CHAPTER 7 PERMANENT DEFORMATION PROPERTIES OF EMULSION TREATED MATERIALS

7.1 INTRODUCTION

The development of permanent deformation in emulsion treated materials with cement is assumed to be similar to that of granular materials. The same principles therefore apply for emulsion treated materials as for granular unbound materials in terms of permanent deformation. The development of a permanent deformation model in this study is based on the linear elastic theory.

The permanent deformation models developed from the laboratory study and the Heavy Vehicle Simulator, are presented in this chapter and a recommendation is made on the use of a permanent deformation model in the mechanistic analysis of emulsion treated materials.

7.2 FACTORS INFLUENCING THE DEVELOPMENT OF PERMANENT DEFORMATION UNDER REPETITIVE LOADING

A number of factors are important and influences the development of permanent deformation under repeated loading. These factors are well researched and the mechanism behind them fully described. Most researchers (Maree: 1978, Barenberg: 1971, Wolff 1992) reported that the following factors are important when defining the permanent deformation behaviour of an unbound granular material:

- degree of saturation of the material at the time when the load are applied
- the density to which the material was compacted,
- the magnitude of the applied load, which influences the stress state in the material,
- the grading of the material, and
- the load history of the material.

7.3 PERMANENT DEFORMATION MODEL FROM HEAVY VEHICLE SIMULATOR DATA

The regression model fitted through the Heavy Vehicle Simulator data in chapter 5 (section 5.7.1) was used to develop a model for permanent deformation. The model is similar to the laboratory model from section 5.6 in Equation 5.14, but is expressed in terms of wheel load and not stress ratio. The model is presented in Figure 7.1.

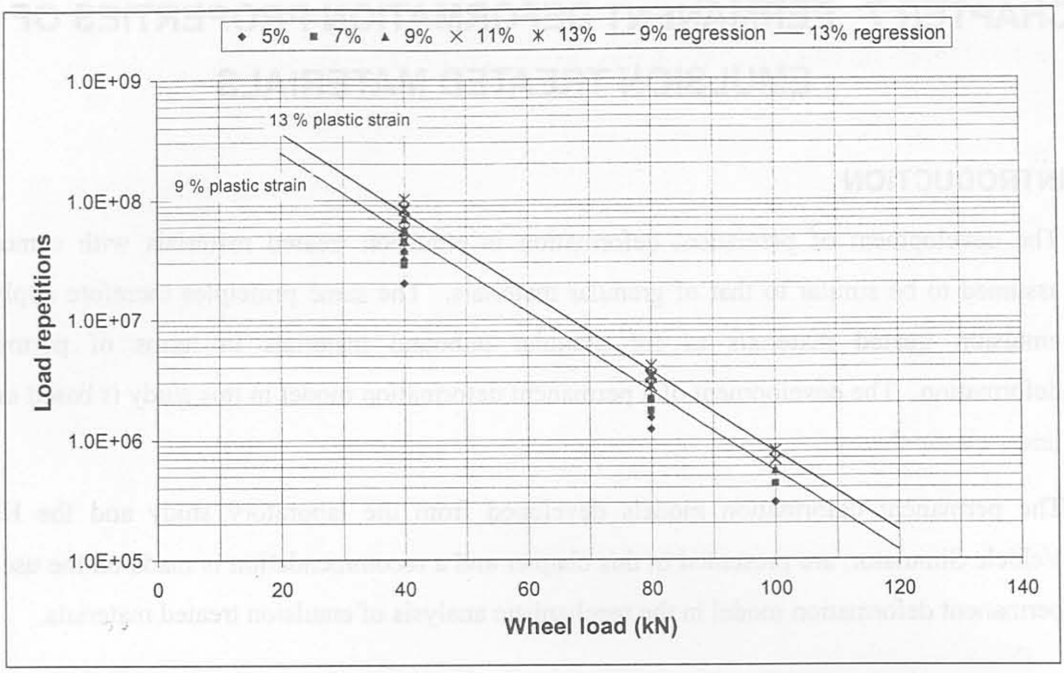


Figure 7.1 HVS permanent deformation model

The model presented in Figure 7.1 is only applicable to the pavement structure and conditions of the HVS site and is in terms of wheel load and not an engineering parameter (e.g. stress ratio).

7.4 MECHANISTIC ANALYSIS OF HEAVY VEHICLE SIMULATOR PAVEMENT FOR PERMANENT DEFORMATION

In order to use the results from this research in different pavement structures and load conditions, it is necessary to have a generic function in terms of an engineering parameter that can be easily calculated. In the current South African Mechanistic Pavement Design Method, pavement structures are modelled using the multi-layer linear elastic theory. This theory cannot directly predict the behaviour of unbound materials and the permanent deformation response of these materials. It also can not accommodate the non-linear behaviour of unbound materials. More appropriate advanced models have not yet been calibrated and are complex to use. These complex models are difficult to use and are not widely used in pavement engineering yet. To fit in with the current South African Mechanistic Pavement Design Method, the structural design models for permanent deformation of emulsion treated materials are also based on the multi-layer linear elastic theory.

