STRESSES AND STRAINS IN ASPHALT-SURFACING PAVEMENTS

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INTRODUCTION

The response of a pavement structure to traffic loading is mechanistically modelled by computing stresses and strains within its layers. If excessive, stresses may cause pavement fatigue cracking and/or surface rutting. This may result in both structural and functional failure, thus causing a safety hazard to motorists. These failure distresses are minimised among others by use of effective balanced pavement designs. Pavement stress-strain analysis is an ideal tool for analytical modelling of pavement behaviour and thus, constitutes an integral part of pavement design and performance evaluation. It is the fundamental basis for the mechanistic design theory.

With the ever increasing truck tyre loading and inflation pressures, a better understanding of the pavement stress-strain behaviour is an enhancement in the development of more constitutive design models centred on pavement-traffic load response and distress minimisation. The wide use of thin asphalt surfacings (≤50mm) in Southern Africa which are considered economical, entails that more studies are needed into understanding the traffic load response of these layers.

In this paper, a simplified linear elastic analysis of the stress-strain behaviour of an "Asphalt Surfacing Layer" under static traffic loading is presented. The top asphalt layer was modelled by investigating the effects of the variation of the following parameters:

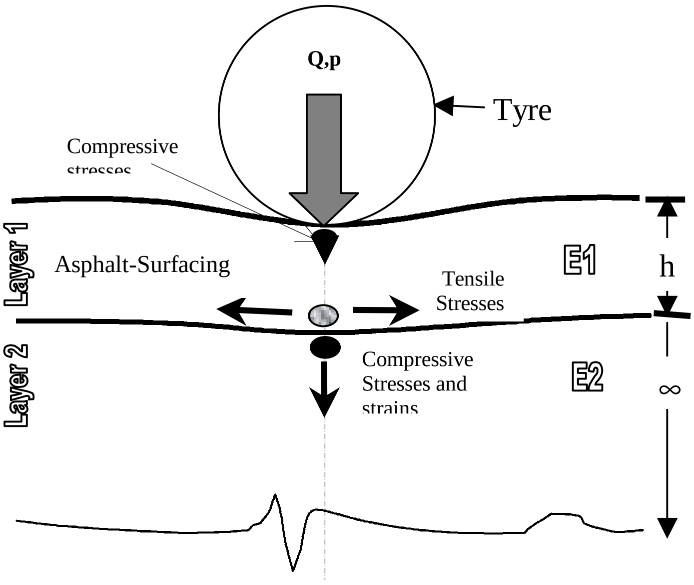
(1) the asphalt surfacing layer thickness (h)
(2) the material elastic constants (the elastic modulus (E) and the Poisson's ratio (ν))
(3) the traffic loading (the axle load (Q) and tyre contact pressure (p))

These parameters were subsequently correlated to the pavement service life in terms of the number of load repetitions to initiation of fatigue cracking (relative fatigue life). The stress-strain distributions, and the three-dimensional stress state in relation to the asphalt surfacing layer thickness are also presented. Stresses in two layer pavement systems were extensively studied by Meier et al and Molenaar (1993).

METHODOLOGY

The analysis was based on a mechanistic design approach (Croney et al, 1998 and Huang HY, 1993), and a linear elastic two-layer pavement system as shown in Figure 1 was adopted. All the layers under the asphalt surfacing (top-layer) were theoretically characterised by one composite elastic modulus (E_2). Consequently, the following design criteria have been discussed;

- The stresses-strain distribution and the three-dimensional stress state over the height of the asphalt-surfacing layer.
- The horizontal tensile stresses and strains in the bottom zone ([h-1]mm) of the asphalt surfacing layer which are the failure distress parameters for pavement fatigue cracking.



For a multi-layer pavement system, the above simplification and characterisation of layer 2 may not hold. However, for the purpose of this paper it is considered justifiable since the interest is in the asphalt layer. Also, this is a simplified model assuming static traffic loading conditions and isotropic linear-elastic characterisation of materials. In Figure 1, Q is the tyre load in kN, p is the tyre pressure in kPa, h is the asphalt surfacing layer thickness in mm, and E1, E2 are the elastic moduli in MPa.

Figure 1: Simplified Two-Layer Pavement System

All the calculations were done directly under the center of the tyre load at zero radial distance where principal stresses are assumed to be maximum.

Stresses and Strains

The common analytical method to model pavement-traffic load response is stress-strain analysis.

Stress (σ) is defined as load (in this case caused by a wheel) per unit area measured in Mega Pascals (1MPa = 1 N/mm^2). The simplified stress equation for a uniform contact stress with circular loading is:

$$\sigma = \frac{1*10^3 Q}{A} \approx p = \frac{1*10^3 Q}{\pi a^2} \qquad \text{..........(Eq.1)}$$

Where: σ or p is stress in MPa, Q is the load (vertical tyre load) in kN, A is the load-surface contact area in mm^2, and a is the tyre-pavement surface contact radius in mm.

Strain (ε) is defined as the relative deformation (tensile or compressive) of a material in response to stress normally expressed in microns (dimensionless unit x 10^6). The following equation relates strain to stress, the Poisson's ratio, and the material stiffness;

$$\varepsilon_X = \frac{(\sigma_X - \nu(\sigma_Y + \sigma_Z))}{E} \qquad \text{..........(Eq.2)}$$

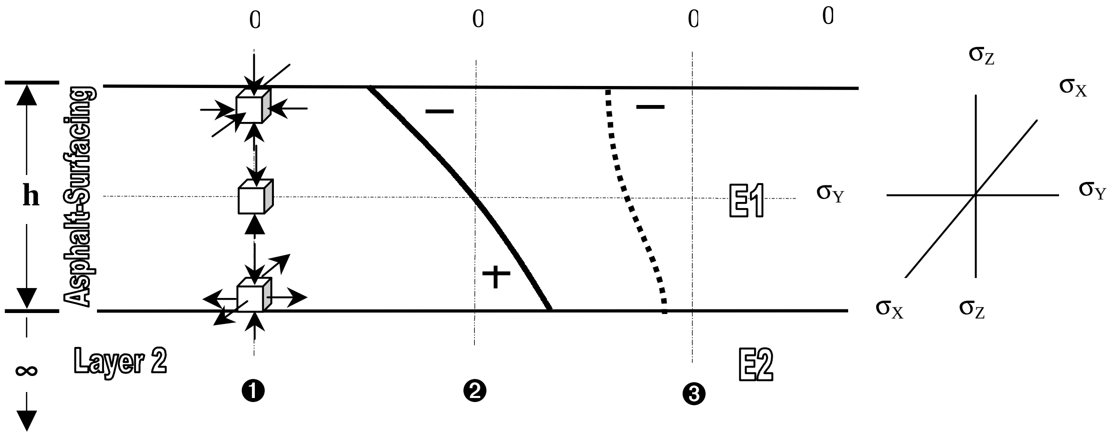
Where: ε is strain in microns (ε_X is the strain in the X-direction), σ is stress in MPa ($\sigma_{X,Y,Z}$ are the three-dimensional stress components in the X-Y-Z directions), ν is the Poisson's ratio, and E is the material stiffness measured in MPa. Equation 2 holds for strain in the other directions (i.e Y and Z), by interchanging the subscripts $_{(X,Y,Z)}$.

Poisson's ratio (ν) is the ratio of the strains perpendicular to the direction of the applied load divided by the strains in the direction parallel to the load. It is a property of inear-elastic, homogeneous and isotropic materials relating lateral to longitudinal strain relative to the direction of load application.

$$\nu = -\frac{\varepsilon_{\perp}}{\varepsilon_{\parallel}} \quad \text{………………………………………………………………………………(Eq. 3)}$$

Where: ν is the Poisson's ratio, $\varepsilon_{\perp}$ is the strain perpendicular to the direction of load application, and $\varepsilon_{\parallel}$ is the strain parallel to the direction of load application.

