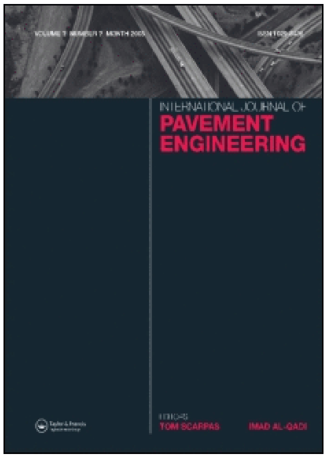

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Effect of temperature variation on pavement responses using 3D multilayered elastic analysis

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Effect of temperature variation on pavement responses using 3D multilayered elastic analysis

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The response of flexible pavement is largely influenced by the resilient modulus of the pavement profile. Different methods/approaches have been adopted in order to estimate or measure the resilient modulus of each layer assuming an average modulus within the layer. To account for the variation in the modulus of elasticity with depth within a layer, the layer should be divided into several sublayers and the modulus should be gradually varied between the layers. A powerful and innovative program has been developed utilizing the unique propagator matrix method and the cylindrical system of vector functions. Our new program can predict accurately and efficiently the response of flexible pavements of any number of layers/sublayers. Numerical results in this paper showed that, instead of assuming one response due to an average modulus, modulus variation with depth should be considered in any pavement analysis since it can capture the response envelopes of the pavement.

Keywords: Multilayered elastic analysis; Pavement; Temperature; Resilient modulus

1. Introduction

The response of flexible pavement is largely influenced by the resilient modulus of the pavement profile. Different methods/approaches have been adopted in order to estimate or measure the resilient modulus of each layer assuming an average modulus within the layer. The resilient modulus can be estimated either by laboratory testing or by in-site nondestructive testing such as the Falling Weight Deflectometer (FWD). The resilient modulus of pavement material is affected by many factors, including the temperature profile in the pavement, pavement drainage and moisture, frost and pavement compaction.

Temperature variation along the pavement profile is mainly affected by the temperature variation along the surface of the pavement which varies continuously during the year. Such variation is anticipated to affect the stiffness of the pavement profile and therefore to affect the pavement responses such as rutting and load carrying capacity. In general, the pavement-temperature variation can be divided into four different periods (Scrivner *et al.* 1969): (1) deep frost and high strength period, (2) rapid strength loss period, (3) rapid strength recovery period and (4) slow strength recovery period.

Assuming a single modulus of elasticity for the pavement based on averaging the temperature during the year can overestimate or underestimate the stiffness properties of the pavement depending on the prevailing climate conditions during the year. A site, or more appropriately, a statewide study of the temperature variation can be of significant importance to pavement engineers due to the variation in the environmental and climatic conditions between different sites. Such studies can provide information regarding the assumptions made during pavement analysis and design, thus controlling the load capacity and the cost associated with each design.

Temperature variation along the pavement profile has been studied by many researchers in order to address its variation with depth and its relation to the surface temperature. Other researchers studied the variation of the

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resilient modulus due to temperature variation to address the load carrying capacity of the pavement profile and to study the responses of the pavement during different temperature cycles. In most of the previous studies, the resilient modulus along the pavement profile was averaged to eliminate the complexity of the modulus variation with depth within the same layer. Such a simplified approach is mainly due to the lack of appropriate analytical tools that can handle such variations in appropriate timely, costly and user-friendly manners.

2. Mechanistic-empirical pavement design guide

The Mechanistic-Empirical Pavement Design Guide (MEPDG 2004) addresses the importance of temperature and other environmental factors in the pavement analysis and design. The change in temperature in the pavement profile is considered using a sophisticated climatic model called the Enhanced Integrated Climatic Model (EICM). The EICM model is a one-dimensional coupled heat and moisture flow program that uses the climatic conditions of the material over several years to predict the temperature, resilient modulus adjustment factors, pore water pressure, water content, frost and thaw depth, frost heave and drainage performance at any point within the entire pavement/subgrade profile of asphalt concrete (AC) or Portland Cement Concrete (PCC) pavements. The EICM model uses data from the Long Term Pavement Performance (LTPP) Seasonal Monitoring Program (SMP) test sections.

Based on the MEPDG guide and the EICM model, a software product was developed to incorporate the power of both (MEPDG 2004). The MEPDG software applies an adjustment factor at the desired point within the pavement/subgrade profile to an initial user supplied resilient modulus. Initial resilient modulus of unbound material is the modulus at or near the optimum water content and maximum dry density. The adjustment is used to estimate the new resilient modulus at any time and depth.

The MEPDG method suggests the use of average temperature values for the analysis period, with a minimum of one year of hourly temperature data, to estimate the resilient modulus of the AC layer for rutting and fatigue cracking predictions. The MEPDG software allows the analysis to include only a maximum of three asphalt layers including the surface, binder and base layers. Sub-layering of the asphalt layer is recommended to account for the temperature variation within the pavement.

Sub-layering of the pavement layers is done internally in the MEPDG program for different layers to account for the temperature and resilient modulus variation in all layers/sublayers. Temperature variation in layers through sub-layering is recommended to study the distress in the pavement due to seasonal variation. Pavement distress includes asphalt fatigue fracture (top down and bottom up), permanent deformation and asphalt thermal fracture. Sub-layering is controlled by the number of layers and the depth of each layer. As the thickness of layers increases or the number of sublayers increases, more computational time is required using the current available methods. Furthermore, the maximum allowed number of sublayers in the MEPDG software cannot exceed 20 or the maximum number of evaluation points cannot exceed 26 points. These limitations can highly influence the modeling of modulus vs. temperature variation with depth especially when the variation is nonlinear.

Sub-layering of the AC layer is carried out to estimate the thermal stresses and crack propagation within the AC sublayer as a function of time and depth. A typical sub-layering of the AC layer is shown in figure 1 where the top 13 mm are typically the first sublayer (Witczak *et al.* 2000). A typical sub-layering for a flexible pavement section is shown in figure 2.