The engineering parameter used in the permanent deformation models for emulsion treated materials is the Stress Ratio as described by Theyse (1999).

The stress ratio is a function of the principal stresses and the shear stress parameters and is the Inverse of the Factor of Safety as defined by Maree (1978). Theoretically, a stress ratio in excess of 1 will lead to failure although such a stress condition cannot exist in practice. It is however possible that the Stress Ratio can exceed 1.0 if the time of loading is very short. In such a case the stresses in a soil mass cannot be redistributed timeously and the maximum shear strength may be exceeded for a fraction of time.

7.4.1 Stress ratio

The calculation of the stress ratio is given in Equation 5.10, and is repeated below:

$$SR = \frac{\sigma_1^a - \sigma_3}{\sigma_1^m - \sigma_3} = \frac{\sigma_1^a - \sigma_3}{\sigma_3\left[\tan^2\left(45° + \frac{\phi}{2}\right) - 1\right] + 2.c.\tan\left[45° + \frac{\phi}{2}\right]} \tag{7.1}$$

where: SR = Stress ratio

σ_3 = minor principal stress or confining pressure

c = cohesion

ϕ = internal angle of friction

σ_1^a = working or applied major principal stress

σ_1^m = maximum allowable major principal stress for given ϕ, c, and σ_3

One of the major shortcomings of the linear elastic theory is that tensile stresses are allowed in the material. For asphalt and cemented materials it may be applicable, but unbound materials are not able to withstand tensile stresses. This is illustrated in the beam in Figure 7.2 below.

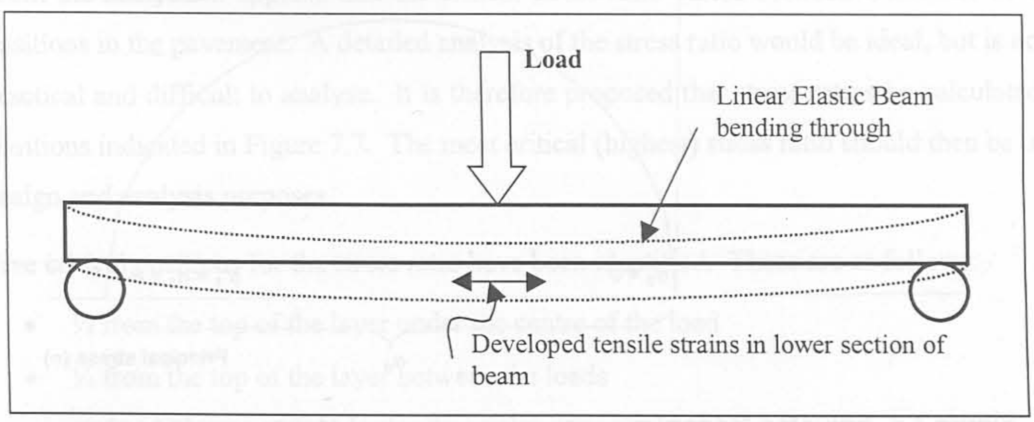


Figure 7.2 Illustration of tensile strains and stresses developed in the linear elastic theory

From the Figure above, the development of tensile strains at the bottom of the beam are indicated clearly. Since $\sigma = \varepsilon.E$, where E is the modulus of elasticity, the stress (σ) will be negative if strain (ε) is negative (E is always positive). In practice, granular materials will "redistribute" the stresses so that the tensile stresses at the bottom are eliminated. Models to effectively model this behaviour are not widely in use.