The three-dimensional Stress State



Legend: - = (negative) compression, + =(positive) tension, ❶-Principal stresses, ❷-Horizontal stresses, ❸-Vertical stresses

Figure 2: Three-Dimensional stress-State under the Centre of the Wheel Load

Figure 2 above illustrates a possible stress profile within an asphalt layer. In the immediate top zone, all the stress components $\sigma_{X,Y,Z}$ are compressive. This concentration of compressive stresses can cause surface deformation in the asphalt layer. Somewhere around the mid-depth, where horizontal stresses σ_X and σ_Y change from compression to tension, only the vertical stress component σ_Z exist. σ_X and σ_Y are zero. At the bottom zone, σ_X and σ_Y are tensile. σ_Z is still compressive but its magnitude has significantly decreased with depth. The existence of tensile stresses (σ_X and σ_Y) subjects the bottom zone to tension and thus cracking.
In the special case of no shear stresses as shown in Figure 2, the normal stress become principal stresses. Maximum deviator (shear) stresses can be deduced easily from principal stresses. Deviator stress is the difference between the maximum and minimum normal principal stress, and maximum shear stress is half the maximum deviator stress.

$$\sigma_d = (\sigma_1 - \sigma_3) \ldots\ldots \Rightarrow \tau = \frac{1}{2}\sigma_d \approx \frac{1}{2}(\sigma_1 - \sigma_3) \quad \text{…………………………………………….(Eq. 4)}$$

Where: σ_d is the maximum deviator stress in MPa, σ_1 is the maximum normal principal stress in MPa, σ_3 is the minimum normal principal stress in MPa, and τ is the maximum shear stress also measured in MPa.

Computations

Computer programs BISAR 3.0 (Shell Bitumen, 1998) and Elsym 5 (Ahlborn, 1969) were used for computing the stresses and strains. Equation 6 (page 5) was used for computing the relative fatigue life (number of load repetitions) of the asphalt layer, based on the horizontal strain levels at the bottom zone.

TRAFFIC LOADING

In view of the current traffic regime, this study's emphasis was focused on high traffic loading which is considered as a major factor responsible for most pavement damage world-wide. The 1997 South African traffic statistics revealed that 35% of the 90 000 weighed heavy trucks were overloaded (De Beer et al, 1999). At one of the Zambian weighbridge stations (Kafue) which was physically visited in 1998, 6 of the 25 weighed trucks between 08.00hrs to 16.00hrs were on average 12.5% overloaded above the 80kN legal axle-load limit. Thus, on average, one in every five trucks on the Zambian road could be overloaded. According to the "fourth power law", 12.5% overload results in about 60% more pavement damage compared to an 80kN legal axle load. There is therefore an imperative need to seriously look into the current standard design loads if modern pavements are to sustain these extreme high loads. Traffic laws and regulations also need to be effectively enforced to minimise pavement damage.

FATIGUE CRACKING AND RUTTING

Pavement performance is normally evaluated using fatigue cracking and rutting models. Fatigue cracking and rutting are primarily caused by stresses and strains due to cumulative repetitive and/or high traffic loading. Other factors such as material mix-design, temperature, moisture, ageing, oxidation, etc directly or indirectly contribute to pavement distress. However, these factors are not discussed in this paper.

"Fatigue Cracking" is the progressive cracking of the asphalt surfacing or stabilised base layers due to cumulative repeated traffic loading. This occurs as a result of tensile stresses and strains in the bottom zone and propagates upward to the top. On the pavement surface, it finally manifests as alligator cracks along the wheel tracks.

Fatigue cracking in asphalt layers is considered a major structural distress and is predominantly caused by traffic loading. In addition, ingress of rainwater through the cracks can lead to serious structural failure of the underlying layers particularly granular and unbound materials including the subgrade. The cracks are measured in square meters of the surface area.

(a) Crack development under wheel load (b) Cracks in wheel tracks

Figure 3: Fatigue Cracks in Asphalt Layer

Logarithmic equations are normally used to relate tensile stresses or strains to the number of load repetitions to fatigue cracking (Manuel Ayres Junior, 1997). The general fatigue life prediction equation is of the following format:

$$N_f = k_1(\Gamma)^{-k_2} \quad \text{(Eq 5)}$$

Where: N_f is the number of allowable load repetitions to prevent fatigue cracking, Γ is the horizontal tensile stress (σ) or strain (ε) at the bottom zone of the asphalt beam, and k_1, k_2, are fatigue regression coefficients obtained from laboratory fatigue tests.

YH Huang (1993) and Theyse et al (1996) expressed the fatigue crack failure criterion by the following Equations respectively:

$$N_f = f_1(\varepsilon_t)^{-f_2}(E_1)^{-f_3} \quad \text{(Eq.6)}$$

$$N_f = 10^{A\left(\frac{Log[\varepsilon_t]}{B}\right)} \quad \text{(Eq.7)}$$

Where: N_f is the number of allowable load repetitions to prevent fatigue cracking, ε_t is the horizontal tensile strains at the bottom zone of the asphalt beam, E_1 is the elastic modulus of the asphalt, and f_1, f_2, f_3, A, B are fatigue regression coefficients (Asphalt Institute, 1993; Huang YH, 1993; and Theyse et al, 1996) for crack initiation. Regression coefficients A and B are a function of the asphalt mix-stiffness. The asphalt modulus (E_1) is dependent on the material mix-design and is a function of temperature and loading speed. In both Equations, shift factors need to be used to account for crack propagation to the surface. Equation 7 is the general form of the fatigue crack initiation functions used in the South African Mechanistic Design Method (SAMPDAM), and it must be used with fatigue crack propagation shift factors when determining the relative fatigue life of thicker asphalt bases (h>50 mm) (Theyse et al, 1996).

"Rutting" is defined as the permanent deformation of a pavement due to the progressive accumulation of visco-plastic vertical compressive strains under traffic loading. On the pavement surface, it manifests as longitudinal depressions in the wheel tracks. Significant rutting can lead to major structural failures and hydroplaning potentials.

Hugo et al (1999) related rutting to pavement functional performance, and defined rutting as the vertical gap left under an imaginary straightedge, 1.2m long straddled across the wheel path with both ends on the pavement, as illustrated in Figure 4.

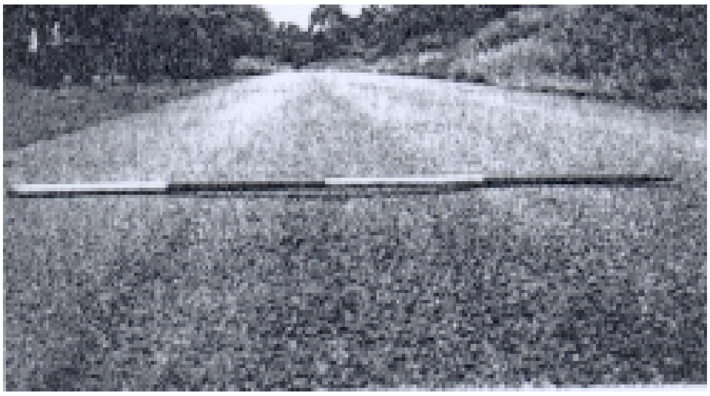


Figure 4: Surface Rut in Wheel Track

Surface ruts may occur in the asphalt-surfacing layer under the action of heavy vehicle loading, particularly in areas of extreme high temperatures. Principally, the surface rutting in the asphalt layer is mainly caused by shear deformation (Long F, 1999) coupled with high-localised vertical compressive stresses in the top zone. Asphalt-mix densification due to traffic loading is another contributing factor. Pavement uplift (shoving) may also occur along the sides of the rut. In many instances, ruts are only noticeable during and/or after rainfall, when the wheel tracks are filled with water.

Most existing models do not adequately predict the permanent deformation response of asphalt concrete nor directly relate traffic load repetitions to asphalt surface rutting. Long F (1999) has however, reported an on-going research into the development of more constitutive asphalt-surface rut models based on the SHRP mix-design procedures.

Besides pavement structural damage, surface rutting poses a serious safety threat to motorists. Pooling of water in the ruts may result in hydroplaning, making vehicle steering, and braking difficult. The water can also result into loss of asphalt stiffness due to degradation and stripping (Walubita LF et al, 2000). Water infiltration through pores generally weakens the pavement structure, and therefore, water ponding on the pavement surface is undesirable.

INPUT PARAMETERS

An overview of the input variables into the computer programs is given in Table 1 below.