The MEPDG software calculates the resilient modulus in the AC layer using Witczak's equation (MEPDG 2004):

$$\log(E_\mathrm{d}) = \delta + \frac{\alpha}{1+\exp\{\beta+\gamma[\log(t) - c(\log(\eta) - \log(\eta_{\tau t})]\}} \quad (1)$$

where E_d is the dynamic modulus (psi), t the time of loading (sec), η viscosity at temperature of interest (CPoise), $\eta_{\tau t}$ viscosity at the reference temperature (CPoise) and α, β, δ, γ and c are mixture specific fitting parameters.

In addition, the software calculates the resilient modulus of the unbound and subgrade materials using Witczak-Uzan's equation (MEPDG 2004)

$$E = k_1 p_\mathrm{a}\left(\frac{\theta}{p_\mathrm{a}}\right)^{k_2}\left(\frac{\tau_\mathrm{oct}}{p_\mathrm{a}}+1\right)^{k_3} \quad (2)$$

where E is the resilient modulus, k_1, k_2 and k_3 the parameters from physical testing or estimates, p_a standard atmospheric pressure, θ the bulk stress ($\theta = \sigma_1+\sigma_2+\sigma_3$), and τ_oct the octahedral stress defined as

$$\tau_\mathrm{oct} = \frac{1}{3}\sqrt{\left((\sigma_1-\sigma_2)^2+(\sigma_1-\sigma_3)^2+(\sigma_2-\sigma_3)^2\right)}.$$

3. Seasonal variation of resilient modulus

Temperature variation output using MEPDG software for a flexible pavement section in Iowa was reported by Coree *et al.* (2005). Data extracted from the output report were plotted and presented below (figures 3–5). The data

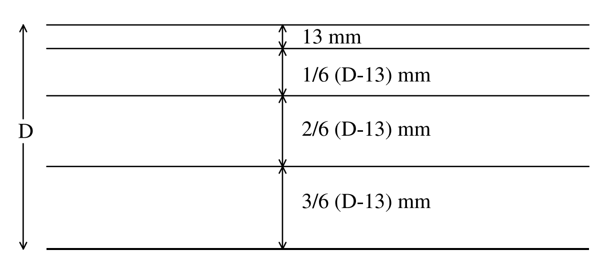

Figure 1. Typical AC sublayering (modified from Witczak *et al.* 2000).

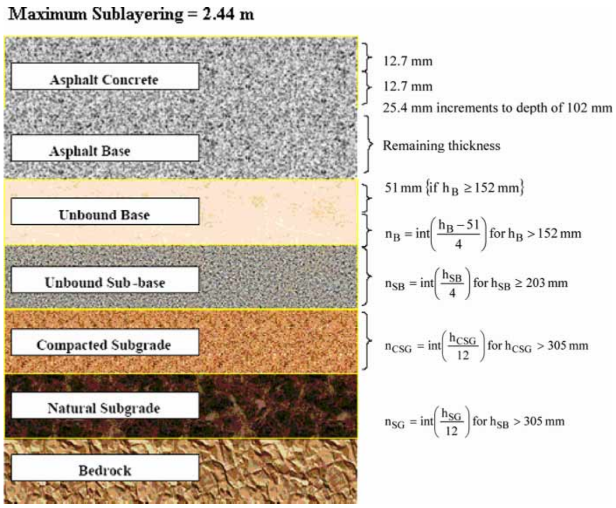

Figure 2. Typical sublayering of flexible pavement (modified from MEPDG 2004).

represent the calculated resilient modulus using weather stations input data as well as other hot mix, unbound material and subgrade material data. The flexible pavement section and the sub-layering of the layers are shown in figure 3. The dashed lines represent the sublayer limit within each layer. The subgrade was divided into four sublayers with thicknesses of 0.62, 0.62, 0.62 and 6.48 m, respectively. The sublayers of the subgrade layer are not shown in figure 3. The water table at the site was

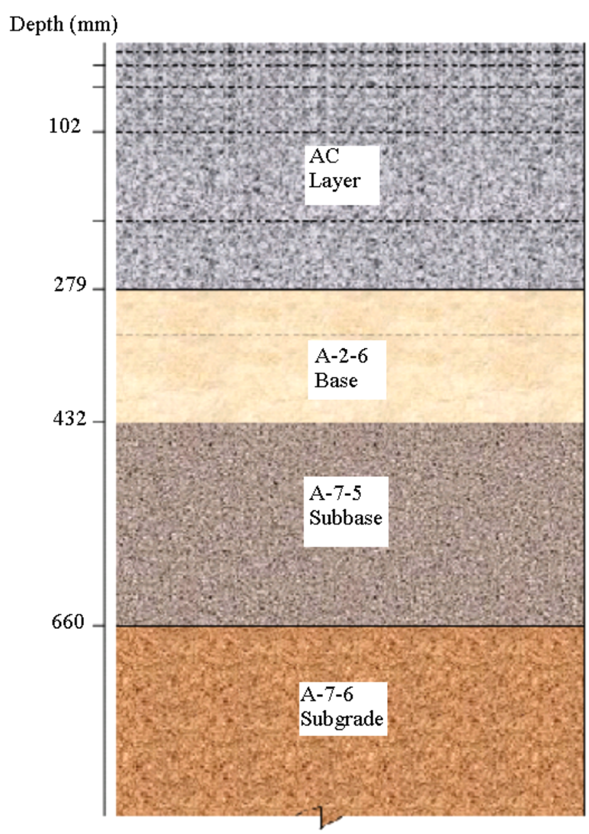

Figure 3. Sublayering of the flexible pavement study (data from Coree *et al.* 2005).

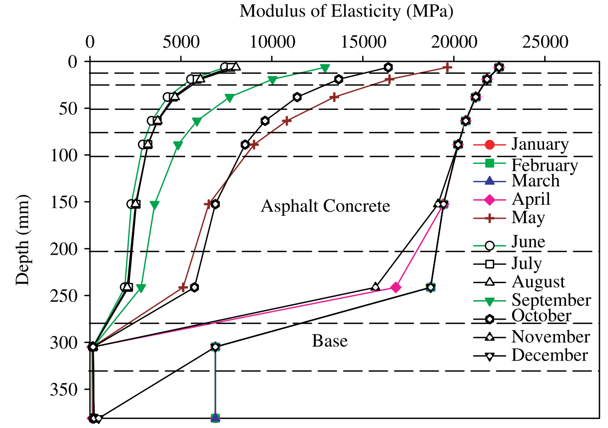

Figure 4. Resilient modulus vs. depth (horizontal dashed lines are sublayers) (data from Coree *et al.* 2005).

reported to be at 3.66 m below the surface. The Poisson's ratio for all layers was reported to be constant during the year with a value of 0.35. Presented in figures 4 and 5 are some typical curves for modulus variation vs. depth in different sublayers and for different months based on the profile and sublayers of figure 3.

