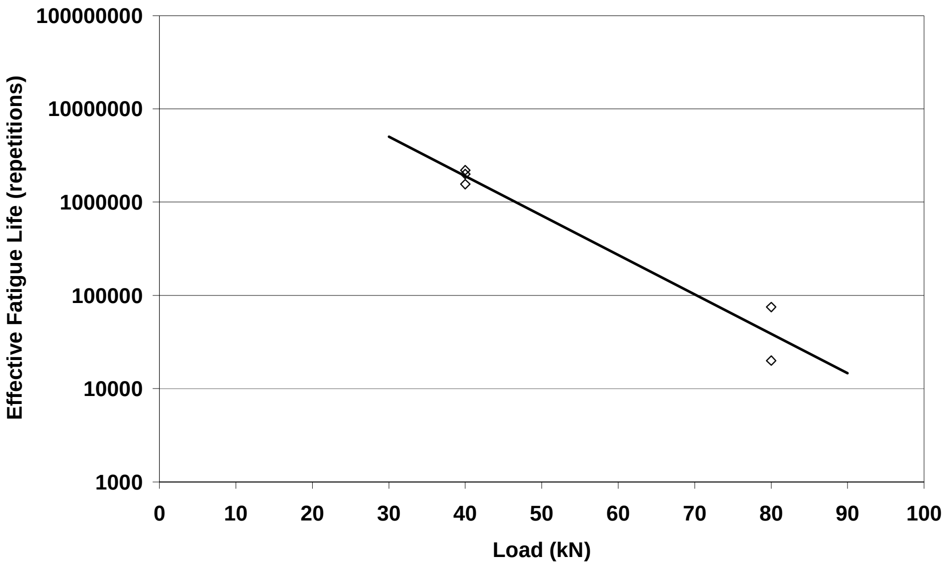


Figure 12. Effective Fatigue Life for Foamed Bitumen Treated Base Material

Curves were fit to the stiffness data for each MDD from the emulsion treated sections. The repetitions to reach the equivalent granular state were determined from the curve fit.

Figure 12 shows the regression model determined from the data for the foamed bitumen treated base, the form of which is given in Equation (4). This model is only valid for this material, with 1.8 percent foamed bitumen and 2 percent cement, the same environmental conditions and pavement structure as at the HVS test sections, and an equivalent granular state stiffness of 400 MPa. The model for the emulsion treated material is similar, although an equivalent granular state stiffness of 500 MPa is used.

$$N_{F,FB} = 10^{(a-bWL)} \tag{4}$$

where $N_{F,FB}$ = effective fatigue life
WL = wheel load (kN)
a, b = regression coefficients

The effective fatigue life model shown in Equation (4) is limited in application as it is specific to the pavement structure and conditions on the HVS test site and are a function of the wheel load and not the applied stress. For general design and analyses purposes it is necessary to have a transfer function that estimates the effective fatigue life of any pavement structure with a foamed bitumen treated layer. The transfer function therefore needs to be adjusted to determine the structural capacity as a function of a parameter determined from mechanistic analyses. One such parameter is the strain ratio, which has been used for cemented materials [Theyse, 2000a]. The strain ratio is the ratio of the tensile strain at the bottom of the base layer, calculated using linear elastic mechanistic analyses, and the strain-at-break from the flexural beam fatigue test.

The tensile strain at the bottom of the base layer of the HVS test sections was calculated with linear elasticity using the applicable load, the actual thicknesses from testpit data, and the back-calculated stiffnesses. The strain ratio was then calculated using the strain-at-break values discussed in Section 4.2.1 for the treated materials with 2 percent cement and 1.8 percent residual binder. Effective fatigue transfer functions were developed with the strain ratio and effective fatigue life data. These models are shown in Equation (5) and in Figure 13. The value of the regression coefficients a and b are 6.619 and 0.708 for the foamed bitumen treated material, and 6.344 and 0.857 for the emulsion treated material.

$$N_F = 10^{\left[a-b\left(\frac{\varepsilon}{\varepsilon_b}\right)\right]} \tag{5}$$

where N_F = effective fatigue life
a, b = regression coefficients
$\varepsilon/\varepsilon_b$ = strain ratio
ε = maximum horizontal tensile strain at the bottom of the layer
ε_b = strain-at-break from laboratory testing