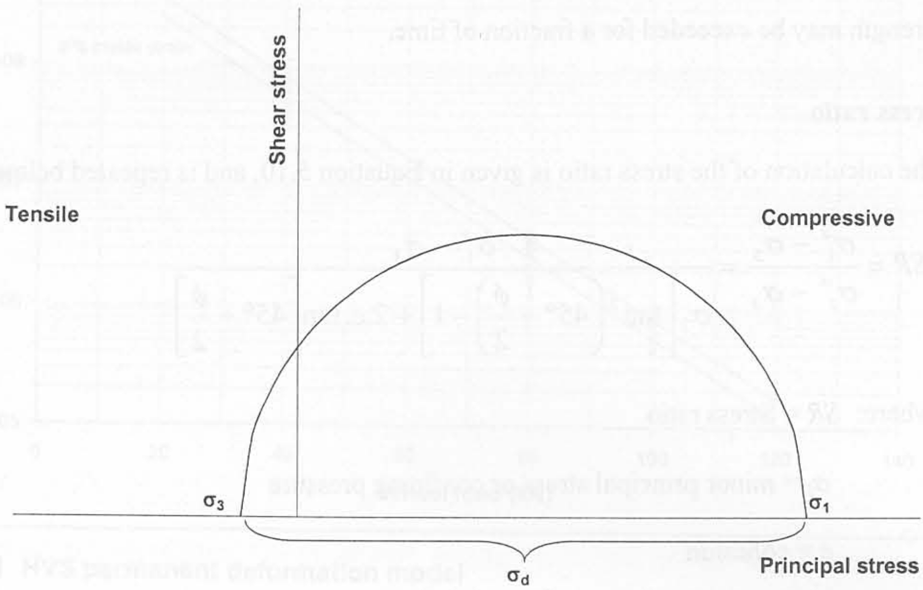


Figure 7.3 Möhr circle with tensile minor principal stress

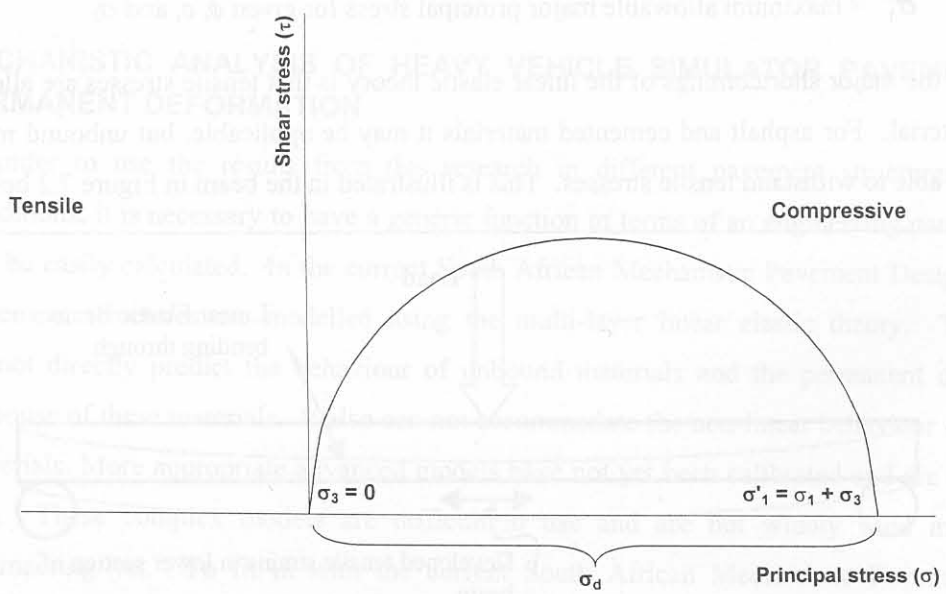


Figure 7.4 Adjusted Möhr circle with minor principal stress equals to zero

The current practice in the South African Mechanistic Pavement Design Method, is to "shift" the Möhr circle that the minor principal stress (σ_3) became zero, and increase the major principal stress (σ_1) by the same magnitude. The radius of the Möhr circle remains the same, which means that the deviator stress (σ_d) remains the same.

This adjustment gives a more reasonable result and is a better approximation of the stress state in an unbound pavement layer. It is recommended that the same practice be followed in the analysis of emulsion treated materials.

Critical positions of the Stress Ratio

The current practice in the South African Mechanistic Pavement Design Method is to calculate the critical parameter in the centre of the layer, either under the load or between the loads, in the case of a dual wheel load. Figure 7.5 shows a contour plot of stress ratio for the HVS pavement under a 40 kN, 620 kPa dual wheel load. The contour plots were determined using a linear elastic software program by calculating the stresses and strains at a grid in the layer under consideration. Areas with the same stress or strain were connected to form a contour of stresses or strains.

Unbound materials fail when the shear strength of the materials is exceeded. An analysis of the deviator stress and octahedral shear stress indicated that the critical shear stresses are in the upper quarter of the layer underneath the load (Figure 7.6). The octahedral shear stress is a stress invariant that provides an indication of the total shear distortion applied by any given stress state. The risk of the shear strength being exceeded is critical at these points. The analysis shows that the stress ratio at the centre of the layer is actually the lowest and not the critical location (Figure 7.5). The critical stress ratio is in most cases in the upper quarter of the layer between the centre of the load and the edge of the load. The position of the critical stress ratio varies as the composition of pavement structures varies.

From the analysis it appears that the critical stress ratio varies between a number of definite positions in the pavement. A detailed analysis of the stress ratio would be ideal, but is not often practical and difficult to analyse. It is therefore proposed that stress ratios be calculated at the positions indicated in Figure 7.7. The most critical (highest) stress ratio should then be used for design and analysis purposes.

Five critical positions for the stress ratio have been identified. These are as follows:

- ¼ from the top of the layer under the centre of the load
- ¼ from the top of the layer between the loads
- ¼ from the top of the layer at the outer edge of the load
- ¼ from the bottom of the layer under the centre of the load
- ¼ from the bottom of the layer between the loads