Figure 4 shows the variation of the resilient modulus with depth in the top 381 mm of the flexible pavement system. The calculated resilient modulus was plotted at the mid-depth for each sublayer/layer to show the influence of temperature variation on the modulus as a function of depth and time.

As can be seen from figure 4, averaging the resilient modulus within the top layers based on values of one month might not be appropriate since the difference in the average monthly resilient modulus between two consecutive sublayers within the AC layer can be up to 30%. As expected, the difference in the average monthly resilient modulus between two consecutive sublayers within the base, subbase, and subgrade is slightly affected by the temperature variation. It is known that the influence of the moisture within the base, subbase and subgrade layers is larger than the influence of the temperature. However, moisture variation within the unbound layers is influenced in turn by the seasonal temperature variation.

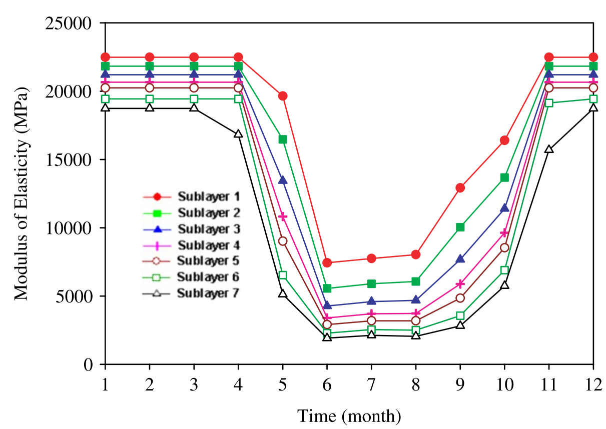

Figure 5. Resilient modulus vs. time in the AC sublayers (data from Coree *et al.* 2005).

Resilient modulus variation as a function of time within the AC sublayer is shown in figure 5. The figure shows that the temperature variation in the AC layer can reduce the maximum resilient modulus of the sublayer by a factor between 2 and 3. Therefore, averaging the modulus over a certain period of time, or over the entire thickness of the layer, such as the AC layer, may not be appropriate since the averaging may not capture the extreme temperatures and thus the extreme (high or low) resilient moduli.

4. Pavement modulus variation

Several researchers proposed simplified equations to estimate the resilient modulus as a function of temperature based on laboratory and/or field-testing. Some typical equations are reviewed below briefly.

Ullidtz (1987) proposed the following equation to estimate the resilient modulus of the AC with temperatures between 0 and 40°C:

$$E = 15000 - 7900\log(T) \tag{3}$$

where E is the AC modulus (MPa) and T the pavement temperature (°C).

Witczak (1989) proposed the following equation:

$$\log(E) = 6.53658 - 0.006447T - 0.00007404T^2 \tag{4}$$

where E is the AC modulus (psi) and T the pavement temperature (°F).

Janoo and Berg (1991) proposed the following equation based on the backcalculation of the AC modulus during a thaw cycle:

$$E = 5994 - 242T \tag{5}$$

where E is the AC modulus (MPa) and T the pavement temperature (°C).

Ali and Lopez (1996) proposed the following equation to estimate the AC modulus when the asphalt layer temperature is known at a depth of 25 mm below the surface:

$$E = \exp(9.37196 - 0.03608145T) \tag{6}$$

where E is the AC modulus (MPa) and T the temperature at a depth of 25 mm in the asphalt layer (°C).

A comparison among these simple equations for the estimation of the modulus of elasticity in the AC layer is shown in figure 6. As can be seen, the resilient modulus is highly dependent on the pavement temperature and therefore a more sophisticated model which can capture the detailed variation of the modulus of elasticity with depth (say due to the pavement temperature variation) should be used.

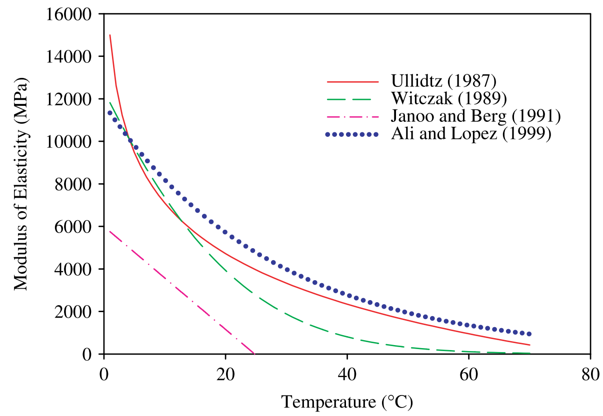

Figure 6. Resilient modulus vs. temperature.

5. Daily temperature variation

It has been shown that the modulus of elasticity can strongly depend on the temperature (figure 6). The temperature gradient along the surface of the pavement varies with time during the day, which in turn changes the temperature in the pavement section. For instance, temperature variation in a flexible pavement section in Los Angeles (Ongel and Harvey 2004) is shown in figure 7. It can be seen that the temperature variation in the AC layer is larger than the variation within the base and subbase layers where the temperature gradient decreases as the depth increases. Therefore, assuming an average temperature may be misleading during the design or analysis of the pavement section. On the other hand, as the temperature changes during the day, the resilient modulus changes, resulting in the change of pavement susceptibility to rutting and distresses (fatigue).

