ANALYSIS OF FLEXIBLE PAVEMENTS INCORPORATING NONLINEAR RESILIENT BEHAVIOR OF UNBOUND GRANULAR LAYERS

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ABSTRACT

ANALYSIS OF FLEXIBLE PAVEMENTS INCORPORATING NONLINEAR RESILIENT BEHAVIOR OF UNBOUND GRANULAR LAYERS

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Traditionally, the resilient modulus values obtained from repeated unconfined or triaxial compression tests are used as the elastic modulus of granular layers in structural analysis of flexible pavements. Sometimes, the resilient modulus of granular materials are estimated from known California bearing ratios (CBR) or stabilometer resistance (R) values by simple regression equations. On the other hand, it is well known that stress-strain relation for unbound granular materials is non-linear and the resilient modulus increases with the increase in stress intensity.

There exist several models for stress dependent non-linear behavior of unbound granular materials. These models are incorporated into elastic layered analysis by applying a method of successive approximations in order to get more realistic pavement responses. KENLAYER is a popular computer program incorporating non-linear behavior of granular materials in elastic layered system. In this computer program, the resilient modulus of granular materials are varied in vertical direction only, without considering variations in radial direction.

In this study, simplest model namely K-θ model for stress dependency of granular layer is applied in structural analysis of flexible pavements. This model is adopted for use in finite element analysis carried by SAP90 software. Analyses are performed over 24 different three-layered pavement structures by changing asphaltic concrete modulus values, granular base thicknesses, base materials and subgrade modulus values. Critical pavement responses, namely tensile strains at the bottom of asphaltic surface layers and compressive strains on top of subgrade, are obtained for each pavement by linear layered elastic, non-linear layered elastic and non-linear finite element solutions. The pavement lives are calculated by using selected performance equations. The results of layered systems and finite element solutions are compared. It is obsereved that, results obtained from finite element model and linear elastic solutions differ considerably.

Keywords: unbound granular materials, non-linear resilient behavior, finite element method.

ÖZ

BAĞSIZ GRANÜLER TABAKALARIN LİNEER OLMAYAN ELASTİK DAVRANIŞI DAHİL EDİLEREK ESNEK KAPLAMALARIN ANALİZİ

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Geleneksel olarak esnek kaplamaların yapısal analizinde granüler tabakaların elastisite modülü olarak tekrarlı serbest basınç deneylerinden veya üç eksenli basınç testlerinden elde edilen değerler kullanılmaktadır. Bazen, granüler malzemelerin esneklik modülü basit regresyon denklemleri kullanılarak bilinen Kaliforniya taşıma oranlarından (CBR) veya stabilometre dayanım değerlerinden de (R) tahmin edilir. Öte yandan, bağsız granüler malzemeler için gerilme – birim şekil değiştirme ilişkisinin lineer olmadığı bilinmektedir ve esneklik modülü gerilme yoğunluğunun artması ile artış gösterir.

Bağsız granüler malzemelerin gerilmeye bağlı lineer olmayan davranışı için birçok model bulunmaktadır. Bu modeller daha gerçekçi kaplama tepkileri elde etmek için basitleştirilmiş bazı yaklaşımlar uygulanarak elastik tabakalı analize dahil edilirler. KENLAYER, granüler malzemelerin lineer olmayan davranışını elastik tabakalı sisteme ekleyen popüler bir bilgisayar programıdır. Bu programda granüler malzemelerin esneklik modülleri radyal yöndeki değişim dikkete alınmadan sadece düşey yönde değiştirilir.

Bu çalışmada, esnek kaplamaların yapısal analizinde, granüler malzemelerin gerilmeye bağlılığı için en basit model olan K-θ modeli uygulanmıştır. Bu model SAP90 yazılımı kullanılarak sonlu elemanlar yöntemine de adapte edilmiştir. Analizler asfalt betonunun elastisite modülü, granüler temel tabakasının kalınlığı, temel malzemesi ve zeminin elastisite modülü değiştirilerek, 24 farklı üç tabakalı kaplama yapısında gerçekleştirilmiştir. Asfalt yüzey tabakalarının altındaki çekme birim şekil değiştirmeleri ve zemin üzerindeki basınç birim şekil değiştirmeleri olarak adlandırılan kritik kaplama tepkileri her bir kaplama için lineer tabakalı teori, lineer olmayan tabakalı teori ve lineer olmayan sonlu elemanlar çözümü kullanılarak elde edilmiştir. Kaplama ömürleri, seçilen performans denklemleri kullanılarak hesaplanmıştır. Tabakalı sistemler ve sonlu eleman çözümlerinden elde edilen sonuçlar karşılaştırılmıştır. Sonlu elemanlar modeli ve lineer elastik çözümlerin birbirlerinden oldukça farklı sonuçlar verdiği gözlemlenmiştir.

Anahtar kelimeler: bağsız granüler malzemeler, lineer olmayan esneklik davranışı, sonlu elemanlar yöntemi.

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ABBREVIATIONS

SYMBOL

a	:	load radius.
CBR	:	California Bearing Ratio.
D_2	:	Amount of displacement in stabilometer test.
E_1	:	Elastic modulus of A.C. layer.
E_2	:	Elastic modulus of granular base layer.
E_3	:	Elastic modulus of subgrade.
f_1, f_2, f_3	:	Coefficients of fatigue criterion.
f_4, f_5	:	Coefficients of permanent deformation criterion.
K_0	:	Coefficient of earth pressure.
k_1,k_2,k_3	:	Nonlinear coefficients of granular materials.
M_r	:	Resilient modulus.
N_d	:	Allowable number of load repetitions to limit permanent deformation.
N_f	:	Allowable number of load repetitions to prevent fatigue cracking.
p	:	Mean normal stress $(\sigma_1 + 2\,\sigma_3) / 3$.
p_h	:	Transmitted horizontal pressure in stabilometer test.
p_v	:	Applied vertical pressure in stabilometer test.
P	:	Concentrated load.

P_a : Reference pressure of 1 psi.

q : Deviatoric stress ($\sigma_1 - \sigma_3$) ; tire pressure.

R : Stabilometer resistance value.

ε_c : Vertical compressive strain on the surface of subgrade.

ε_r : Radial strain or recoverable strain.

ε_t : Tensile strain at bottom of asphalt layer.

ε_z : Vertical strain.

$\sigma_{1,2,3}$: Three principal stresses.

σ_c : Confining pressure.

σ_d : Deviator stress ($\sigma_1 - \sigma_3$).

σ_r : Radial stress.

σ_t : Tangential stress.

σ_z : Vertical stress.

τ : Shear stress.

τ_{oct} : Octahedral stress.

μ : Poisson's ratio.

θ : First stress invariant ($\sigma_1+\sigma_2+\sigma_3$) or ($\sigma_x+\sigma_y+\sigma_z$).

CHAPTER 1

INTRODUCTION

1.1 General

Unbound granular materials are generally used as base and subbase layers in road pavements. They may be some natural materials like gravel or crushed rock, or may be artificial materials such as crushed slag or clinker obtained as by products of some industrial processes. Although the granular layers in a flexible pavement system play an essential role in the overall structural performance of the pavement, until recently, unbound granular materials for road construction has received less research interest than other paving materials. Because their resilient behavior was oversimplified in the past by limited research findings based on classical tests, namely plate loading, stabilometer and in-situ or field CBR tests. In addition to this, technical difficulties posed by laboratory testing of materials having large particle sizes, encouraged researchers to concentrate past studies on similar materials.

However, during the last 25 years the situation has changed and a significant research effort has been undertaken towards the characterisation of unbound granular materials. Because it has been understood that although these materials are intermediary elements of the pavement structure, the correct functioning of the unbound granular layers is vitally important. A number of researchers have studied the resilient behavior of the unbound granular base materials subjected to traffic loading. They have shown that unbound granular materials have non-linear, stress dependent resilient behavior when responding to load. And also the degree of this non-linearity is a function of the stress state, moisture content, dry density, level of load and particle size distribution of the unbound granular material.

For better understanding of non-linear resilient behavior, laboratory tests where adequately simulated in-situ stress conditions and traffic loads are needed. During its service life, a pavement experiences a large number of stress pulses each consisting of vertical, horizontal and shear stress components. Repeated load triaxial testing is the most commonly used laboratory work for the determination of stress dependent behavior of the unbound granular materials.The test can be performed with different stresses, densities, moisture contents and gradings that are representative of the materials within the road structure. The most important parameters evaluated in repeated load triaxial test are the stiffness characteristics of the material as well as the ability to withstand the accumulation of permanent deformation during pulsating loading.

One of the current main research topics in highway engineering is the analytical design of flexible pavement structures. Many of the popular pavement design techniques are based on this analytical method with an assumption that pavement performance is directly related to critical pavement responses under the traffic loads. Hence, the fundamental requirement for an analytical approach towards a pavement design is the proper understanding of the mechanical properties of the constituent materials. Because the granular base and subbase layers in a flexible pavement system play an essential role in the overall structural performance of the pavement, their complex mechanistic characteristics should be carefully investigated.

As explained earlier, layered analytical models are still commonly used in pavement design phase by pavement engineers. For example; the present French pavement design method is based on mechanistic pavement analysis using the multi-layer linear elastic Burmister model (Burmister 1943). Analysis done by several researchers show that this approach gives relatively good results for heavy traffic pavements, with bound bituminous or cement treated base layers. However, it is less satisfactory for flexible pavements for low traffic, with a limited thickness of bituminous materials (less than about 15 centimeters) and a granular base [*Akou, Heck, Kazai, Hornych, Odeon and Piau*]. For this type of pavements, the non-linear behavior of unbound granular materials has to be taken into account in modelling to obtain realistic results.

In this thesis, this type of modelling is utilized by using both KENLAYER computer program based on layered elastic model and SAP90 finite elements computer program. Although, software KENLAYER is based on the multi-layer linear elastic Burmister model, it has non-linear analysis option also. This is the major advantage of this program compared to similar programs based on the same calculation principles like ELSYM5, CHEVRON and BISAR.

In KENLAYER program, non-linear resilient model of granular material is defined in the input phase and program calculates stresses, strains and displacements at specified points by using this non-linear model. Calculation procedure is simply;

- Dividing granular layer into several sub-layers
- Calculating the stresses at previously specified stress points in each sub-layer
- Application of non-linear model defined in input phase
- Calculation of new modulus values for each layer by using model
- Iterative process until the values of elastic modulus of each layer converge

Although, this method gives relatively realistic results compared to solutions generated from other softwares using Burmister's layered linear elastic theory, it does not truly represent the actual in-situ behavior of granular materials. Major disadvantage of this type of analysis is that because KENLAYER is a software based on the Burmister's layered linear elastic model, user can only change modulus values of each layer in vertical direction and modulus is assumed constant throughout the layer. This does not represent the actual behavior of the granular material whose resilient modulus is also varying in the horizontal direction within the layer. Actually modulus values change throughout the layer because stress is variable within the layer. This type of modelling can only be achieved by using "Finite Element Method". User can change modulus values within the layer in both vertical and horizontal directions. This type of modelling is more approximate method that resembles the in-situ behavior of the unbound granular materials. In this thesis, finite element method based SAP90 computer program is used for modelling flexible pavement systems having granular base layers.

1.2 Flexible Pavements

The main structural function of a pavement is to support the loads induced by traffic and to distribute these loads safely to the foundation. Figure 1.1 shows the typical cross-section of a flexible pavement system. This pavement comprises a number of bituminous layers placed over the road base (unbound or bound material) over a similar unbound subbase material placed on the natural subgrade. This pavement is referred to as "flexible" because the bituminous materials are capable of flexing slightly under traffic loading. For thinly surfaced pavements, the road base is often unbound granular material. The base course immediately beneath the surface course can be composed of crushed stone, crushed slag or other untreated or stabilized materials. The subbase course is the layer beneath the base course. The reason that two different granular materials are used is for economy. Instead of using the more expensive base course material for the entire layer, local and cheaper materials can be used as a subbase course on top of the subgrade [*Huang,2004*],[*Witczack and Yoder,1975*].

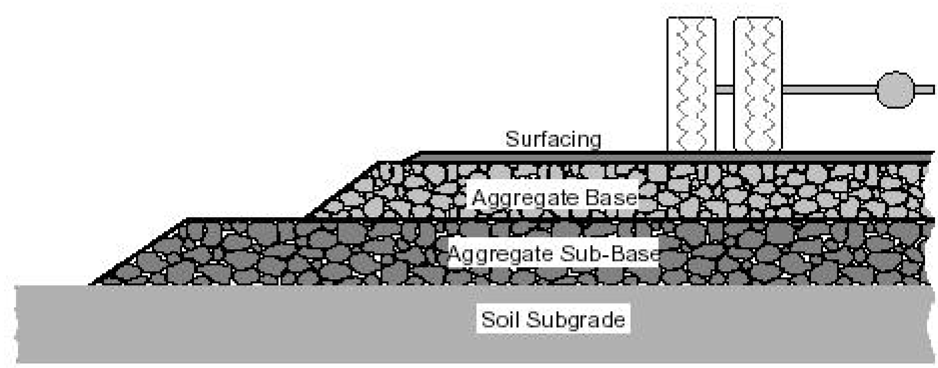


Figure 1.1 Typical cross-section of a flexible pavement system [*COURAGE*, 1999]

1.3 Use of Unbound Granular Base Layers in Road Construction

The performance of any base material whether bituminous treated, cement treated or unbound aggregate, relies primarily on the interaction of the individual stones within the mix. The basic stone-to-stone behavior is then modified by the binding agent between the particles. In the case of an unbound granular base this modification is achieved by the combined effect of the finer aggregate particles and the water which rests in the pores of the mix. It is for this reason that untreated aggregates may be classed as being "hydraulically" bound.[*Dawson,2003*]

In order to meet its role as the main structural component of the pavement, the aggregate base has to perform the following principal functions;

- Subgrade protection against over - stressing which results in permanent deformation of subgrade
- Support for surfacing (reducing the stresses and strains in the surface layer)
- To provide a working platform for construction of above layers
- To provide adequate drainage
- Subgrade protection against frost
- Subgrade protection against environmental damage

1.4 Critical Responses for Flexible Pavements and Prediction of Life

For some years, the "analytical-empirical" (or"mechanistic-empirical") method has been widely applied in flexible road pavement design. This mechanistic-emprical method of design is based on the mechanics of the materials that relates an input, such as a wheel load, to an output or pavement response, such as stress or strain. This approach consists of two parts; calculating the response of the pavement materials to the applied loading and predicting the pavement performance from these responses [*Zhang and Macdonald, 2002*],[*Huang, 2004*].

Kerkhoven and Dormon (1953) first suggested the use of vertical compressive strain on the surface of the subgrade as a failure criteria to reduce the permanent deformation of subgrade which is the main reason of subgrade rutting. After that

Saal and Pell (1960) recommended the use of horizontal tensile strain at the bottom of the asphaltic concrete to minimize fatigue cracking which limits the fatigue life of pavements [*Huang, 2004*]. In figure 1.2, these two types of critical responses of simple three layered flexible pavement system is shown.

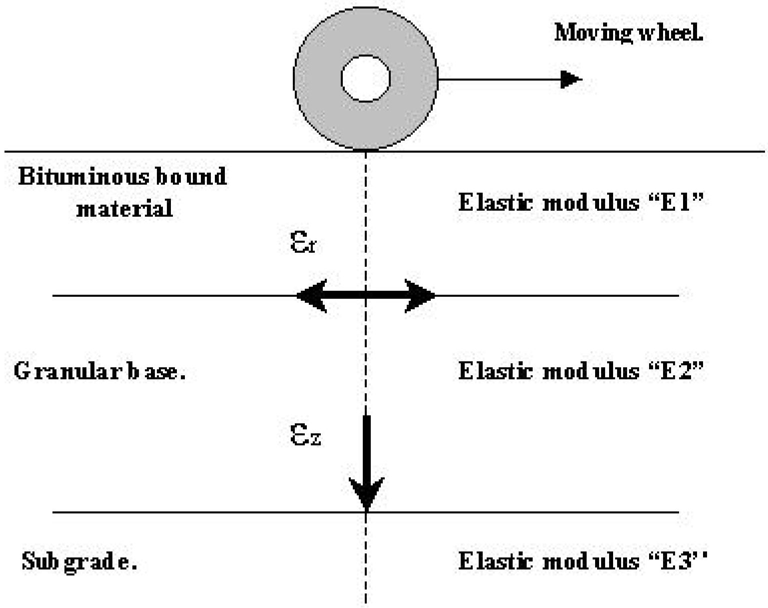


Figure 1.2 Critical pavement responses in a typical three layered system

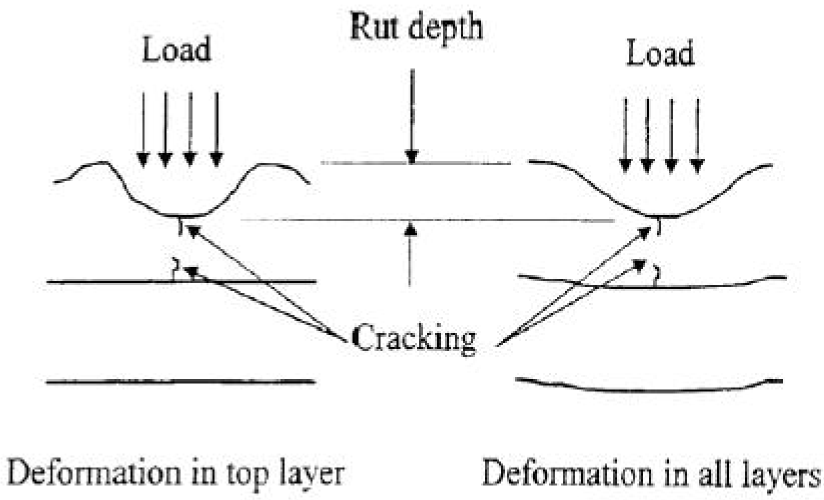


Figure 1.3 Diagrams showing the two types of failure mechanisms in pavements

Two main structural failure mechanisms for flexible pavements which are the fatigue cracking of the asphaltic concrete layer and permanent deformation of the subgrade (rutting) are also shown in figure 1.3.

The use of vertical compressive strain to control permanent deformation is based on the fact that plastic strains are proportional to elastic strains in paving materials. For this reason, by limiting the elastic strains on the subgrade, the elastic strains in other components of the pavement above the subgrade will also be controlled; hence, the magnitude of permanent deformation on the pavement surface will be controlled in turn [*Huang, 2004*]. These two criteria have since been adopted by Shell Petroleum International and Asphalt Institute in their mechanistic emprical methods of design.

The failure criteria for fatigue cracking is expressed as generally ;

$$Nf = f1(\varepsilon_t)^{-f2}(E_1)^{-f3} \tag{1.1}$$

in which Nf is the allowable number of load repetitions to prevent fatigue cracking; ε_t is the tensile strain at the bottom of the asphaltic layer; E_1 is the elastic modulus of asphaltic layer; and $f1$, $f2$ and $f3$ are constants determined from laboratory fatigue tests [*Huang, 2004*]. The Asphalt Institute used 0.0795, 3.29 and 0.854 [*AI,1982*] for $f1$, $f2$ and $f3$ respectively in their analytically based design procedure; the corresponding values used by Shell are 0.0685, 5.671 and 2.363 [*Claussen, Edwards and Sommer, 1977*].

The failure criterion for permanent deformation is expressed as ;

$$Nd = f4(\varepsilon c)^{-f5} \tag{1.2}$$

in which Nd is the maximum allowable number of load repetitions to limit permanent deformation, εc is the compressive strain on the top of subgrade, and $f4$ and $f5$ are constants determined from road tests or field performance [*Huang,2004*]. Values of $f4$ and $f5$ are suggested as 1.365E-9 and 4.477 by the Asphalt Institute [*AI,1982*], and 6.15E-7 and 4.0 by Shell [*Claussen, Edwards and Sommer, 1977*].

CHAPTER 2

NON-LINEAR RESILIENT BEHAVIOR OF GRANULAR MATERIALS

2.1 General

It is generally known that unbound granular materials have a non-linear elastic stress-strain behavior. Because the unbound base courses have a substantial influence on the load carrying capacity of the pavements, proper characterization of the mechanical response of unbound aggregate materials is a crucial factor. As explained earlier, in flexible pavements, particularly when thinly surfaced, granular layers play an important role in the overall performance of the pavement [*Lekarp,Isacsson and Dawson*]. Consequently, to establish more rational pavement design and construction criteria, it is essential that the response of granular layers under traffic loading be thoroughly understood.

