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STRESS DISTRIBUTION IN SUBGRADE SOILS AND APPLICATIONS IN THE DESIGN OF FLEXIBLE PAVEMENTS

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ABSTRACT

A comprehensive study of stress distribution in highway subgrades of flexible pavements was conducted. A stress-dependent non-linear finite element method (FEM) program, ARKPAVE, was used to generate structural responses of pavements under vehicle loads. The subgrade depth of interest was found to be around 1500 mm. The confining pressure within this depth of interest ranges from 15 to 40 kPa and averages about 20 kPa. This average confining pressure is recommended to be the chamber pressure in triaxial and/or repeated load testing in the evaluation of subgrade soils. The distribution of deviator stress along the subgrade depth was found to be more or less independent of the layer thickness combinations. It is shown that the stress at the top of the subgrade is a better criterion than the vertical resilient strain. This stress was mapped out in accordance with the various thickness selections including full-depth asphalt concrete (AC) pavements which can be readily incorporated into a modern pavement management system. The contours of deviator stress at the top of the subgrade also facilitate the optimum design of flexible pavements as demonstrated in the paper by a design example. This approach advocates the feasibility and promptness of the adoption of rational mechanistic-empirical (M-E) design methods for pavement structures.

INTRODUCTION

Given traffic and environment, subgrade soils govern the succeeding layer combination and thickness selection in the design of pavement structures. Subgrades beneath a pavement also have a controlling influence on how long and how well a pavement performs. The major forms of distress that causes an asphalt pavement to fail are fatigue cracking and surface rutting. The development of both types of distresses is largely controlled by the support the pavement receives from the subgrade when subjected to vehicle loads. The support provided by the subgrade is controlled by the load deformation behavior of the soil, which can be divided into two components:

$$\varepsilon = \varepsilon_r + \varepsilon_p \quad (1)$$

where:

ε	=	load-induced subgrade strain
ε_r	=	resilient (or recoverable) strain
ε_p	=	permanent or residual strain

The pronounced influence of subgrade soils on both distress modes was recognized long ago (Seed et al., 1962). The resilient modulus (defined in Eq. 2) and permanent deformation (or permanent strain) are usually used to characterize the resilient and residual deformation behaviors of subgrades, which in turn are thought to be the direct factors governing the initiation-propagation of fatigue cracking and accumulation of rutting, respectively.

$$M_R = \sigma_d / \varepsilon_r \quad (2)$$

where:

M_R	=	resilient modulus (kPa)
σ_d	=	deviator stress ($\sigma_1 - \sigma_3$) (kPa)

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The resilient modulus of subgrade soils has been found to be stress dependent (Thompson and Robnett, 1979; Elliott et al., 1988). On the other hand, rutting, defined as the permanent deflection accumulated over pavement component layers, is also associated with the stress level existing in a pavement structure. The dependencies of resilient modulus and permanent strain of cohesive highway subgrades on stress state are illustrated in Eq. (3) (Thompson and Robnett, 1979) and Eq. (4) (Elliott et al., 1998), respectively.

$$M_R = K_1 + K_3 (K_2 - \sigma_d) \quad \text{when } \sigma_d < K_2 \quad (3)$$

$$M_R = K_1 - K_4 (\sigma_d - K_2) \quad \text{when } \sigma_d > K_2$$

where:

$K_1, K_2, K_3,$ and K_4 = material constants (derived from results of resilient modulus tests with different deviator stresses);

$$\epsilon_p = \epsilon_p(1) \times f(N) \quad (4)$$

$$\epsilon_p(1) = p_1 r_\sigma^{p_2} \quad (4a)$$

$$f(N) = N^{p_3 r_\sigma^{p_4}} \quad (4b)$$

where:

$\epsilon_p(1)$ = permanent deformation under the first load application;
 $f(N)$ = accumulation function;
 N = number of load applications;
 r_σ = stress ratio, defined as the ratio of deviator stress (σ_d) to static strength (q_u).
 $p_1, p_2, p_3,$ and p_4 = material constants (derived from results of permanent deformation tests with different deviator stresses and moisture contents);