Furthermore, temperature variation in AC layers can be divided into two distinct variations. The first variation is characterized by temperature gradients that increase with depth which mainly can be observed when the surface of the pavement is colder than the bottom; i.e. cold temperature seasons or during nights. The second

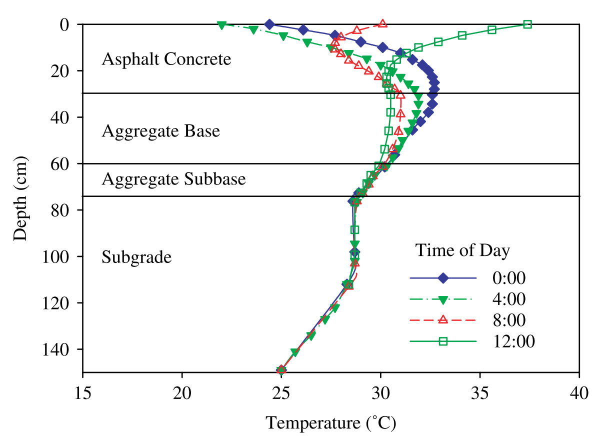

Figure 7. Daily temperature variation (modified from Ongel and Harvey 2004).

variation is characterized by temperature gradients that decrease with depth which can be observed mainly when the surface of the pavement is warmer than the bottom of the pavement; i.e. warm temperature seasons or during the daylight. The temperature variation is influenced by the viscoelastic nature of the AC layer and the physical nature of the underlying layers. Again, temperature variation will cause resilient modulus variation with depth, which in turn will influence the pavement response and performance.

6. Resilient modulus variation example

It is clear now that due to complicated temperature variation, a variety of modulus profiles with depth are possible. To demonstrate the pavement responses due to the resilient modulus variation, a flexible pavement section with different modulus profiles was analyzed using the *MultiSmart3D* program. The *MultiSmart3D* program is a fast and accurate software tool developed by the Computer Modeling and Simulation Group at the University of Akron, and it is based on the innovative computational and mathematical techniques for multi-layered elastic systems (Pan 1989a,b, 1990, 1997). The program is capable of analyzing any pavement system regardless of the number of layers, the thickness of each layer, the number of response points, and the shape of the applied pressure at the surface of the pavement.

The analyzed pavement section was summarized in Table 1. The contact pressure at the surface of the pavement was assumed to be 690 kPa acting on a circle with a diameter of 220.3 mm. Pavement responses below the center of the contact pressure were calculated using the *MultiSmart3D* program.

A total of twenty-three cases were analyzed to study the effect of the resilient modulus variation on the deformation, strain and stress fields. Five typical Cases are summarized in Table 2 whilst the corresponding modulus variation is depicted in figure 8. In all cases the average modulus for the AC layer was kept at 3500 MPa and the Poisson's ratio was 0.3 for all layers and sublayers. In each case, the responses at 120 points within the AC layer were obtained and plotted against the depth to visually inspect the response of the pavement. While the modulus variation due to temperature could be much more complicated than the ones we assumed here, the intention is to show the importance of the modulus variation on the pavement response and to demonstrate the versatility of the *MultiSmart3D*.

Table 1. Parameters for the flexible pavement example.

Layer	Thickness (cm)	Resilient modulus (MPa)	Poisson's ratio
AC layer	15	3500	0.3
Base layer	25	700	0.3
Subbase layer	25	300	0.3
Subgrade layer	Infinite space	100	0.3

Table 2. Studied cases of the modulus variation.

Case No.	Modulus variation	No. of AC sublayers
1	Constant	1
2	Linear increase	2, 4,8,10,20
3	Linear decrease	2, 4,8,10,20
4	Quadratic increase	20
5	Quadratic decrease	20

7. Discussion of numerical results

Vertical pavement displacements (u_z) are shown in figure 9. It can be clearly seen from figure 9(c) that Case 1 (constant modulus) underestimates the displacements in the entire AC layer as compared to Cases 2 and 4 (linear/quadratic increase), whilst it overestimates the displacements at the top and bottom as compared to Cases 3 and 5 (linear/quadratic decrease). It is further noticed that for the linear variation cases (Cases 2 and 3 in figure 9(a),(b)), using a small number of sublayers (e.g. 1, 2, 4) could result in a pavement response different than that due to the true linear variation of modulus. However, increasing the number of sublayers can improve the predicted displacements (i.e. for sublayer number = 10 and 20 as in figure 9(a),(b)).

Figure 10 shows the variation of the horizontal normal stress in x-direction (σ_{xx}) for different modulus profiles in the AC sublayer. As can be seen in these figures, the effect of the number of sublayers is noticeable especially when the number is less than eight sublayers and negligible when the number is larger than eight sublayers (figure 10(a),(b)). The 20-sublayer case was selected to demonstrate the power of the *MultiSmart3D* program for more than 20 layers as compared to the current available programs which can consider only a maximum of 20 layers/sublayers

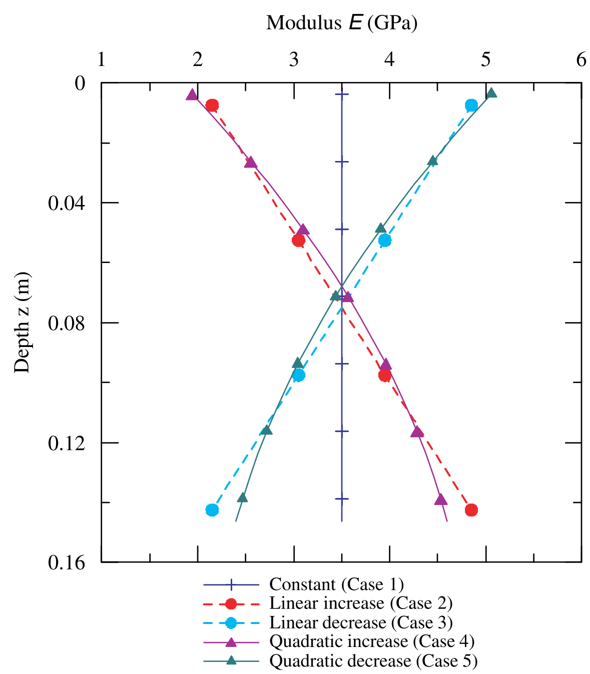

Figure 8. Modulus variation with depth.

