ANALYSING A PAVEMENT STRUCTURE WITH A CRUSHED STONE OVERLAYING ON AN EXISTING THICK ASPHALT LAYER

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ABSTRACT

It is a rare practice in South Africa's engineering industry to keep the existing asphalt intact and to construct a granular subbase and / or base above it. This study investigates such a pavement structure in order to gain a better understanding of how it functions. Therefore, the influence of slippage between a granular layer on top of an older asphalt layer was determined as well as the structural capacity of the pavement which was then compared to more conventional pavement structures. Also, possible economic benefits were identified. A case study (N1 Section 17) was selected for investigation. Theoretical models were evaluated using Linear Elastic Analysis (LEA) for various slip conditions and scenarios. The elastic surface deflections were calculated for various slip rates and the results showed that the surface deflection increased exponentially as the slip rate increased. Both the LEA and Finite Element Analysis (FEA) calculations indicated that the bearing capacity of the pavement structures evaluated was sensitive to slippage between the base and the older asphalt layer. This study consequently found the inverted pavement structure to be a viable construction option within the limits of this study.

1 INTRODUCTION

The concept of an inverted pavement is well established in South Africa where it is understood to be an unbound granular base supported by a bound subbase with a significant higher stiffness. (TRH4 (CSRA,1996), SAPEM (2014))

In this paper the concept of an inverted pavement (demonstrated in Figure 1) will be applied to the rehabilitation of an existing pavement with a thick asphalt base. The thick asphalt base will become the subbase and overlain by a granular base, thus forming an inverted pavement. The design guidelines such as the TRH4 (CSRA,1996) recommend various pavement design options, including among others:

- A granular base with a cement stabilised subbase (CSSB),
- An asphaltic base with a cement stabilised subbase,
- A cement stabilised base (CSB) also with a cement stabilised subbase, and
- A bitumen stabilised base (BSB) with a cement stabilised subbase.

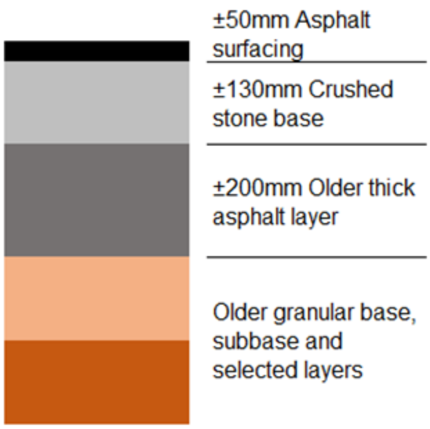

Figure 1: Inverted pavement concept relative to this study

Nowhere in the general design guidelines a rehabilitation option is recommended in which the older asphalt surfacing and asphalt base are kept intact and a new base and/or subbase is constructed on top of the existing pavement, without carrying out any modifications to the existing pavement surface or structure. There is therefore no counsel of any sort provided by general design guidelines applied in South Africa on using inverted pavement structures, yet South African roads have been constructed in this manner. Fundamental questions thus generates from an engineering perspective include:

- What is the advantage of constructing such an inverted pavement structure?
- Why is it not a more popular option for rehabilitation?
- What are the risks in constructing an inverted pavement structure for rehabilitation? Including:
    - Could infiltrating surface water be trapped on top of the asphalt sub layer? What effect would this have on the pavement's structural capacity?
    - Could slip between the base layer and older asphalt sub layer occur? What effect would this have on the pavement's structural capacity?
    - Can this type of rehabilitation option be more economical when compared to more conventional rehabilitation options?
    - Lack of compaction due to limited opportunity for dissipation of pore pressures due to an intact asphalt layer below?

- o Limited studies have shown that slushing only influences the upper 75mm of the granular layer, and what effect does this issue have on this type of pavement structure?