Equation (3) reveals that the stress state in the subgrade has a direct influence on the resilient modulus. In fact, it has been the only structural design input for subgrade soils in current design methods such as the American Association of State Highway and Transportation Officials (AASHTO) method, the Asphalt Institute (AI) method, and the Shell Petroleum International (Shell) method (ERES, 1987; Huang, 1993) since it replaced the California Bearing Ratio (CBR) and the soil support value (S) in the early 1980s. More rational mechanistic-empirical (M-E) design methods require both resilient modulus and permanent strain as the subgrade properties in order to directly estimate the amount of distresses occurring in a pavement structure over the repetitions of vehicle loads (Brown, 1996; Thompson, 1996). A prediction model, such as the stress-ratio-associated model illustrated in Eq. (4), is indispensable to the prediction of pavement rutting. Therefore, the stress state in a highway subgrade is more or less related to the design of a pavement structure. A thorough investigation of stress distribution in the subgrade is likely to promote a better understanding of the working mechanism of pavements and refinement of design methods. This paper reports a comprehensive study of the stress distribution in the highway subgrades of flexible pavements. A finite element (FE) program, ARKPAVE (Selvam et al., 1994), capable of incorporating the stress-dependent model, as shown in Eq. (3), was used to calculate the stress distribution in the subgrade soils in flexible pavements along with updated tire pressure information. Asphalt concrete was modeled as linear elastic solids while gravel base was modeled as stress hardening materials. Confining pressure and deviator stress in the subgrade were studied to determine the practical selection of subgrade depth of interest in M-E design methods. The deviator stress at the top of the subgrade was graphically presented in accordance with different layer combinations including full depth asphalt concrete (AC) pavement under different environmental conditions. An example of application in the design of flexible pavements is also presented.

COMPARISON OF MECHANISTIC PROGRAMS FOR FLEXIBLE PAVEMENTS

Current mechanistic-empirical design methods for flexible pavements are based on Burmister's general multi-layer elastic system (MLES) theory, such as the AI method and the Shell method, while functional design methods totally depart from the structural modeling, such as the AASHTO method. Layer theory serves as the main tool for structural response of pavements under traffic loading. On the other hand, the finite element method (FEM) has gained widespread application in various engineering fields, including pavement engineering. The main advantage of FEM is that it can account for irregular boundary conditions, non-linear behavior of paving materials, and versatile load locations. Although layer theory can also consider the stress dependency of the resilient modulus along the depth of pavements by dividing the component layers into thinner

sub-layers, there is no means of incorporating the non-linear stress dependency of layer materials into layer theory along the horizontal direction. The finite element method, however, can handle the stress-dependency of material properties in any direction. Since each element in the mesh has its own stress state, it has its own resilient modulus accordingly. Plain strain, axisymmetric and 3-D models have been used in the FEM analysis for pavement structures over the years (Cho et al., 1996). The application of stochastic or probabilistic FEM methods in pavement design has also been reported (Parvini and Stolle, 1996). Available programs for pavement analyses can be divided into three categories: (1) MLES-based programs, such as BISAR, CHEVRON, DAMA, ELSYM5, and KENLAYER; (2) FEM-based programs, such as ARKPAVE, GTPAVE, ILLIPAVE, and MICHPAVE; (3) general-purpose commercial programs such as ABAQUS.

In order to evaluate the correctness and relative accuracy of various programs, a pavement structure illustrated in Fig. 1 was analyzed using various elastic programs. Four programs: ARKPAVE, MICHPAVE, KENLAYER, and ELSYM5 were used to compute structural responses of pavements. Linear elastic properties were used in all programs such that the results could be compared. Tire pressure was set to 552 kPa. This tire pressure, coupled with standard single axle load of 80 kN, resulted in a circular load with a radius of 152 mm. The vehicle load is the same as that used in the AASHTO Road Test and has been employed in succeeding structural analyses for pavement systems ever since. Young's modulus and Poisson's ratio of layer materials are given in Fig. 1. Representative structural responses of pavement layers under a circular load obtained with the four programs are summarized in Table 1.

Comparison of the linear elastic numerical results in Table 1 shows that ARKPAVE gives reliable and accurate results for flexible pavement structures. Basically, ARKPAVE, KENLAYER, and ELSYM5 have similar and consistent stress, strain, and deflection responses, especially the stress distribution in the lower part of base layer and subgrade. The numerical results of MICHPAVE deviate from those of other programs, especially the stress distribution in the upper layers. Note that ARKPAVE yields a close approximation of ELSYM5 whose solution is analytical results based on closed-form equations. As a result, ARKPAVE was used in all further computations presented in this paper.

CRITICAL RESPONSES

The load-induced horizontal resilient tensile strain at the bottom of the asphalt layer, ϵ_{AC} , and the vertical resilient compressive strain at the top of the subgrade, ϵ_{VC} , have been used as the critical structural response parameters of transfer functions in M-E design methods since they were introduced three decades ago. Common practice is to use ϵ_{VC} to limit permanent deformation or rutting (Kerhoven and Dorman, 1953) and ϵ_{AC} to control cracking (Saal and Pell, 1960). This is illustrated in Fig. 2. Other candidate response parameters that have been used to evaluate structural responses of pavement structures include, but not limit to, surface deflection, vertical stress at the top of the subgrade, subbase and/or base (Chen and Bhatti, 1997).