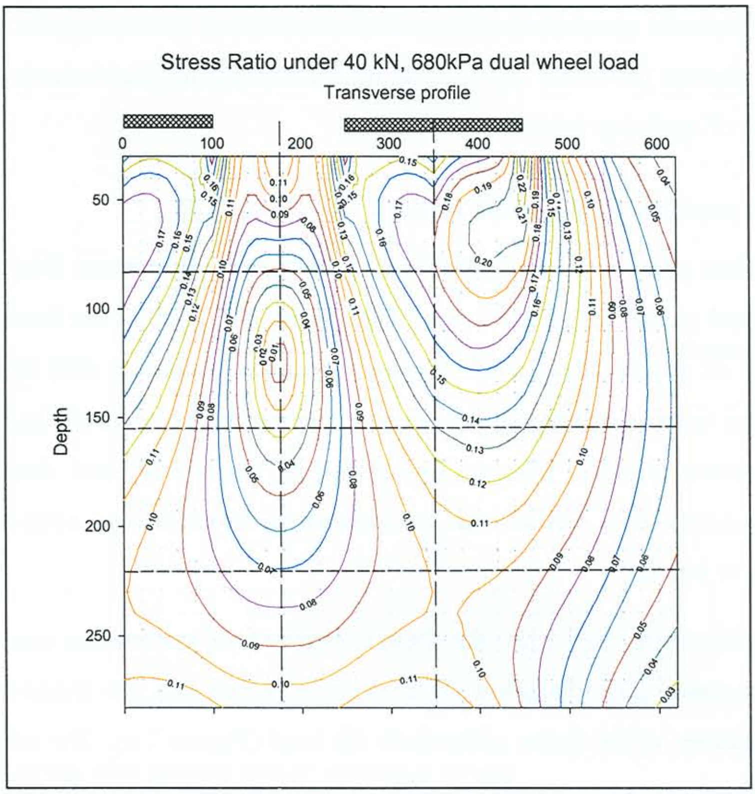


Figure 7.5 Contour plot of the stress ratio on the HVS pavement under 40 kN, 620 kPa dual wheel load.

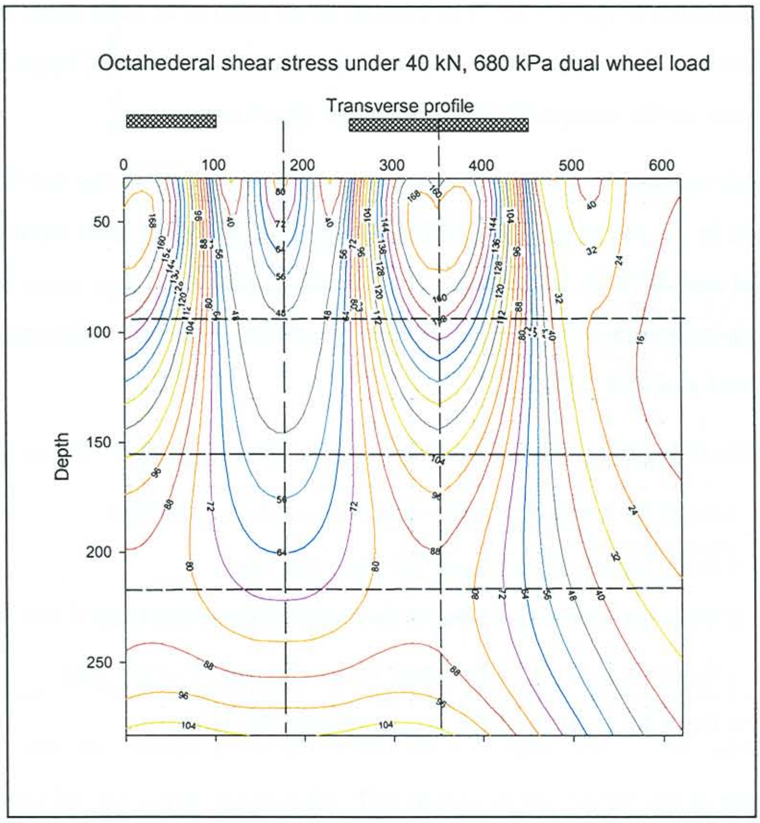


Figure 7.6 Contour plot of octahedral shear stress under a 40 kN, 620 kPa dual wheel load in a 250 mm thick emulsion treated layer.