2.2 In-situ Behavior and Laboratory Work

The stress pattern induced in a pavement due to a moving wheel load is quite complex. Figure 2.1 shows an element in a pavement structure subjected to stress pulses, each consisting of vertical, horizontal and shear components.

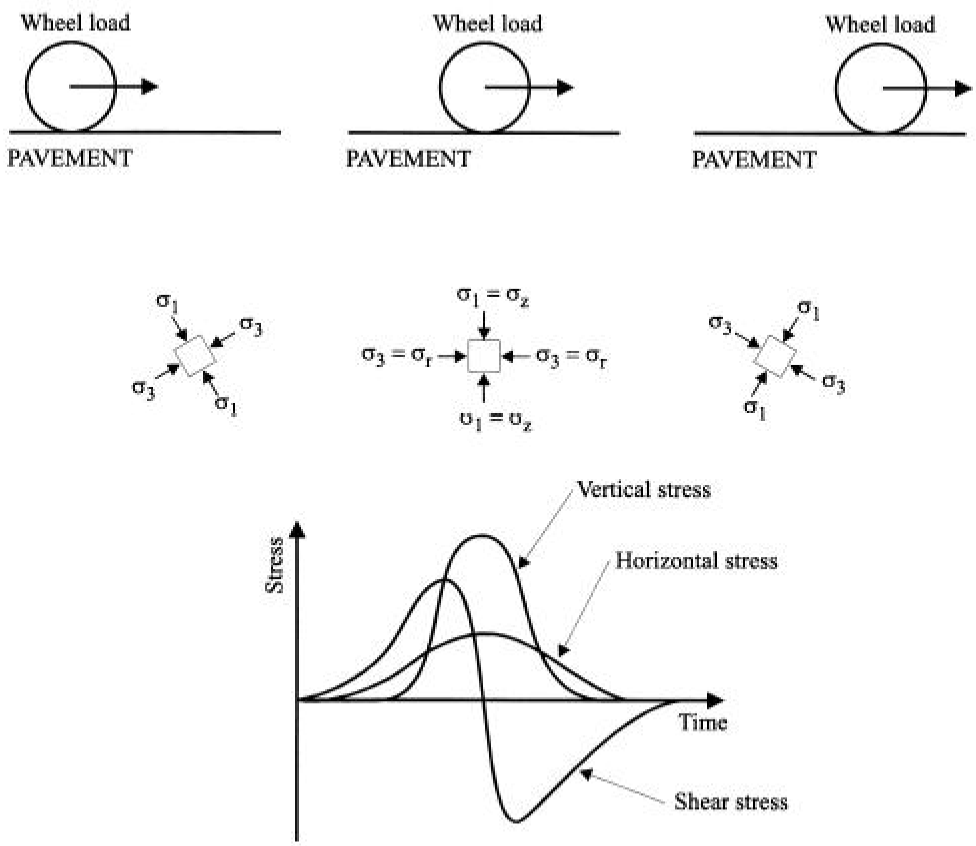


Figure 2.1 Stresses beneath rolling wheel load [*Lekarp,Isacsson and Dawson,2000*]

To better characterize aggregate behavior, it is important to properly simulate the actual loading conditions in laboratory. As can be seen from the figure 2.1, the pavement in the field is usually loaded by moving wheel loads, which at any time impose varying magnitudes of vertical, horizontal and shear stresses in the aggregate layer accompanied by the rotation of the principal stresses. This type of loading can only be ideally simulated in the laboratory by the variable confining pressure (VCP) type repeated load triaxial tests by both changing confining and deviatoric stresses [*Tutumluer and Seyhan*], [*Dawson and Hill, 1998*]

After the use of repeated load triaxial tests to determine the stress-strain characteristics of unbound granular materials, test results showed that granular materials are not elastic, but experience some permanent deformation after each load application [*Huang*]. Therefore the deformational response of granular layers under traffic loading is conveniently characterized by a recoverable (elastic) deformation (or strain) and permanent (plastic) deformation (or strain) [*Tutumluer and Seyhan*]. Figure 2.2 shows the stress-strain characteristics of a specimen under a repeated load test.

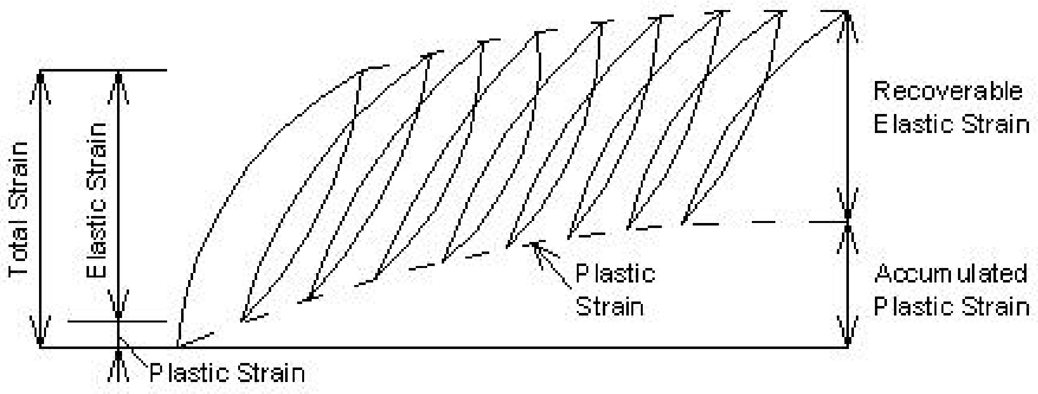


Figure 2.2 Strains under repeated loading [*Huang, 2004*]

At the initial stage of load applications, there is considerable permanent deformation, as indicated by plastic strain in the figure. When the number of load repetitions increase, the plastic strain due to each load repetition decreases. After 100 to 200 repetitions, the strain is practically all recoverable as shown in the figure.

2.3 Resilient Modulus Concept for Granular Materials

The concept of resilient behavior of granular materials was first introduced by Hweem and Carmany (1948) and Hweem (1955). Seed et al. (1955) at the University of California at Berkeley followed the lead established by Hweem, who had developed the repeated load test. They have introduced the concept of "resilient modulus" (Mr) for soils. This modulus was defined as the ratio of applied dynamic deviatoric axial stress "σ_d" to the recoverable elastic axial strain "ε_r", under a dynamic load pulse. Years later, resilient modulus concept gained recognition by the pavement community as a good property describing the resilient behavior of granular materials [*Angelone and Martinez*].

$$Mr = \frac{\textit{deviatoric axial stress}}{\text{recoverable axial strain}} = \frac{\sigma d}{\varepsilon r} \tag{2.1}$$

It is clear from equation 2.1 that "Mr" is stress dependent, thus, the use of "non-linear elastic" hypotesis could be more accurate to describe the variation of "Mr" with the applied stress state. Some models have been developed describing this type of behavior for use in computational pavement design methods and they are based on "Mr" results obtained from the repeated load triaxial test.

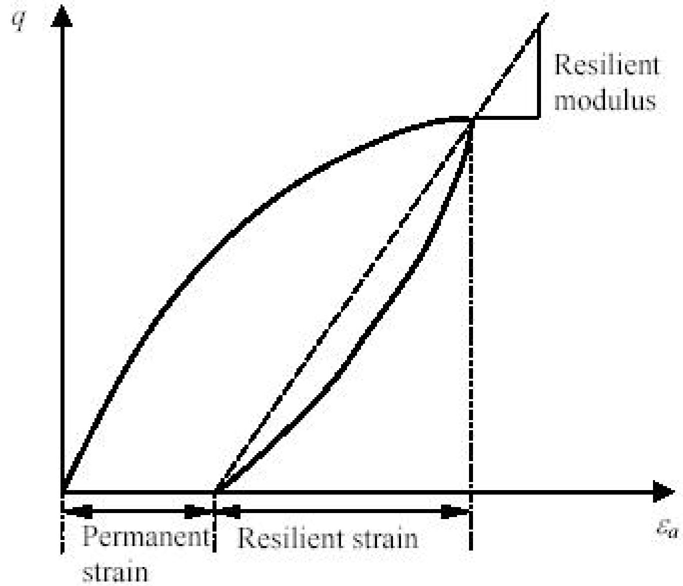


Figure 2.3 Graphically representation of resilient modulus

2.4 Repeated Load Triaxial Test

The repeated load triaxial test apparatus was developed in order to investigate the mechanichal behavior of unbound pavement materials. The apparatus aims to simulate traffic loads by subjecting a cylindrical specimen to repeated cyclic stresses. A cylindrical specimen is placed in a triaxial cell, where it is subjected to a confining pressure σ_c and a vertical deviatoric stress σ_d. It is possible to cycle both stress components σ_c and σ_d in phase. This allows to carry out cyclic loadings following different stress paths [*Hornych and Gerard*], [*Gidel, Hornych and Chauvin*]. Figure 2.4 shows the basic loading principle of triaxial test.

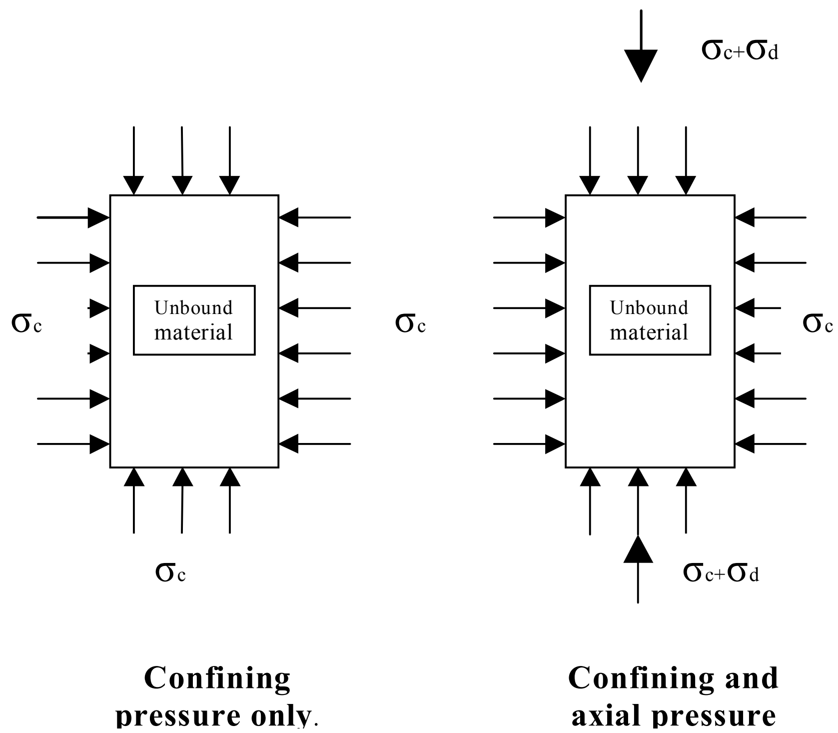


Figure 2.4 Principle of the repeated load triaxial test

Where;

σc (confining pressure) = $\sigma 3$ (minor principal stress)
$\sigma c + \sigma d = \sigma 1$ (major principle stress)
σd (deviatoric stress) = $\sigma 1 - \sigma 3 = q$
$(\sigma 1 + 2\sigma 3)/3$ = mean normal stress = p

The procedure for determining the resilient modulus is specified by AASHTO (T274) (1989). Figure 2.5 shows the triaxial cell for testing cylindrical specimens. The sample size for unbound aggregates in a triaxial test is recommended as 150 mm in diameter and 300 mm in height.

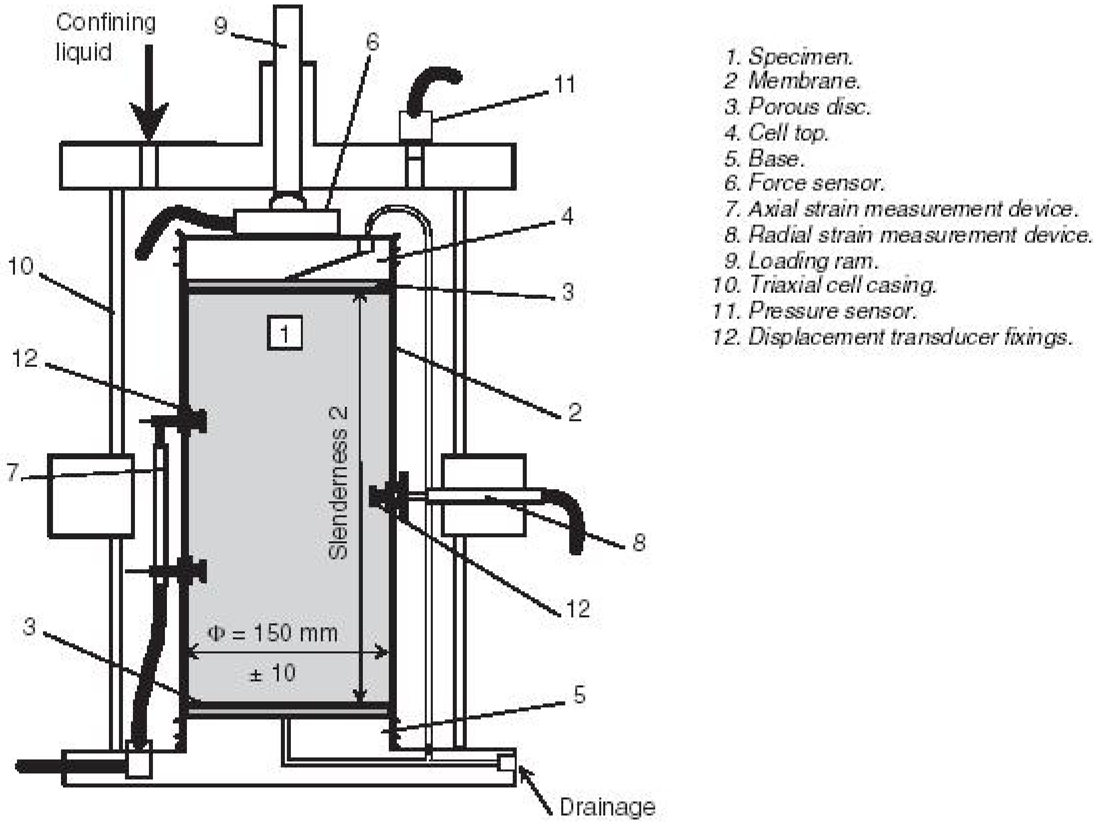


Figure 2.5 Triaxial cell for testing cylindrical specimens [*Gidel,Hornych,Chauvin*]

According to test procedure recommended by AASHTO (1989), sample conditioning can be accomplished by applying various combinations of confining pressures and deviator stresses, as follows;

1) Set the confining pressure to 5 psi, and apply a deviator stress of 5 psi and then 10 psi, each for 200 repetitions.
2) Set the confining pressure to 10 psi, and apply a deviator stress of 10 psi and then 15 psi, each for 200 repetitions.
3) Set the confining pressure to 15 psi, and apply a deviator stress of 15 psi and apply a deviator stress of 15 psi and then 20 psi, each for 200 repetitions.

After sample conditioning, the following constant confining pressure and increasing deviator stress sequence are applied. The results are recorded at the 200th repetition of each deviator stress;

1) Set the confining pressure to 20 psi, and apply deviator stresses of 1, 2, 5, 10, 15 and 20 psi.
2) Reduce the confining pressure to 15 psi, and apply deviator stresses of 1, 2, 5, 10, 15 and 20 psi
3) Reduce the confining pressure to 10 psi, and apply deviator stresses of 1, 2, 5, 10, 15 and 20 psi.
4) Reduce the confining pressure to 5 psi, and apply deviator stresses of 1, 2, 5, 10, 15 and 20 psi.
5) Reduce the confining pressure to 1 psi, and apply deviator stresses of 1, 2, 5, 7.5 and 10 psi. Stop the test after 200 repetitions of the last deviator stress level. [*Huang, 2004*]

2.5 Review of Resilient Modulus Models

The resilient modulus concept has become an important parameter in the new mechanistic pavement design methods. Several testing protocols for determining the resilient moduli have been proposed and evaluated by different agencies. A significant number of models describing the non-linear behavior of this type of materials have been proposed. Models used for determining the "Mr" value can be classified into two main catagories;

1) Old models, actually not based on the stress dependent characteristics of materials , generated from some emprical correlations based on the California Bearing Ratio (CBR) test or stabilometer test (R).
2) Models, developed from the repeated load triaxial test results, describing the stress-dependent non-linear behavior of the materials.

2.5.1 Models Based on Empirical Correlations with CBR and R Value

The California Bearing Ratio test (CBR) is a penetration test, wherein a standart piston having an area of 3 in^2 is used to penetrate the soil at a standart rate of 0.05 in. per minute. The pressure at each 0.1 in. penetration up to 0.5 in. is recorded and its ratio to the bearing value of a standard crushed rock is termed as CBR. The standart values of a high-quality crushed rock are as follows:

Penetration	Pressure
0.1 in.	1000 psi
0.2 in.	1500 psi
0.3 in.	1900 psi
0.4 in.	2300 psi
0.5 in.	2600 psi

As a general rule, the CBR will decrease as the penetration increases, so the ratio at the 0.1 in. penetration is used as CBR [*Witczak and Yoder*, *1975*], [*Huang, 2004*]

Similar to CBR, R value is also the resistance value of soil determined from the stabilometer test. The stabilometer test was developed by the California Division of Highways. Figure 2.6 shows the schematic diagram of the stabilometer.

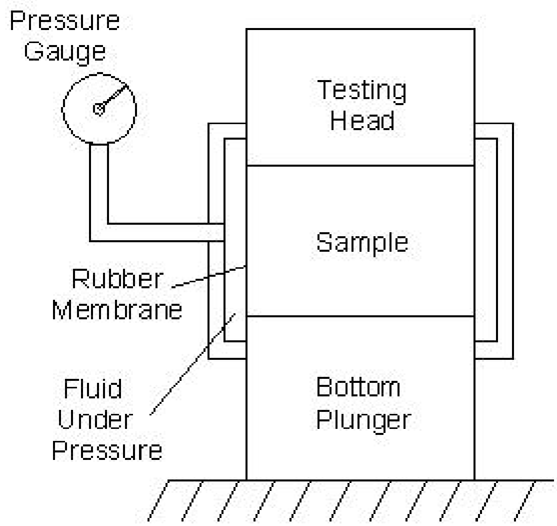


Figure 2.6 Schematic diagram of stabilometer

A vertical pressure of 160 psi is applied to sample, 4 in. in diameter and about 4.5 in. in height, and the resulting horizontal pressures induced in the fluid within the rubber membrane are measured. The test procedure is adopted so that the resistance to deformation is expressed as a function of the ratio of the transmitted lateral pressure to that of the applied pressure. The resistance value "R" is computed as;

$$R = 100 - \frac{100}{(2.5/D_2)(p_v/p_h - 1) + 1} \quad (2.2)$$

where, R is the resistance value; p_v is the applied vertical pressure of 160 psi, p_h is the transmitted horizontal pressure at pv of 160 psi and D_2 is the displacement of stabilometer fluid necessary to increase horizontal pressure from 5 to 100 psi, measured in revolutions of a calibrated pump handle. The value of D_2 is determined after the maximum vertical pressure of 160 psi is applied. If the sample is a liquid with no shear resistance, the $p_h = p_v$, or from equation 2.2, R=0. If the sample is rigid with no deformation at all, then ph=0, or R=100. Therefore R values ranges from 0 to 100 [*Witczack and Yoder, 1975*], [*Huang, 2004*].

As explained, the simplest type of model for determination of "Mr" value includes only empirical correlations with the laboratory test results introduced above. But, they are not appropriate to describe the stress dependence of "Mr".

Heukelom and Foster (1960) have developed a correlation between modulus and CBR [*Witczack and Yoder, 1975*]. Which is;

$$Mr = 1500\,(CBR) \quad (2.3)$$

where, Mr is the resilient modulus in psi. Available data indicate that eq. 2.3 provides better results at values of CBR less than about 20. In other words, the correlation appears to be more reasonable for fine-grained soils and fine sands than for granular materials [*Huang, 2004*].