Asphalt Concrete Surface Layer, 100-mm-thick
 $E = 3,450 \text{ MPa}, \nu = 0.4, K_0 = 0.67, \gamma = 23 \text{ kN/m}^3$

Subgrade Soil, semi-infinite
 $K_1 = 48 \text{ MPa}, K_2 = 41 \text{ kPa},$
 $K_3 = 1.00 \text{ MPa/kPa}, K_4 = 200 \text{ kPa/kPa}$
 $\nu = 0.45, K_0 = 0.82, \gamma = 19 \text{ kN/m}^3$

Fig. 1 Pavement Structure Used for Nonlinear Analysis (Not to Scale)

Table 1 Comparison of Results Based on Linear Elasticity Using Different Methods

Layer	Depth	Value	ARKPAVE	MICHPAVE	KENLAYER	ELSYM5
Asphalt Concrete (AC)	0mm	d	0.058	0.071	0.080	0.067
	0.03 mm	ϵ_h	308	294	386	320
		σ_v	298	552	349	375
	50 mm	ϵ_h	-6	-14	-18	-9
		σ_v	190	0	132	175
	101 mm	ϵ_h	-318	-312	-418	-330
σ_v		157	143	132	175	
Base	102 mm	d	0.058	0.070	0.079	0.066
	254 mm	σ_v	79	75	82	87
		σ_v	48	75	53	46
Subgrade	407 mm	d	0.037	0.050	0.050	0.044
		σ_v	41	5	53	46
		ϵ_v	543	159	690	625
	508 mm	σ_v	34	9	41	35
		ϵ_v	458	159	552	485

Note: d = deflection; σ_v = vertical stress; ϵ_h = horizontal strain (10^{-6}); ϵ_v = vertical strain (10^{-6}), (Deflection in mm, Stress in kPa).

Table 2 Average soil properties for resilient modulus testing (based on 50 samples from Illinois)

Moisture Content	OMC		OMC + 1%		OMC + 2%	
	Mean Value	standard deviation	Mean Value	standard deviation	Mean Value	standard deviation
K_1 (MPa)	61.64	23.44	50.75	23.44	42.75	22.06
K_2 (kPa)	42.75	6.90	40.68	8.96	42.54	7.86
K_3 (MPa/kPa)	1.21	0.6	1.14	0.6	1.01	0.6
K_4 (kPa/kPa)	186	90	171	110	170	100

Note: (1) Data from Thompson and Robnett (1979); (2) OMC = Optimum Moisture Content

Material properties listed in Fig. 1 are "typical" values recommended by ILLIPAVE, KENLAYER, MICHPAVE, and ARKPAVE. Although no comprehensive review of "average" highway subgrades was available, research work reported by Thompson and Robnett (1979) does indicate that the values listed in Fig. 1 are representative. Table 2 summarizes the "average" properties of a total of 50 individual soils samples from 27 pedologic sites representing nearly 39% of the land area of the state of Illinois (Thompson and Robnett, 1979). A previous study found that the Arkansas subgrade soils fit this general pattern (Elliott et al., 1988). A standard axle load, 80 kN, was used. Tire pressure was set to 0.7 MPa. This is the average tire pressure found in Arkansas in a recent study (Elliott et al., 1991) and contrasts with the tire pressure of 0.55 MPa generally used in analyses as typical at the time of the AASHO Road Test.

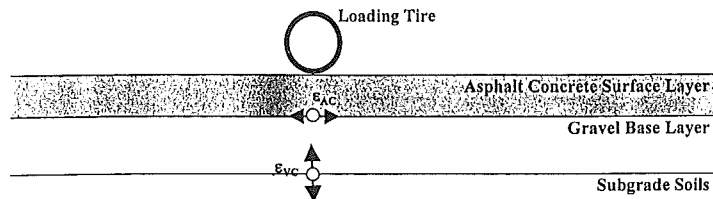


Fig. 2 Critical Parameters of Pavement Structures Used in Transfer Functions (Not to Scale)

The bilinear model of resilient modulus of subgrade soils, expressed by Eq. 3 has been widely accepted since it was proposed two decades ago. Parameter K_1 is the dominant factor in the model while the other three material parameters have less influence on pavement responses (Thompson and Elliott, 1985). Preliminary research suggests that the variation of K_1 does not change the stress distribution in the subgrade significantly (Elliott et al., 1998). Therefore the "typical" properties listed in Fig. 1 were used in the rest of this study. The stress distributions determined from these "typical" analyses can then be used to evaluate the potential in deformation accumulation and predict the amount of permanent deformation of specific subgrade soils using the stress-ratio-associated model given by Eq. (4).