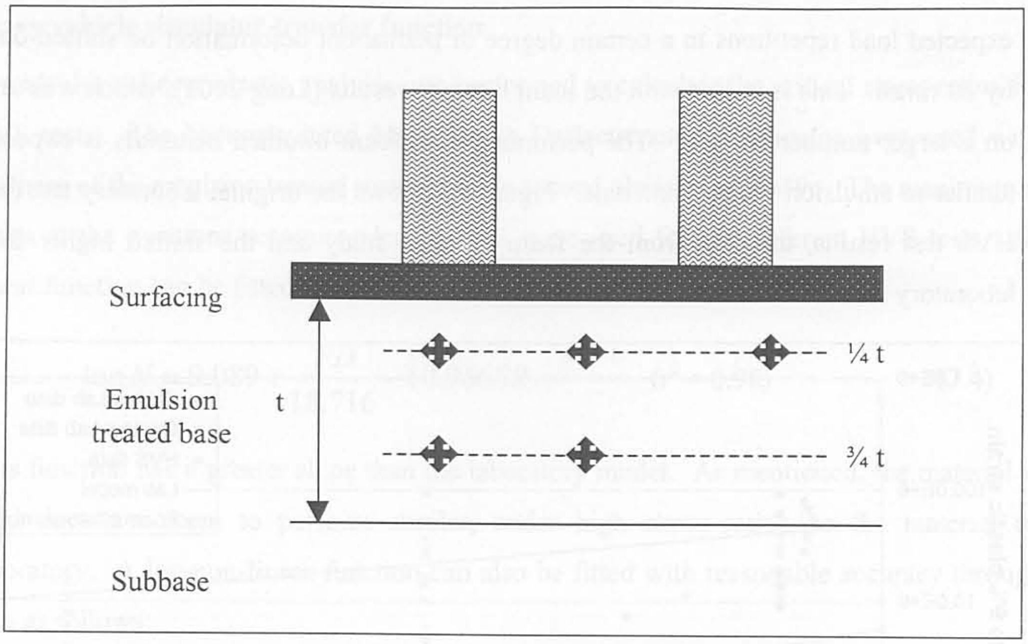


Figure 7.7 Recommended positions to calculate the critical Stress Ratio

7.5 PERMANENT DEFORMATION TRANSFER FUNCTION

7.5.1 Laboratory transfer function

The laboratory transfer function was developed from different saturation, relative densities and stress ratios. The function was developed from the dynamic triaxial test results described in chapter 5. At low stress ratios the results were similar to that of the Heavy Vehicle Simulator, but at high stress ratios the laboratory model gives more repetitions to a certain level of plastic strain than measured under the HVS. The dynamic triaxial test, tests only one layer with ideal confinement and support conditions. It is assumed that these factors played a role at high stress ratios. The function in Equation 7.2 could be fitted through the laboratory data in terms of stress ratio. The degree of saturation and relative density did not provide a significant influence on the permanent deformation to be included in the equation.

$$\log N = 7.4266 + \frac{PD}{25.2465} - \frac{SR}{1.2415} \qquad (r^2 = 0.51) \qquad (7.2)$$

where: N = Number of repetitions to certain degree of permanent deformation

PD = degree of permanent deformation (%)

SR = Stress ratio calculated according to equation (7.1)

At high stress ratios, the number of repetitions to a certain degree of permanent deformation, is approximately 20 times higher than expected for the Heavy Vehicle Simulator data. This coincides with the observations, described by Long (2002), during the testing of the adjacent foam bitumen section. It was therefore proposed that at higher stress ratios (0.55 and 0.9) the expected load repetitions to a certain degree of permanent deformation be shifted downwards by 20 times. This is in line with the foam bitumen results (Long 2002), which was undertaken on a larger number of tests. The performance of foam bitumen materials is expected to be similar to emulsion treated materials. Figure 7.8 shows the original laboratory test results, the HVS test results, the data from the foam bitumen study and the shifted higher stress ratio laboratory results.

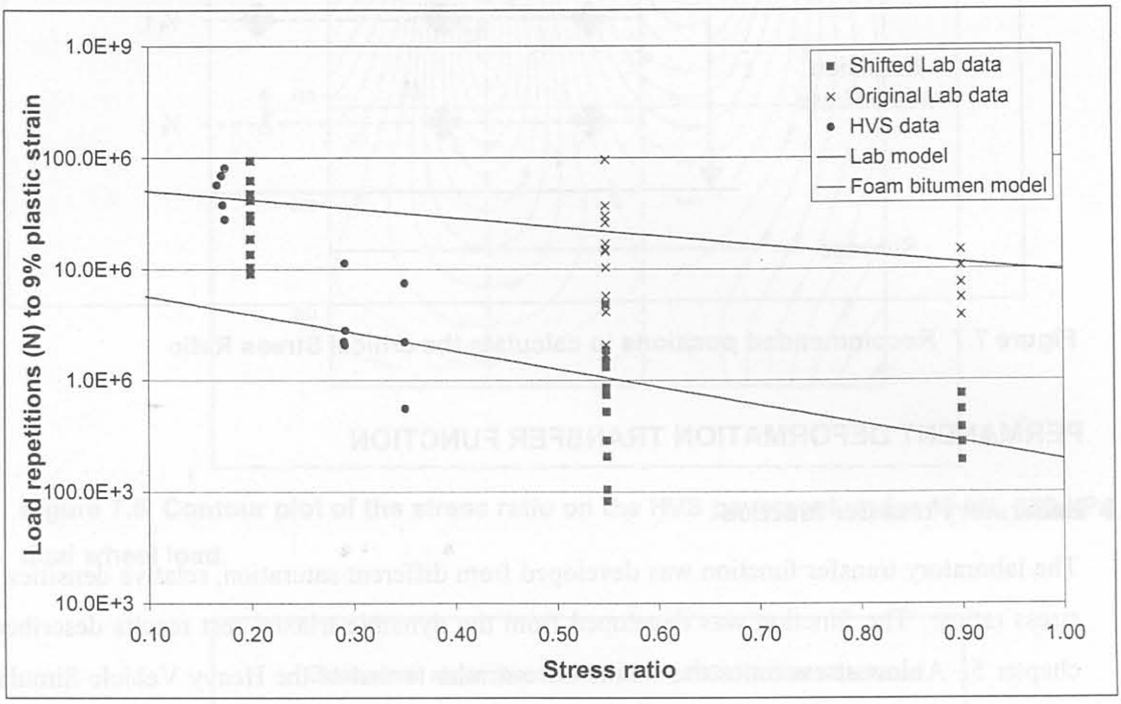


Figure 7.8 Comparison between laboratory test results, HVS test results and foam bitumen study.