The Asphalt Institute (1982) proposed the following correlation between "Mr" and "R" value.

$$Mr = 1155 + 555 R \tag{2.4}$$

where, Mr is the resilient modulus in psi. This equation generates similar results with eq. 2.3. But analyses have shown that eq. 2.4 is also not suitable for granular materials similar to CBR-Mr relationship. After the investigation of CBR-Mr and R-Mr relationships by the Asphalt Institute, it was reported that, estimates from CBR values of 25 or higher and R values above 60 would appear to overestimate Mr by equations 2.3 and 2.4 [*Huang, 2004*], [*Angelone,Martinez*].

It is clear that the correlations among CBR, R and Mr are practically the same no matter whether the material is used as a base, a subbase or a subgrade. This assumption is not realistic for the resilient modulus which directly depends on the stress state, which is variable with the location of the material to be placed. In order to overcome this disadvantage, Van Till (1972) has developed the correlation charts for estimating resilient modulus values by also considering the location of the material in the pavement system. These correlation charts were originally developed to determine the structural layer coefficients of the AASHTO design method. These can also be used to determine the resilient modulus. Correlation chart used for estimating resilient modulus of granular bases is shown in figure 2.7 [*Witczack and Yoder, 1975*].

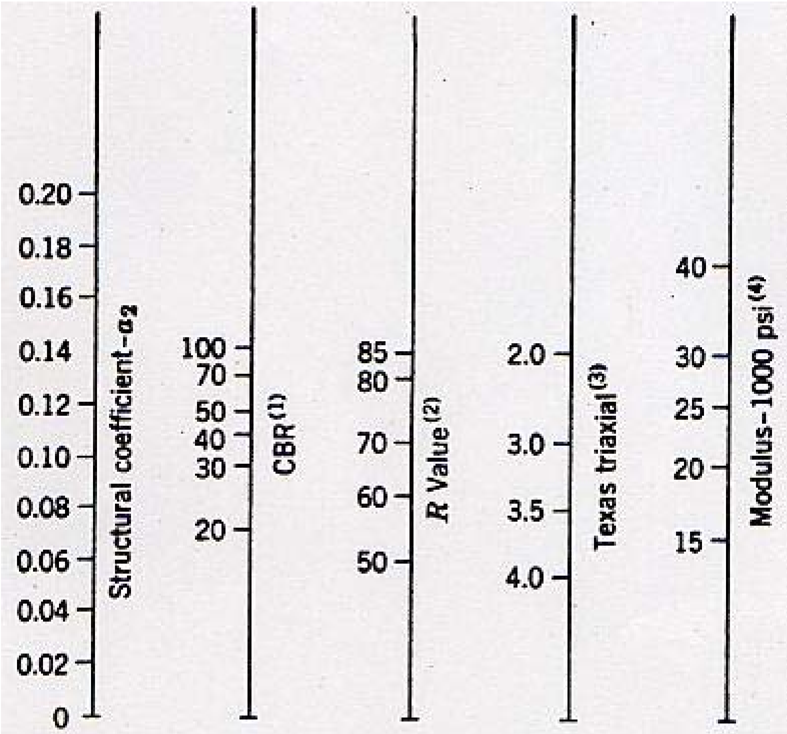


Figure 2.7 Correlation chart for estimating resilient modulus of granular bases [*Witczack and Yoder, 1975*]

2.5.2 Models Based on the Stress Dependencies of Materials

Several resilient modulus models have been succesfully used to describe the non-linear stress-strain relationships of the granular materials. These models are based on "Mr" results obtained in the laboratory from the repeated load triaxial test.

Dunlap (1963) indicated that the resilient modulus increases with confining pressure and the linearity of the relation (see fig.2.8) between the logarithm of the resilient modulus and the logarithm of the confining pressure allows the results to be expressed in the following form;

$$Mr = k1\ (\sigma_3)^{k2} \quad (2.5)$$

where;

Mr = resilient modulus in psi

σ_3 = confining pressure in psi

k1, k2 = constants depending on material properties

[*Nataatmadja, 1992*],[*Lekarp, Isaccson and Dawson, 2000*].

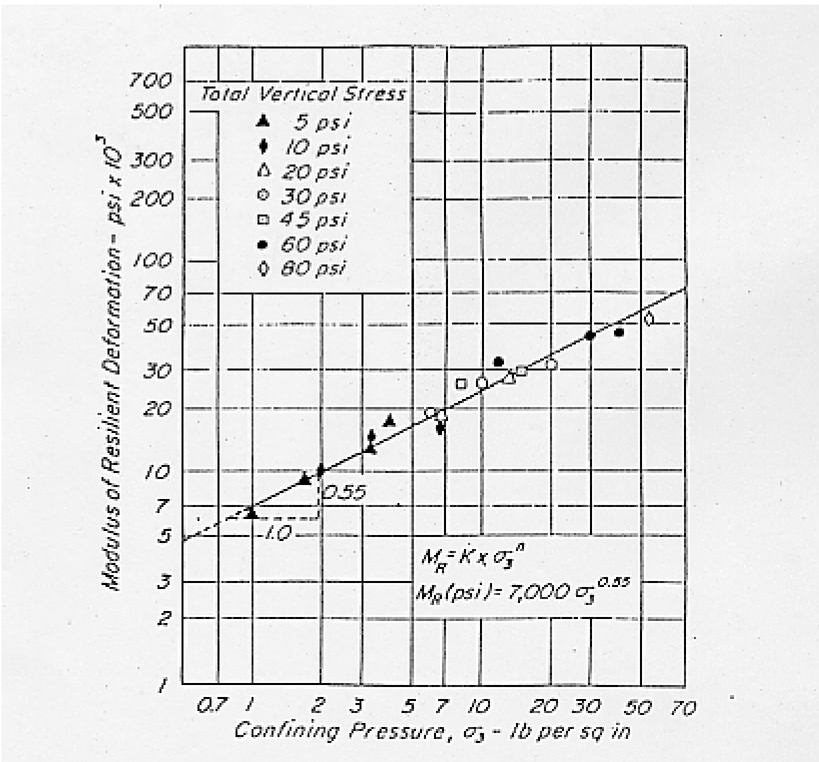


Figure 2.8 Sample relationship between Mr and confining pressure [*Monismith*]

Seed at al, (1967), suggested that the resilient modulus is a function of the sum of principal stresses or the bulk stress (first invariant of stress) and the relation between resilient modulus and bulk stress can be expressed as a straight line in a log-log scale (see fig. 2.9). Later studies by Hicks and Monishmith (1971) confirmed this theory. Then the model is written in the form of ;

$$Mr = k1\,(\theta)^{k2} \tag{2.6}$$

where;

Mr = resilient modulus in psi

θ = first stress invariant (bulk stress) in psi = $\sigma 1 + \sigma 2 + \sigma 3 = \sigma x + \sigma y + \sigma z$

k1, k2 = constants depending on material properties.

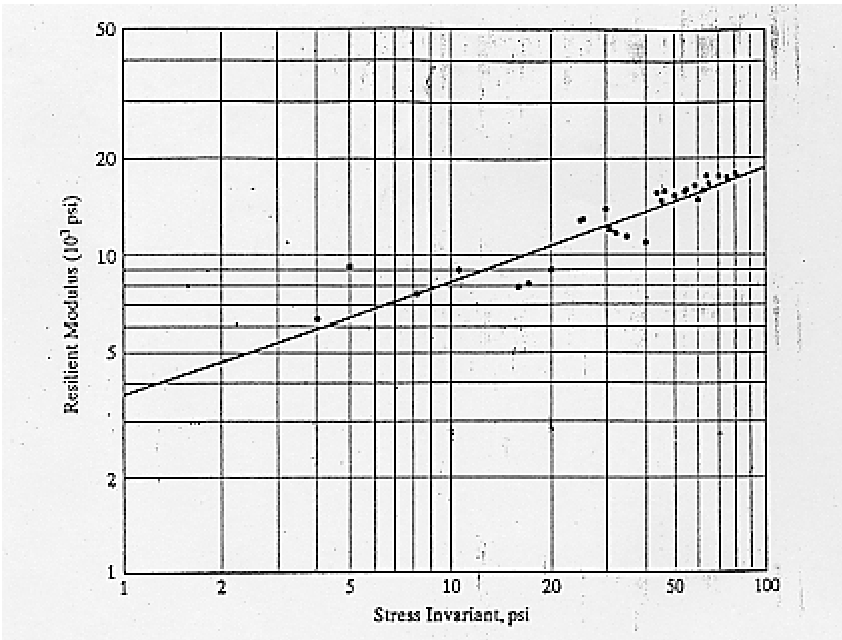


Figure 2.9 Sample relationship between Mr and θ [*Huang, 2004*]

Equation 2.6 can also be represented in non-dimensional form as follows;

$$Mr = (k1.Pa)\left(\frac{\theta}{Pa}\right)^{k2} \tag{2.7}$$

where, Pa is the reference pressure of 1 psi introduced to express the coefficients in non-dimensional form. This equation is generally known as widely used K-θ model and is supported by the data obtained from repeated load triaxial tests. The simplicity of the K- θ model has made it extremely useful and widely accepted for analysis of stress dependence of material stiffness [*Lekarp, Isaccson and Dawson, 2000*], [*Correia, Hornych and Akou*], [*Nataadmadja, 1992*]

Because the K- θ model is the most widely used model to characterize the stress dependent modulus behavior of granular materials, there exists lots of laboratory work and generated model parameters for different materials in the literature. Table 2.1 shows the ranges of nonlinear constants k1 and k2 for different granular materials generated after the investigations of different researchers.

Table 2.1 Ranges of k1 and k2 for untreated granular materials [*Asphalt Ins.,1982*]

Investigator(s)	Material	k1 (psi)	k2
Hicks (1970)	partially crushed gravel, crushed rock	1600 - 5000	0.57 - 0.73
Hicks and Finn (1970)	untreated base at San Diego Test Road	2100 - 5400	0.61
Allen (1973)	gravel, crushed Stone	1800 - 8000	0.32 - 0.70
Kalcheff and Hicks (1973)	crushed stone	4000 - 9000	0.46 - 0.64
Boyce, Brown and Pell (1976)	well-graded crushed limestone	8000	0.67
Monismith and Witczack (1980)	in service base and subbase materials	2900 - 7750	0.46 - 0.65

May and Witczack (1981) noted that the insitu resilient modulus of a granular layer is a function not only of the bulk stress but also of the deviator stress. Uzan (1985) included deviator stress into the K- θ model and expressed relationship as follows ;

$$Mr = k1\ (\theta)^{k2} (\sigma d)^{k3} \quad (2.8)$$

or in non-dimensional form;

$$Mr = (k1.Pa)\ (\frac{\theta}{Pa})^{k2} (\frac{\sigma d}{Pa})^{k3} \quad (2.9)$$

where ;

Mr = resilient modulus in psi

θ = first stress invariant (bulk stress) in psi = σ1+ σ2 + σ3 = σx+ σy + σz

σd = deviator stress = σ1 - σ3

Pa = reference pressure of 1 psi

In the three dimensional case, the deviator stress is replaced by the octahedral stress as follows;

$$Mr = (k1.Pa)\ (\frac{\theta}{Pa})^{k2} (\frac{\tau_{oct}}{Pa})^{k3} \quad (2.10)$$

Where, in general case ;

$$\tau_{oct} = \frac{1}{3}\sqrt{(\sigma 1 - \sigma 2)^2 + (\sigma 2 - \sigma 3)^2 + (\sigma 3 - \sigma 1)^2} \quad (2.11)$$

and in the triaxial case ;

$$\tau_{oct} = \frac{\sqrt{2}}{3}\,\sigma d \qquad (2.12)$$

Equation 2.10 is known as "universal materials model" for both granular and fine grained soils. When the material changes from granular to fine grained, coefficient k2 will approach to zero and the equation will reduce to a model for fine grained soils [*Bonaquist and Witczak, 1992*], [*Lekarp, Isaccson and Dawson, 2000*], [*Uzan, 1999*], [*Uzan, Witczak, Scullion and Lytton, 1992*].

CHAPTER 3

STRUCTURAL ANALYSIS OF PAVEMENTS

3.1 General

Structural models used for the analysis of pavement responses under traffic and environmental loads range in complexity from simple emprical techniques to more complicated models to describe the material properties and behavior of the materials realistically. The selection of the structural model depends on the ability of the designer to quantify the required material inputs and interpret the results of the models. Mainly there are two basic approaches for the structural analysis of pavements;

- Analytical or classical methods
- Numerical methods

Elastic layer theory is an example of the analytical approach. Finite difference method and finite element method are the examples of the numerical approach.

It is not possible to obtain analytical mathematical solutions for many engineering problems. An analytical solution is a mathematical expression that gives the values of the desired unknown quantity at any location in a body, and as a consequence it is valid for an infinite number of locations in the body [*Desai and Abel, 1972*]. Analytical solutions can only be obtained for certain simplified situations. For problems involving complex material properties and boundary conditions, designer should prefer numerical methods, that provide approximate but acceptable solutions. In most of the numerical methods, the solutions yield approximate values of the unknown quantities only at a discrete number of points in the body [*Desai and Abel, 1972*], [*Reddy, 1993*].

3.2 Elastic Layer Theory

Analysis of pavement structure by using elastic layer theory is widely used by designers because of its simplicity compared to numerical methods like finite element method. This analytical models are generally based on the Burmister's (1943) multi-layered elastic solutions. They are often referred to as mathematically excact solutions, where the fourth order differential equation is solved for the given boundary conditions using numerical integration [*AMADEUS Project, 2000*]. These models give the responses (stresses and strains) in any point of the pavement structure induced by the wheel load. Figure 3.1 illusturates the general concept of a multilayered elastic system.

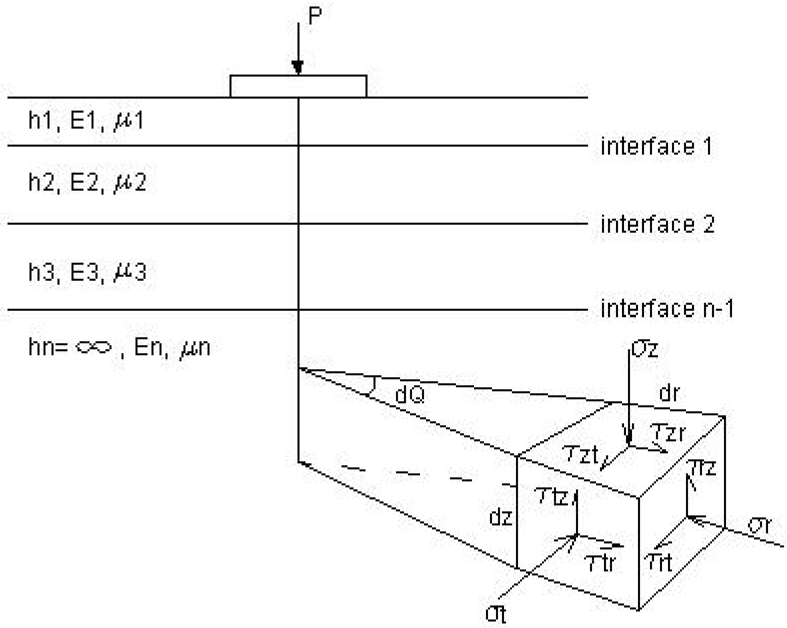


Figure 3.1 Generalized multi-layered elastic system [*Witczack and Yoder, 1975*]

This analytical solution based on the Burmister's multi-layered elastic theory has several assumptions:

- The material properties of each layer are homogeneous, that is, the property at point Ai is the same at point Bi.
- Each layer has a finite thickness except for the lowest layer, and all are infinite in lateral directions.
- Each layer is isotropic, that is, the property at a specific point such as Ai is the same in every direction and orientation.
- Full friction is developed between layers at each interface.
- Top surface of the system is free of shear.

- The stress solutions are characterized by two material properties for each layer which are poisson's ratio μ and the elastic modulus E [*Witczack and Yoder, 1975*].

From figure 3.1 it can be seen that at a given point within any layer, 9 stresses exist. These stresses are comprised of 3 normal stresses (σz,σr,σt) acting perpendicular to element face and 6 shearing stresses (τrt,τtr,τrz,τzr,τtz,τzt) acting parallel to the face. From equilibrium conditions; shear stresses acting on the intersecting faces are equal. Thus; τrt = τtr, τrz = τzr and τtz = τzt. at each point in the system, there exists a certain orientation of the element such that the shear stresses acting on the element such that shear stresses acting on the each face are zero. The normal stresses under this condition are defined as principal stresses and are denoted by σ1(major stress), σ2(intermediate) and σ3(minor stress). The bulk stress θ is defined as the sum of the principal stresses at a point. Given the triaxial state of stress of any element, the strains can be computed by the following equations;

$$\varepsilon z = \frac{1}{E}[\sigma z - \mu\ (\sigma r + \sigma t)] \tag{3.1}$$

$$\varepsilon r = \frac{1}{E}[\sigma r - \mu\ (\sigma t + \sigma z)] \tag{3.2}$$

$$\varepsilon t = \frac{1}{E}[\sigma t - \mu\ (\sigma r + \sigma z)] \tag{3.3}$$

Various computer programs based on Burmister's layered theory have been developed. CHEVRON (Chevron Research Company), BISAR (Shell) and ELSYM5 (University of California, Berkeley) softwares are the well known and widely used programs based on this approach.

3.3 Finite Element Method

The use of finite element method has been increasing with the availability of high-speed computers and the growing emphasis on numerical methods for engineering analysis. The method was first developed in 1956 for the analysis of aircraft structural problems. Although the method was originally developed for structural analysis, the general nature of the theory on which it is based has also made possible its successful application for solutions of problems in other fields of engineering [*Desai and Abel, 1972*], [*Rao, 1982*], [*Reddy, 1993*].

As explained earlier, in most of the numerical methods, the solutions yield approximate values of the unknown quantities only at a discrete number of points in the body. The process of selecting only a certain number of discrete poins in the body is known as "discretization". In finite element method, discretization of a body or a structure is achieved by dividing it into an equivalent system of smaller bodies. The assemblage of such units then represents the original structure. Instead of solving the problem for the entire body in one operation, the solutions are formulated for each constituent unit and combined to obtain the solution for the original body (see fig. 3.2). This approach is known as "going from part to whole" which is the basic principle of the finite element method. Although the analysis procedure is thereby considerably simplified, the amount of data to be handled is dependent upon the number of smaller bodies into which the original structure is divided. For large number of subdivisions, it is difficult to handle the volume of data manually, and automatic electronic calculations by using computers are needed [*Desai and Abel, 1972*], [*Rao, 1982*].

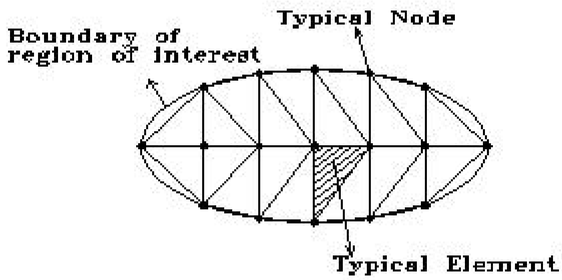


Figure 3.2 Two-dimensional region represented as an assemblage of triangular elements [*Desai and Abel, 1972*].

One of the main reasons for the popularity of the method in different fields of engineering is that once a general computer program is written, it can be used for the solution of any problem simply by changing the input data. This systematic generality of the finite element procedure makes it a powerful and versatile tool for a wide range of problems. As a result of this, flexible general purpose computer programs have been constructed. Primary examples of these programs are the several structural analysis packages, which include a variety of element configurations and which can be applied to several categories of structural problems. Two examples of these packages are SAP (Structural Analysis Program, Professor E.L. Wilson, University of California, Berkeley), and NASTRAN (NASA Structural Analysis, U.S. National Aeronautics and Space Administration) [*Desai and Abel, 1972*], [*Reddy, 1993*]. The general structure of finite element technique based program involves the following modules ;

- Module to enter data (Preprocessing).
- Module to perform analysis (Processing).
- Module to interpret and display the result (Post Processing)

The preprocessing step must accomplish the following functions ;

- Description of geometry (node coordinates, element connectivity, etc.).
- Description of material properties (poisson's ratio, density, elastic modulus).
- Mesh generation
- Load definition and boundary condition

The post-processor describes the results of variables computed at the various nodes of the structure and involves the following ;

- Nodal displacement values
- Elemental stress values
- Reactions at constrained nodes
- Graphical display of displacements
- Graphical display of stress contours

CHAPTER 4

KENLAYER COMPUTER PROGRAM

4.1 General

KENLAYER is a computer program developed at University of Kentucky and used for the solution of an elastic multi-layered system under a circular loaded area. Its calculation principle is based on the Burmister's multi-layered elastic theory similar to other programs based on the analythical method. Solutions are superimposed for multiple wheels like dual or dual tandem wheels. The superiority of KENLAYER over the other elastic layer programs is its capability of solving systems either linear-elastic, nonlinear-elastic or viscoelastic [*Huang, 2004*]. Program also performs damage analysis to evaluate the design life considering the damage caused by fatigue cracking and permanent deformation by using basic expressions given in equations 1.1 and 1.2.