It is observed in Fig. 3 that the confining pressure (the combined effect of load-induced horizontal stress and geo-static pressure) for conventional AC pavement (AC surface over gravel based layer at the top of the subgrade soils) is relatively constant up to a depth of 600 mm measured from the top of subgrade. Beyond this depth, there is a steady and gradual increase of confining pressure due to the geo-static (overburden) effect. The vertical load-induced deviator stresses, as illustrated in Fig. 4, decrease throughout the subgrade depth. However, the distributions of deviator stresses for various layer combinations assume a similar shape along the subgrade depth. The deviator stress decays to an insignificant value at a depth of about 1500 mm. This depth interval (0 to 1500 mm) can therefore be taken as the subgrade depth of interest since the deviator stress below this depth decreases to such a magnitude that it does not constitute a significant factor to affect pavement performance. Within this depth of interest, the confining pressure ranges from about 15 to 40 kPa and averages about 20 kPa for conventional AC pavements illustrated in Fig. 3. For full-depth AC pavements and gravel roads with chip-seal, the confining pressure keeps decreasing to a subgrade depth of 500 mm and then gradually increases due to the overburden effect. However, the confining pressure within the subgrade depth of interest can also be averaged around 20 kPa for practical purposes. This average of the confining pressure is commensurate with the chamber pressure used in soil testing and model development (Eq. 4) (Elliott et al., 1998). This allows the direct application of the prediction model in design activities.

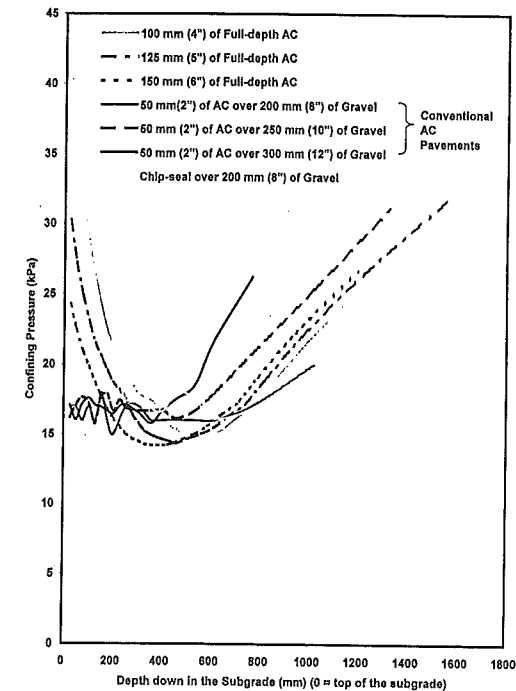


Fig. 3 Variation of Confining Pressure Along the Subgrade Depth (Based on Data from Fig. 1)

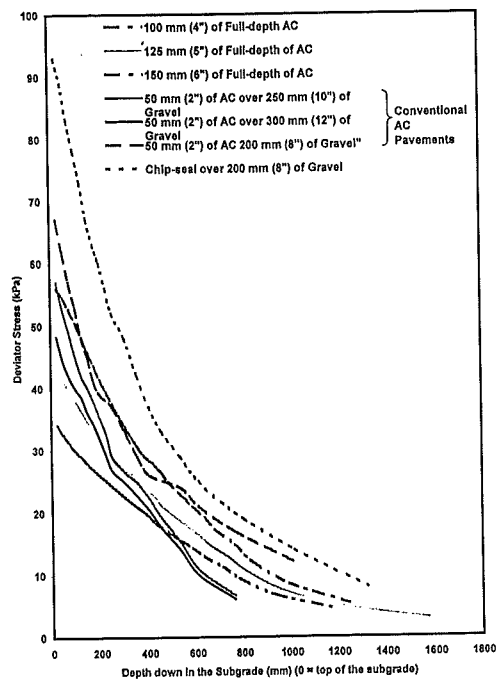


Fig. 4 Variation of Vertical Deviator Stress Along the Subgrade Depth (Based on Data from Fig. 1)

STRESS DISTRIBUTION IN THE SUBGRADES

Two new features are likely to be included in the next edition of *AASHTO Guide for Design of Pavement Structures*. One is the M-E design concept that allows the exact amount of distress to be predicted over a given number of load applications that will facilitate a practical implementation of modern pavement management systems. The other is the replacement of the vertical compressive strain by the vertical deviator stress at the top of the subgrade as the design criteria for rutting that will make the tedious calculation of rutting occurring in the subgrade easy to address. This is demonstrated in the following section. In fact, the use of permissible stress at the top of the subgrade along with strain has been reported in the literature (Chen and Bhatti, 1997).