The number of load repetitions to a certain degree of permanent deformation can also be plotted against the bulk stress. This indicates that there is a decrease in the number of load repetitions to permanent deformation with an increase in bulk stress. This approach does not allow the material properties to be taken into account, and only considers the stress condition. From the complexity of the equation it is difficult to write it in terms of load repetitions and this should be solved by iterations.

$$\Theta = 4780.935 * \left(1 - e^{-\frac{181.534}{N^{0.379701}}}\right) \qquad (7.3)$$

Where: Θ= bulk stress ($\Theta = \sigma_1 + \sigma_2 + \sigma_3$)

N= Load repetitions to 9 % plastic strain

This equation is similar to the one proposed by Wolff (1992) for the elasto-plastic analyses of granular material.

7.5.2 Heavy vehicle simulator transfer function

A multi layer linear elastic analysis was performed to calculate the critical stress ratios for the HVS tests. The backcalculated Multi Depth Deflectometers stiffnesses were used with the stiffness of the emulsion treated material in its second phase as 500 MPa. The maximum stress ratios at the positions recommended in 7.5.1 were used for the different HVS tests. A log-linear function can be fitted through the data as follows:

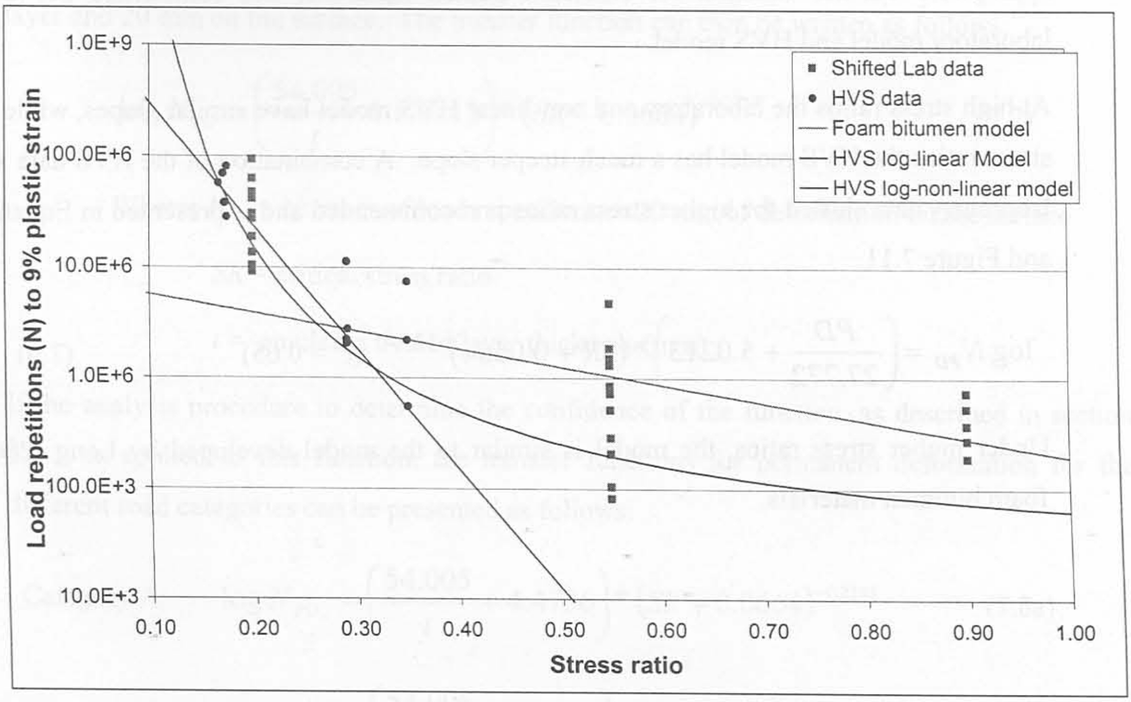
$$\log N = 9.089 + \frac{PD}{18.716} - 10.966SR \qquad (r^2 = 0.98) \qquad (7.4)$$

This function has a greater slope than the laboratory model. As mentioned, the material in the field does not seem to perform similar, under high stress ratios, to the material in the laboratory. A log-non-linear function can also be fitted with reasonable accuracy through the data as follows:

$$\log N = 3.725 + \frac{PD}{18.486} + \frac{0.598767}{SR} \qquad (r^2 = 0.39) \qquad (7.5)$$

This function gives very high load repetitions at low stress ratios and is not expected to be very accurate at low stress ratios. At high stress ratios, the function converges to the same slope as that of the laboratory and foam bitumen function.