Table 1: Input Parameters

Definition	**Unit of Measurement**	**Variables**
Traffic loading -axle load -tyre pressure	kN kPa	80,90,100,110,120,130,140,150,160,200 520, 550, 600, 690,700,750,800,900 1000
Asphalt-surfacing layer thickness **h**	mm	20,30,50,70,75,100,120,150,200
Composite elastic modulus $\mathbf{E_2}$	MPa	50, 100, 150, 200, 400, 500, 1000
Modular ratio (MR) $\mathbf{E_1/E_2}$	Unit-less	1, 3, 5, 7, 8, 10, 15, 20
Poisson's ratio $\boldsymbol{\nu}$	Unit-less	0.25, 0.35, 0.5

$\mathbf{E_1}$ is the asphalt modulus in MPa. $\mathbf{E_2}$ is the composite modulus of all the underlying layers beneath the asphalt-surfacing layer in MPa.

In the mechanistic linear-elastic static design theory, the tyre pressure (p) is assumed to be equal to the vertical tyre-pavement surface contact stress measured in MPa. 80kN and 520kPa were designated as the standard single axle load with dual tyres and tyre pressure, respectively. For the super single axle loading, 700kPa tyre pressure is often used as the standard design value, and the vertical tyre load (in kN) is half the total axle load. These are the values used in the South African design standards (Theyse et al, 1996).

RESULTS AND ANALYSIS

The results of the calculations based on linear-elastic theory are presented in Figures 5-13 on appendix A. An E_2 value of 50MPa was often used to conservatively represent the worst scenario. In this analysis as well as in Figures 5-13, negative (-) and positive (+) refer to compressive and tensile, respectively, and 80kN-700kPa to axle load and tyre pressure.

Stress-Strain Distribution

Figure 5 shows the stress-strain distribution within the asphalt surfacing layers for the selected thickness 20, 50, 75, 150 and 200 mm, respectively, for the same traffic loading and material elastic constants. In all the surfacings, there is a high concentration of compressive (negative) stresses in the immediate top zone (Figure 5 (a)). The 20mm surfacing is virtually subjected to compressive stresses within the entire surfacing depth and there are no tensile stresses. The vertical compressive stress at the bottom is almost equal to the tyre-surface contact stress (0.7MPa), and hardly decreases over the surfacing depth. A higher vertical load is thus transferred to the immediate underlying layers.

The intermediate surfacing 50 and 75 mm exhibited the highest magnitude of horizontal stress and strain as well as vertical strain compared to the 20, 150, and 200 mm surfacings.

In the thicker surfacing base (200mm), the vertical stress significantly decreased with depth, and is infact reduced by about 75% from 0.7MPa at the top to about 0.18MPa at the bottom. Much traffic loading is absorbed within the layer depth compared to the 20mm surfacing. Like for the intermediate surfacings, horizontal stresses change from compression (negative) in the top zone to tension (positive) at the bottom. However, the horizontal stress magnitude is relatively lower than for 50, 75 and 150 mm, where as it is all compressive for the 20mm surfacing (Figure 5 (a)).
The horizontal strains are all compressive (negative) within the 20mm surfacing (Figure 5 (b)). This is an indication of less sensitivity to fatigue. In the other layers, the trend is the same as for the horizontal stress, and again the intermediate layers exhibited more sensitivity in terms of strain magnitude. The vertical (compressive) strains generally increased with depth, and are in fact tensile (positive) in the immediate top zone of the 20, 50 and 75 mm thickness. This is due to the effect of the horizontal stresses and the Poisson's ratio. It must be observed that, in all the layers, horizontal stresses are compressive (negative) in the top zone. Also from the vertical strain profile, the marked influence of the Poisson’s ratio on the thin and intermediate surfacings is evident.

From the above analysis, it appears that thick asphalt layers (surfacing and base) significantly contribute to the structural integrity of the pavement structure and are regarded as structural members. Thin asphalt surfacing layers appear to be essentially load transfer components with little susceptibility to fatigue damage, but require high strength support layers to sustain the traffic loads.

Variation of the Asphalt-Surfacing Layer Thickness (h) and Modular Ratio (E_1/E_2)

The results for a composite modulus (E_2) of 50MPa are plotted in Figure 6. The surfacing (h) was varied from 20 to 200 mm, and the modular ratio (MR) from 1 to 20. The traffic loading remained constant at 80kN-700kPa. A similar stress-strain profile was obtained for E_2=400MPa, except the horizontal strains were of smaller magnitude. Stresses for both moduli were of the same magnitude for the respective h-values. The effect of the composite modulus of the underlying layers on the asphalt stress-strain response is discussed subsequently.

Tensile stresses are highly dependent on the asphalt stiffness, and increased as the modular ratio increased (Figure 6 (a)). At modular ratio 1 (Boussinesq space), all horizontal stresses are compressive (negative), because the entire pavement structure behaves like one elastic homogeneous layer with infinite depth. Relative fatigue life is highest at this ratio, particularly for the thin and intermediate surfacing layers (Figures 10 and 11). From Figure 6 (a), it could also be observed that the vertical stress in the 20mm surfacing at the bottom zone (h-1 mm) is equal to the tyre-contact stress (0.7MPa) and is insignificantly affected by the modular ratio. In the thicker surfacings, an inverse relationship between the horizontal strains and the asphalt stiffness could be observed. The strains decreased as the modular ratio increased. The opposite behaviour is evident in the thin surfacing layers (<50mm) (Figure 6 (b)).

At modular ratio 1 (Boussinesq space), although all the stress components are compressive (negative), strains in the surfacings ≥50mm are tensile (Figure 6 (b)). This is due to the effect of the Poisson's ratio. The question then is, "if these tensile strains are caused by compressive stresses, can they be used to determine the fatigue behaviour of the asphalt"??

With increased thickness i.e. 200mm, the load is absorbed over a greater depth of influence, and hence the low stress-strain values. Increase in the asphalt stiffness increases the resistance to strain. This together with the low vertical stress explains the decreasing strains with modular ratio for thicker surfacings (Figure 6 (b)).

Variation of the Composite Elastic Modulus (E_2)

Figure 7 shows the effect of the composite modulus (E_2) of the immediate underlying layers on the stress-strain response of the asphalt layer for the selected thickness 20 and 150 mm, for the same traffic loading of 80kN-700kPa. As can be seen in Figure 7 (a), stresses in the asphalt layer are independent of the stiffness of the underlying layers. Variation of the composite modulus E_2, had no effect on the magnitude of both the horizontal and vertical stresses. For all the values of E_2, the stress remained the same, but varied only with the change in the modular ratio (Figure 7 (a)). From this, it is apparent that the modular ratio has a significant effect on the stress-strain response of the asphalt layer. Horizontal tensile strains showed an inverse relationship, and increased as E_2 decreased. In both the surfacing layers, the highest strain values are shown for E_2=50MPa and the least for E_2=1000MPa. Thus, surfacings resting on low strength support layers (base, subbase, and subgrade) may be potentially susceptible to traffic damage. This is further evident when comparing the relative fatigue life of h=30mm in Figure 10 and 11 at 80kN-700kPa traffic loading.

As observed previously in Figure 6, thin asphalt surface layers have good tensile stress-strain behaviour at low modular ratio, and vice versa for the thicker asphalt bases.

The Effects of the Poisson's Ratio
Results for the selected asphalt layer thickness are shown in Figure 8. Traffic loading of 80kN-700kPa and a composite modulus of E_2 = 400MPa with a modular ratio (MR) of 5 were used. The notation 0.25/0.25 on the horizontal axis in Figure 8 indicate that the Poisson's ratio for the asphalt layer is 0.25 and it is also 0.25 for the composite underlying layers. As can be seen in Figure 8, ν = 0.25 and 0.35 gave the lowest stress-strain values. Most design procedures use 0.35. The asphalt's optimal performance appears to be at low Poisson's ratio (0.25). However, the Poisson's ratio is dependent on the asphalt stiffness and temperature.

The stress-strain graphs for the thicker asphalt layers (150 and 200 mm) seem to approach a straight line, implying that the horizontal stresses and strains are insignificantly affected by the Poisson's ratio. The large-scale variations of the stress-strain values of the intermediate and thin surfacings for the different Poisson's ratios indicate that these layers are significantly affected by the Poisson's ratio. This effect was also observed in Figure 5 (b). Subsequently, their fatigue characteristics could equally be sensitive to the Poisson's ratio.