To answer some of these questions, the inverted pavement structure (aligning with the case study) was investigated structurally and economically, to determine its viability and associated risks, as well as to:

- gain an understanding of how an inverted pavement structure functions,
- determine the influence of slippage between the base course and the older asphalt layer,
- determine the structural capacity of the pavement and compare it to more conventional pavements.

2 CASE STUDY (NATIONAL ROUTE N1 SECTION 17)

The N1 Section 17 consists of a pavement structure with a granular layer on top of an older, thick asphalt layer. This road is currently in the process of being reconstructed and therefore ideal for this study. Constructed in 1989, this section has withstood 24 years of heavy traffic loading. A sensitivity analysis was carried out due to the lack of traffic information and it was found that the most probable traffic loading was 13 to 18 million equivalent standard axle loads, between 1989 and 2013.

Falling Weight Deflectometer (FWD) measurements were also analysed. The maximum deflection (Y_{max}) and the Base Layer Index (BLI) showed that approximately 95% of the road was still in a sound condition (SAPEM, 2014). The rut depth measurements showed that the majority of the rut depths are below 10 mm, which also verified that the pavement structure is performing satisfactory. The International Roughness Index (IRI) however, indicated some sections (approximately 25%) to be between states of warning and severe distress. This was due to shoving, which was one of the major distresses on the road. It could not be determined from the visual assessment whether the shoving was due to the asphalt instability or interlayer slippage.

The shoving was predominantly witnessed in the outer wheel path. This is an indication that the surfacing and/or the pavement structure has failed in the outer wheel path, close to the joint where the pavement structure was widened. An excavated slot of where the road shoved is presented in Figure 2 and Figure 3.

Figure 1: Shoving in the outer wheel path of the N1 Section 17

Figure 3: Profile of pavement structure where road has shoved

The asphalt surfacing, the crushed stone base and possibly the shoulder subbase were the layers that shoved. This can be attributed to transition zones being the weak point since it is difficult to compact in such confined areas, as well as water often infiltrating at the joints, causing further deterioration. An attempt was made to back-calculate the layer E-moduli from the FWD data. However, it proved to be difficult to fit the deflection bowl to the theoretical bowl. The deflection bowl fits that gave acceptable errors produced unrealistic E-moduli results, which were considerably higher than the recommended ranges (Jordaan (1993), Freeme (1983) and De Beer (1994)). Due to the uncertainty of their accuracy, the E-moduli values were discarded.

3 ANALYSING THE INTERLAYER SLIP

The purpose of this section is to analyse the interface between the granular base layer and the older asphalt layer. The slip was analysed by looking at the effect it had on the base layer, using a stress-dependency method. The slip was further analysed with Finite Element Analysis (FEA) and Linear Elastic Analysis (LEA).

3.1 Stress-dependency analysis of the slip

Given the unrealistic results yielded by the attempt to back-calculate the layer E-moduli (Section 2) for various pavement structures and their subsequent exclusion, the E-moduli for the base and subbase were determined using a stress-dependency method instead. The influence of the slip on the E-modulus of the granular base was analysed for various degrees of slip. Calculations were carried out using mePADS (CSIR, 2007) design software, and the Hicks and Monismith (1971) Bulk-stress log-log model, shown in Eq. (1.1), was implemented. The model parameters k_1 and k_2 can be calculated from back-calculations with various applied FWD loadings. However, for this study only the applied 40kN load measurements were available. Therefore, the model parameters were based on a study done by Bredenhann and Jenkins (2004). Their study used G2 base course material, which being the same as those used in the case study. A logic test on the results was carried out to assess the soundness of the results.

$$M_R = k_1 \theta^{k_2} \tag{1.1}$$

where M_R is the resilient modulus, k_1 and k_2 model parameters and $\theta = \sigma_1 + \sigma_2 + \sigma_3$ the bulk stress. Model parameters were taken as 7.5 and 0.66 from the Bredenhann and Jenkins (2004) study. Where the slip caused a negative (tensile) stress of less than 50 kPa, the principal stress was adjusted based on the bi-linear model from Theyse (2000), the suction study Rubuluza (2011) and the residual compaction stresses calculated by Uzan (1985) and recommended by Theyse (2007). These are graphically presented in Figure 4.