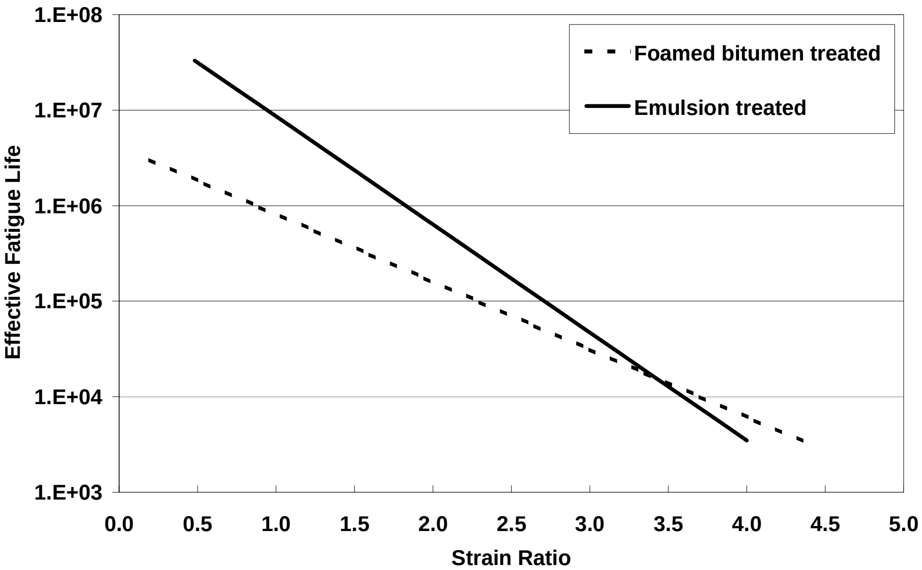


Figure 13. Effective Fatigue Life Transfer Functions

The effective fatigue life models for the two materials are not significantly different. For the most part the emulsion treated material has a longer fatigue life than the foamed bitumen treated material, for the same strain ratio. The slope of the line is steeper, which indicates the emulsion treated material is more load sensitive in effective fatigue than the foamed bitumen layer. The difference in the support conditions may also have influenced these results, especially at the lower strain ratios.

5.2 Permanent Deformation

The structural design models for permanent deformation of the foamed bitumen and bituminous emulsion treated materials were developed from the in-depth permanent deformation measured by the MDD.

5.2.1 Regression Model for MDD Data

The first step in developing a structural design model is to fit a regression model of the form shown in Equation (6) to the MDD permanent deformation data, examples of which are shown in Figure 3 for the foamed bitumen treated sections. Justification for the selection of this model is discussed in Theyse [2000b].

$$PD = mN + a\left(1 - e^{-bN}\right) \tag{6}$$

where PD = permanent deformation (mm)
m, a, b = regression coefficients
N = load repetitions

Because of the variation in MDD data along a test section, the model was fit 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 was subtracted from the deformation of the top MDD module (25 mm), and the model fit to this difference. The model fits and the data were shown in Figure 14. All the model fits were reasonable. Only the data from the first loading sequence for each test section were used in these analyses. The higher wheel load data used in the second sequence has a load history, which is difficult to account for and was therefore excluded from the analyses.