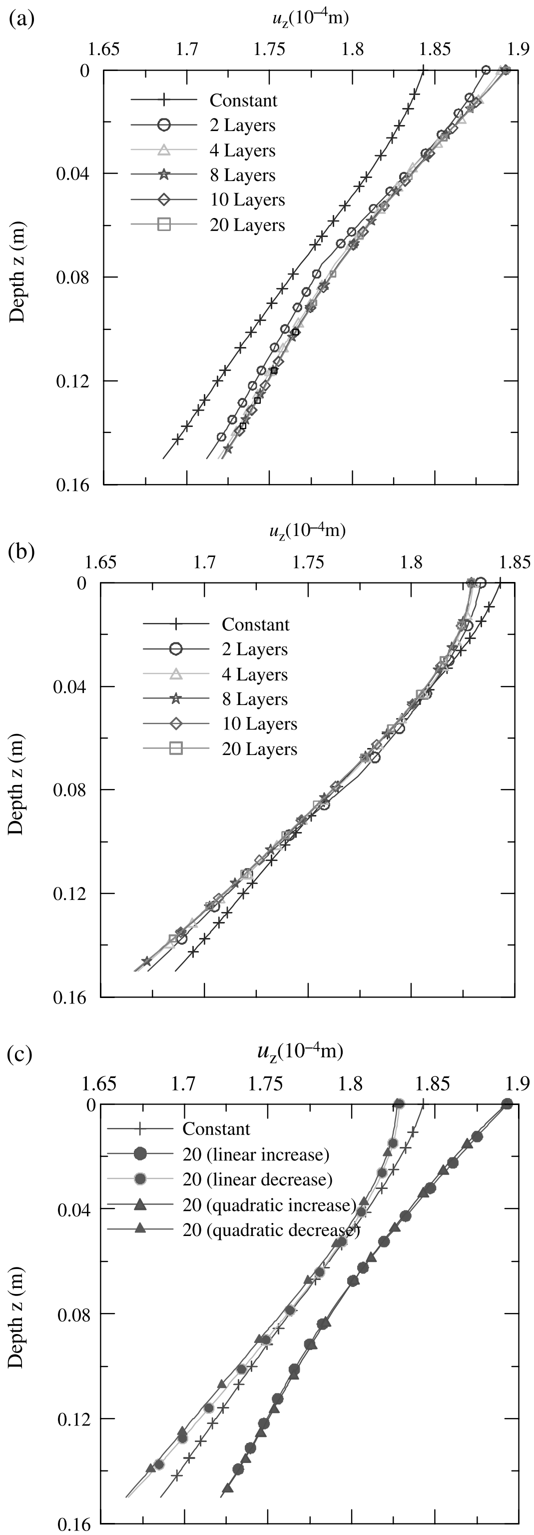

Figure 9. Variation of displacement u_z with depth for (a) Cases 1 and 2; (b) Cases 1 and 3; (c) Cases 1, 2, 3, 4 and 5.

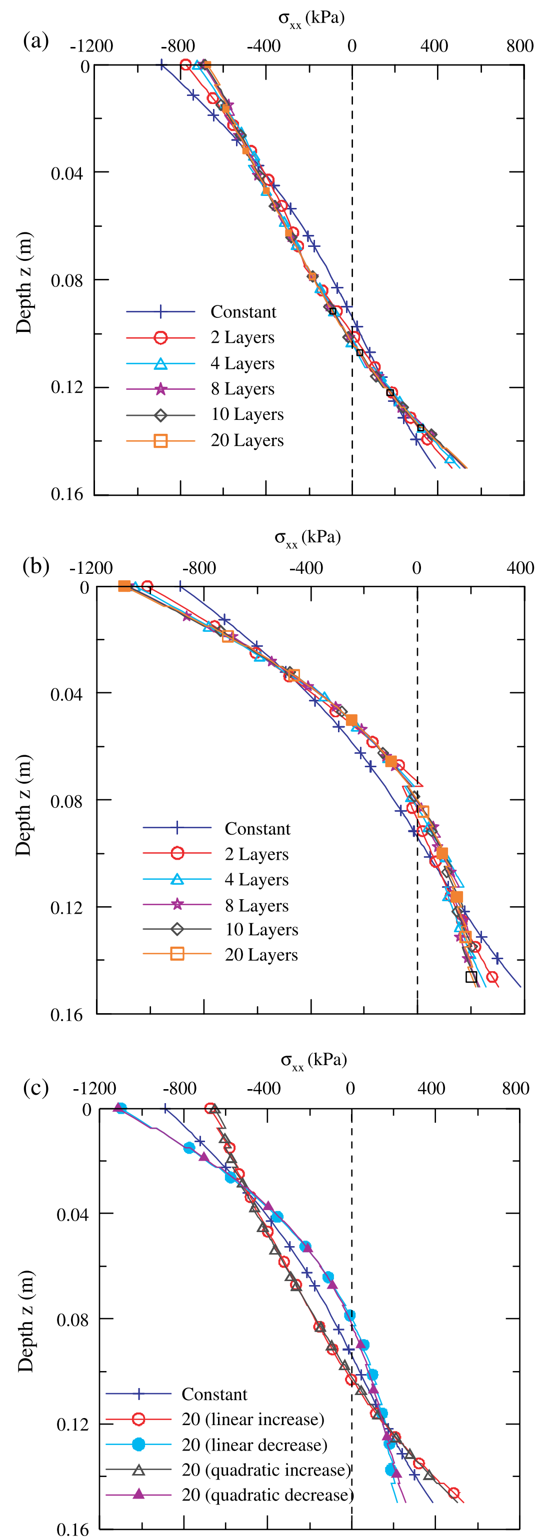

Figure 10. Variation of horizontal normal stress component σ_{xx} with depth for (a) Cases 1 and 2; (b) Cases 1 and 3; (c) Cases 1, 2, 3, 4 and 5.

(the total number of layers for the 20 sublayer case in our examples is 23). On the other hand, it can be seen (figure 10(c)) that the variation of the modulus with depth, in this example, largely controls the horizontal stress component. For example, the average resilient modulus can underestimate the stress magnitude within the top 20% while it can overestimate the stress magnitude within the bottom 20% of the AC layer for Cases 3 and 5 (linear/quadratic decrease). The stresses were overestimated within the top 20% while they were underestimated within the bottom 20% of the layer for Cases 2 and 4 (linear/quadratic increase). The stress magnitude between 20 and 80% of the layer thickness was underestimated for Cases 2 and 4 and overestimated for Cases 3 and 5. Stresses using Case 1 are approximately equal to the average of stresses from either Cases 2 and 3 or Cases 4 and 5. Due to symmetry, a similar behavior can be observed for the horizontal normal stress in *y*-direction (σ_{yy}). In addition, the stress jump between the adjacent sublayers can be clearly observed in the linear decrease Case 3 (figure 10(b)).