Since current design methods use only resilient responses (ϵ_{AC} and ϵ_{VC}) in transfer functions (Huang, 1993), they cannot estimate the exact amount of distress (which is a residual accumulation in nature) over given service periods expressed as number of load applications or equivalent single axle loads (ESALs). One of the requirements of rational M-E design methods is the direct estimation of rutting by summing up the permanent deformations of pavement component layers (Huang, 1993; Brown, 1996; Thompson, 1996). Such a direct approach requires the division of pavement layers into sub-layers within which the stresses in each sub-layer can be controlled since paving materials are stress-dependent in nature. However, it is not practical for design agencies to conduct the tedious calculations and to evaluate the actual stress distribution in the pavement depth in order to meet the design criteria. A more convenient response should be used instead to serve the design purposes.

As demonstrated in Fig. 4, the deviator stress distribution along the subgrade depth does not change significantly with respect to different layer combinations and subgrade properties (That is to say, the "trend lines" of deviator stresses are "parallel" to one another). Considering that the confining pressure in the subgrade depth of interest varies in a limited range, soil strength, as a function of confining pressure, can be assigned with an average value for all sub-layers in the subgrade. Therefore, the stress ratio has the same distribution shape as the deviator stress. As a result, the distribution of vertical residual strain and permanent deformation along the subgrade depth is also relatively stable since the residual strain is directly related to the stress ratio, as demonstrated in Eq. (4). With this scenario, it is meaningful to adopt the vertical deviator stress at the top of the subgrade as the criterion for permanent deformation of subgrade soils. With the permanent deformation of subgrades controlled, pavement rutting can also be controlled since a large amount of it comes from subgrade deformation with minimized rutting occurring in AC for thin pavement. In fact, permanent deformation in the AC layer can be ignored, even in thick AC pavements, as a result of refined AC mix design and proper material selection in accordance with the implementation of the Strategic Highway Research Program (SHRP) Superpave mix design system (Cominsky, 1994). Groenendijk et al. (1997) reported that no evidence was found of shear deformation within the AC layer after 4 million load applications for full-depth AC pavements with 150 mm of AC layer. The pavement was subjected to a 75 kN super-single wheel with tire pressure ranging from 500 to 1100 kPa in a linear tracking device (LINTRACK). All 18 mm of maximum rutting could be ascribed to subgrade deformation. Chen et al. (1997) found no decrease of AC thickness in field tests for pavements with 50 to 70 mm of AC on top of lime-treated base/subgrade. The equipment used for this accelerated pavement test (APT) was a Texas Mobile Load Simulator (TxMLS) with a dual-tandem wheel configuration and 75.8 kN of axle load and 689 kPa of tire pressure. No portion of the 22 mm of rutting was attributed to the AC layer. Therefore, the stress at the top of the subgrade can be used to control the pavement rutting for both full-depth and thin AC flexible pavements. A reasonable contention is that the vertical stress at the top of the granular base can also be used as the critical response and rutting criterion in the design of conventional AC pavement structures. Therefore, a thorough understanding of the deviator stress at the top of the granular base and/or subgrade can be very helpful in the design of flexible pavements.

Although the distribution of deviator stress within the subgrade is relatively independent of the succeeding layers, the magnitude of deviator stress varies with respect to layer combination. Figure 5 presents the contours of deviator stresses at the top of the subgrade for flexible pavements at design temperature of 70°C. The pavement structure varies from full-depth AC to gravel road with an asphalt chip-seal. In the actual calculation, the chip-seal was treated as a thin lift of AC with low modulus. The design temperature is 70°C at which the modulus of AC is 3,450 MPa. Stress contours of other design temperatures, i.e. 30°C and 100°C, are also presented in Figs. 6 and 7, respectively. These figures provide a simple means for designers to choose an optimum design strategy. However, detailed data on subgrade soils have to be acquired in order to facilitate an M-E design rationale. The allowable stress ratio at the top of the subgrade and the static strength of subgrade soil need to be known to calculate the allowable deviator stress at the top of the subgrade. Elliott et al. (1998) reported a rational approach for the determination of the allowable stress ratio of subgrade soils through repeated load testing.

APPLICATION IN THE M-E DESIGN OF FLEXIBLE PAVEMENTS

The current AASHTO design method is an empirical procedure which is mainly based upon field test results of AASHTO Road Test. Succeeding analysis of the test data as well as other research findings resulted in several revisions. An *AASHTO Interim Guide for the Design of Rigid and Flexible Pavement Structures* was first assembled by the AASHTO Committee on Design in 1961 and was revised in 1972 and again in 1981. With the introduction of the resilient modulus M_R and completion of the NCHRP Project 20-7-24, a new version, *AASHTO Guide for the Design of Pavement Structures---1986*, was published in 1986, marking a new M_R era of design methodology. Updated overlay technology and rehabilitation techniques were incorporated in the latest revision in 1993. Although the AASHTO guide has been well accepted by design agencies in the United States, it is an empirical design method and engineering judgement plays an important role in the selection of the resilient modulus and layer coefficients. In order to overcome the inadequacies embedded in any empirical approach, a more rational M-E design method will be the key feature of the next version of the AASHTO guide which is expected to be published in 2002.