The Effect of Traffic Loading
Figure 9 shows a simultaneous change in both axle loading and tyre pressure for an arbitrary selected thin surfacing (30mm) and E_2, 200MPa. As expected, stresses and strains substantially increased as the traffic loading was increased. This is the normal material response to loading, and implies more pavement damage as evident from the relative fatigue lives shown in Figure 11. The highest stress-strain values (Figure 9), and the lowest number of fatigue load cycles (Figure 11) are shown for 120kN-1000kPa traffic loading compared to 80kN-520kPa.

For axle load variation at constant tyre pressure, the general trend was a decrease in both horizontal stress and strain with axle loading in the thinner surfacings. Actually, the 20mm surfacing exhibited extremely good stress-strain (horizontal) response at higher axle loading. These layers are less susceptible to fatigue under traffic loading, but may risk high surface deformation (due to high-localized compressive stresses) and rutting particularly in the lower layers. In the thicker surfacing bases greater than 100mm, stresses and strains increased with axle loading. Summarized, and with regard to horizontal stresses and strains, a change in axle loading appears to have more detrimental effects in the thick asphalt surfacing layers compared to thin layers.

At constant axle loading, stresses and strains almost varied linearly with the tyre pressure. Horizontal stresses and strains increased substantially as the tyre pressure was increased from 520kPa to 1000kPa. The expected fatigue damage equally increases. The intermediate thickness 50 to 100 mm seemed to be highly affected by the tyre pressure variation. The extreme thickness, 20 and 200 mm were the least affected.

From the comparative variation between the axle loading and the tyre pressure, it was observed that the horizontal tensile stresses and strains were more sensitive to tyre pressure than axle loading. In the thicker surfacing layers (≥100mm), a 25% increase in axle loading resulted in a corresponding increase of about 7% and 15% for the horizontal stress and strain respectively, where as, a 14% increase in tyre pressure caused an increase of about 8% in horizontal stress and 11% for the strain. This phenomenon is related to the tyre-pavement surface contact area, and clearly shows that the tyre pressure has a substantial effect on the horizontal stress and strain.

RELATIVE FATIGUE LIFE (N_f)

Equation 6 (page 5) with fatigue regression coefficients; f_1= 0.0796, f_2= 3.291, and f_3= 0.854 was used for calculating the relative fatigue life (number of load repetitions) of the asphalt layer (Asphalt Institute, 1993; and Huang YH, 1993) based on tensile strains at the bottom zone. Regression coefficient f_1 is inclusive of the crack propagation factor. The elastic modulus E_1 was expressed in MPa and strains in microns (unit-less).

N_f versus h and modular ratio (MR)
In thin surfacings (≤50mm) fatigue life is highest, and tends to decrease with increasing modular ratio (Figure 10). This concurs with the tensile strains plotted in Figures 6-8. The least number of fatigue load cycles was obtained at 20 modular ratio.

In the thicker surfacings (≥100mm), relative fatigue life increased with modular ratio. In contrast to the thin surfacing, the highest number of fatigue load cycles for 150mm was obtained at a modular ratio of 20.

The intermediate surfacing layers 50mm to 100mm appeared to be less affected by the modular ratio, but had the least fatigue life. With the exception of MR = 1, their relative fatigue life fell below $1x10^6$ load cycles.

N_f versus MR, axle loading, and tyre pressure.
The relative number of fatigue load cycles to failure versus modular ratio for the four different traffic loading, for similar material constants are shown in Figure 11. The least number of fatigue load cycles was obtained under the high traffic loading, 120kN-1000kPa. This is an indication of more damage compared to the other traffic loading. At modular ratio of 10, the 80kN-700kPa traffic loading had a relative fatigue life of about $5x10^6$ load cycles whilst 1200kN-1000kPa had only $0.2x10^6$. This represents a reduction of about 96% in fatigue life, clearly indicating the potential damage of high traffic loading. Figure 11, further indicates that the thin surfacing layer (30mm) has relatively high fatigue life at low modular ratios. The effect of tyre pressure is also evident when comparing the relative fatigue lives of 80kN-520kPa and 80kN-700kPa at 20 modular ratio.

N_f versus axle loading
Figure 12 shows the effect of variation of axle loading on the relative fatigue life of the respective asphalt surfacing layers. The tyre pressure was maintained constant at 700kPa, and the material constants remained unchanged. It is clearly evident that the thin surfacing layers have higher fatigue life, which appears to increase with axle loading, and it is infact over 5×10^6 load cycles for 20 mm. Up to about 75mm, the highest fatigue life is shown for 200kN, which is about 150% overload above 80kN standard axle load. The relative fatigue life of the 100mm surfacing appear to be little affected by axle loading, whilst in the thicker layers, the relative number of fatigue load cycles to failure decreased with increase in axle loading.

N_f versus tyre pressure.
For similar axle loading and material constants, the relative fatigue life of all the layers decreased with increase in tyre pressure (Figure 12). For all the values of h, the smallest number of fatigue load cycles is indicated for 1000kPa and the highest for 520kPa. However, the intermediate surfacing layers have the least relative fatigue life, whilst the 20mm exhibited the best fatigue performance followed by the 200mm surfacing base.

DISCUSSION

It has been analytically shown that tensile strains as well as relative fatigue damage in the thick asphalt bases decrease with both thickness and material stiffness. In the thin surfacings, tensile strains and fatigue damage increase with both surfacing thickness and material stiffness. Tensile stresses generally increase with material stiffness.

Tensile stresses, strains, and fatigue damage increase with traffic loading, particularly in the thicker surfacing bases (>50 mm), and appear to be more sensitive to change in tyre pressure than axle loading. High traffic loading should thus be effectively controlled to reduce pavement damage.

The Poisson's ratio has no significant effect on the stress-strain response of the asphalt layer particularly thicker ones. In the thinner surfacing like 20mm, the effect may be substantial, and the best performance appears to be at lower values.

Thin surfacings contribute little to the structural integrity of the pavement structure. They merely act as load transfer members with little susceptibility to fatigue damage. Failure design criteria for such pavement structures should be based on the underlying layers to limit deformation. Thicker asphalt-surfacings (>50mm) are structural members with great potential for load protection against damage in the lower layers.

The stress-strain variability with the surfacing thickness and material elastic constants implies that a balanced combination of these parameters is inevitable to achieve optimal pavement response and performance. For instance, it appears unwise to use a very stiff thin surfacing or a thick surfacing base with very low modulus value. The effect of the modular ratio is also quite significant and needs to be taken into account when designing. This calls for a balanced design approach.

The high three-dimensional compressive stress concentration in the top zone needs to be checked against permanent deformation. A constitutive surface rut model based on compressive stresses as well as shear failure (shear stress model) needs to be developed to check surface deformation in the asphalt surfacing layers.

CONCLUSIONS

Based on linear-elastic theory static models, and using the tensile strains as the fatigue criteria as used in this paper, it can be concluded that:

Asphalt Surfacing Layer Thickness

As well as being economical, very thin asphalt layers (h<50mm) exhibited extremely good stress-strain behaviour relative to fatigue under traffic loading, particularly at low modular ratio. However, the vertical stress levels hardly decrease over the thickness depth, and the underlying layers must be of high quality and strength to support the top thin asphalt layer. Most of the traffic loading is transferred to the underlying layers.

The intermediate thickness (50<h<100 mm) showed the highest horizontal tensile strain levels at almost all modular ratios, and are probably sensitive to fatigue. A considerable amount of the horizontal tensile strain is contributed by the vertical compressive stress due to the effect of the Poisson's ratio.

The larger thickness (h>100mm) exhibited the lowest tensile strains at higher modular ratios, and the lowest vertical stress levels in the second underlying layer at all modular ratios. They have the greatest structural advantage particularly at high stiffness values. However, they appear to have a poor fatigue performance at lower modular ratios. Even at modular ratio of 1, they were subjected to tensile strains due to contribution from the vertical compressive stresses and the effect of the Poisson's ratio.

Surface Deformation in the Asphalt Layer

The development of surface deformation models in the asphalt layers should be based on the vertical stress criterion. The strain criterion under-estimates the effect of traffic loading due to horizontal stresses and the effect of the Poisson's ratio, and may thus not be appropriate.

The high concentration of three-dimensional compressive stresses in the asphalt top zone effectively and conservatively represents the real effects of traffic loading with regard to vertical deformation.

Vertical Compressive Stresses

Vertical compressive stresses significantly contribute to the horizontal tensile strains particularly at low modular ratio due to the effect of the Poisson's ratio. The question then is: "Are the horizontal tensile strains due to compressive stresses to be used to determine the fatigue characteristics of asphalt under traffic loading?