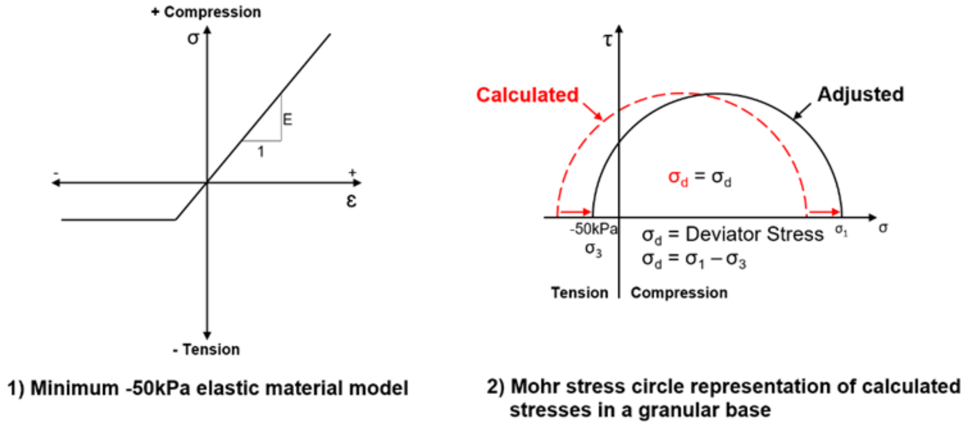

Figure 4: Bi-linear model with suction taken into consideration

Two values were used for the E-moduli of the old asphalt, i.e. 1500 MPa (relatively stiff) and 5000 MPa (very stiff). The pavement structures used are illustrated in Figure 5. The models were tested in the design software with a 40 kN circular load with a 150 mm radius and the results are summarized in Table 1. The summary of the Bulk-Stress calculation for the base course, shown in Table 1, indicate a significant reduction in the moduli when slip occurred.

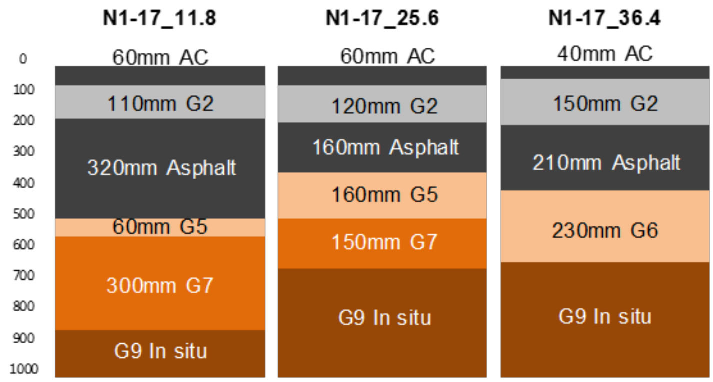

Figure 2: Illustration of the pavement structure used

Table 1: Summary of the Bulk-stress calculation for the base course

Model	M_r for Base course (MPa)						Old AC thickness (mm)	Base thickness (mm)
	1500MPa Old AC			5000MPa Old AC				
	No slip	Full slip	% Reduction	No slip	Full slip	% Reduction		
N1-17_11.8	506	389	23%	558	450	19%	320	110
N1-17_25.6	474	395	17%	526	389	26%	160	120
N1-17_36.4	503	410	18%	542	427	21%	210	150

The results appear reasonable and present a more realistic picture compared to the back-calculated moduli. Table 1 also compares the percentage reduction in the moduli of no-slip conditions with full-slip conditions, showing a significant reduction in the moduli of the base course due to slip, by a maximum of 26%. The reduction in the slip values with stiffness is shown in Figure 6.