An example is presented in the following section with respect to the application of the stress contours presented in Fig. 5. A flexible pavement is to be designed over an Enders subgrade (Liquid Limit = 21, Plasticity Index = 4). The allowable stress ratio of Enders subgrade, $[r_{\sigma}]$, is 0.40 for an allowable rutting of 12

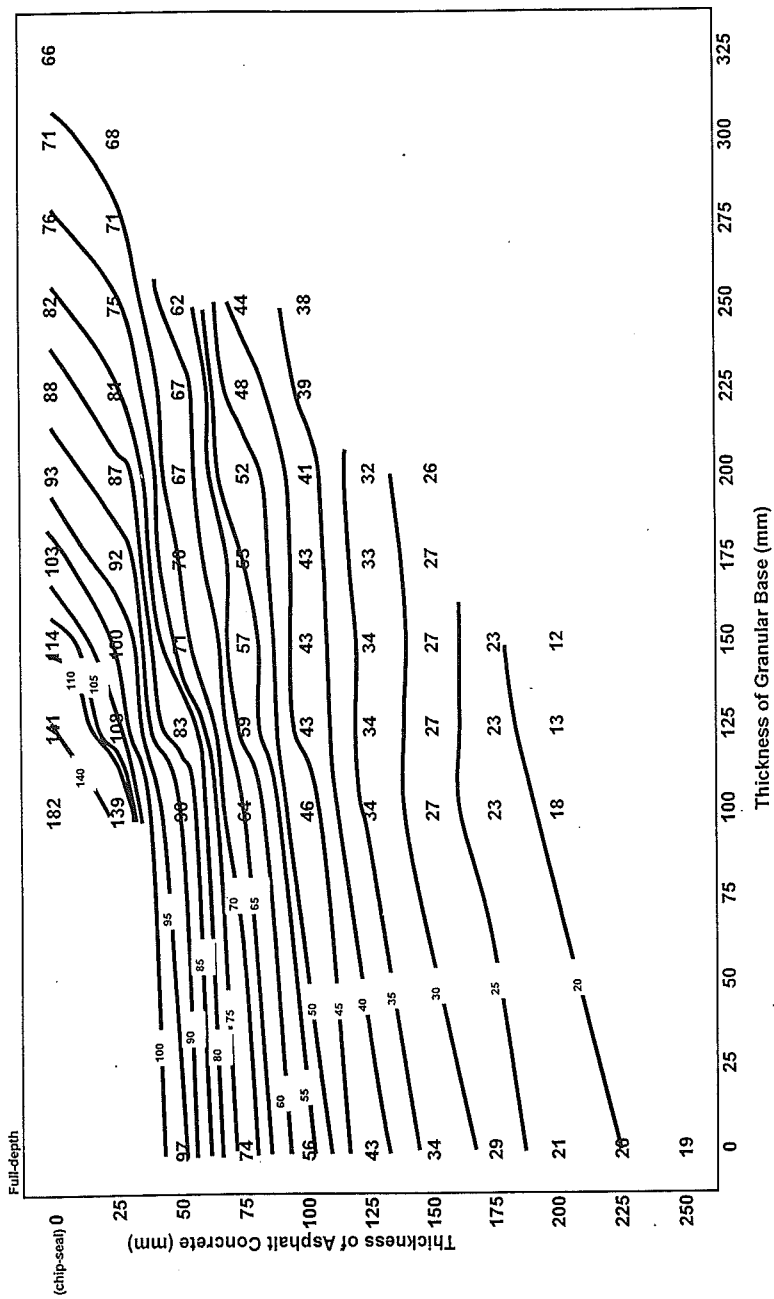


Fig. 5 Contours of Deviator Stress at the Top of Subgrade (Numbers in the Contour Lines are Interpolated Values; Other Numbers in the Plot are Values from ARKPAVE; Stress Unit in kPa), Temperature = 70°C