Also the three-dimensional strain situation needs to be considered more precisely. Is the positive strain as a result of compressive stress in the other direction the same as the positive strain directly due to tensile stresses? This is specifically important for the intermediate asphalt surfacing layer thickness between 50 and 100 mm.

High Traffic Loading

The effect of high traffic loading and its potential damage has been illustrated. Actual present tyre-pavement contact pressure for heavy trucks is revolving around 700kPa (De Beer et al, 1999), which is about 35% higher than the normally assumed 520kPa. And most often, trucks are overloaded. It is subsequently recommended that "traffic laws and regulations be effectively enforced to monitor both axle loading and tyre pressure", and that the "design standards be improvised to cater for the current high traffic regime".

Stress-Strain Modelling

Pavement stress-strain analysis has been demonstrated as a tool for analytical modelling of pavement behaviour in terms of traffic load-response and performance evaluation. Stress-strain modelling thus constitutes an integral part of pavement design.

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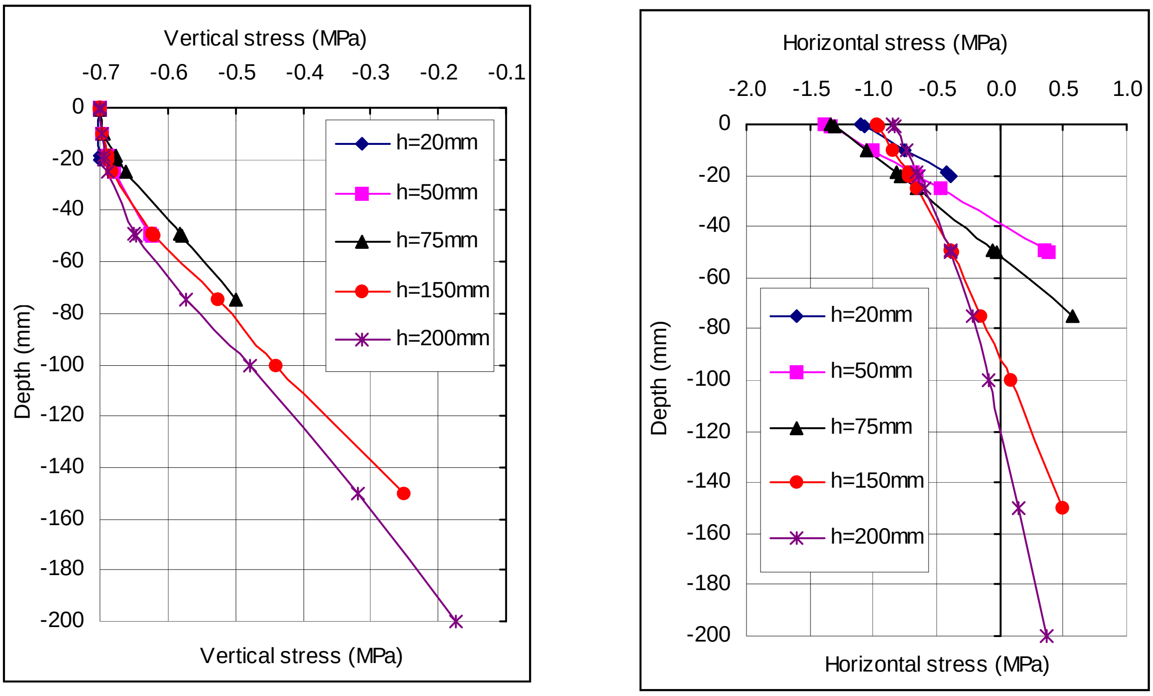
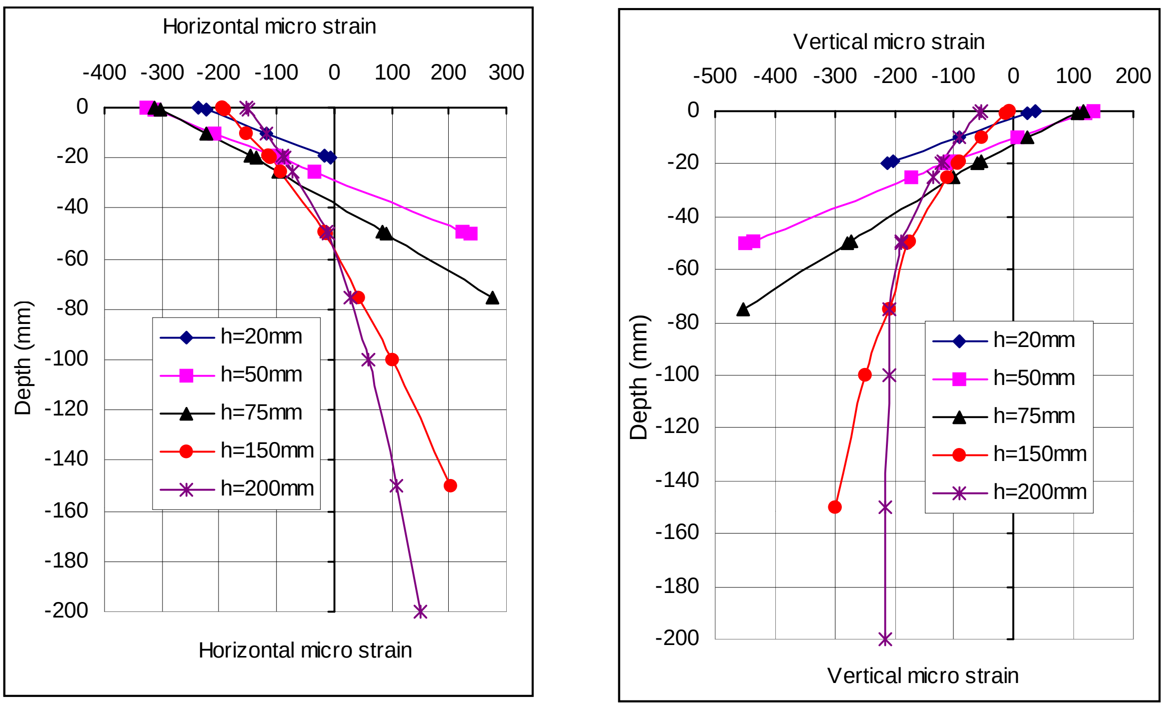
APPENDIX A

[Figures 5-13]