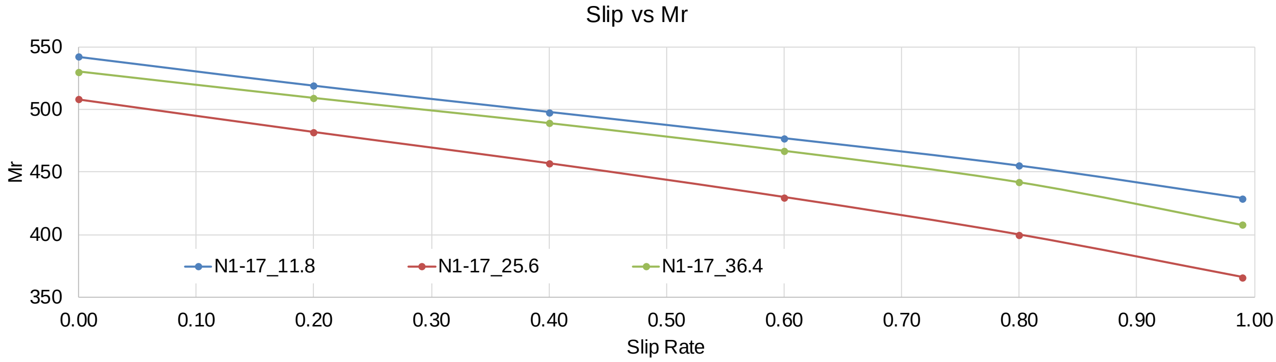

Figure 3: Reduction of base course moduli with incremental increased slip rate

Figure 6 indicates the reduction of the modulus with the slip rate taken in increments of 0.2 from no-slip (slip rate of 0.00) to full slip (slip rate 0.99). The results from mePADS (CSIR, 2007) were based on a modulus of the old asphalt of 3000 MPa, which is the rounded average value of 1500 MPa and 5000 MPa.

Figure 7 shows that the modulus of the base course reduces as the slip rate increases.Table 1 indicates the pavements with the thinner asphalt subbase layer are more prone to reduction in modulus. However, further study would be required to determine the effect the old subbase and subgrade may have had on the reduction. Figure 7 also shows the percentage theoretical reduction of the modulus caused by slip, using 1500 MPa and 5000 MPa for the modulus of the asphalt subbase layer, compared to the thickness of the older asphalt subbase and base layer.