These two functions are illustrated in Figures 7.9 and 7.10.



Function 7.9 HVS transfer functions compared to foam bitumen model.

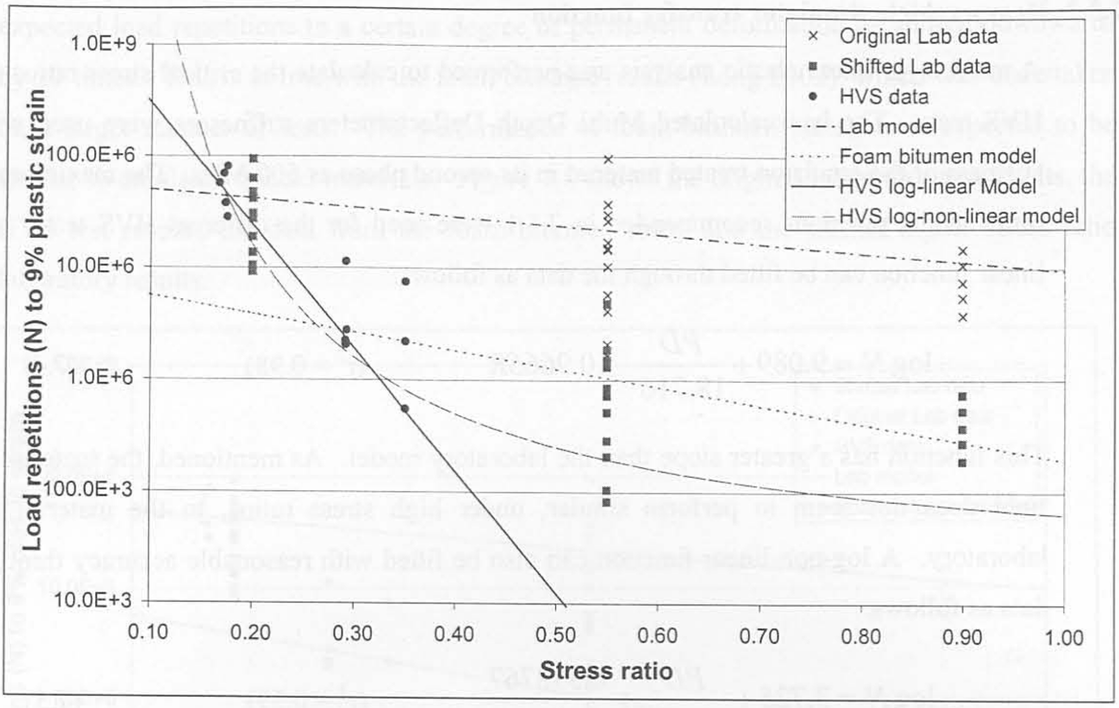


Figure 7.10 HVS transfer functions compared to original laboratory data, shifted laboratory data and foam bitumen model.

7.5.3 Permanent deformation transfer function

From the analysis of the laboratory test results and the HVS test results, it is assumed that the appropriate transfer function for emulsion treated materials, lies somewhere between the laboratory model and HVS model.

At high stress ratios the laboratory and non-linear HVS model have similar slopes, while at low stress ratios the HVS model has a much steeper slope. A combination of the HVS data and the laboratory data shifted for higher stress ratios is recommended and is presented in Equation 7.6 and Figure 7.11.

$$\log N_{PD} = \left(\frac{PD}{27.772} + 5.0213\right) * (SR + 0.0664)^{-0.2313} \qquad (r^2 = 0.65) \qquad (7.6)$$

Under higher stress ratios, the model is similar to the model developed by Long (2001) for foam bitumen materials.