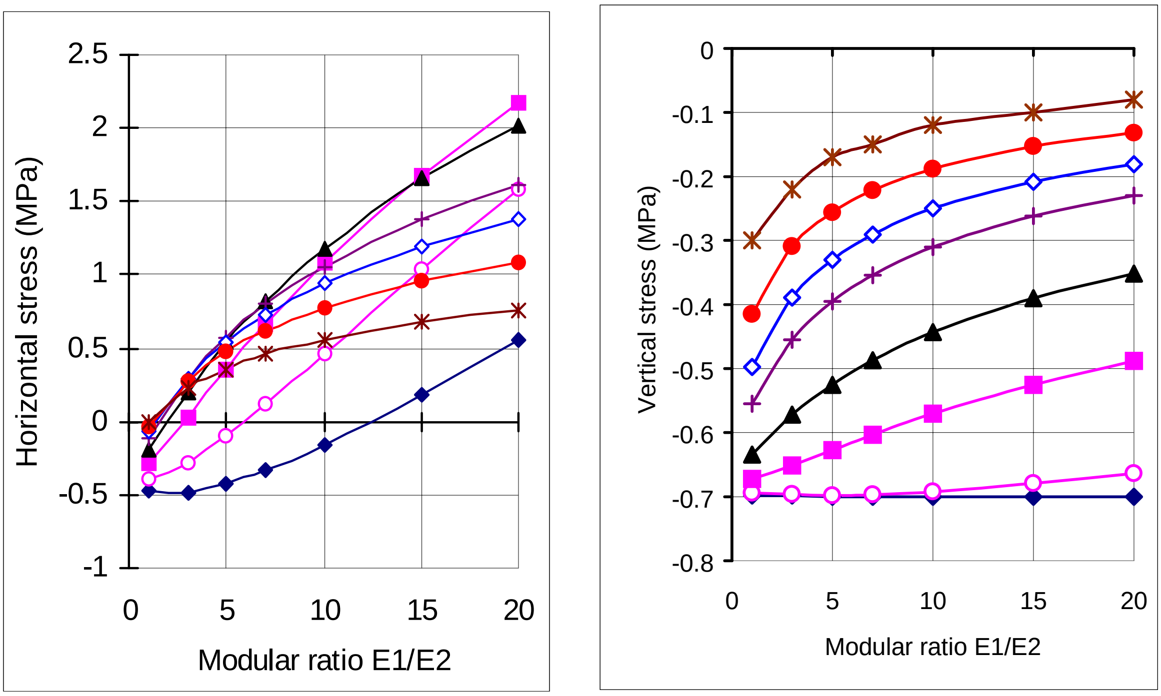
(a): Stresses



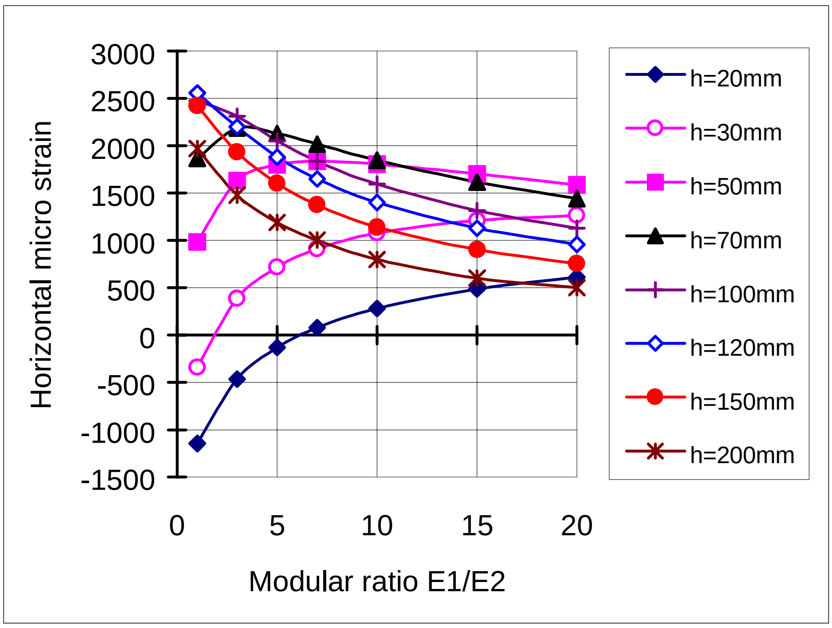
(b): Strains

Figure 5: Stress-strain Distribution

[80kN-700kPa, E_1=2000MPa, E_2=400MPa, MR=5, ν=0.35]



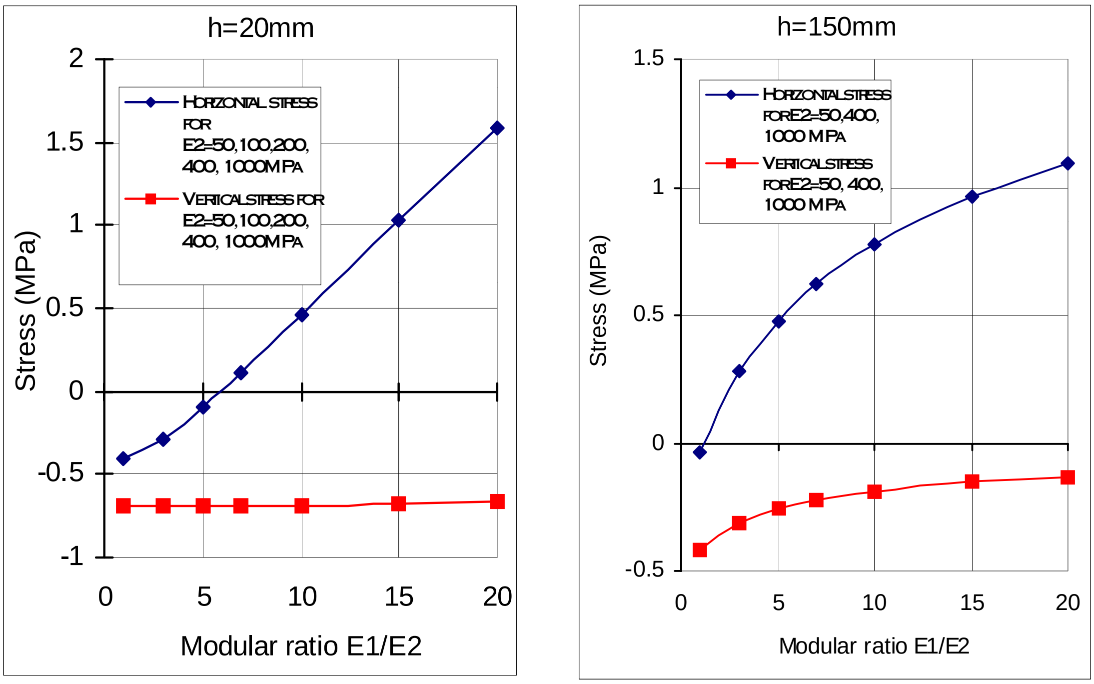
(a) Stresses



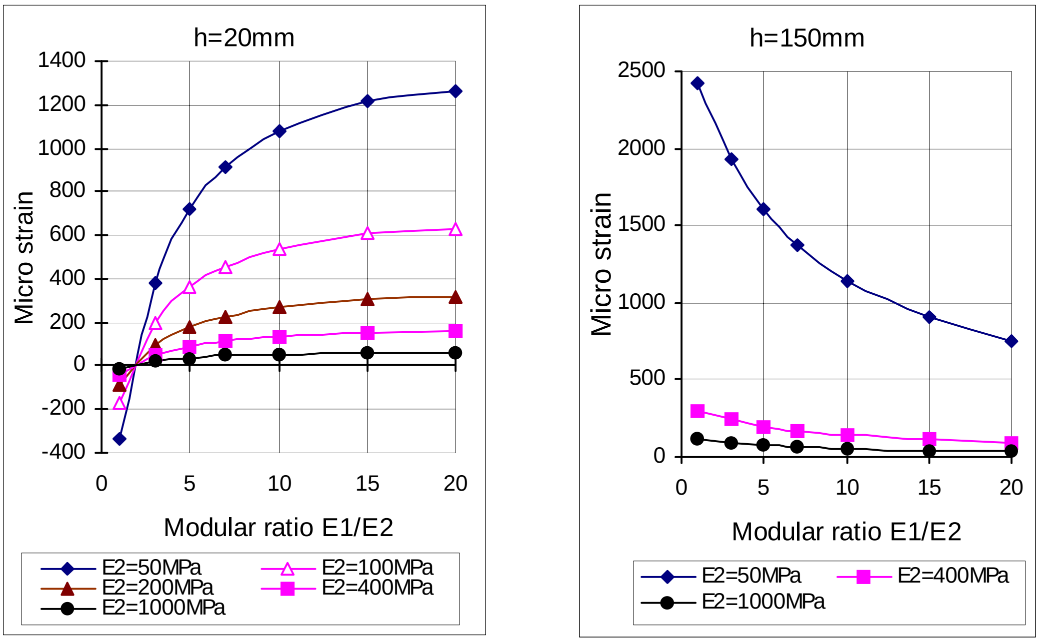
(b) Horizontal strains

Figure 6: Stresses and Strains versus Asphalt-Surfacing Layer Thickness (h) and Modular ratio (MR) at [h-1] mm depth

[80kN-700kPa, E_2=50MPa, ν=0.35]