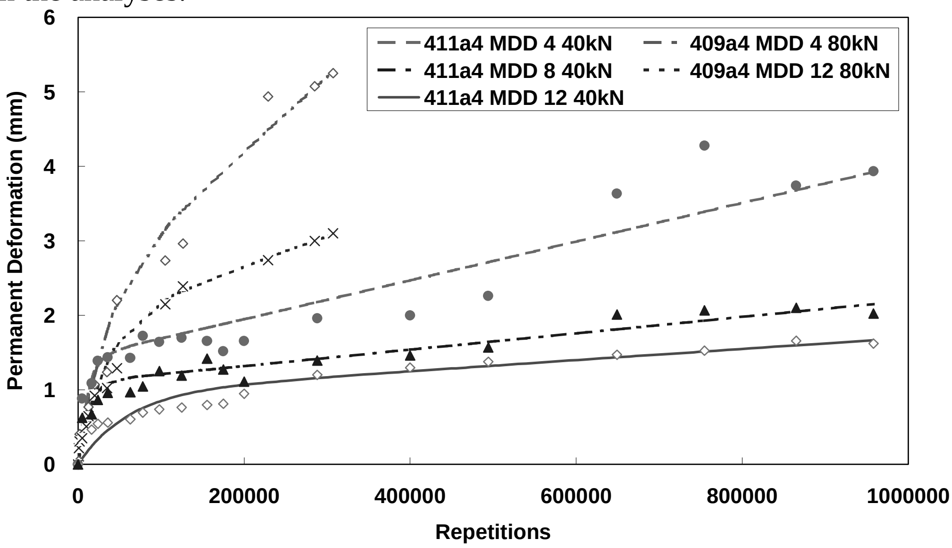


Figure 14. Base Layer Permanent Deformation Regression Model Fits to MDD Data

5.2.2 Permanent Deformation Model

Using the model fits from the MDD data it was possible to determine a simple model to predict the repetitions to a certain level of permanent deformation or plastic strain. The model was formulated in terms of plastic strain, to account for different layer thicknesses. The plastic strain is the permanent deformation divided by the initial layer thickness.

The model was calibrated by determining the permanent deformation (or plastic strain) for a series of repetitions using Equation (6). This gives a range of data for each wheel load and MDD. These data, for all the MDDs, were then used to fit a model, shown in Equation (7).

$$N_{PD} = aPS^{b}WL^{c} \quad (7)$$

where $N_{PD,FB}$ = load repetitions for permanent deformation
PS = plastic strain (%)
WL = wheel load (kN)
a, b, c = regression coefficients

The model shown in Equation (7) can be used to predict the expected laboratory load repetitions when the material properties and environment are similar to the HVS test sections.

Models were fit to the foamed bitumen and emulsion treated materials. Some of the data used to fit the models, and models themselves are shown in Figure 15 for 5 and 10 percent plastic strain. The slope of the emulsion treated materials is larger than the foamed bitumen treated materials. The difference is support for the 40 kN test sections contributes to the difference in the slopes.

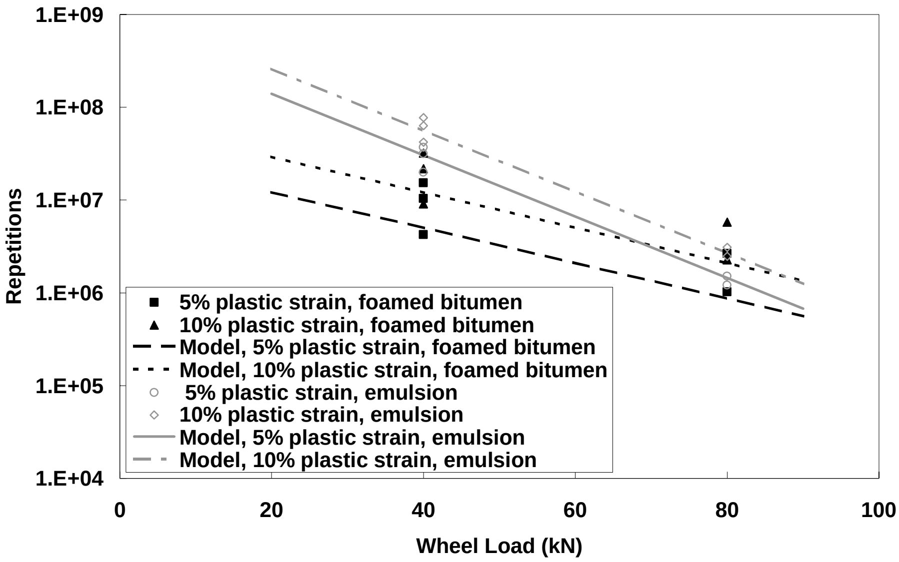


Figure 15. Permanent Deformation Model for Foamed Bitumen and Emulsion Treated Materials

For pavement design and analyses purposes it is necessary to have a transfer function that estimates the structural capacity of any pavement structure with a foamed bitumen or emulsion treated layer. The transfer function therefore needs to be adjusted to determine the structural capacity as a function of a parameter determined from mechanistic analyses. The stress ratio has been recommended for granular and granular type materials and were used in the further development of the transfer functions [Theyse, 2000b].