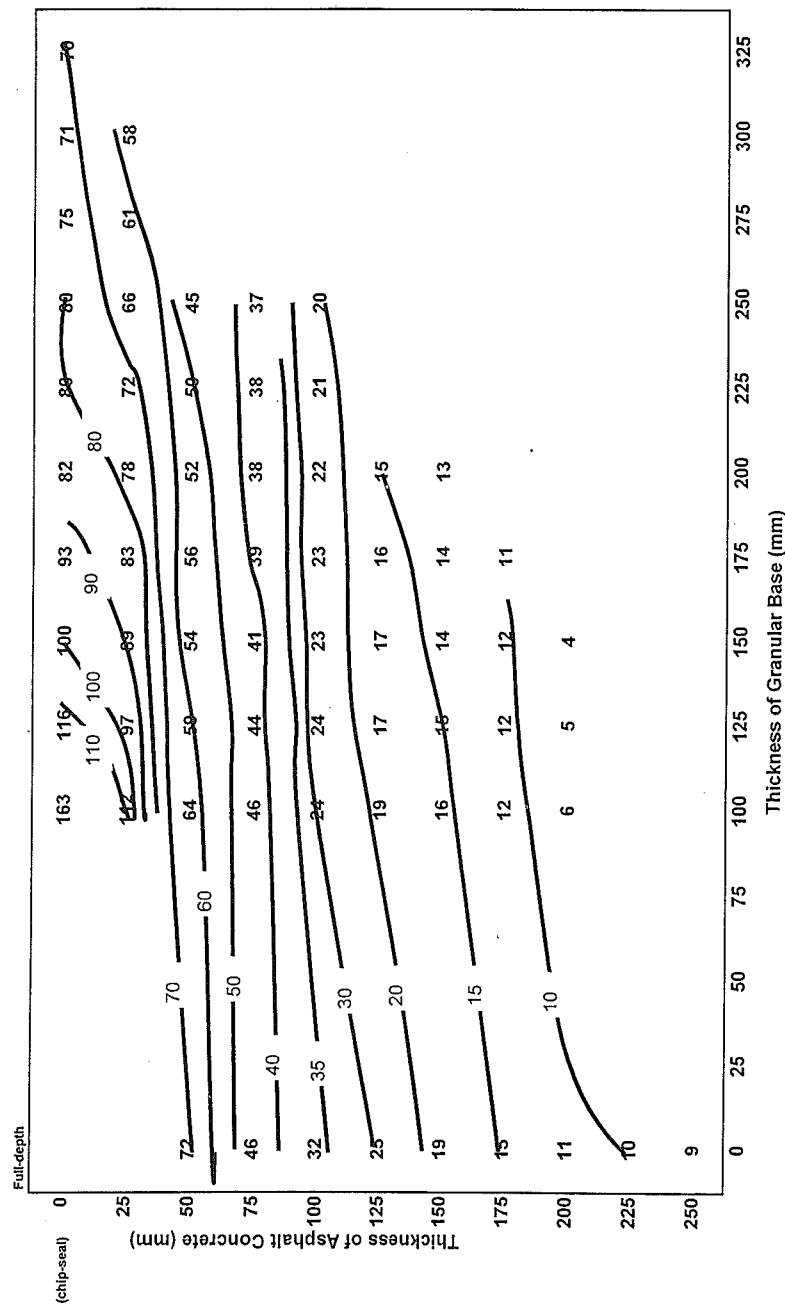


Fig. 6 Contours of Deviator Stress at the Top of Subgrade (Numbers in the Contour Lines are Interpolated Values; Other Numbers in the Plot are Values from ARKPAVE; Stress Unit in kPa), Temperature = 30°C