The effect of different resilient modulus profiles on the vertical normal stress in *z*-direction (σ_{zz}) is shown in figure 11. It is observed from figure 11(c) that, compared to figure 10 for horizontal stresses, the vertical stress is relatively insensitive to the different profiles used. It can be seen (figure 11(c)) that the average resilient modulus can underestimate the vertical stress magnitude for Cases 2 and 4 whilst it can overestimate the magnitude for Cases 3 and 5. The difference between the stresses using Case 1 and those using other cases is more noticeable between 15 and 85% of the layer thickness (figure 11(c)).

The effect of the resilient modulus profiles on the normal strain in *x*-direction (ε_{xx}) is shown in figure 12. Similar to figure 10 for vertical stress, it can be seen that the average resilient modulus can either underestimate or overestimate slightly the strains (figure 12(c)). The difference between the strains using Case 1 and those using other cases is more noticeable between 15 and 85% of the layer thickness. Due to symmetry, a similar behavior can be observed for the normal strain in *y*-direction (ε_{yy}).

Figure 13 shows the vertical strain variation (ε_{zz}) with depth below the center of the contact pressure. It can be seen that the average resilient modulus can overestimate the strain magnitude within the top half of the AC layer whilst it can underestimate the strains within the bottom half for Cases 3 and 5 (figure 13(c)). On the other hand, the average resilient modulus can underestimate the strains within the top half of the AC layer whilst it can overestimate the strains within the bottom half for Cases 2 and 4 (figure 13(c)). It is observed that the number of sublayers beyond four in Case 2 (figure 13(a),(b) for linear increase) could be enough for estimating the strain at the bottom of the AC layer whilst it showed a considerable difference near the top part of the AC layer (which requires at least eight sublayers). An opposite trend is observed for the linear decrease case (figure 13(b)). Therefore, the vertical strain component is very sensitive to the variation of the modulus profile and its value is highly dependent on the number of sublayers. Furthermore, just as for the horizontal stress case, one can also observe sharp jumps in the strain across the interface of the adjacent sublayers (figure 13(a),(b)).

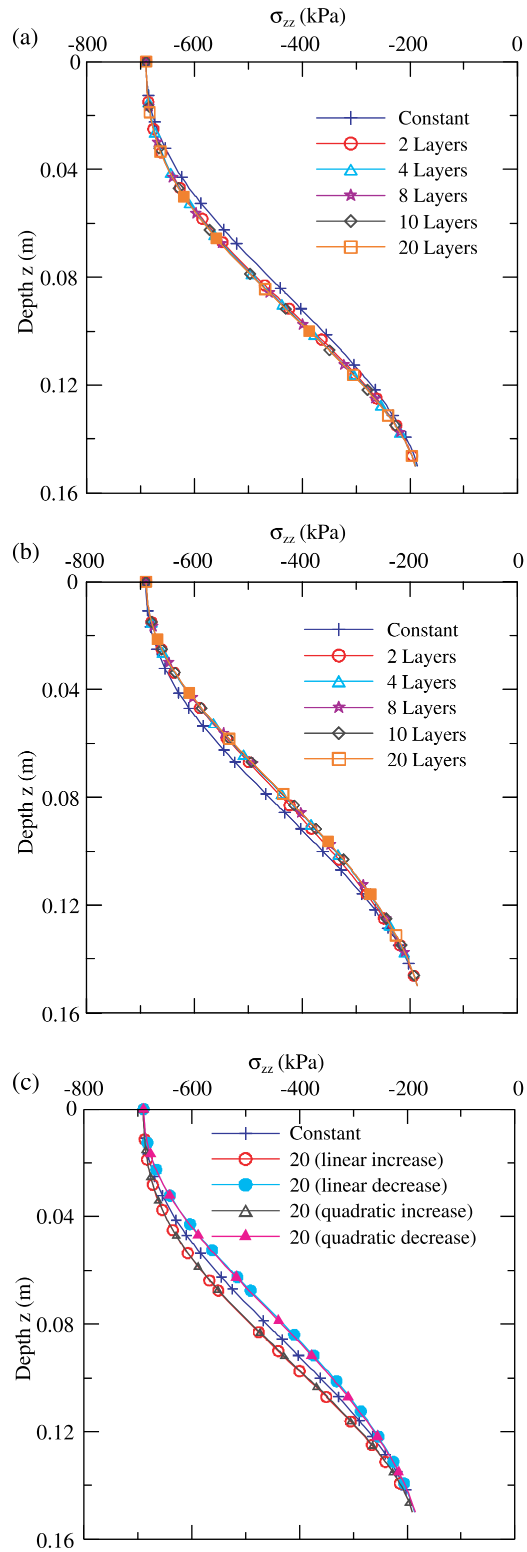

Figure 11. Variation of vertical normal stress component σ_{zz} with depth for (a) Cases 1 and 2; (b) Cases 1 and 3; (c) Cases 1, 2, 3, 4 and 5.

8. Pavement damage prediction

The predicted strain field could be applied to the damage prediction of pavement. The damage of flexible pavements can be assessed by predicting the number of loads needed to initiate cracks (fatigue cracking). The Shell Model (Bonnaure *et al.* 1980) and the Asphalt Institute Model (Shook *et al.* 1982) are frequently used for fatigue cracking analysis in flexible pavements.