The stress ratio for the HVS test sections was calculated with linear elasticity using the applicable load, the actual thicknesses from testpit data, and the back-calculated stiffnesses. Because most of the permanent deformation in the life of the pavement occurs when the pavement has reached the equivalent granular state, the terminal moduli (400 and 500 MPa for the foamed bitumen and emulsion treated bases, respectively) were used to determine the stress ratio.

The stress ratio was calculated at four locations in the pavement structure, one-quarter from the top of the layer, one-quarter from the bottom of the layer, and under and between the wheels. These locations were found to be more critical than the middle of the layer, which is conventionally used [Long, 2001]. The maximum stress ratio from the four locations was used in the analyses. By replacing the wheel load variable in Equation (7) with a stress ratio variable, the model is applicable to any pavement structure with a foamed bitumen or bituminous emulsion treated base layer.

For the foamed bitumen treated material, a comparison of the modified HVS model and the laboratory model (Equation (2)) showed that the laboratory model predicted higher structural capacities than the HVS model, although a linear shift brings both models into close agreement [Long, 2001]. Because the laboratory tests were performed on new materials that had not experienced damage it is reasonable to expect the laboratory model predictions to be greater than the HVS predictions. The laboratory model is more useful in that it accounts for the relative density and the cement to foamed bitumen content ratio. For the final model, the laboratory model was calibrated with a shift factor to be in agreement with the HVS data. This model for the foamed bitumen treated material is shown in Equation (8) and in Figure 16.

$$N_{PD,FB} = \tfrac{1}{30} \times 10^{\left[-1.625+11.938\times RD+0.0726\times PS-1.628\times SR+0.691(cem/bit)\right]} \tag{8}$$

where $N_{PD,FB}$ = structural capacity (load repetitions)
RD = relative density (proportion)
PS = plastic strain (percent)
SR = stress ratio (proportion)
cem/bit = ratio of bitumen and cement contents (percent)

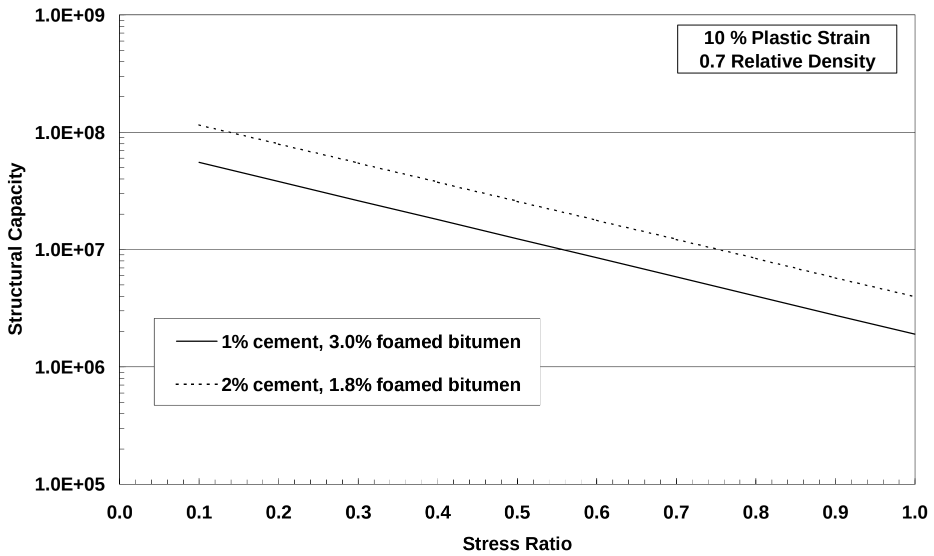


Figure 16. Permanent Deformation Transfer Function

The structural design model predicting permanent deformation of the emulsion treated materials as a function of the stress ratio has not yet been developed.