4.2 Program Description

The four seperate computer programs LAYERINP, KENLAYER, SLABSINP and KENSLABS (for rigid pavements), together with some other graphics programs are combined to form a new software called KENPAVE. This program has been developed at University of Kentucky and was written in Visual Basic. It can be run on computers with Windows 95 or higher. Figure 4.1 shows the main screen of KENPAVE, consisting of two input boxes at the top and 11 command windows at the bottom. The left three buttons are used for flexible pavements, the right five for rigid pavements, and the remaining three for general purposes.

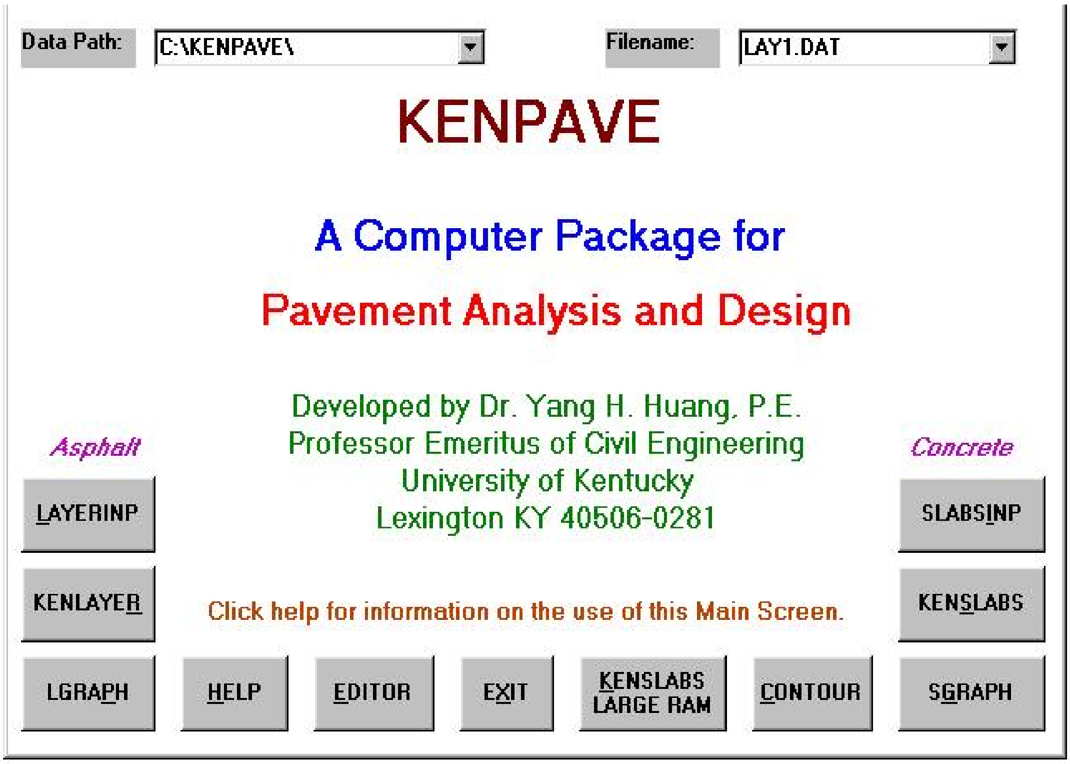


Figure 4.1 Main screen of KENPAVE

Because the subject of this thesis is directly related to the non-linear resilient behavior of unbound granular materials used in flexible pavement systems as base courses, further information about visco-elastic analysis of asphaltic concrete layer or KENSLABS computer program for analysis of rigid pavement systems are not given for brevity. The main interest of this work is the non-linear analysis option of KENLAYER program used for flexible pavement systems. Therefore it is necessary to give extra information for this software.

As explained earlier, KENLAYER, together with input program LAYERINP and graphic program LGRAPH, is part of a computer package called KENPAVE. In its present dimensions, it can be applied to a maximum of 19 layers with output at 25 different radial coordinates and 19 different vertical coordinates, or a total of 475 points. To facilate entering and editing data, a program named LAYERINP is used. The program uses menus and forms for data entry in order to create and edit the data file. Although the large number of input parameters appears overwhelming, default values are provided to many of them, so only a limited number of inputs will be required [*Huang, 2004*].

4.3 Non-linear Analysis Using Kenlayer

It is well known that granular materials and subgrade soils have non-linear resilient behavior varying with the level of stresses. The resilient modulus of granular materials increases with the increase in stress intensity. If the relationship between the resilient modulus and the state of stresses is given (see section 2.4.2), a method of succesive approximations can be used [*Akou, Heck, Kazai, Hornych, Odeon and Piau*], [*Huang, 2004*].

A major disadvantage of the layered elastic theory is the assumption that each layer is homogeneous with the same properties throughout the layer. This assumption makes it difficult to analyze layered systems composed of non-linear materials like untreated granular bases and subbases. The resilient modulus of these materials is stress dependent and varies throughout the layer. In order to consider this behavior of granular materials into the analysis phase, developers of KENLAYER have included the non-linear analysis module for stress dependent materials. This approach can briefly be explained by this simple flowchart ;

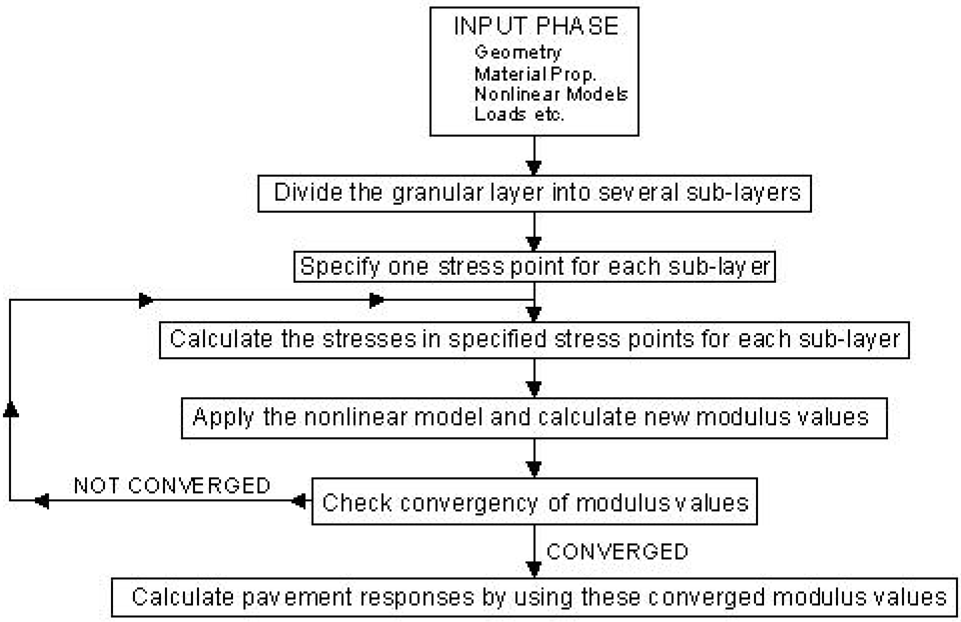


Figure 4.2 Steps of iterative approximation included in KENLAYER

Model employed in KENLAYER is the commonly used K- θ model (eq. 2.6) and model parameters k1 and k2 are defined in input stage for each sub-layer. User can define maximum of 12 non-linear layers in KENLAYER. As explained earlier, the elastic modulus of each non-linear layer is determined from the stresses at a designated point. Then, the question immediately arises; "Which point in the non-linear layer should be selected to represent the entire layer?". If only the most critical stress, strain or displacement is desired, as is usually in pavement design, a point near to the applied load can be reasonably selected [*Huang, 2004*]. In this study, because the responses are calculated under a single wheel load, points just at the mid-depths of each sub-layer along the centerline of the circular loading are selected as stress points. Figure 4.2 shows the graphical representation of this type of analysis.

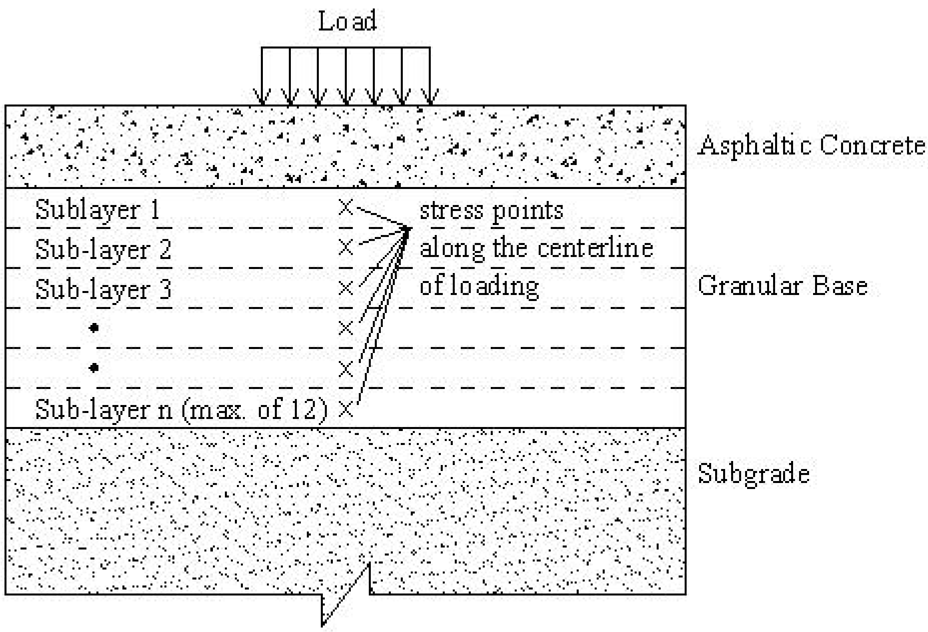


Figure 4.3 Principle of the simplified iterative approach used in KENLAYER

This simplified approach for modelling the stress dependent characteristics of granular materials does not realistically represents the actual in-situ behavior of the material. Because KENLAYER is a program based on the layered elastic theory, modulus values of each sub-layer are still assumed to be constant throughout the layers, but in reality, resilient modulus varies with the state of stresses and changes from point to point within a granular layer. Therefore, in order to represent the actual behavior of granular materials under load conditions, variation of resilient modulus along the radial direction should also be taken into account in addition to variation along the vertical direction. As explained earlier, this type of analysis can be performed by using finite element technique where material parameters can be defined separately for each element.

It is well known that granular materials can not carry tensile stress. But when they are used as base or subbase course on a weaker subgrade, the horizontal stresses due to applied loads are most likely come out to be in tension. However, these materials can still take tension if the tension is smaller than the precompression caused by geostatic or other in situ stresses. The resilient modulus of granular materials depends not on the stress resulting from loading alone but on the combination of the loading stress and precompression. The combined horizontal stress can not become negative, (KENLAYER uses the soil mechanics sign convention where θ is positive in compression and negative in tension) because, when it is reduced to zero, the particles separate and no stress will exist. Therefore, after the granular layer is subdivided into a number of layers and the stresses at the mid-depth of each layer are calculated, if the horizontal stress including the geostatic stress is negative or in tension, it is set to zero. This stress modification is necessary to avoid negative θ. Therefore the stress invariant which is previously defined as the sum of three normal stresses should be modified by including the self-weight of a layered system [*Huang, 2004*]. That gives ;

$$\theta = \sigma_x + \sigma_y + \sigma_z + \gamma \; z\,(1+2\,K_0) \tag{4.1}$$

in which γ is the unit weight, z is the distance below surface at which the modulus is to be determined, and K_0 is the coefficient of earth pressure at rest which is defined as;

$$K0 = \frac{\mu}{1-\mu} \tag{4.2}$$

where μ is the poisson's ratio [*Craig, 1992*], [*Uzuner, 1998*].

Example formats of input and output files of the software KENLAYER are given in Appendices.

CHAPTER 5

SAP90 COMPUTER PROGRAM

5.1 General

In this study, non-linear resilient behavior of unbound granular materials are also modelled by using the finite element method. Calculations are performed by the special computer program named as SAP90 which is in the generation of SAP series of programs developed at the University of California, Berkeley.

Over the past 30 years, the SAP series of computer programs have established a worldwide reputation in the areas of structural engineering and structural mechanics. First SAP program was released in 1970. In following years, further research and development in the area of finite element formulation and numerical solution techniques resulted in the release of a series of SAP programs.

5.2 SAP90 Computer Program

Finite element method based SAP90 computer program has static and dynamic analysis options. These options may be achieved together in the same run. Automatic generation options are available for convenience. Undeformed and deformed shape plotting capabilities exist for data verification of the nodal geometry and for studying the structural behavior of the system. The finite element library of SAP90 consists of four elements, a three dimensional FRAME element, a three-dimensional SHELL element, a two dimensional ASOLID element and a three-dimensional SOLID element. The two dimensional frame, truss, membrane, plate bending, axisymmetric and plane strain elements are all available as subsets of these elements. There is no restriction on combining element types within a particular model. Loading options allow for gravity, thermal and prestress conditions in addition to the usual nodal loading with specified forces [*Habibullah and Wilson*].

5.3 Sap90 Terminology

Data preparation for a structural analysis problem basically involves the following steps:

- Description of the geometry of the structure.
- Description of the material and section properties of the members.
- Definition of the load conditions.

The basic geometric dimensions of the structure are established by placing joints or nodes on the structure. Each joint is given a unique identification number and is located in space with coordinates that are associated with a global three dimensional coordinate system. The structural geometry is completed by connecting the predefined joints with structural elements with specific types, namely: beams, trusses, shells, etc. Similar to joints, each element is assigned a unique identification number [*Habibullah and Wilson*].

Some of the factors that should be considered in generating finite element model of a structure by using SAP90 program are listed below.

- The number of joints should be sufficient to describe the geometry of the structure.
- Joints and element boundaries must be located at points, lines and surfaces of discontinuity, at changes in material properties, section properties, etc.
- Joints should be located at points on the structure where displacements are to be evaluated.
- Joints should be located at all support points. Support conditions are defined in the structure by restricting the movement and/or rotation of the specific joints in specific directions.
- Joints should be defined where concentrated loads are applied.
- Finite element mesh should be refined enough by using small elements and closely spaced joints to capture stress intensities and displacement variations in regions of interest. This may require changing the mesh after a preliminary analysis [*Habibullah and Wilson*].

As a result; in order to prepare a finite element model, system dimensions, mesh, boundary conditions, material properties, element types representing the materials and loading conditions must be determined. After the formation of the model, preliminary analyses are performed to see the behavior of the system and to verify the results. Convergency and verification studies are the two types of methods which can be used in the preliminary analysis phase. Verification study requires the results generated from exact methods solving the system. Depending on these results, selected mesh may be modified to increase the accuracy. In convergency study, the real behavior of the system is not known. Results obtained from each run are examined and after an acceptable convergency in the results is observed, proper mesh dimension is selected. Definition of finite element mesh is very important stage of finite element analysis. This subdivision process is esentially an exercise of engineering judgment. Analyst has to decide on the number, shape, size and configuration of the elements in such a way that the original body is simulated as closely as possible. At the same time, it should be noted that too fine a subdivision will lead to extra computational effort [*Desai and Abel, 1972*].

CHAPTER 6

ANALYSIS OF PAVEMENTS BY USING SAP90

6.1 General

As explained in Chapter 3, one way of performing structural analysis of flexible pavement is the finite element method. Despite its complexity compared to elastic layer theory, analysis of pavement structures having complex tire contact stresses and virtually any geometric condition, including discontinuities, can only be achieved by using finite element method.

6.2 Sap90 Program Model

In the computer model, the pavement structure is approximated as the axisymmetric solid of revolution [*Habibullah and Wilson*]. It is very important that axisymmetric solid of revolution modelling is valid provided that there exists the symmetry of the problem. Therefore when the system symmetry is disturbed by the introduction of any local change, such as additional loads, cracks or changes in the layer thickness in specific location etc., axisymmetric solid of revolution modelling can not be applied.

In axisymmetrical modelling, the displacements are confined to only two directions, axial and radial. Problem is solved in cylindrical coordinate system and analysis is performed in one-radian segment of the system. Element used in SAP90 model is in the nine-node quadrilateral form. Stress resultants are given for the each joint constituting each element. Loads are defined in the joints corresponding to loaded area. The inside nodes has the tributary area width of two times corner nodes [*Habibullah and Wilson*]. Hence, load intensities at joints are calculated depending on the tributary areas of the nodes within the radius of the loaded area. In figure 6.1, pavement structure with a single, circular uniformly distributed load represented in cylindrical coordinate system is shown.

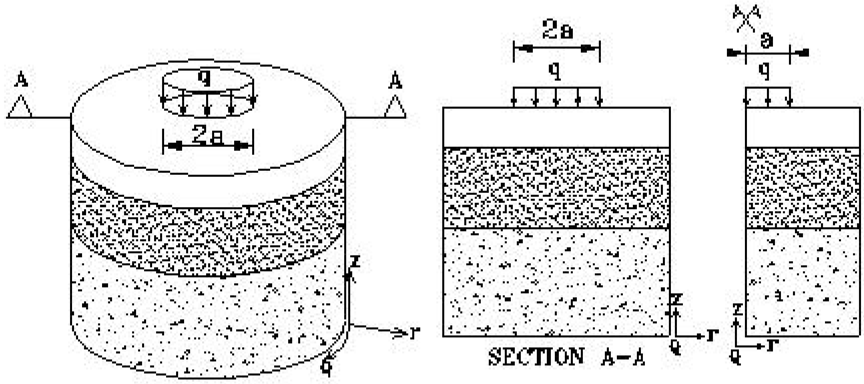


Figure 6.1 Pavement structure in a cylindrical coordinate system

The axisymmetric SAP90 model of a structure with a uniformly distributed circular load is shown in figure 6.2.

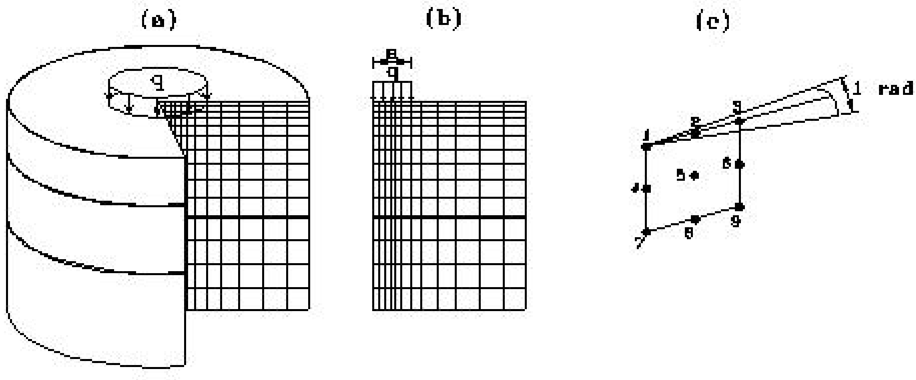


Figure 6.2 Axisymmetric model of pavement structure

a) Structure in cylindrical coordinate system b) Program model c) Nine-node quadrilateral elements forming the system

6.3 Sap90 Input File

SAP90 input file is composed of different data blocks. Each data block starts with a command line which represents the unique identifier for single block and continues until a new command representing a new data block. All required inputs for each block are given in lines following the command line that defining the data block. All SAP90 input data is prepared in free format, therefore, data blocks do not have to be in sequence. Any line (except the first line) having the letter C in column1 and a blank column2, is treated as a comment line and is ignored by the program. In order to generate a flexible pavement model as shown in figure 6.2, the required data blocks are as follows :

1) TITLE LINE
2) SYSTEM
3) JOINTS
4) RESTRAINTS
5) ASOLID
6) LOADS

TITLE LINE must be the first line in the input data and it can be prepared up to 70 characters for output labeling. This line is compulsory for every input file. In the SYSTEM data block, basic informations about analysis are given. This data block is also compulsory for every input file similar to TITLE LINE. In the JOINTS data block, the mesh of joints defining the pavement system is given. Boundary conditions of the system by means of joint restraints are given in the RESTRAINTS data block. Elements representing the materials are input in the ASOLID block. Finally the joint loads are given in the LOADS data block.