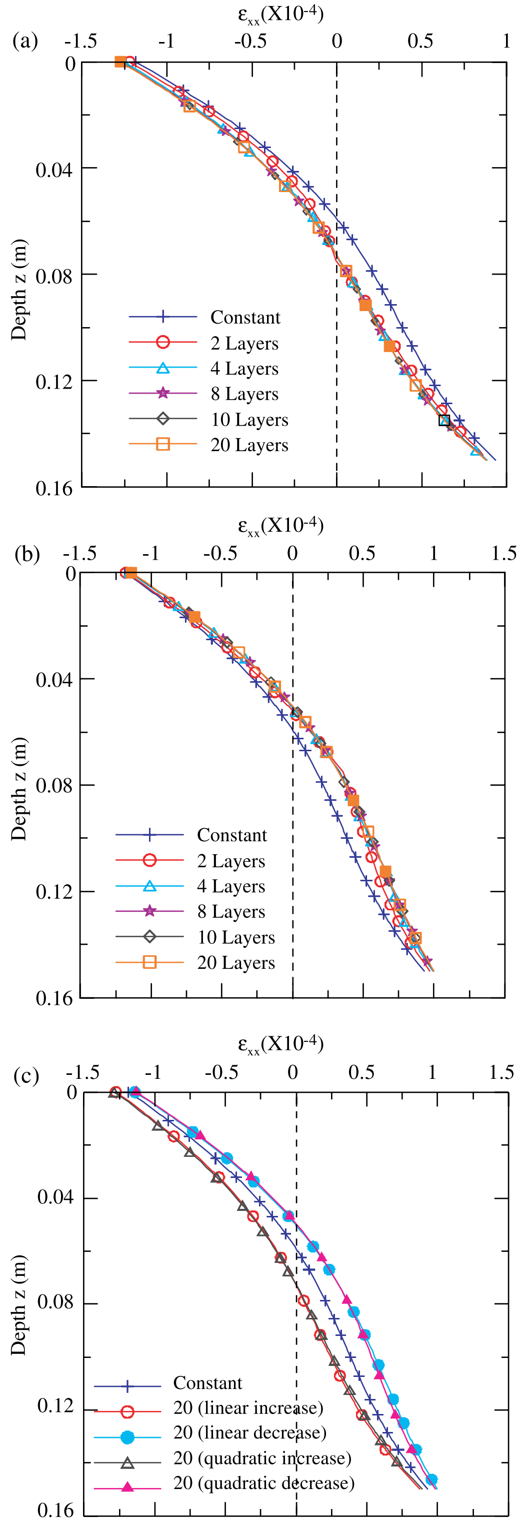

Figure 12. Variation of horizontal normal strain component ε_{xx} with depth for (a) Cases 1 and 2; (b) Cases 1 and 3; (c) Cases 1, 2, 3, 4 and 5.

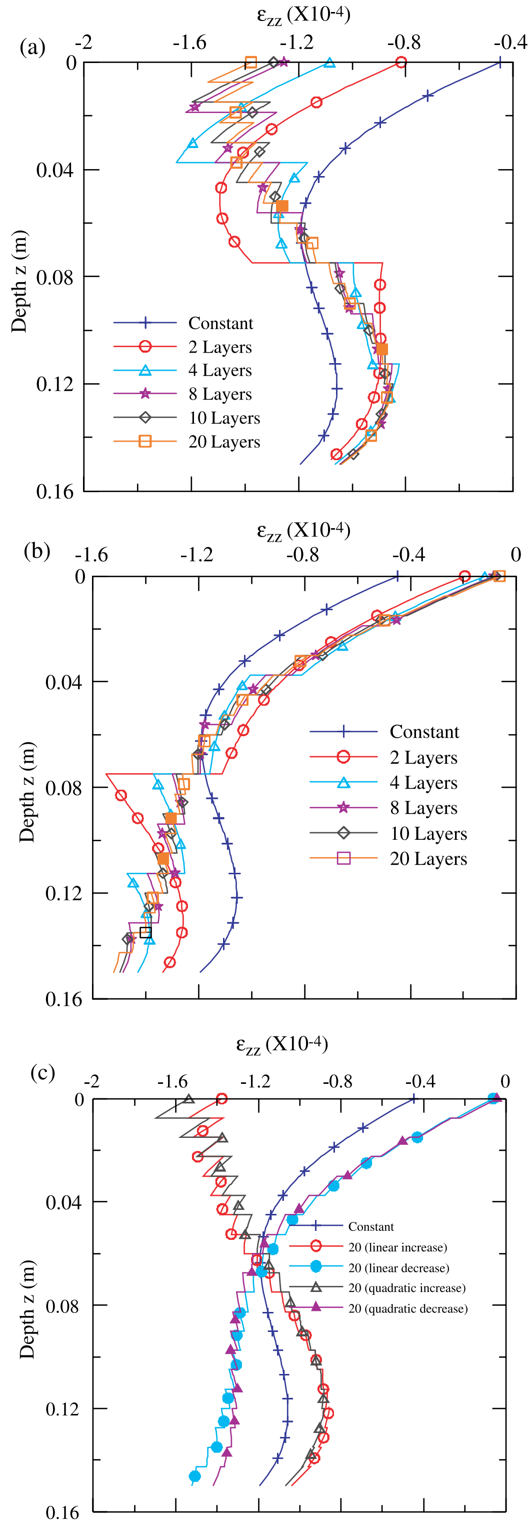

Figure 13. Variation of vertical normal strain component ε_{xx} with depth for (a) Cases 1 and 2; (b) Cases 1 and 3; (c) Cases 1, 2, 3, 4 and 5.

The Shell Model is based on two different loading modes, as given by Shell Constant Strain Model:

$$N_\varepsilon = 13909 A_f K \left(\frac{1}{\varepsilon_t}\right)^5 E_s^{-1.8} \tag{7}$$

and Shell Constant Stress Model:

$$N_\sigma = A_f K \left(\frac{1}{\varepsilon_t}\right)^5 E_s^{-1.4} \tag{8}$$

where N_ε and N_σ are the number of load repetitions to fatigue cracking using the constant strain and constant stress analysis, respectively, A_f and K are empirical parameters based on the material properties, ε_t is the tensile strain at the critical location and E_s is the stiffness of the material. The constant strain model is applicable to thin asphalt pavement layers usually less than 51 mm, whilst the constant stress model is applicable to thick asphalt pavement layers usually more than 203 mm. The Shell Model was calibrated and generalized for any thickness as given below (MEPDG 2004):

$$N_f = A_f K F'' \left(\frac{1}{\varepsilon_t}\right)^5 E_s^{-1.4} \quad (9)$$

where N_f is the number of load repetitions to fatigue cracking, $F''$is a constant that depends on the layer thickness and the stiffness of the material.