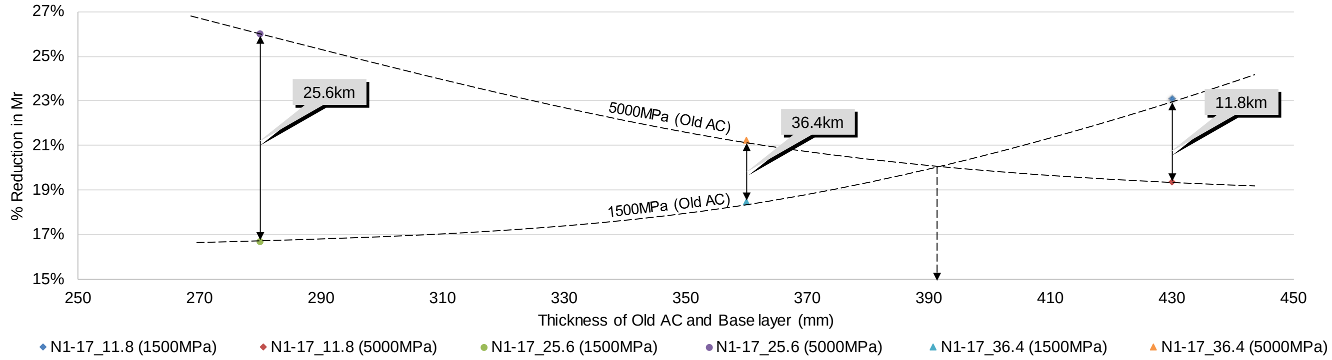

Figure 4: Theoretical reduction in base moduli compared to thickness

It is deduced from Figure 7 that the thicker the base and subbase combination, for the stiffer old asphalt layer, the smaller the percentage reduction in moduli there was for the base when slip was introduced. It was further deduced that it was the opposite with the pavement structure with the lesser stiff older asphalt layer. It was also deduced that the stiff and less stiff older asphalt layer were equal in terms of percentage reduction in moduli of the base for a thickness of approximately 390 mm (base and subbase together). The significance of this was not further investigated. The case study pavement structure in Figure 5 varies in supporting layers and materials and to neutralise the effect of variation in the subbase and subgrade, a theoretical model was created and modelled in mePADS (CSIR, 2007), with only the thickness of the old asphalt layer changing. This allowed the testing of the sensitivity of the modulus of the base course towards slippage compared to the underlying older asphalt. The results from the calculation for the various combinations are shown in Figure 8.

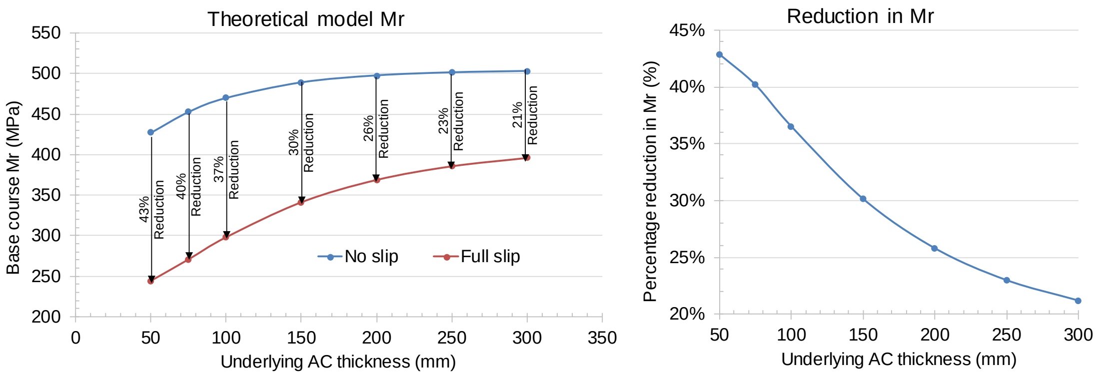

Figure 8: Sensitivity analyses for the modulus of a base course with varying underlying asphalt layer thicknesses

It is evident in the above theoretical model that there is an increase in sensitivity of the modulus of the base course to slippage between the base course and the underlying asphalt layer, in response to a decrease in thickness of the underlying asphalt layer. The stress dependency was calculated with a simplified method which analysed the entire pavement structure as well as only the base layer.

3.2 The influence of slip on the surface deflection (LEA)

The influence of the slip on the surface deflection was analysed with LEA (using mePADS (CSIR, 2007)) and the pavement models from Figure 5. The surface deflections were calculated for various degrees of “slip rate” and are shown to increases exponentially as the slip rate increase (see Figure 9).