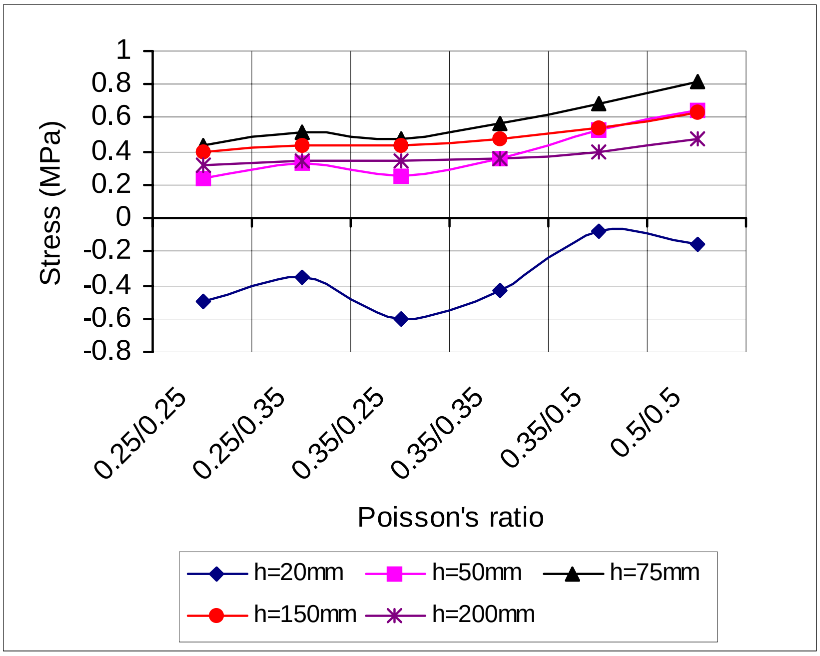


(a) Stresses @ [h-1] mm

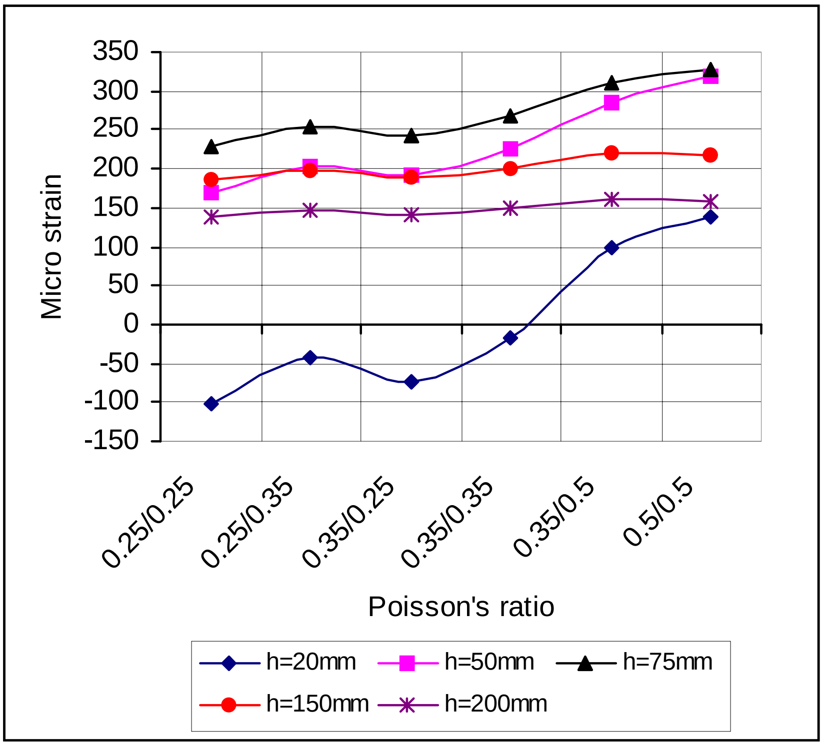


(b) Horizontal strains @ [h-1] mm

Figure 7: Effect of the Composite Modulus (E_2)
[80kN-700kPa, ν=0.35]

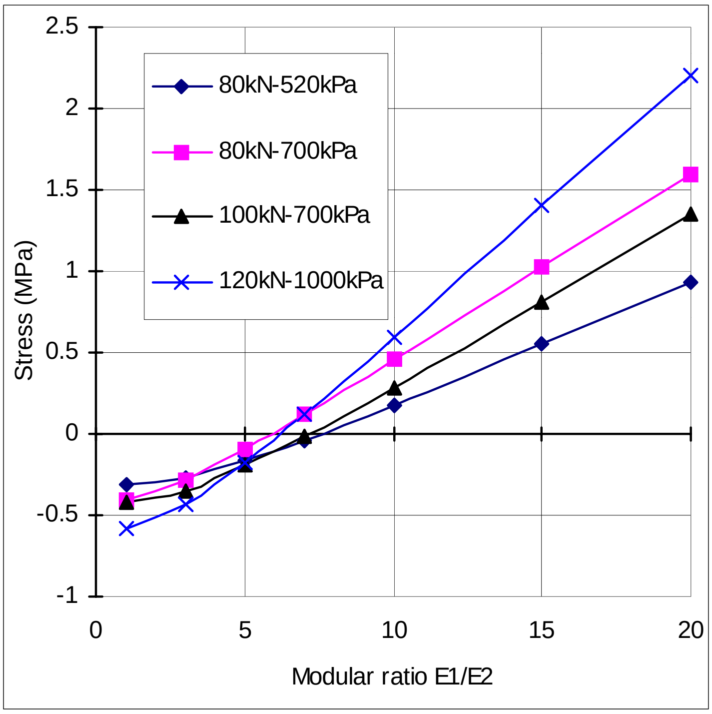


(a) Horizontal tensile stresses @ [h-1] mm

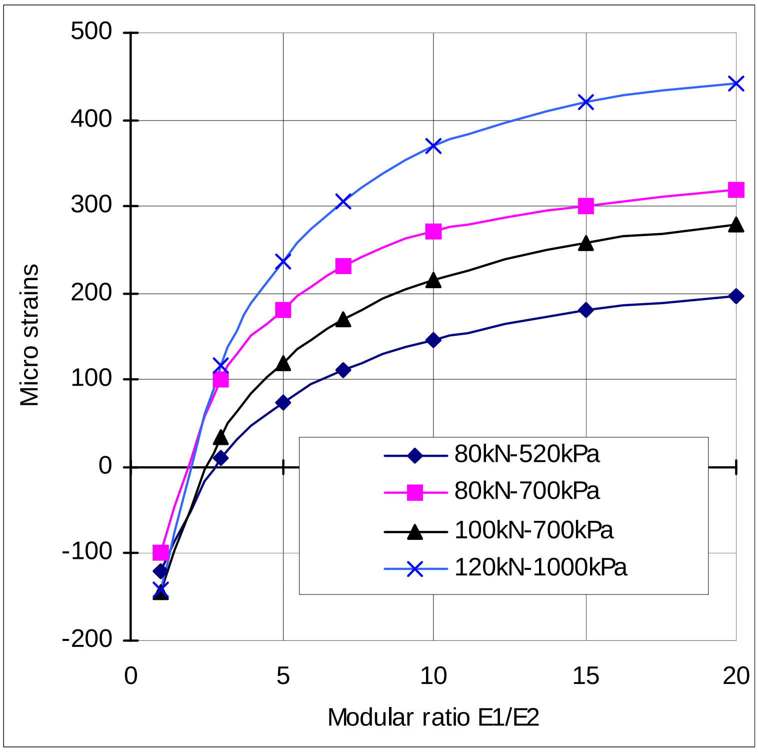


(b) Horizontal strains @ [h-1] mm

Figure 8: Effect of the Poisson's Ratio (ν)
[80kN-700kPa, E_2=400MPa, MR=5]



(a) Horizontal stress @ [h-1] mm



(b) Horizontal strain @ [h-1] mm

Figure 9: Variation of Traffic Loading

[h = 30mm, E_2 = 200MPa, ν = 0.35]