5.2.3 Load Sensitivity and Damage Factor

The HVS data were used to determine load sensitivity and damage factors for these materials. The damage factor, n, is used in Equation (9) to determine the damage caused by a particular wheel load, relative to the damage caused by a standard wheel load.

$$\left(\frac{N_{std}}{N_x}\right) = \left(\frac{P_x}{P_{std}}\right)^n \tag{9}$$

where N_x = load repetitions at wheel load
N_{std} = load repetitions at standard wheel load
P_x = wheel load
P_{std} = standard wheel load
n = damage factor

The damage factor was calculated by relating the distress under the 80 kN wheel load to the distress under the 40 kN wheel load. The 40 kN HVS wheel load is equivalent to an 80 kN standard axle load. For the permanent deformation damage factors, the number of load repetitions to a selected level of percent plastic strain was calculated for each MDD. This plastic strain value is arbitrary, and the choice of a different value would not significantly affect the results. For each material type this gave three values for the 40 kN load repetitions and two for the 80 kN load repetitions. Similarly for effective fatigue, the repetitions to reach the equivalent granular state for each MDD were used. Because of the variability in the MDD data on each test section, and because the 40 kN and 80 kN wheel loads were used on two different test sections, all combinations of data were used to calculate the damage factor. The effective fatigue and permanent deformation damage factors for these combinations are shown in Table 3.

Table 3. Effective Fatigue and Permanent Deformation Damage Factors

Effective Fatigue	**Average**	**Standard Deviation**
Foamed bitumen treated material	5.6	1.1
Bituminous emulsion treated material	5.3	0.4
Permanent Deformation	**Average**	**Standard Deviation**
Foamed bitumen treated material	2.4	1.1
Bituminous emulsion treated material	4.4	0.4

The range in damage factors is fairly large, as indicated by the standard deviation, particularly of the foamed bitumen treated sections, however, this is reasonable given the range in the MDD data. A permanent deformation damage factor of approximately 2 to 4 is expected for these types of materials [Mancotywa, 1999], therefore the results are reasonable, although the bituminous emulsion value is slightly higher. In pavement design a damage factor of 4 is often assumed, which could result in significant errors in the design and analyses of these materials. This error is conservative for permanent deformation distress.

The damage factor for effective fatigue is considerably higher than for permanent deformation, which is as expected. Again, assuming a value of 4 would introduce errors, in this case non-conservative errors. It must be emphasised that these damage factors were calculated from the observed behaviour of one material with one combination of stabilising agents, in one environmental condition, and should therefore be used with caution for other materials or different environmental conditions.

5.3 Limitations in Structural Design Models

The structural design models were developed from the materials used in the HVS test sections, and from both laboratory and HVS data. The treated materials had a relatively high cement content, which resulted in the materials behaving in a similar manner as cement treated materials. The specific combination of residual binder and cement is not the optimal combination. It is thought that the models are applicable to materials with different combinations of cement and residual bitumen, because of the variables used in the transfer function. Both the strain and stress ratios are dependant on the material properties measured in the laboratory, and are therefore applicable to all materials. The models do however need validating with field data from other parent materials and with different combinations of cement and binder contents.

The transfer functions for the foamed bitumen treated materials have been included in an interim guideline document. This document will be used by industry in the design and construction of foamed bitumen treated pavements, and the feedback will aid in the validation of the models.

6. CONCLUSIONS

This paper presents data and analyses from on-going projects on deep in situ recycling using bituminous emulsion and foamed bitumen treated materials. The project involves accelerated pavement testing with the HVS and a laboratory testing program.

The HVS test sections performed very well in the dry condition, and once water was added during trafficking, moisture accelerated distress occurred. The fatigue distress on the test sections was more critical than the permanent deformation. The elastic deflection data were used to back-calculate the effective elastic stiffnesses, and these data showed that the stiffness of the treated materials rapidly decreased initially, with a more gradual decrease to an equivalent granular state. This gradual decrease was load dependent. For the foamed bitumen treated material, regardless of the load, an equivalent granular state was reached at approximately 400 MPa, whereas the 500 MPa was reached for the emulsion treated material. The 40 kN test was stopped before this stiffness was reached, although the data indicates that with further trafficking the stiffness would continue to decrease, and it is assumed that it would reach the same equivalent granular state. From the HVS results, it appears that the bituminous emulsion treated material has slightly improved performance compared to the foamed bitumen treated material. The emulsion treated sections, specifically the 40 kN test section had stronger support from the underlying layers than the corresponding foamed bitumen treated layers.