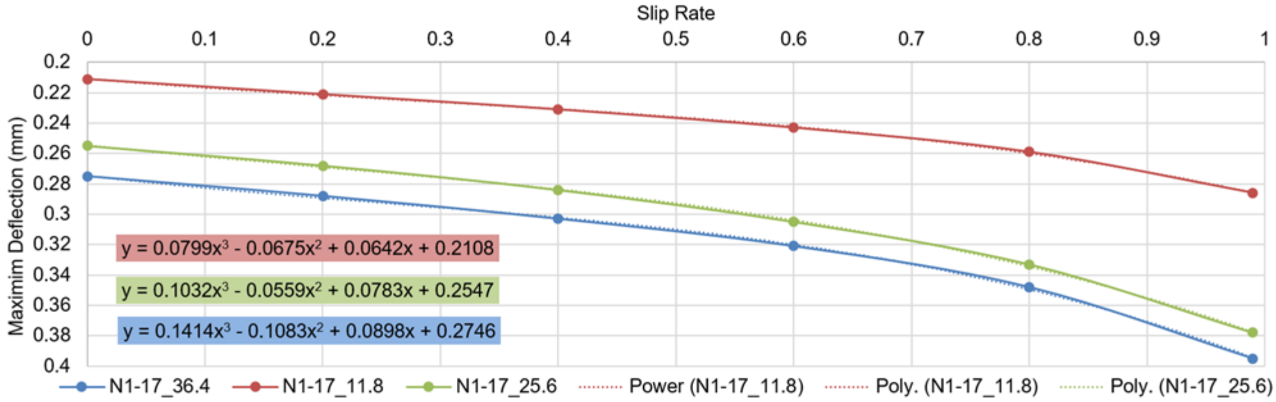

Figure 9: Slip compared to the maximum deflection

The increase in surface deflection will have an influence on the structural capacity of the pavement structure and will be further discussed in Section 4.

3.3 Finite Element Analysis (FEA) with slip

"Standard" pavement design software uses multi-layer linear-elastic tools to calculate the stresses and strains within the pavement structure. However, road building material are not necessarily homogenous-isotropic-linear-elastic in nature. In an effort to model the material in more detail, the pavement structures shown in Figure 5 was modelled with FEA, using the software package Abaqus (Dassault Systèmes Simulia Corp., 2010), utilizing the stress-dependency of the base layer resulted in semi-nonlinear model. This allowed the properties of the material to be altered to some extent, to better represent the actual material properties. The slip surface was created in the FEA model by introducing a 1 mm thick layer between the granular base and the older asphalt layer. The slip surface was then given cohesive properties that would represent the shear between the two elements (in this case the base layer and the older asphalt subbase layer). The properties of the cohesive layer can be adjusted in order to create various degrees of slip, which can include no slip (full friction). The FEA focused on the slip distance (the difference in horizontal movement, between the top and bottom node of the cohesive layer) at the interface between the base and the subbase (old asphalt layer), the principal stresses (maximum and minimum), as well as the influence of the slip on the stresses and strains within the pavement structure. The moduli calculated and used with the Bulk-stress method was implemented in the FEA as the E-moduli for the various pavement layers. The sensitivity of the slip to the stiffness of the older asphalt layers was also tested. It was deduced from the analyses that the slip distance is not sensitive to changes in the E-moduli of the older asphalt layers. The FEA results indicating the maximum slip and the slip distance from centre load for the various models are summarised in Table 2.

Table 2: Maximum slip distance

Model	Max horizontal slip distance	Distance of max slip from center of plate/load
N1-17_11.8	41 µm	200 mm
N1-17_25.6	44 µm	200 mm
N1-17_36.4	51 µm	200 mm

The graphs in Figure 10 show the stress and strain distribution throughout the pavement structure to illustrate in greater detail how the pavement structure reacts under loading. The FEA model did not allow for reduced tensile stresses caused by suction in granular material, which requires complex programming. Also, the material used in the FEA model behaves as linear-elastic homogenous isotropic, which in reality might be not be the case.