6.4 Sap90 Output Files

After the analysis, SAP90 produce various output files. The most important ones are the output files related to stresses and displacements after the ASOLID analysis of flexible pavement model. The file having an extension of SOL gives the radial and axial displacement values for each joint in the finite element mesh. In the output file with an extension of F5F, normal and principal stresses for the nodal points of the each element are given. Example formats of input file and created output files with extensions of SOL and F5f are given in Appendices.

CHAPTER 7

COMPUTER ANALYSES

7.1 General

In order to investigate the effects of non-linear resilient behavior of unbound granular materials on critical flexible pavement responses, three types of analyses have been performed on 24 different pavement structures. These analyses are ;

1) Linear elastic analysis by using KENLAYER computer program.
2) Non-linear analysis by using KENLAYER's simplified iterative approach by dividing granular layer into several sub-layers and by applying the previously defined K-θ model for the material.
3) Non-linear analysis by using finite element method. Similar iterative technique has been performed by using SAP90 computer program but variation of resilient modulus values are taken into account in both vertical and radial directions within a layer. This type of analysis better approximates the actual in-situ behavior of unbound granular material and gives more realistic results compared to other two type of analysis. Illustrations of these three type of analysis are shown in figures 7.1, 7.2 and 7.3 respectively.

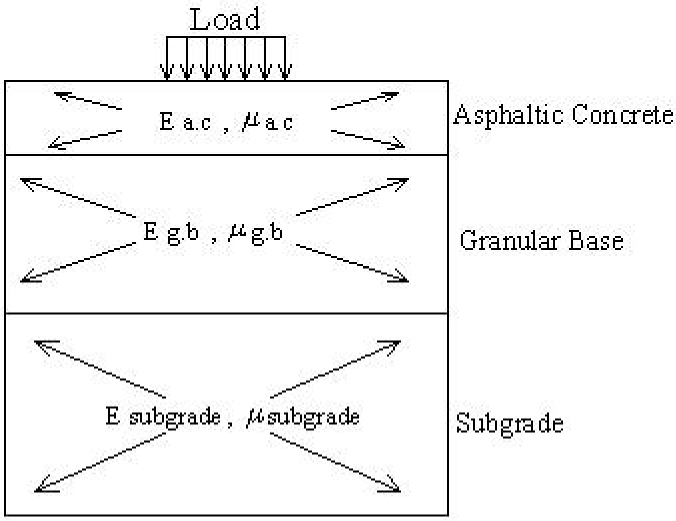


Figure 7.1 Illustration of linear-elastic analysis performed by using KENLAYER

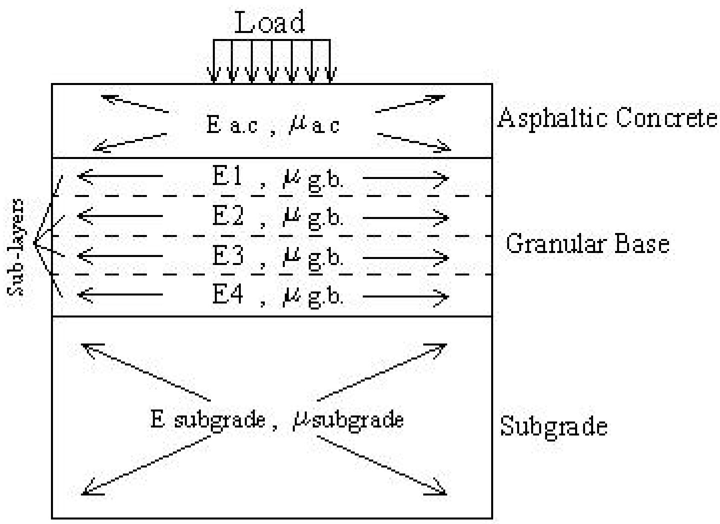


Figure 7.2 Illustration of non-linear analysis performed by using KENLAYER

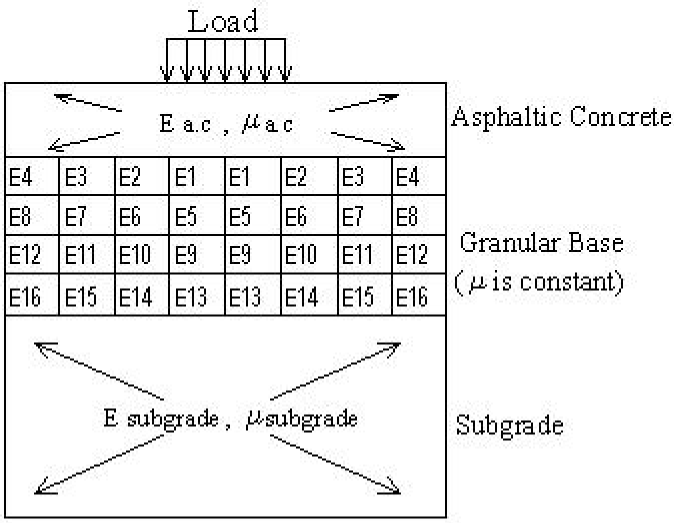


Figure 7.3 Illustration of non-linear analysis performed by using SAP90

7.2 Variables Used in The Analyses

In order to investigate the effects of stress dependent behavior of granular materials on the behavior of flexible pavement system and the reliability of selected analysis technique used for determination of critical pavement responses, 24 different three-layered flexible pavement systems with unbound granular base courses have been analysed. As explained earlier, critical responses for the flexible pavement system are the tensile strain at the bottom of the asphaltic concrete layer and the compressive strain at the top of the subgrade layer which are then used for the prediction of life. Therefore, calculations of these two types of strains should be correctly achieved in order to predict the pavement performace realistically.

As mentioned earlier ; in the design of flexible pavements especially with a limited thickness of bituminous materials (less than about 15 centimeters) and a granular base, the nonlinear behavior of unbound granular materials has to be taken into account. Therefore in this study, the thickness of the asphaltic concrete layer is taken as 4 inches to observe the differences between predicted responses generated from 3 different types of analyses explained above. Circular load used in calculations is 4500 lbs single wheel load with 80 psi tire pressure.

For asphaltic concrete course, which is considered to be linear elastic material with constant thickness of 4 inches, three different elastic modulus values of 300000 psi, 500000 psi and 700000 psi are used in analyses. Poisson's ratio for asphaltic concrete layer is assumed to be 0.35. This value is taken from table 7.1 which shows the recommended values of poisson's ratio for different pavement materials. These modulus values and poisson's ratios are considered to be constant throughout the layer.

Table 7.1 Recommended values of Poisson's ratio for different pavement materials. [*Pavement Design- Lecture Notes*]

MATERIAL TYPE	Range of Poisson's Ratio	Recommended Value
Portland cement concrete	0.15 ~ 0.20	0.15
Asphaltic concrete	0.25 ~ 0.35	0.35
Cement stabilized base	0.20 ~ 0.30	0.30
Asphalt stabilized base	0.25 ~ 0.35	0.35
Unbound granular base	0.20 ~ 0.50	0.40
Granular subgrade	0.30 ~ 0.50	0.45
Clayey or silty subgrades	0.40 ~ 0.50	0.40

For granular base layer which is modelled as non-linear elastic material, variables used in analyses are the thickness of the granular layer and the material used as a base course. Two different thickness values (12 inches and 16 inches) and two different material types (crushed stone and sand-gravel) are used in calculations. Poisson's ratio for granular base course is taken as 0.40 (from table 7.1) and assumed to be constant throughout the layer. K-θ model parameters (see eq. 2.6) for these two types of granular materials generated after the repeated load triaxial test results and their CBR values are tabulated in table 7.2.

Table 7.2 K-θ model parameters and CBR values of two different granular materials used in analyses [*Rada and Witczak, 1981*].

Granular Material	**Model parameters**		**CBR**
	k1	**k2**	**%**
Crushed stone	7210	0.45	90
Sand-gravel	4480	0.53	60

In all models, thickness of the subgrade is fixed as semi-infinite. In the models, two different elastic modulus values are used for subgrade layer which are 5000 psi and 10000 psi. Poisson's ratio used for the subgrade is 0.45 and assumed to be constant throughout the layer similar to the other layers. The consideration of subgrade as linear-elastic material is a reasonable approximation because the variation of modulus due to the change of subgrade stresses is usually quite small and a reasonable subgrade modulus can be assumed [*Huang, 2004*]. In table 7.3, 24 different pavement system identifications and variables used in the analyses are tabulated. Also in figure 7.4, schematic view of variables are shown.

Table 7.3 Pavement system identifications and variables used in analyses

Pavement	Asphaltic Concrete					Subgrade					Granular Base						
System Code	h (inches)	Modulus (psi)	Unit Weight (pcf)	Poisson's Ratio	ko	h (inches)	Modulus (psi)	Unit Weight (pcf)	Poisson's Ratio	ko	h (inches)	Unit Weight (pcf)	Poisson's Ratio	ko	Material	k1	k2
p01	4	300000	139.97	0.35	0.54	semi-inf	5000	125.00	0.45	0.82	12	133.06	0.40	0.67	Crushed Stone	7210	0.45
p02	4	500000	139.97	0.35	0.54	semi-inf	5000	125.00	0.45	0.82	12	133.06	0.40	0.67	Crushed Stone	7210	0.45
p03	4	700000	139.97	0.35	0.54	semi-inf	5000	125.00	0.45	0.82	12	133.06	0.40	0.67	Crushed Stone	7210	0.45
p04	4	300000	139.97	0.35	0.54	semi-inf	10000	125.00	0.45	0.82	12	133.06	0.40	0.67	Crushed Stone	7210	0.45
p05	4	500000	139.97	0.35	0.54	semi-inf	10000	125.00	0.45	0.82	12	133.06	0.40	0.67	Crushed Stone	7210	0.45
p06	4	700000	139.97	0.35	0.54	semi-inf	10000	125.00	0.45	0.82	12	133.06	0.40	0.67	Crushed Stone	7210	0.45
p07	4	300000	139.97	0.35	0.54	semi-inf	5000	125.00	0.45	0.82	12	133.06	0.40	0.67	Sand-Gravel	4480	0.53
p08	4	500000	139.97	0.35	0.54	semi-inf	5000	125.00	0.45	0.82	12	133.06	0.40	0.67	Sand-Gravel	4480	0.53
p09	4	700000	139.97	0.35	0.54	semi-inf	5000	125.00	0.45	0.82	12	133.06	0.40	0.67	Sand-Gravel	4480	0.53
p10	4	300000	139.97	0.35	0.54	semi-inf	10000	125.00	0.45	0.82	12	133.06	0.40	0.67	Sand-Gravel	4480	0.53
p11	4	500000	139.97	0.35	0.54	semi-inf	10000	125.00	0.45	0.82	12	133.06	0.40	0.67	Sand-Gravel	4480	0.53
p12	4	700000	139.97	0.35	0.54	semi-inf	10000	125.00	0.45	0.82	12	133.06	0.40	0.67	Sand-Gravel	4480	0.53
p13	4	300000	139.97	0.35	0.54	semi-inf	5000	125.00	0.45	0.82	16	133.06	0.40	0.67	Crushed Stone	7210	0.45
p14	4	500000	139.97	0.35	0.54	semi-inf	5000	125.00	0.45	0.82	16	133.06	0.40	0.67	Crushed Stone	7210	0.45
p15	4	700000	139.97	0.35	0.54	semi-inf	5000	125.00	0.45	0.82	16	133.06	0.40	0.67	Crushed Stone	7210	0.45
p16	4	300000	139.97	0.35	0.54	semi-inf	10000	125.00	0.45	0.82	16	133.06	0.40	0.67	Crushed Stone	7210	0.45
p17	4	500000	139.97	0.35	0.54	semi-inf	10000	125.00	0.45	0.82	16	133.06	0.40	0.67	Crushed Stone	7210	0.45
p18	4	700000	139.97	0.35	0.54	semi-inf	10000	125.00	0.45	0.82	16	133.06	0.40	0.67	Crushed Stone	7210	0.45
p19	4	300000	139.97	0.35	0.54	semi-inf	5000	125.00	0.45	0.82	16	133.06	0.40	0.67	Sand-Gravel	4480	0.53
p20	4	500000	139.97	0.35	0.54	semi-inf	5000	125.00	0.45	0.82	16	133.06	0.40	0.67	Sand-Gravel	4480	0.53
p21	4	700000	139.97	0.35	0.54	semi-inf	5000	125.00	0.45	0.82	16	133.06	0.40	0.67	Sand-Gravel	4480	0.53
p22	4	300000	139.97	0.35	0.54	semi-inf	10000	125.00	0.45	0.82	16	133.06	0.40	0.67	Sand-Gravel	4480	0.53
p23	4	500000	139.97	0.35	0.54	semi-inf	10000	125.00	0.45	0.82	16	133.06	0.40	0.67	Sand-Gravel	4480	0.53
p24	4	700000	139.97	0.35	0.54	semi-inf	10000	125.00	0.45	0.82	16	133.06	0.40	0.67	Sand-Gravel	4480	0.53

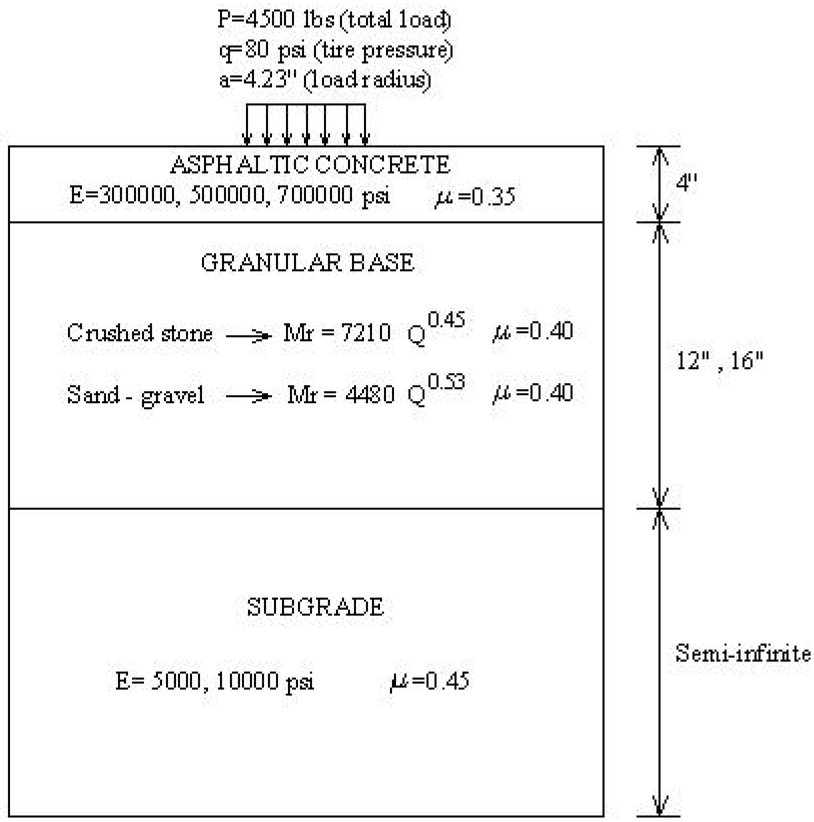
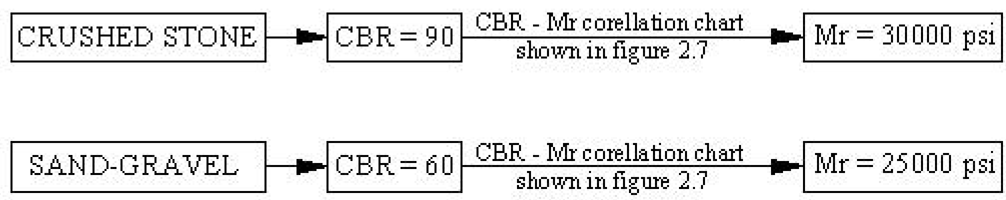


Figure 7.4 Schematic view of constants and variables used in analysis of three-layer flexible pavement system

7.3 Linear Elastic Analysis by Using KENLAYER

KENLAYER program uses the multi-layered elastic theory. The basic assumption for linear elastic analysis is that elastic modulus values and poisson's ratios are assumed to be constant throughout the layer. Because the asphaltic concrete layer and the subgrade are modelled as linear elastic materials in this work, the only problem becomes selection of approximate moduli for granular base layer which actually represents non-linear behavior. For the determination of approximate elastic modulus values of these two different granular materials (crushed stone and sand-gravel) which will be used as input parameters for KENLAYER linear elastic solutions, previously defined CBR-Mr relationships can be used. If CBR-Mr correlation chart given in figure 2.7 is used to determine the modulus values of these two different granular base materials, estimated values become ;



7.4 Non-linear Elastic Analysis by Using KENLAYER

As mentioned earlier, the KENLAYER computer program also has the capability of solving flexible pavement systems including unbound granular base and/or subbase courses which actually represent the stress dependent resilient characteristics. This non-linear analysis option is originally based on simple iterative procedure previously explained in Section 4.3. K-θ model parameters (k1 and k2) of two different granular base materials (crushed stone and sand-gravel) are defined into the program in input stage. Because the KENLAYER program can solve systems having up to 12 non-linear layers in order to increase the sensitivity of the analyses, granular base layers (with the thicknesses of 12 inches and 16 inches) are divided into 12 sub-layers having equal thicknesses. Stress points for each sub-layer are defined as the points placed under the centerline of loading at the mid-depth of each sub-layer (see figure 4.2). Calculations are performed by assuming that each sub-layer has constant elastic modulus and poisson's ratio which is not the realistic representation of in-situ behavior of unbound granular materials. Therefore in order to generate more accurate model which better represents the actual behavior of granular material, variations of modulus values in radial direction should be implemented into the analysis and this type of modelling can be achieved by using finite element method.

7.5 Non-linear Elastic Analysis by Using SAP90

Axisymmetric solid analysis is performed because of the symmetry of the structure. Therefore, problem is solved in cylindrical coordinate system and the analysis is performed in one-radian segment of the system. Elements used in the model are in nine-node quadrilateral form. Adequate finite element mesh is decided after the verification study by comparing the results generated from both linear elastic analysis (KENLAYER) and the finite element method (SAP90) for different sample pavement structures. Basic representation of SAP90 computer model of the system is represented in figure 7.5. The nodal points under the centerline of loading are restricted to move in radial direction because of the symmetry of the system. Nodal points on the bottom boundary are fixed that means they can note move or rotate in any direction. The mesh of nodes defining the structure is finer under the loaded area and becomes coarser as moving away from the load because the critical response values are calculated near the loaded area and more sensitive analysis should be achieved in this region.