Various laboratory tests were performed on combinations of the untreated material treated with cement, foamed bitumen, bituminous emulsion or no treatment. The tests showed that treating the material improved the behaviour, with the cement treated material having the highest resistance to permanent deformation. The addition of a bituminous binder reduced the permanent deformation resistance, and only increased the flexibility of the material at higher binder contents (3.0 percent) than were used in the HVS test sections. The bituminous emulsion treated material appears to have slightly improved performance in comparison to the foamed bitumen treated material. Increasing the residual binder content and decreasing the cement content of the foamed bitumen treated material resulted in a decrease in the permanent deformation resistance, but an increase in the flexibility of the material. This is advantageous considering the permanent deformation resistance of the HVS test sections was greater than the fatigue resistance. Modifying the mix design is therefore likely to result in longer pavement lives.

Preliminary structural performance models for the treated materials were determined from the MDD and laboratory test data, for both permanent deformation and fatigue. The models determine the number of load repetitions to the selected failure criteria as a function of a mechanistic parameter. The strain ratio is used for effective fatigue, and the stress ratio of permanent deformation. The use of a mechanistic parameter in the transfer functions allows the use of the models for a wider range of conditions.

Using the structural design models, damage factors were estimated for both effective fatigue and permanent deformation. The damage factors for effective fatigue were higher, approximately 5.5, than the typically assumed value of 4. The permanent deformation damage factors are approximately equal to and less than 4. This shows that the effective fatigue response of the treated materials is much more load sensitive than the permanent deformation response, and using the assumed values for fatigue analyses could result in a non-conservative error.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

Liebenberg, J., *The influence of various emulsion and cement contents on an emulsion treated ferricrete from the HVS Test Sections on Road P243/1*, CSIR Transportek, CR2001/77, 2002a.

Long, F.M. and H.L. Theyse, *Laboratory Testing for the HVS Sections on Road P243/1*, Transportek, CSIR, Contract Report CR-2001/22, 2002a.

Long, F.M. and H.L. Theyse, *Second Level Analysis of the HVS Data from Road P243/1*, Transportek, CSIR, Contract Report CR-2002/23, 2002b.

Long, F.M., *The Development of Structural Design Models for Foamed Bitumen Treated Pavement Layers,* Transportek, CSIR, Contract Report CR-2001/76, 2001.

Mancotywa, W.S., *Phase 1 testing of experimental sections on Road 2388 near Cullinan*, Transportek, CSIR, Contract Report CR-99/011, 1999.

Mancotywa, W.S., *First Level Analysis Report: 2nd phase HVS Testing of the Emulsion Treated Gravel and Foam Treated Gravel Base Sections on Road P243/1 near Vereeniging*, Transportek, CSIR, Contract Report CR-2001/53, 2002.

Robroch, S., *Laboratory Testing on Foamed Bitumen and Cement Treated Material from the HVS Test Section on Road P243/1*, CSIR Transportek, CR2001/69, 2002.

Steyn, W.J.vdM., *Level one data analysis of HVS tests on Foam Treated Gravel and Emulsion Treated Gravel on Road P243-1: 80 kN and 100 kN test sections*, Transportek, CSIR, Contract Report CR-2001/5, 2001.

Theyse, H.L., The development of mechanistic-empirical permanent deformation design models for unbound pavement materials from laboratory and accelerated pavement test data, *Proceedings of the Fifth International Symposium on Unbound Aggregates in Roads*, Nottingham, 2000b.

Theyse, H.L., *Overview of the South African Mechanistic Pavement Design Method*, South Africa Transport Conference, July 2000a.

World Highways, April 2001.

9. KEYWORDS

Deep in situ recycling, foamed bitumen, bituminous emulsion, transfer function, heavy vehicle simulator