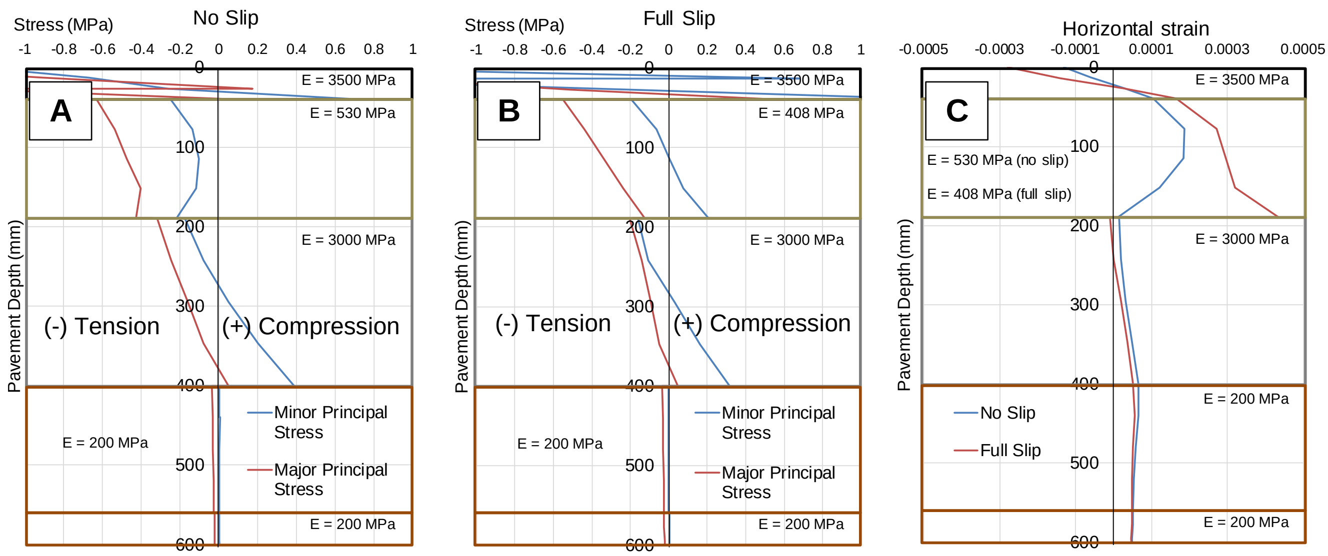

Figure 10: Stress and strain distribution of FEA pavement model

Graph A in Figure 10 shows the stress distribution with full friction between the base and subbase. Graph B shows the stress distribution when slip with zero friction was introduced between the base and subbase. Graph C shows the strain distribution between full friction and slip with zero friction. The results showed that the introduction of the slip between the base layer and the older asphalt layer increased the stresses at the bottom of the asphalt surfacing (Graph B). It was also found that there was a reduction in stresses at the bottom of the base layer (Graph B), which led to a reduction in stresses in the upper part of the older asphalt layer, especially with the Major Principal Stresses. It was therefore deduced that the performance of the pavement structure is greatly reduced if slip occurs between the older asphalt layer and the new granular material overlay. Furthermore, the horizontal tensile strain is the principal design parameter for asphalt layers. Graph C showed that there was an increase in horizontal strain at the bottom of the surfacing asphalt layer as well as a decrease in strain at the top of the older asphalt layer, which were demonstrated across all models. Therefore, less strains and stresses under the applied load were transferred to the older asphalt layers due to slippage. This implies that the structural capacity of the surfacing layer was reduced, and the benefit of a strong subbase (i.e. old asphalt) was lessened.

4 PAVEMENT STRUCTURAL BEARING CAPACITY

There are numerous methods capable of determining the structural capacity of a pavement structure. For this analysis three methods were used to determine the structural capacity of the three pavement structures in Figure 5, as well as two alternative models of more conventional pavement designs, for comparison purposes. The three methods were:

- Pavement Number (PN) method: As described in the TG2 (2009) manual,
- Linear elastic analysis (LEA) with mePADS (CSIR, 2007) software,
- Finite element analysis (FEA) in Abaqus (Dassault Systèmes Simulia Corp., 2010); used to calculate stresses and strains in various pavement layers, the pavement structures' estimated capacity calculated manually using transfer functions and equations from the South African Mechanistic-Empirical Design Method of 1995 (Theyse et al, 1995 and Theyse et al 1996), as well as Collings et al. (2011).