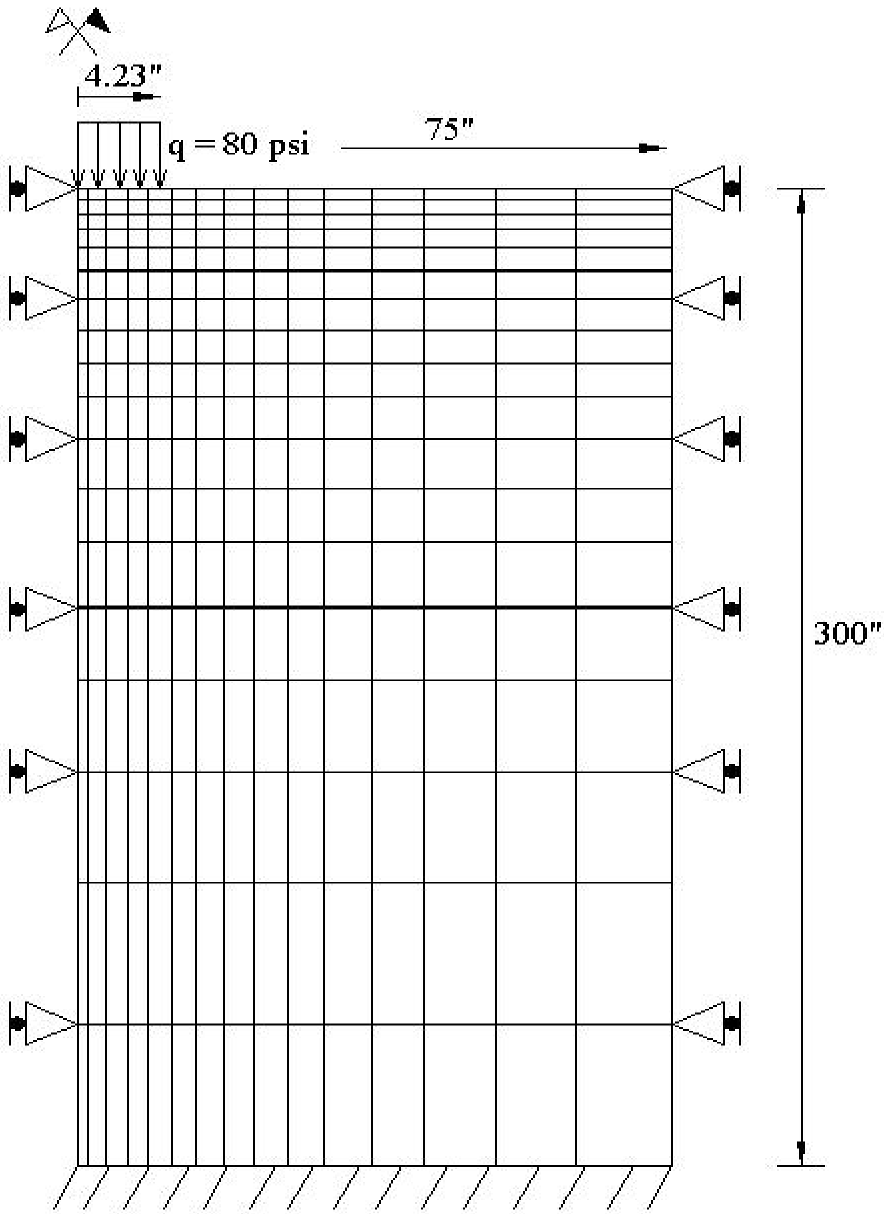


Figure 7.5 Schematic representation of SAP90 computer model of the system

In the SAP90 model, 5217 joints and 1265 nine-node quadrilateral elements are defined for the finite element mesh in order to get acceptable response values compared to results obtained from elastic layer theory. Because two different thickness values for granular base course are used in the analyses (12 inches and 16 inches), there exist two types of structural geometry of the structure. In figures 7.6 and 7.7 joint and element numbering of these two systems are shown.

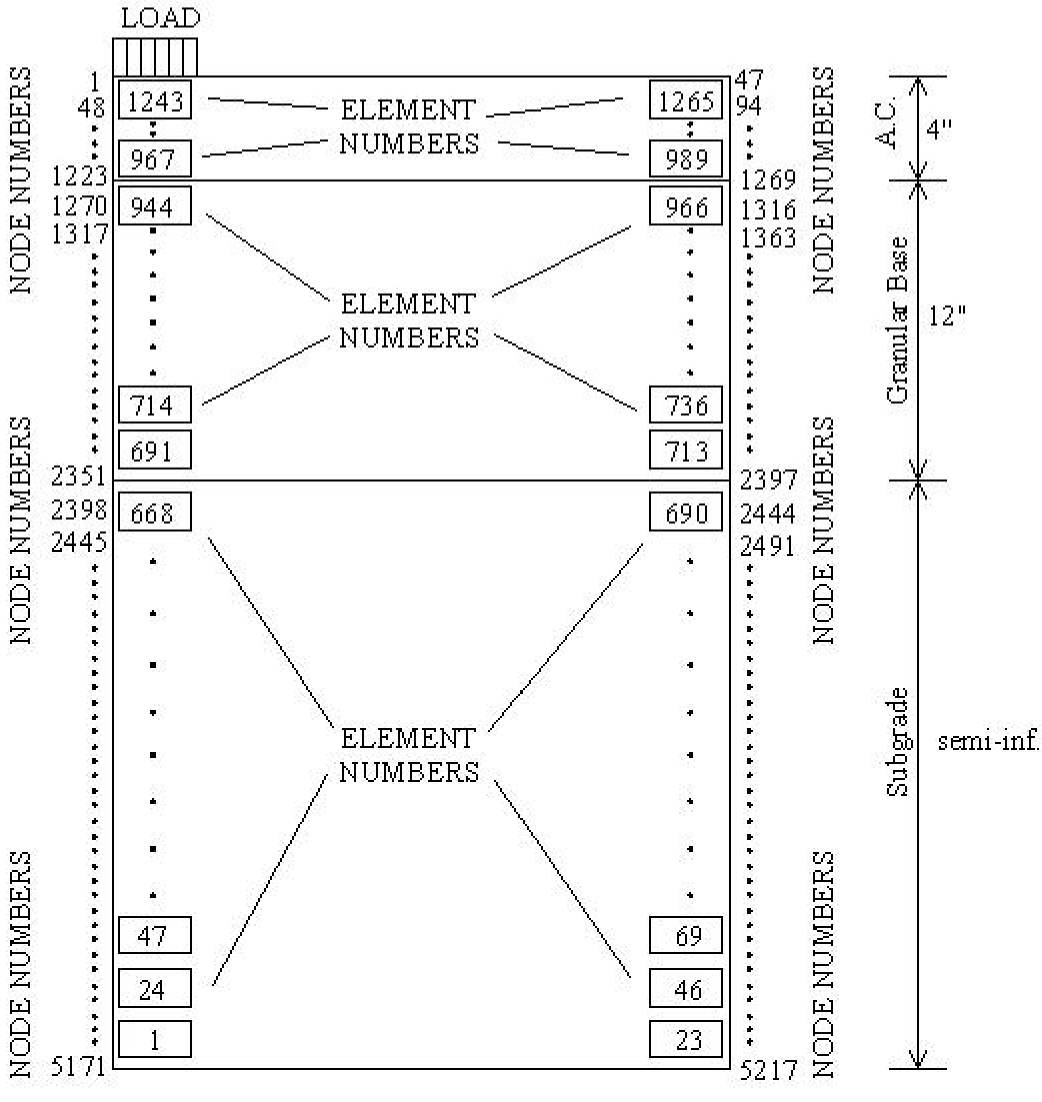


Figure 7.6 Joint and element numbering scheme for pavements having granular base thickness of 12 inches

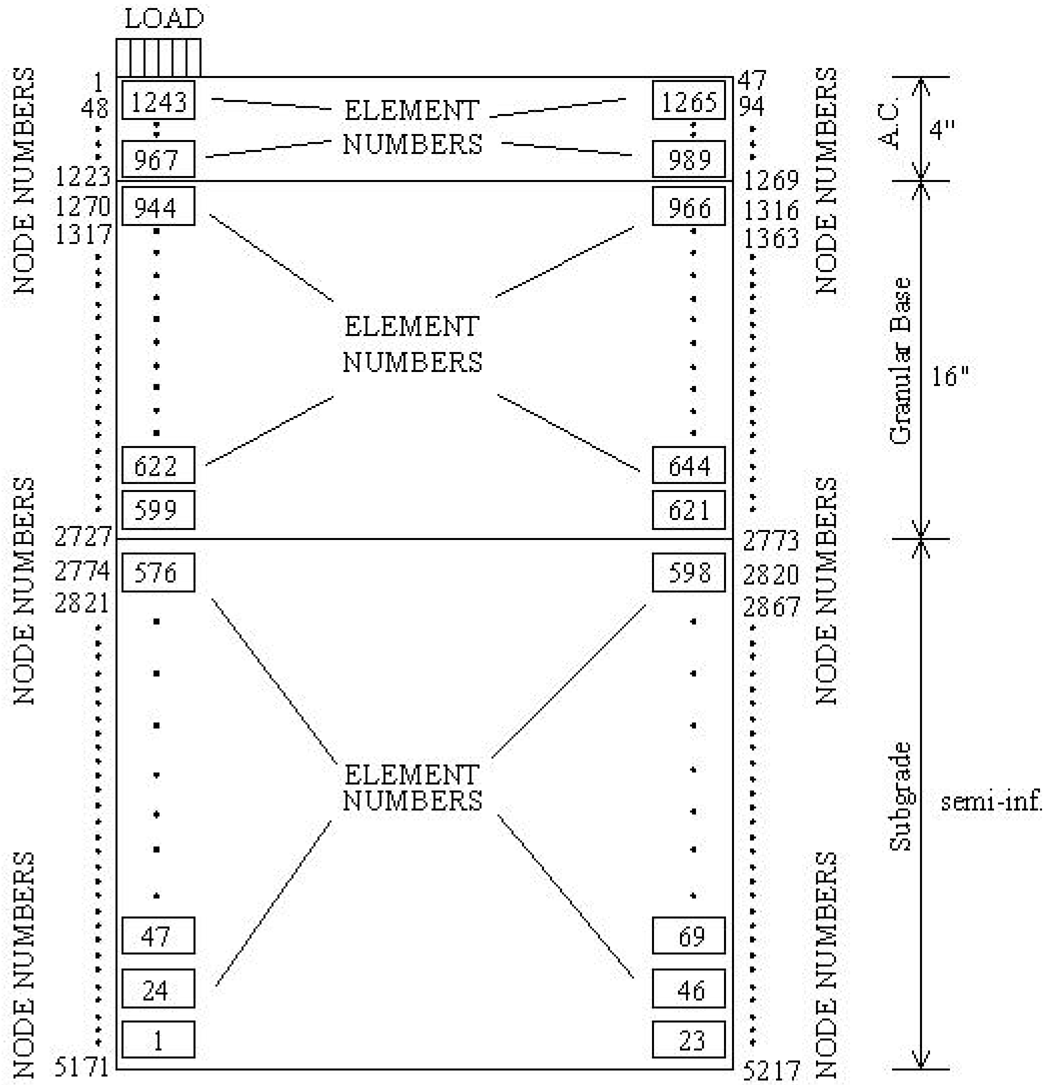


Figure 7.7 Joint and element numbering scheme for pavements having granular base thickness of 16 inches

In tables 7.4 and 7.5, radial and axial coordinates of finite element mesh are shown respectively. By using these coordinates, mesh used in this work can be easily created.

Table 7.4 Radial coordinates of finite element mesh along the surface

SAP90 Node Number	Distance from centerline
	(inches)
1	0.00
3	0.05
5	0.10
7	0.15
9	0.35
11	0.55
13	0.75
15	1.15
17	1.55
19	1.95
21	2.75
23	3.55
25	4.23
27	5.08
29	5.98
31	7.00
33	9.00
35	11.00
37	15.00
39	25.00
41	35.00
43	45.00
45	60.00
47	75.00

Table 7.5 Axial coordinates of finite element mesh along the load centerline

SAP90 Node Number	Depth from surface
	(inches)
1	0.00
95	0.05
189	0.10
283	0.20
377	0.30
471	0.40
565	0.60
659	0.80
753	1.00
847	1.50
941	2.00
1035	2.50
1129	3.00
1223	4.00
1317	5.00
1411	6.00
1505	7.00
1599	8.00
1693	9.00
1787	10.00
1881	11.00
1975	12.00
2069	13.00
2163	14.00
2257	15.00
2351	16.00
2445	17.00
2539	18.00
2633	19.00
2727	20.00
2821	21.00
2915	22.00
3009	23.00
3103	24.00
3197	25.00
3291	26.00
3385	27.00
3479	28.00
3573	29.00
3667	30.00
3761	33.00
3855	36.00
3949	39.00
4043	42.00
4137	48.00
4231	54.00
4325	60.00
4419	70.00
4513	80.00
4607	90.00
4701	110.00
4795	130.00
4889	150.00
4983	200.00
5077	250.00
5171	300.00

Load used in calculations is the single wheel load of 4500 lbs having a 80 psi tire pressure which is the single wheel load of the standart 18000 lbs single axle load applied to the pavement on two sets of dual tires [*Asphalt Institute, 1982*]. Corresponding load radius is 4.23 inches. As explained earlier, elements used in the analysis are in the form of nine-node quadrilateral and loads are defined in the joints under the loaded area. An important parameter of distributing load to the corresponding nodes is to consider that the inside nodes has the tributary area width of two times the corner nodes [*Habibullah and Wilson*]. Hence load intensities of related joints are calculated by considering the tributary areas of the nodes at the surface of the model within the load radius. In figure 7.8, example distribution of load intensities with respect to tributary area widths is shown.

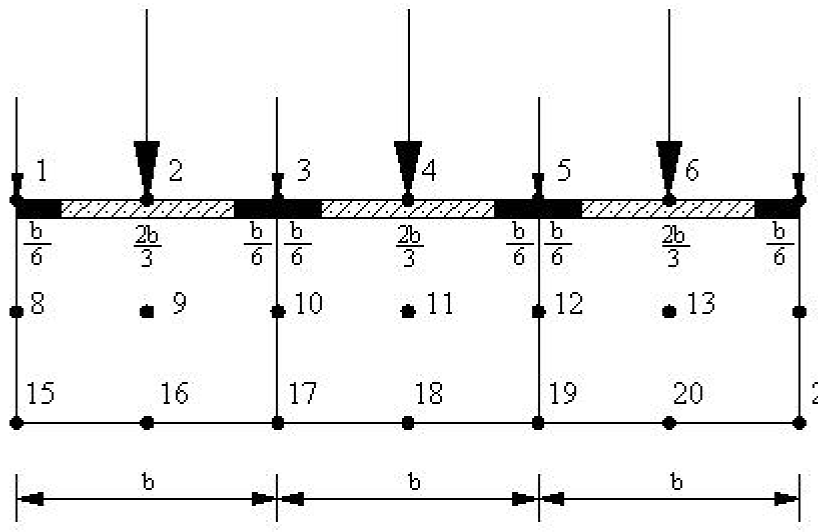


Figure 7.8 Representation of tributary area widths and load distribution

For the circular load of 4500 lbs with 80 psi tire pressure, the load intensities distributed to the nodal points within the loaded area by considering tributary area widths are tabulated below in table 7.6.

Table 7.6 Load intensities distributed to the nodes within load radius

SAP90 Joint No	Distance from centerline (in.)	Load Intensity (lbs)
1	0	0.0028
2	0.025	0.0668
3	0.05	0.0664
4	0.075	0.2004
5	0.1	0.1328
6	0.125	0.3340
7	0.15	0.5408
8	0.25	2.6680
9	0.35	1.8648
10	0.45	4.8024
11	0.55	2.9304
12	0.65	6.9368
13	0.75	6.1336
14	0.95	20.2616
15	1.15	12.2728
16	1.35	28.7928
17	1.55	16.5416
18	1.75	37.3240
19	1.95	31.7328
20	2.35	100.2792
21	2.75	58.6520
22	3.15	134.4168
23	3.55	69.8960
24	3.8905	141.3030
25	4.231	37.9020
		Total = 716.05 lbs

$$A = (4.231)^2 / 2 = 8.95 \text{ in}^2$$

$$P = 80 * 8.95 = 716.05 \text{ lbs}$$

An iterative process similar to technique performed by the program KENLAYER is applied to the non-linear system. Different from KENLAYER's analysis, variations of resilient modulus values in radial direction within the granular layer are also taken into account. The basic aim of this work is to represent the in-situ behavior of unbound granular materials more accurately by utilizing such a complex model. Modulus values are defined for each element seperately by selecting stress point for the element as the center joint of the nine-node quadrilateral element. Convergency of the system is observed by controlling the modulus values of each element. Similar stress modification which is incorporated into KENLAYER for nonlinear analysis in order to avoid negative θ (see section 4.3) is applied to calculations. In figure 7.9, schematic representation of selected stress points for elements are shown. K-θ model is applied for each element by calculating first stress invariant of θ at designated stress point. Then the modulus value estimated from K-θ model is assigned as the modulus of entire element which will be used as an input parameter for the next run. In this way, an iterative process can be applied until the modulus values of each element converge.

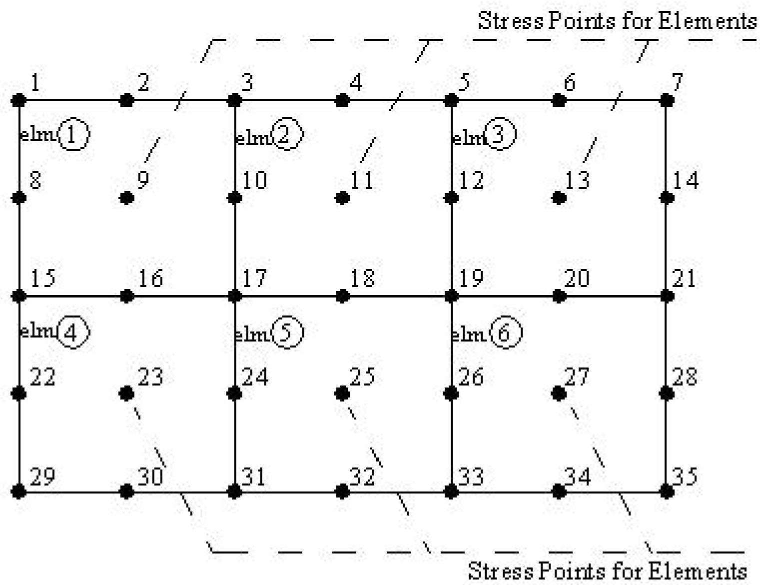


Figure 7.9 Stress points used in the determination of Mr

CHAPTER 8

VERIFICATION OF FINITE ELEMENT SOLUTION USING SAP90

8.1 General

In order to show the accuracy of the generated finite element model, critical responses of the sample flexible pavement system (see table 7.3, "p05") are calculated by using both KENLAYER and SAP90 programs by performing previously similar iterative process for stress sensitivity of granular base course.

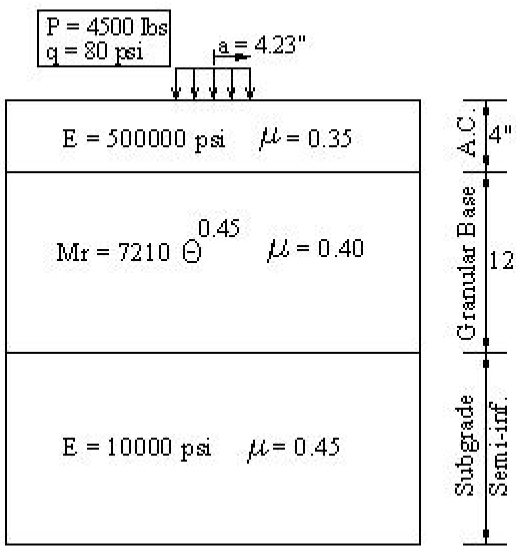


Figure 8.1 Pavement system "p05" used in the comparison study

8.2 KENLAYER Analysis

Non-linear analysis option of KENLAYER is used and K-θ model parameters are defined in the input stage. Granular layer is divided into 12 sub-layers each sub-layer having a thickness of 1 inch. Stress points used for calculation of modulus values for each sub-layer are placed at the mid-depth of each layer along the centerline of the circular loading (figure 8.2). An iterative process is applied until the values of elastic modulus of each sub-layer converge. After this iteration, critical responses are calculated by using converged modulus values.