The Asphalt Institute Model is given below:

$$N_f = 0.00432C\left(\frac{1}{\varepsilon_t}\right)^{3.291}\left(\frac{1}{E_s}\right)^{0.854} \quad (10)$$

where, similarly, N_f is the number of load repetitions to fatigue cracking, C is a constant depending on the material properties, ε_t is the tensile strain at the critical location and E_s is the stiffness of the material. The Asphalt Institute Model can be used for AC layers of any thickness.

It can be seen from the above equations, that the critical tensile strain and the stiffness of the AC layer are the key factors affecting the number of load repetitions needed to initiate fatigue failure. Understanding the effect of the modulus variation with depth (due to temperature variation with depth) on the fatigue cracking can be studied by finding the ratio between the estimated number of repeated loads (N_f) using the modulus variation with depth and that using the traditional assumption of a constant modulus for the entire layer. In other words, the ratio is equal to N_f (modulus variation) over N_f (constant modulus).

Figures 14 and 15 show the ratios based on the Asphalt Institute Model and the Shell Model, respectively, using the estimated tensile strains (ε_{xx}) at the bottom of the AC layer. Figure 12(c) shows that increasing the modulus with

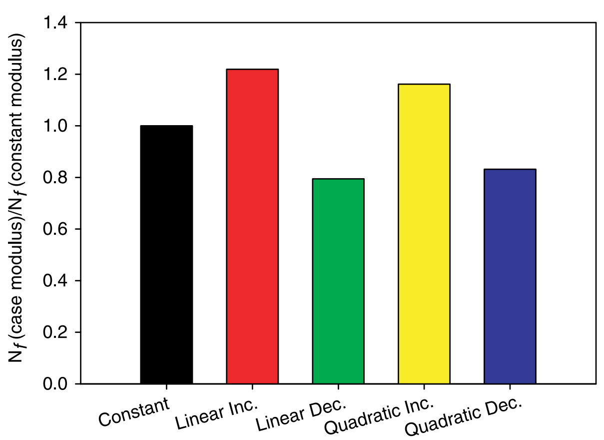

Figure 14. Ratio between the estimated numbers of repeated loads needed to initiate fatigue cracks using the modulus variation with depth and the constant modulus (Asphalt Institute Model).

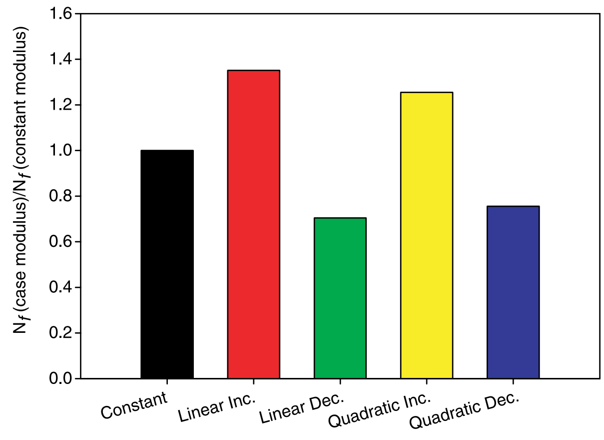

Figure 15. Ratio between the estimated numbers of repeated loads needed to initiate fatigue cracks using the modulus variation with depth and the constant modulus (Shell Model).

depth will produce lower tensile strains at the bottom of the AC layer and therefore the required number of repeated loads to initiate fatigue cracks will be higher than that using the constant modulus. In this example, the increase in N_f from the modulus variation compared to that from constant modulus is approximately 22 and 16% using the Asphalt Institute Model for the linear and quadratic modulus increment case (figure 14), respectively, whilst it is 35 and 26% using the Shell Model for the linear and quadratic modulus increment case (figure 15), respectively.

On the other hand, the decrease of the modulus with depth produces higher tensile strains at the bottom of the AC layer (figure 12(c)) and therefore the required number of repeated loads to initiate fatigue cracks becomes lower than that using the constant modulus. In this example, the decrease in N_f from the modulus variation compared to that from the constant modulus is approximately 21 and 17% using the Asphalt Institute Model for the linear and quadratic modulus decrease case (figure 14), respectively, whilst it is 30 and 24% using the Shell Model for the linear and quadratic modulus decrease case (figure 15), respectively.

It is evident that the modulus variation as a result of the temperature variation with depth highly influences the predicted number of repeated loads needed to initiate fatigue cracks in the AC layer. The predicted N_f value using the constant modulus should be considered as the average value whilst the N_f values from the "increase" and "decrease" modulus variation cases should be considered as the upper and lower values, respectively. Therefore, modulus variation with depth can be used to create an envelope to encompass the extreme conditions that could be encountered in the AC layer.

9. Conclusions

The average resilient modulus is not recommended for the analysis and design of flexible pavements. Average resilient modulus can either overestimate or underestimate the pavement responses depending on the temperature variation in the AC layer. Temperature variations can be observed during the day and during the year which in turn cause different pattern of responses.

Modulus variation as a function of temperature variation can be used to create a "pavement response envelope" instead of the average pavement responses. This envelope can show the extreme pavement responses as well as the average responses, and thus can be a simple and yet a powerful approach for pavement engineers.

The modulus variation as a result of the temperature variation with depth highly influences the predicted number of repeated loads ($N_{\rm f}$) needed to initiate fatigue cracks in the AC layer. The predicted $N_{\rm f}$ using the constant modulus should be considered as the average value whilst those from the increase and decrease modulus variations should be considered as the upper and lower values, respectively.

Increasing the number of layers is very critical especially for the vertical strain. Modeling variation of the resilient modulus using sub-layering can be difficult using most of the current commercially available programs where the maximum allowed number of layers/sublayers can not exceed 20. In addition, most multilayered elastic programs also limit the thickness of each layer, and the total number of observation (response) points. However, the *MultiSmart3D* program can be used for any number of response points and any number of layers with any thickness so that any type of modulus variation with depth can be accurately modeled.

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