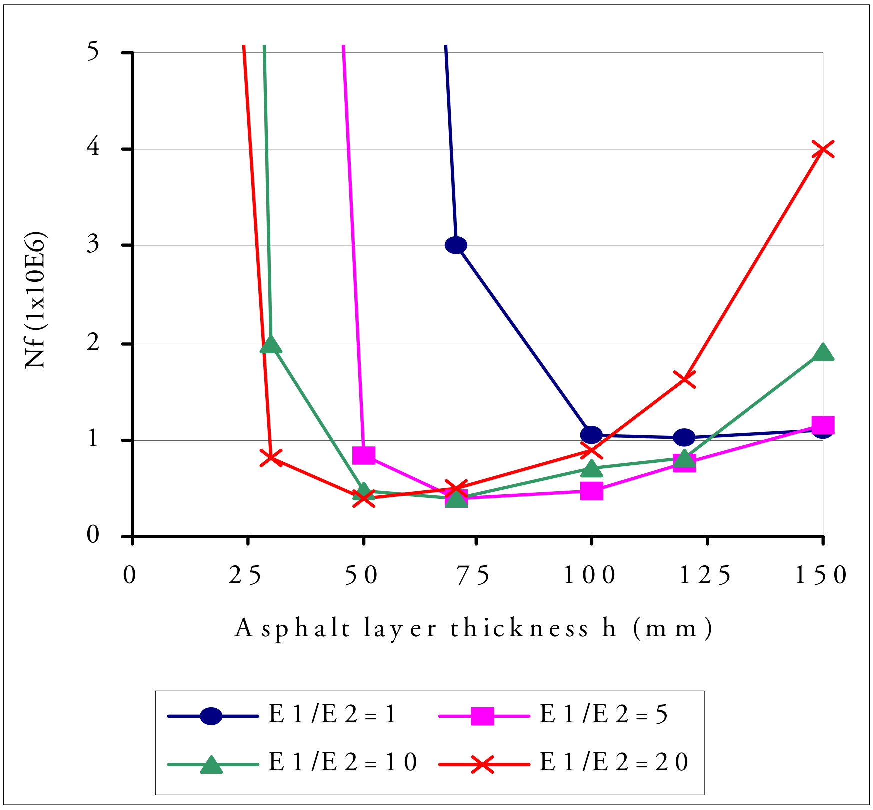


Figure 10: N_f vs h and MR
[80kN-700kPa, E_2 = 50MPa, ν = 0.35]

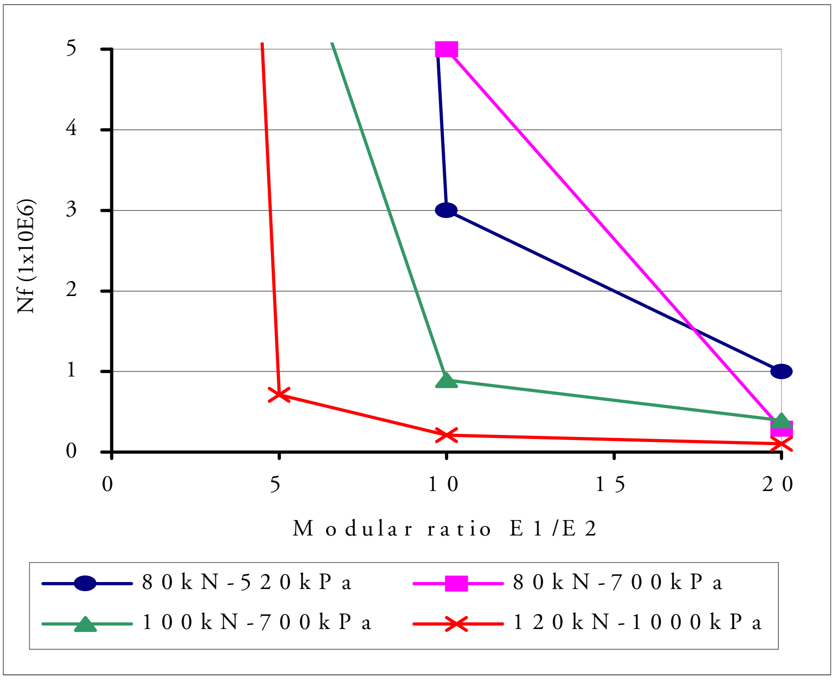


Figure 11: N_f vs MR and Traffic loading
[h = 30mm, E_2 = 200MPa, ν = 0.35]

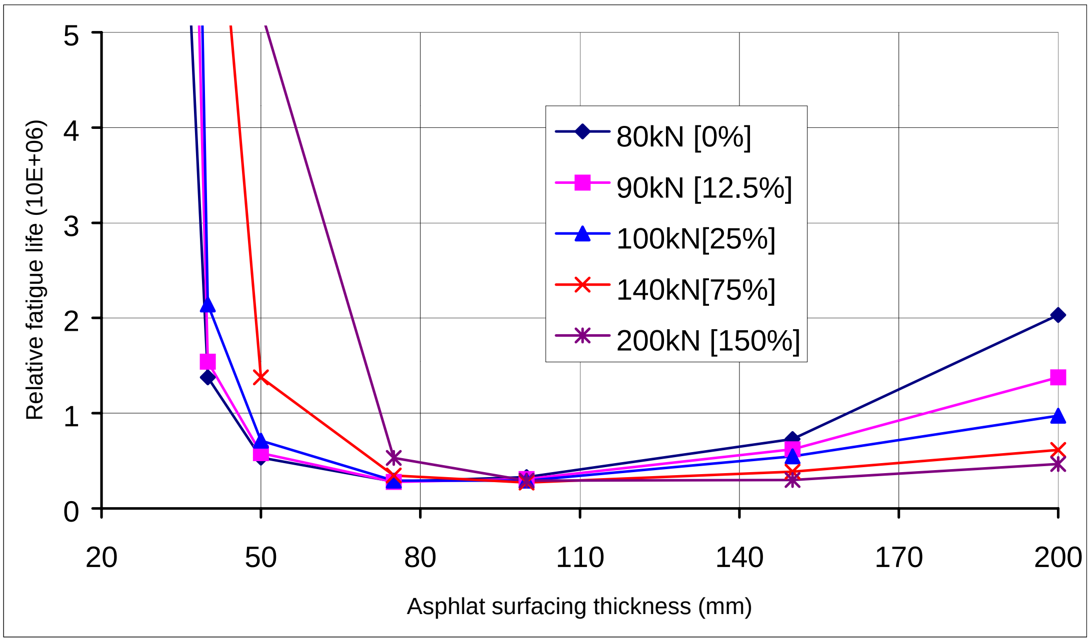


Figure 12: N_f vs Axle Loading
[700kPa, E_2 = 400MPa, MR = 5, ν = 0.35]

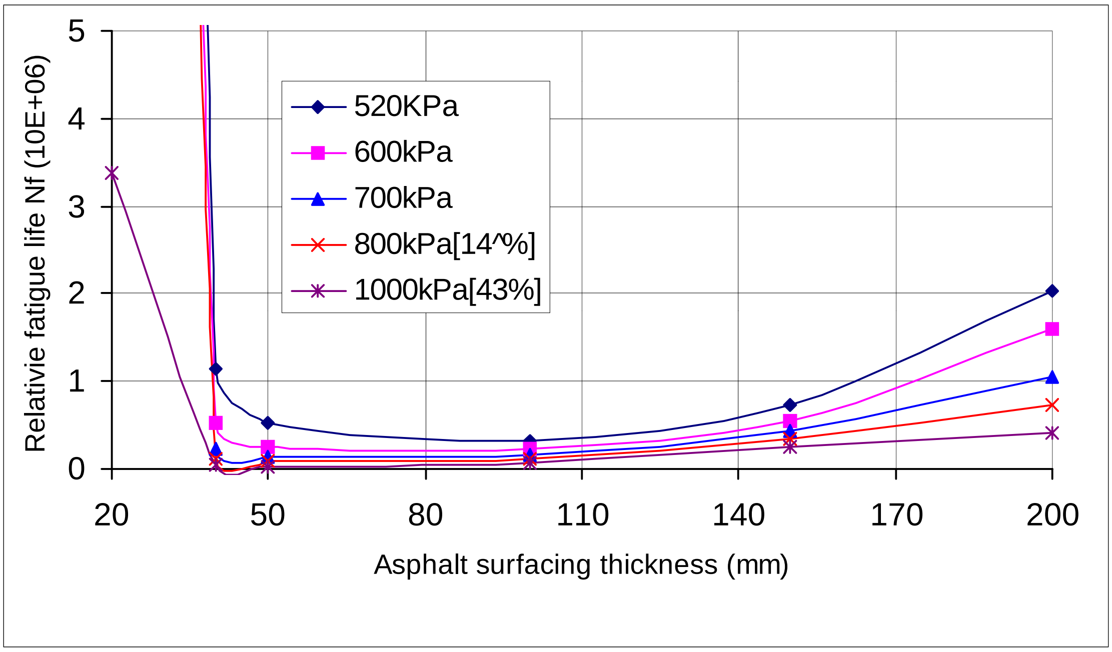


Figure 13: N_f vs Tyre Pressure
[80kN, E_2 = 400MPa, MR = 5, ν = 0.35]

STRESSES AND STRAINS IN ASPHALT-SURFACING PAVEMENTS

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