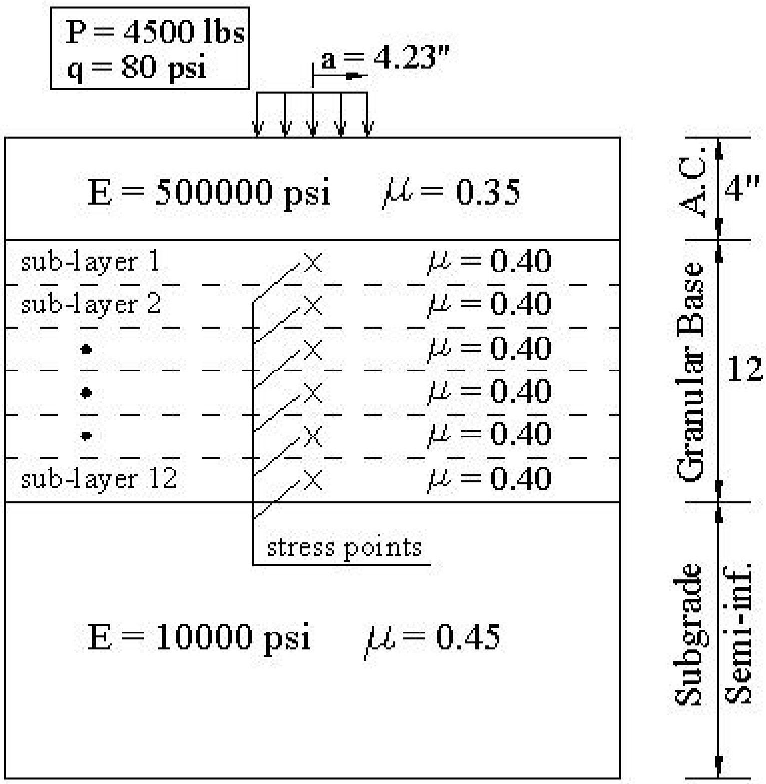


Figure 8.2 Schematical representation of KENLAYER analysis of pavement system "p05" used in comparison study

8.3 SAP90 Analysis

Similar to the KENLAYER analysis, granular layer is divided into 12 sub-layers with thicknesses of 1 inch. Variation of elastic modulus in radial direction is not taken into account and modulus values are considered to be constant within each sub-layer. Hence, instead of selecting different stress points for each element in the mesh, nodes at the mid-depth of each sub-layer along the centerline of loading are selected as stress points for the granular layer (see figure 8.3).

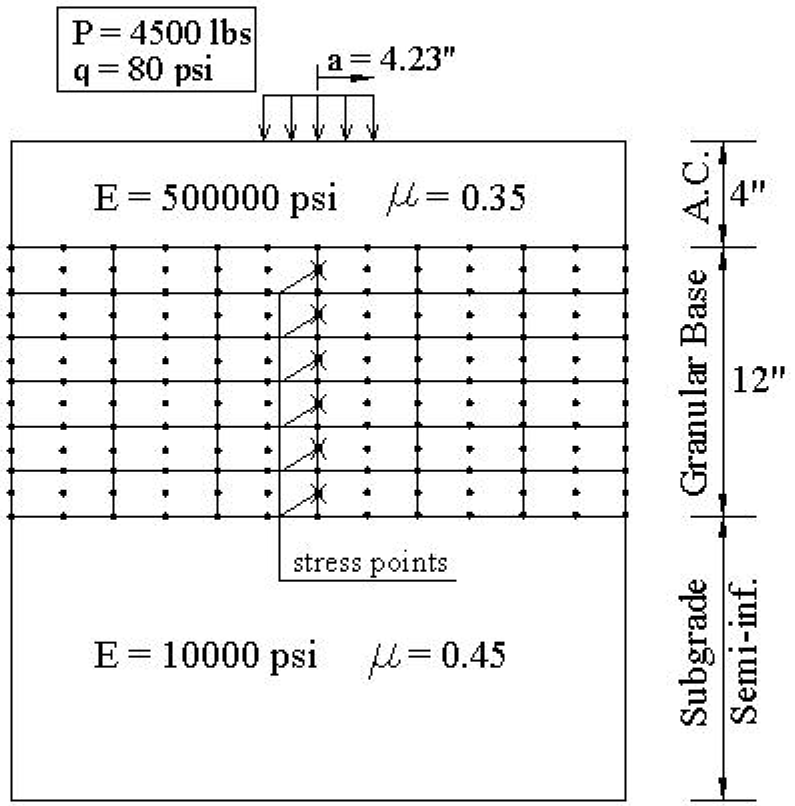


Figure 8.3 Schematical representation of modified SAP90 analysis of pavement system "p05" used in comparison study

By doing so, the same solution technique used by KENLAYER program is also modelled for SAP90 software. This is necessary because there should be a compatibility between analysis techniques in order to compare the results of KENLAYER and SAP90 softwares.

8.4 Comparison of Results

Results obtained from both of the analyses are plotted and tabulated in figures 8.4 through 8.6 and tables 8.1 through 8.3. As seen from the figures, calculated responses and converged elastic modulus values are perfectly matching for two different analysis performed by using KENLAYER and SAP90. These results show that prepared finite element model has adequate mesh spacing and works properly.

Table 8.1 Converged modulus values after iteration for pavement system "p05"

Stress Point	**Depth from surface**	**Converged modulus values (psi)**	
		KENLAYER	SAP90
1	4.50	25590	25102
2	5.50	23370	23050
3	6.50	21720	21475
4	7.50	20420	20204
5	8.50	19290	19116
6	9.50	18320	18168
7	10.50	17480	17357
8	11.50	16760	16648
9	12.50	16130	16048
10	13.50	15590	15534
11	14.50	15150	15104
12	15.50	14790	14754

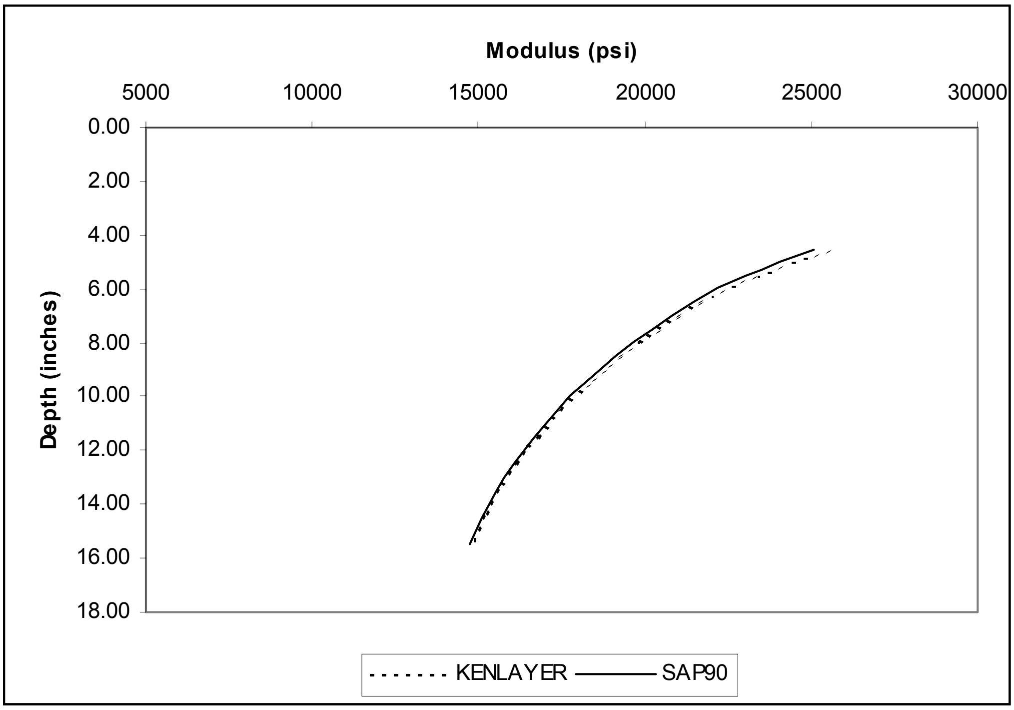


Figure 8.4 Variations of modulus values in granular layer along the vertical direction

Table 8.2 Variation of tensile strain at the bottom of the A.C. layer along the load radius for the pavement system "p05"

Distance from centerline (inches)	**Depth from surface (inches)**	**Tensile strain at the bottom of the A.C. under the load radius**	
		KENLAYER	SAP90
0	4.00	0.0002349	0.0002368
0.025	4.00	0.0002349	0.0002354
0.075	4.00	0.0002349	0.0002353
0.125	4.00	0.0002348	0.0002352
0.25	4.00	0.0002344	0.0002351
0.45	4.00	0.0002333	0.0002339
0.65	4.00	0.0002315	0.0002320
0.95	4.00	0.0002276	0.0002281
1.35	4.00	0.0002201	0.0002205
1.75	4.00	0.0002099	0.0002103
2.35	4.00	0.0001897	0.0001897
3.15	4.00	0.0001542	0.0001545
3.8905	4.00	0.0001159	0.0001168
4.656	4.00	0.0000763	0.0000777

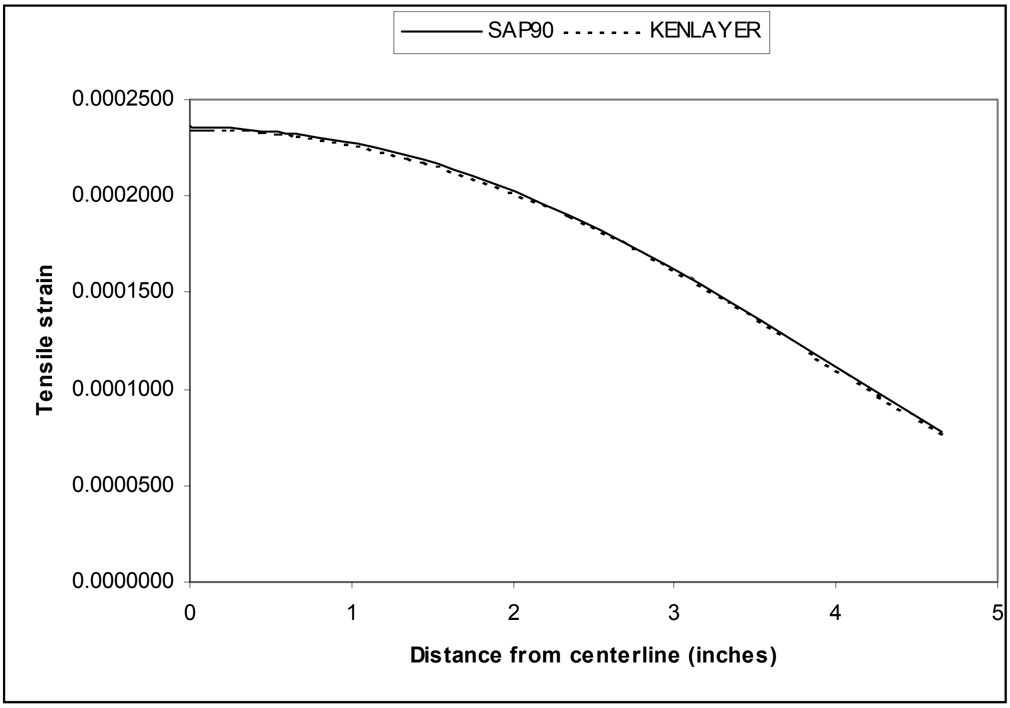


Figure 8.5 Variation of tensile strain at the bottom of the A.C. layer along the load radius for the pavement system "p05"

Table 8.3 Variation of compressive strain at the top of the subgrade layer along the load radius for the pavement system "p05"

Distance from centerline (inches)	Depth from surface (inches)	Compressive strain at the top of the subgrade under the load radius	
		KENLAYER	SAP90
0	16.00	-0.0003356	-0.0003406
0.025	16.00	-0.0003356	-0.0003407
0.075	16.00	-0.0003356	-0.0003407
0.125	16.00	-0.0003356	-0.0003407
0.25	16.00	-0.0003355	-0.0003407
0.45	16.00	-0.0003353	-0.0003407
0.65	16.00	-0.0003349	-0.0003397
0.95	16.00	-0.0003341	-0.0003387
1.35	16.00	-0.0003326	-0.0003373
1.75	16.00	-0.0003305	-0.0003353
2.35	16.00	-0.0003265	-0.0003318
3.15	16.00	-0.0003194	-0.0003249
3.8905	16.00	-0.0003113	-0.0003170
4.656	16.00	-0.0003015	-0.0003067

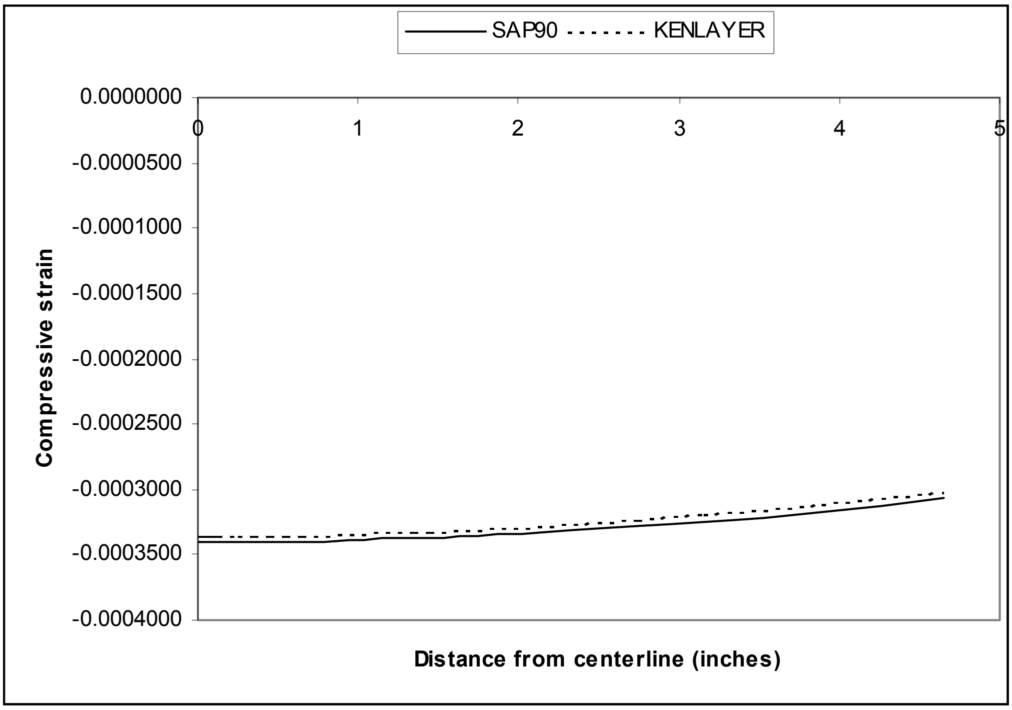


Figure 8.6 Variation of compressive strain at the top of the subgrade layer along the load radius for the pavement system "p05"

CHAPTER 9

DISCUSSION OF RESULTS

9.1 General

Results generated from computer analyses performed over 24 different pavement structures are given in Appendix A. Calculated responses of flexible pavements and predicted lives are discussed in this section and it is understood that observed differences in the results of three analysis methods are mainly due to the basic assumptions of three different solution techniques used in the study. Therefore figures showing the variations of converged modulus values throughout the granular base layers are very important outputs of this study indicating the main reason of calculating such different responses and lives for three solution techniques.

9.2 Modulus Convergence

A sample plot showing the variation of resilient modulus of granular material is shown in Figure 9.1. As can be clearly seen from the figure, converged modulus values along the centerline of loading are decreasing with depth for KENLAYER's simplified iterative technique and SAP90 analysis. This result is expected because stress intensities reduce at points which are far from loading. When the first stress invariant θ becomes less, Mr value calculated from K-θ model will be proportionally reduced at any point. This situation is not valid for linear-elastic model which always assumes constant elastic modulus and poisson's ratio values throughout the layer. It can be also seen that, converged resilient modulus values of SAP90 analysis along the centerline of loading are always greater than modulus values generated from KENLAYER. This result is due to the effect of radial decrease of Mr values defined in the SAP90 analysis. This is more representative solution technique for modelling in-situ behavior of the unbound granular base layer. The radial variation of Mr values within the granular layer generated after finite element analysis can also be observed from the figure. It can be seen that modulus values decrease not only in vertical direction but also in radial direction. In addition to this, after some distance from the load centerline, effect of load on determination of Mr reduces and modulus values are only functions of selfweights of the materials. Away from load centerline, Mr values increase with depth because the stresses due to selfweights of materials are increasing with depth and modulus values attain constant values in radial directions.

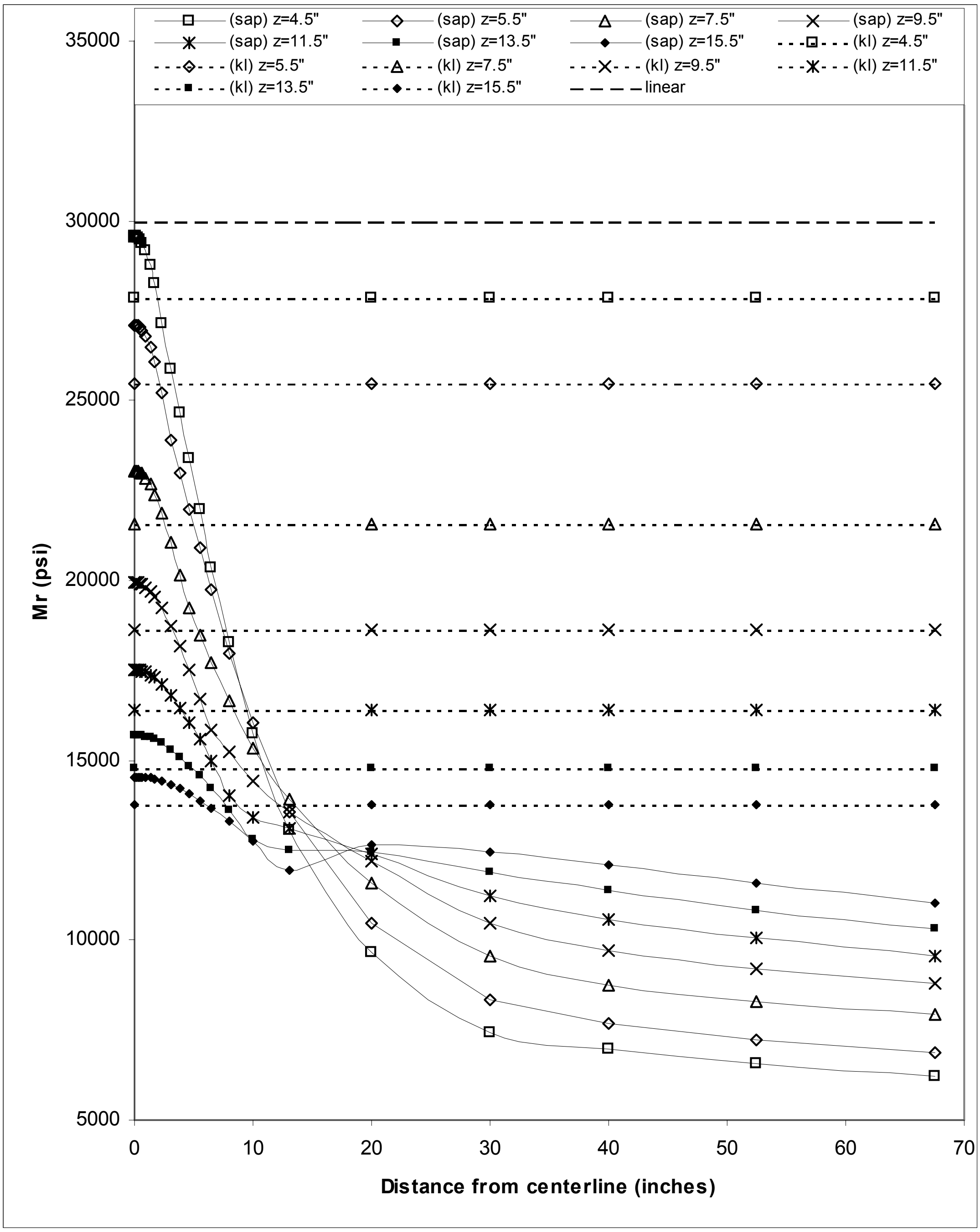


Figure 9.1 Example variation of modulus values within the granular layer for sample pavement system

9.3 Tensile Strains and Estimated Lives for Fatigue Failure of A.C. Layer

From the tables (see Appendix A) tabulating the calculated critical tensile strain at the bottom of the asphaltic concrete layer, it can be clearly seen that both KENLAYER's iterative solution and linear-elastic analyses are underestimating the strains compared to solutions generated after modelling the system by using SAP90. But it is observed that KENLAYER calculates relatively good results (closer to finite element solutions) compared to linear-elastic solution. Although solutions generated from KENLAYER and SAP90 analyses are closer to each other in critical tensile strains and corresponding fatigue lives, KENLAYER's solution still overestimates fatigue life as much as 5 to 25 % higher when compared to SAP90 solution depending on other section properties. Linear elastic theory generates very poor results compared to other two techniques. It predicts fatigue life of the asphaltic concrete layer nearly two times longer in some pavement systems compared to SAP90 solution. The comparison of predicted fatigue lives after performing three different analysis for different pavement systems are shown in Tables 9.1 and 9.2.