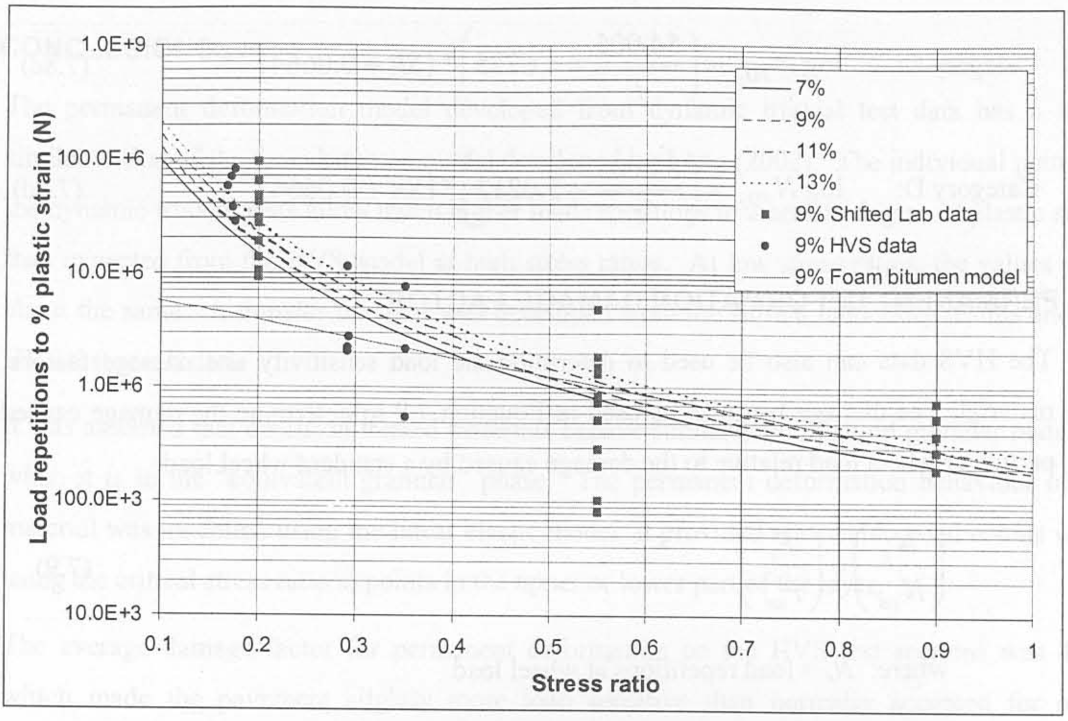


Figure 7.11 Transfer function for permanent deformation of emulsion treated materials

The TRH4 and the South African Mechanistic Pavement Design Method define the end of pavement life when the pavement reaches 20 mm of deformation or rutting on the surface. From the HVS test results discussed in Chapter 5, approximately 75 % of the total deformation of the pavement occurs within the base layer. This will allow 15 mm of deformation in a base layer and 20 mm on the surface. The transfer function can then be written as follows:

$$\log N_{PD} = \left(\frac{54.005}{t} + 5.0213\right) * (SR + 0.0664)^{-0.2313} \qquad (7.7)$$

Where: N_{PD} = Number of load repetitions to 20 mm of deformation on the surface

SR = critical stress ratio

t = emulsion treated layer thickness (mm)

If the analysis procedure to determine the confidence of the function, as described in section 6.5.1, is applied to this function, the transfer functions for permanent deformation for the different road categories can be presented as follows:

Category A: $$\log N_{PD_A} = \left(\frac{54.005}{t} + 4.4736\right) * (SR + 0.0664)^{-0.2313} \qquad (7.8a)$$

Category B: $$\log N_{PD_B} = \left(\frac{54.005}{t} + 4.5389\right) * (SR + 0.0664)^{-0.2313} \qquad (7.8b)$$

Category C: $$\log N_{PD_C} = \left(\frac{54.005}{t} + 4.6775\right) * (SR + 0.0664)^{-0.2313} \quad (7.8c)$$

Category D: $$\log N_{PD_D} = \left(\frac{54.005}{t} + 5.0213\right) * (SR + 0.0664)^{-0.2313} \quad (7.8d)$$

7.6 PERMANENT DEFORMATION DAMAGE FACTOR

The HVS data can also be used to determine the load sensitivity and damage factors for a material. The damage factor, n, is used in Equation 7.9 to determine the damage caused by a particular wheel load relative to the damage caused by a standard wheel load.

$$\left(\frac{N_x}{N_{std}}\right) = \left(\frac{P_x}{P_{std}}\right)^n \quad (7.9)$$

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

Damage factors were calculated by relating a certain defect under a 80 kN and 100 kN wheel load to that defect under a 40 kN wheel load. The 40 kN HVS wheel load is equivalent to a 80 kN standard axle load. The damage factors calculated for permanent deformation are presented in Table 7.1.

The value published in this study was obtained from limited testing and could only be used as an interim guideline, until further research develops more definitive values.

Table 7.1 Permanent deformation life damage factors for emulsion-treated gravel

		40 kN wheel load (section 412A4)		
		MDD4	MDD8	MDD12
80 kN wheel load (section 410A4)	MDD4	5.77	4.89	5.50
	MDD12	5.58	4.70	5.31
100 kN wheel load (section 410B4)	MDD4	5.07	4.40	4.86
	MDD12	4.22	3.55	4.02
	Average		*4.82*	
	Std deviation		*0.68*	

7.7 CONCLUSIONS

The permanent deformation model developed from dynamic triaxial test data has a slope similar to that of the foam bitumen model developed by Long (2002). The individual points of the dynamic triaxial tests allow much higher load repetitions to a certain degree of plastic strain than expected from the HVS model at high stress ratios. At low stress ratios, the values were about the same. A transfer function was developed from the shifted laboratory results and the HVS test result data.

It was assumed that emulsion treated materials behave similarly to unbound granular materials when it is in the "equivalent granular" phase. The permanent deformation behaviour of the material was modelled using the linear elastic model. It provided reasonable good results when using the critical stress ratio at points in the upper or lower part of the layer.

The average damage factor for permanent deformation on the HVS test sections was 4.87, which made the pavement slightly more load sensitive than normally accepted for other pavement materials.

7.8 REFERENCES

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