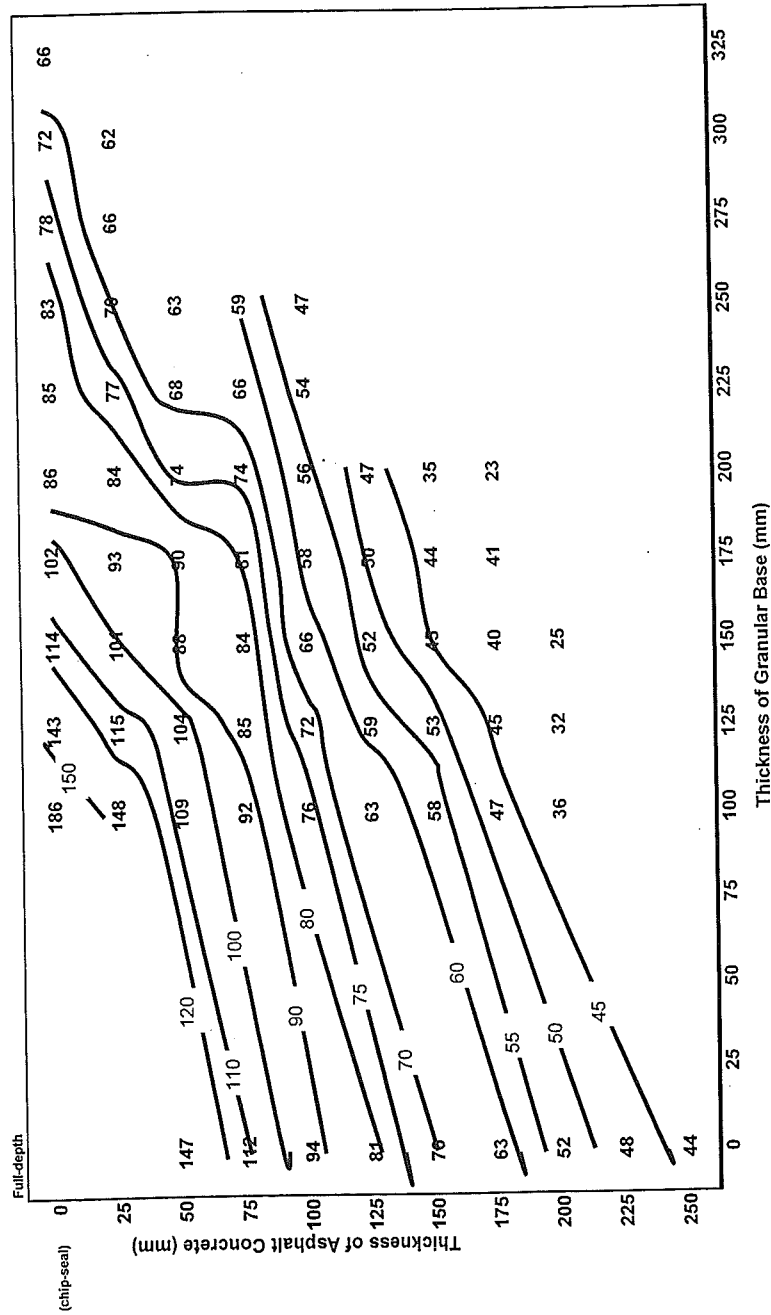


Fig. 7 Contours of Deviator Stress at the Top of Subgrade (Numbers in the Contour Lines are Interpolated Values; Other Numbers in the Plot are Values from ARKPAVE; Stress Unit in kPa), Temperature = 100°C

Table 3 Comparison of costs of different pavement structures

Design Detail	Full-depth AC	Conventional AC	Chip-seal over Gravel
Thickness of AC (mm)	75	50	0
Thickness of Gravel Base (mm)	0	150	300
Deviator Stress at the top of the Subgrade (kPa) (from Figure 5)	74	80	72
Unit Cost (US\$, 1m-wide and 1 km-long)	6300	8700	9000

mm at the end of design age with a design traffic of 1 million ESALs while the static strength, q_s , is 200 kPa for a design moisture content at 100% of OMC (Elliott et al., 1998).

The allowable vertical deviator stress at the top of the subgrade is $[\sigma] = [r_a] * q_s = 0.40 \times 200 = 80$ kPa. It is observed from Fig. 5 that three types of layer combinations meet this allowable deviator stress, namely, full-depth AC, Conventional AC, and chip-seal over gravel. Design strategies are listed in Table 3 with respect to these different layer combinations. The costs of asphalt concrete and gravel (crushed stone) are assumed to be 35 US\$/ton-in place and 15 US\$/ton-in place, respectively. The unit cost is based on the construction practices in the state of Arkansas, USA and is subject to change with market conditions elsewhere. The minimum cost of a 1-m-wide and 1-km-long section is 6300 US\$ for the 75-mm-thick full-depth asphalt concrete pavement. Therefore, the full-depth AC pavement was chosen over the other two alternatives from an economical point of view unless other design and/or operational considerations justify otherwise.

CONCLUSIONS AND RECOMMENDATIONS

Stress distribution in highway subgrades of flexible pavements was studied using numerical methods and nonlinear material properties. A nonlinear stress-dependent FEM program, ARKPAVE was used in the structural analysis of flexible pavements. Stress contours are presented with respect to various layer combinations and three different design temperatures. An example of their applications in optimum pavement design is presented. Conclusions are summarized as follows:

- The load-induced deviator stress decreases to an insignificant value within a subgrade depth of about 1500 mm. This subgrade depth can be selected as a practical limit in mechanistic analysis and/or mechanistic-empirical design methods.
- Within the subgrade depth of interest, the confining pressure ranges from about 15 kPa to 40 kPa with an average of 20 kPa. Any testing program for determining subgrade soil parameters associated with pavement design should be designed in accordance with this level of confining pressure.
- The contour lines of deviator stress at the top of the subgrade soils provide a rational means in M-E design of flexible pavements and facilitate an optimum design strategy.

With more and more deformation data about subgrade soils available, the M-E design strategy will find wider applications in flexible pavement design. More research efforts are needed to study permanent deformation behavior of granular bases. The role of deviator stress at the top of the granular base layer in a pavement is likely to be similar to the role of the deviator stress at the top of the subgrade, which may be a rational method to be justified through further research.

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