The PN Method (TG2, 2009) indicated that all three N1 models were able to carry the required traffic loading. Although, this method was developed based on past performance of a number of roads in South Africa, none of which had such an inverted pavement structure. The results should therefore be confirmed with other design tools, such as LEA and FEA. The results from all three the N1 models indicated that the pavement structure bearing capacity far exceeds the historic traffic load for none-slip conditions. However, when full slip was introduced between the base and the subbase the results indicate that the bearing capacity of all the pavement structure model is severely reduced by up to 90%, which is far below the historic traffic loading. Therefore, it could be concluded from LEA calculation results that this inverted pavement structure is highly sensitive to slip. FEA calculations supported all three N1 models' ability to carry the required traffic loading. Therefore, it is possible that an adequate bond developed on the actual pavement structure between the old asphalt layer and the granular overlay and that little to none slip occurred, seeing as it performed relatively well over the 24 years of its existence. Both the LEA and FEA calculations indicated that the critical layer, before the slip was introduced, was the older asphalt layer (without taking a secondary crushing phase into consideration (SAPEM, 2014)) for all the models. After the slip was introduced the critical layer became the granular base course, also for all the models from the LEA and FEA calculations.

5 CONCLUSIONS AND RECOMMENDATIONS

The following were drawn from the study:

- The majority of the pavement is reported to be in a sound to warning condition in the traveling path. Plenty of failures are present in the form of shoving at the joint between the inverted pavement structure and the shoulder which consists of a more conventional pavement structure.
- The back-calculation results of the N1 Section 17 indicated that the base and older asphalt layers E-moduli values are higher than the recommended ranges in most cases and was therefore excluded from the study.

- The Bulk-stress method gave more realistic moduli values that were within recommended ranges.
- A theoretical model evaluated in mePADS (CSIR, 2007) found that the thinner the older asphalt layer, the more sensitive the modulus of the base course was to slip.

- Results from modelling surface deflection across all three models with LEA calculations including various slip rates ranging from full friction to full slip, showed surface deflections to increase exponentially with an increase in slip.

- FEA calculations across all three models showed the modulus of the older asphalt layers having minimal effect on slip distance, with the maximum slip distance located 200 mm from the centre load point.

- The FEA analyses of all models for full slip showed tensile stresses in the base course in excess of 50 kPa. This was deemed to be unrealistic and adjustment to the deviator stress was made in order to produce more realistic results.

- Three methods used to calculate the bearing capacity of the N1 Section 17, showed that
    - The PN Method indicated that all three N1 Section 17 models were able to carry the required traffic loading.
    - The LEA calculations, carried out with mePADS (CSIR, 2007), showed that the inverted pavement structure is highly sensitive to slip.
    - FEA calculations supported all three N1 section 17 models being able to carry the required traffic loading.

- It is possible that an adequate bond developed on the actual pavement structure between the old asphalt layer and the granular overlay and that little to none slip occurred, seeing as it performed relatively well over the 24 years of its existence.

- The economic analysis found the pavement structure with the lowest present worth of cost to be the inverted pavement structure (existing), given 10% initial repairs of the 210 mm thick asphalt.

- Based on the results of this study, the inverted pavement structure may be considered a viable construction method for rehabilitation of an existing road structure.

The following recommendations are proposed for future research:

- That the FEA models be analysed with a dynamic load, instead of a static load; a maximum tensile stress of 50 kPa for granular materials, modelled as stress dependency materials.

- That a construction energy analysis and emissions analysis be carried out to determine if this pavement structure (as per the case study) is a more sustainable solution.

- The risk of the inverted pavement structure (such as in this case study) in terms of maintenance and performance due to ingress of surface water be determined.

- More studies of such inverted pavement structures be analysed to confirm their feasibility as an alternative pavement rehabilitation/strengthening option.

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