Table 9.1 Fatigue lives (Nf) of pavements having crushed stone base (k1=7210 k2=0.45)

	PAVEMENT SYSTEM I						PAVEMENT SYSTEM II					
Thickness	**Hac=4" Hbase=12" Hsubgrade = semi-inf.**						**Hac=4" Hbase=16" Hsubgrade = semi-inf.**					
E1 (psi)	**300000**		**500000**		**700000**		**300000**		**500000**		**700000**	
E3 (psi)	**5000**	**10000**	**5000**	**10000**	**5000**	**10000**	**5000**	**10000**	**5000**	**10000**	**5000**	**10000**
Linear Elastic	867911	910806	1315414	1431894	1847334	2055581	952978	963619	1478439	1534435	2100035	2218987
KENLAYER	559682	646743	780158	940104	1070868	1332506	619879	674396	862884	987702	1191400	1417387
SAP90	455343	559057	670349	864794	963202	1268923	517739	601023	762549	925288	1090512	1337354

Table 9.2 Fatigue lives (Nf) of pavements having sand-gravel base (k1=4480 k2=0.53)

	PAVEMENT SYSTEM I						PAVEMENT SYSTEM II					
Thickness	**Hac=4" Hbase=12" Hsubgrade = semi-inf.**						**Hac=4" Hbase=16" Hsubgrade = semi-inf.**					
E1 (psi)	**300000**		**500000**		**700000**		**300000**		**500000**		**700000**	
E3 (psi)	**5000**	**10000**	**5000**	**10000**	**5000**	**10000**	**5000**	**10000**	**5000**	**10000**	**5000**	**10000**
Linear Elastic	646035	688034	1034005	1140517	1498849	1690237	708375	723738	1154175	1210989	1687153	1802970
KENLAYER	348280	420136	534387	689602	784779	1042423	374798	431633	575410	711127	853137	1069167
SAP90	297392	390504	489441	654929	743543	993700	329444	403761	542992	671536	819725	1014410

The following figures show the variations of fatigue life with increasing A.C. and subgrade modulus values of the sample pavement systems for KENLAYER and SAP90 solutions. Because the linear elastic method gives unrealistic results compared to KENLAYER and SAP90, it is not illustrasted in these figures in order to see the differences between calculated lives of KENLAYER and SAP90 analyses more efficiently.

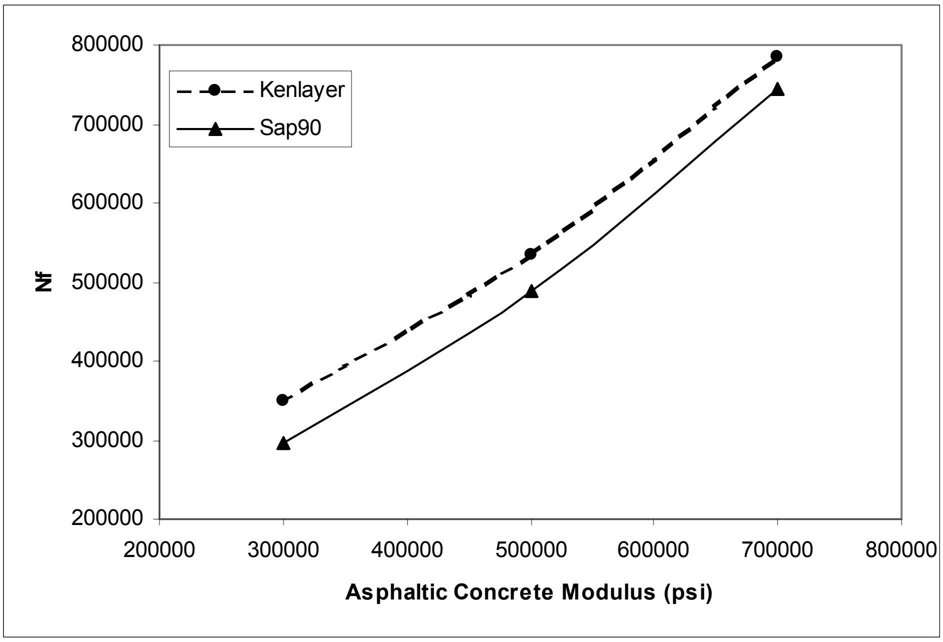


Figure 9.2 Variation of Nf with increasing A.C. modulus values for the pavements having 12" sand-gravel base and subgrade modulus of 5000 psi

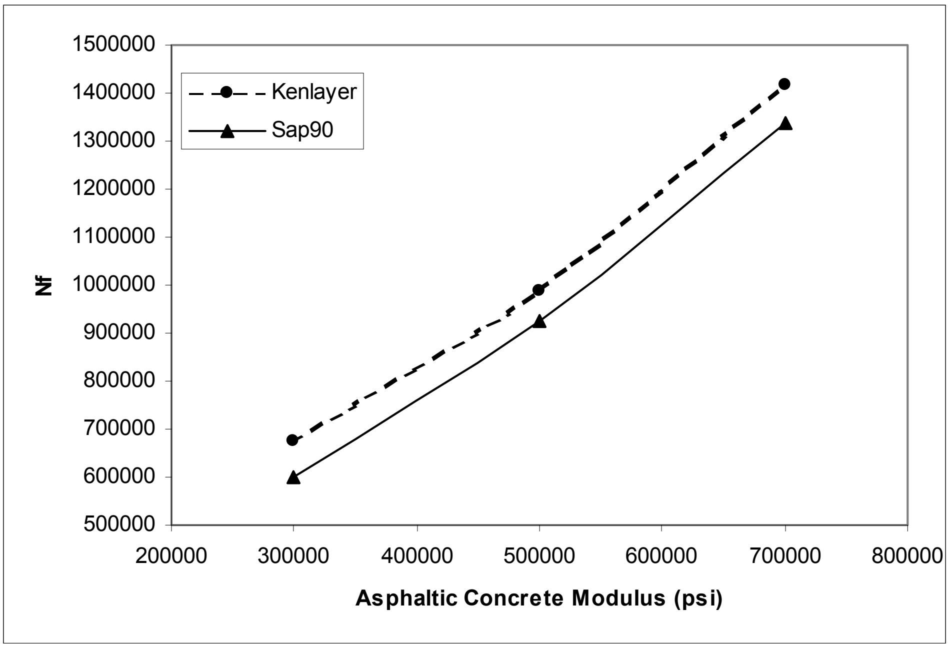


Figure 9.3 Variation of Nf with increasing A.C. modulus values for the pavements having 16" crushed stone base and subgrade modulus of 10000 psi

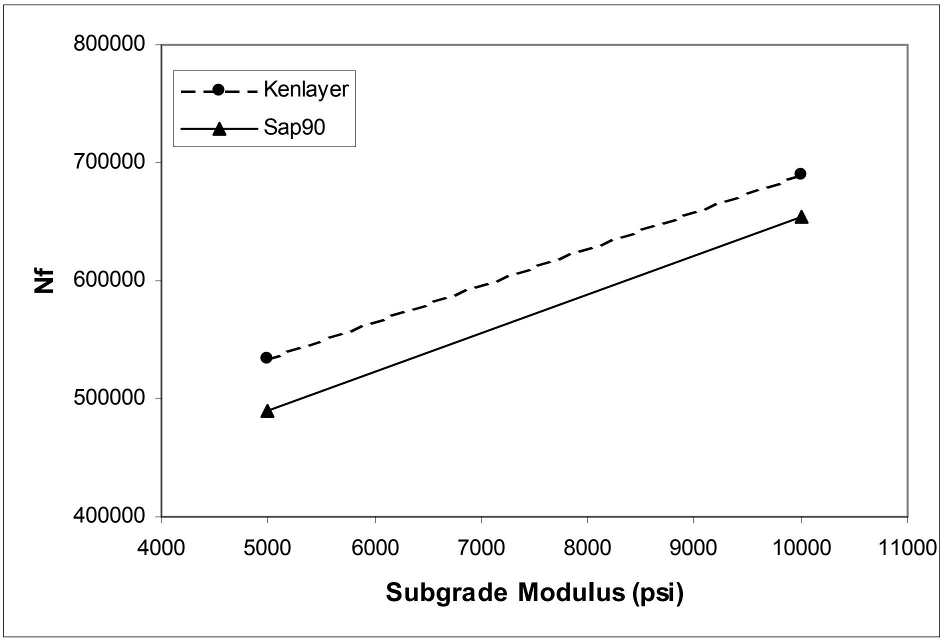


Figure 9.4 Variation of Nf with increasing subgrade modulus values for the pavements having 12" sand-gravel base and A.C. modulus of 500000 psi

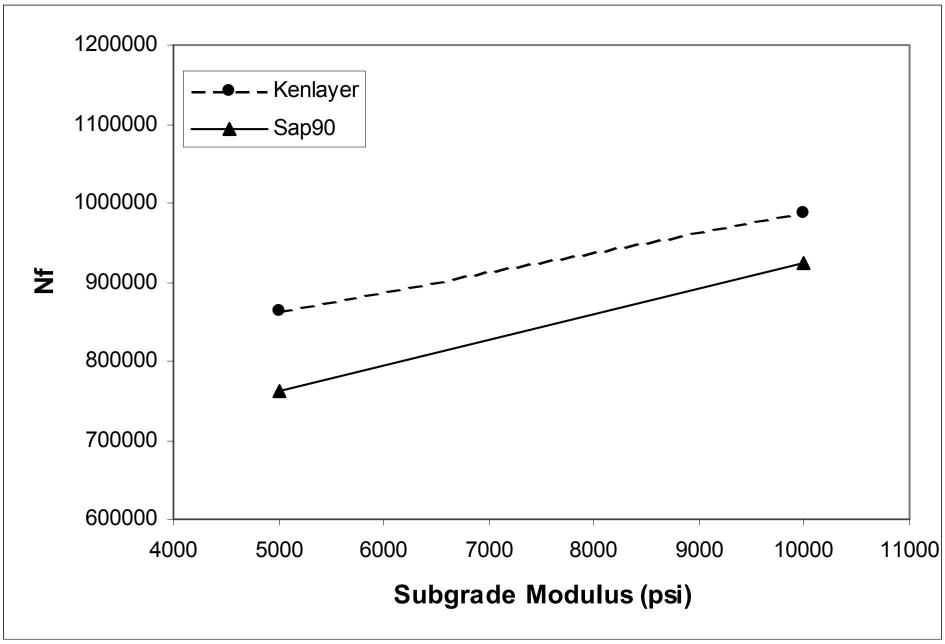


Figure 9.5 Variation of Nf with increasing subgrade modulus values for the pavements having 16" crushed stone base and A.C. modulus of 500000 psi

9.4 Compressive Strains and Estimated Lives for Subgrade Permanent Deformation

From the tables (see Appendix A) showing the calculated critical compressive strain values at the top of the subgrade for different pavement structures, it is observed that both KENLAYER's iterative solution and linear-elastic analysis underestimate the critical compressive strains compared to solutions generated from program SAP90 similar to tensile strains at the bottom of the asphaltic concrete. This results in an overestimation of the life to prevent permanent deformation of subgrade (Nd). It is clear from the results that linear elastic theory predicts unacceptable compressive strain values and lives compared to SAP90. In some systems, linear elastic model predicts up to four times longer life (Nd) compared to the model developed by SAP90. Although KENLAYER's nonlinear analysis predicts relatively good compressive strains and lives (closer to SAP90 solutions) compared to linear elastic theory, in some pavement systems predicted lives are nearly two times higher than values estimated by SAP90. Therefore reliability of this simplified iterative technique for calculating critical compressive strain values is not good enough similar to critical tensile strain predictions. The comparison of predicted lives to prevent permanent deformation of subgrade after performing three different analysis for different pavement systems are shown in Tables 9.3 and 9.4.

Table 9.3 Estimated lives (Nd) of pavements having crushed stone base (k1=7210 k2=0.45)

	PAVEMENT SYSTEM I						PAVEMENT SYSTEM II					
Thickness	Hac=4" Hbase=12" Hsubgrade = semi-inf.						Hac=4" Hbase=16" Hsubgrade = semi-inf.					
E1 (psi)	300000		500000		700000		300000		500000		700000	
E3 (psi)	5000	10000	5000	10000	5000	10000	5000	10000	5000	10000	5000	10000
Linear Elastic	1056418	3987357	1809175	6891205	2723956	10466413	4880322	18035106	7421043	27638299	10221697	38367380
KENLAYER	505347	2778837	861688	4886836	1330124	7733139	1987363	11208743	2937762	17251452	4116947	24839631
SAP90	311235	1820819	597705	3604889	1035651	5947009	1061437	6388787	1793790	10786762	2743173	16308224

Table 9.4 Estimated lives (Nd) of pavements having sand-gravel base (k1=4480 k2=0.53)

	PAVEMENT SYSTEM I						PAVEMENT SYSTEM II					
Thickness	Hac=4" Hbase=12" Hsubgrade = semi-inf.						Hac=4" Hbase=16" Hsubgrade = semi-inf.					
E1 (psi)	300000		500000		700000		300000		500000		700000	
E3 (psi)	5000	10000	5000	10000	5000	10000	5000	10000	5000	10000	5000	10000
Linear Elastic	769890	3195624	1369293	5736186	2120504	8959893	3392717	13810416	5319545	21842750	7508615	31144862
KENLAYER	357705	2355958	671077	4531912	1128336	7575125	1306500	8946220	2101825	14931790	3180161	22590850
SAP90	229676	1556789	503322	3218991	887910	5534434	746543	4979157	1390107	9056324	2172929	14212423

Figures plotted below are showing the example variations of life to prevent permanent deformation of subgrade with increasing A.C. and subgrade modulus values of the sample pavement systems for KENLAYER and SAP90 solutions. Because the linear elastic method gives very poor results compared to KENLAYER and SAP90, it is not illustrasted in these figures to observe differences between KENLAYER and SAP90 results more accurately.

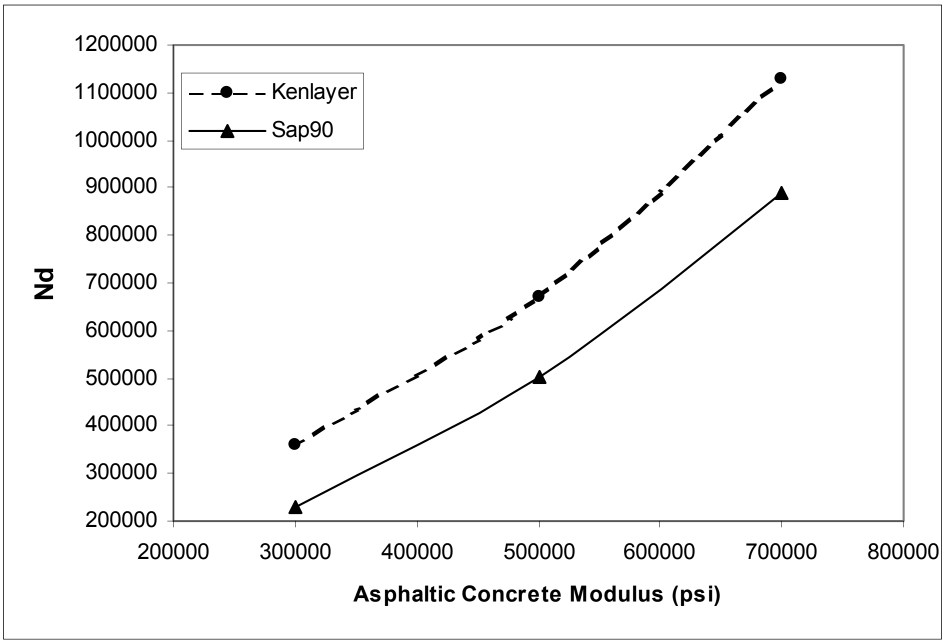


Figure 9.6 Variation of Nd with increasing A.C. modulus values for the pavements having 12" sand-gravel base and subgrade modulus of 5000 psi

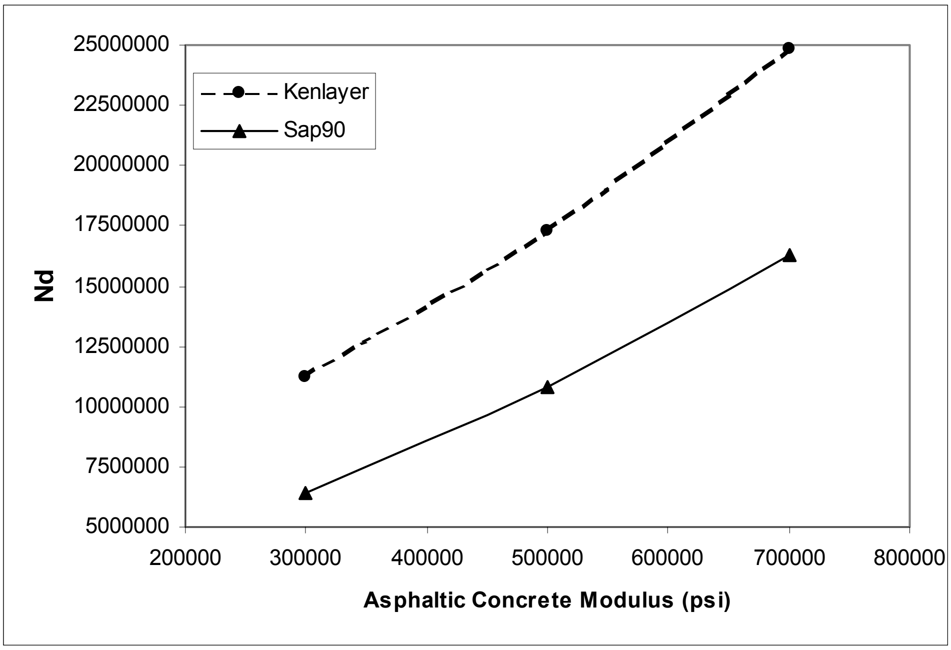


Figure 9.7 Variation of Nd with increasing A.C. modulus values for the pavements having 16" crushed stone base and subgrade modulus of 10000 psi

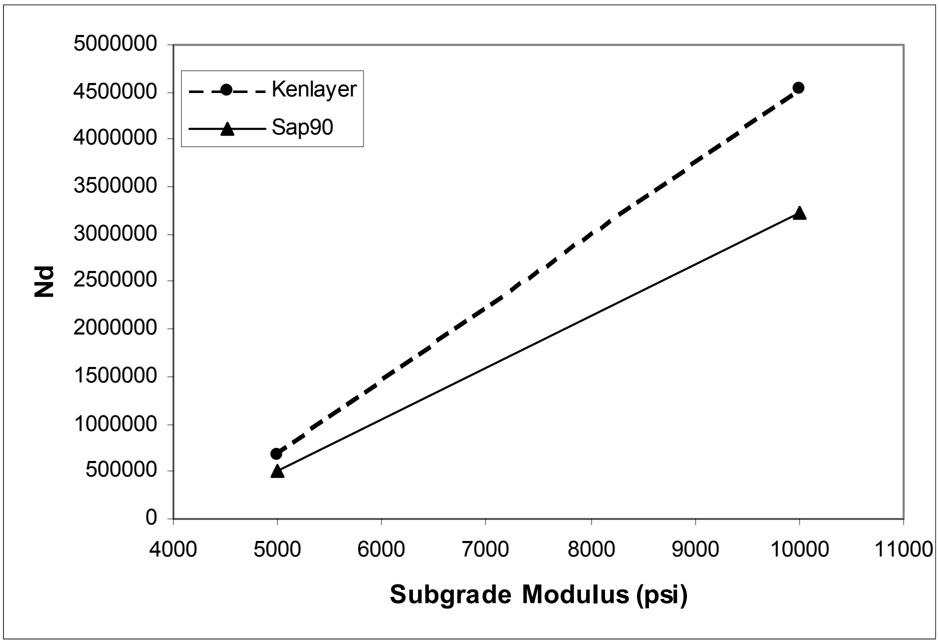


Figure 9.8 Variation of Nd with increasing subgrade modulus values for the pavements having 12" sand-gravel base and A.C. modulus of 500000 psi

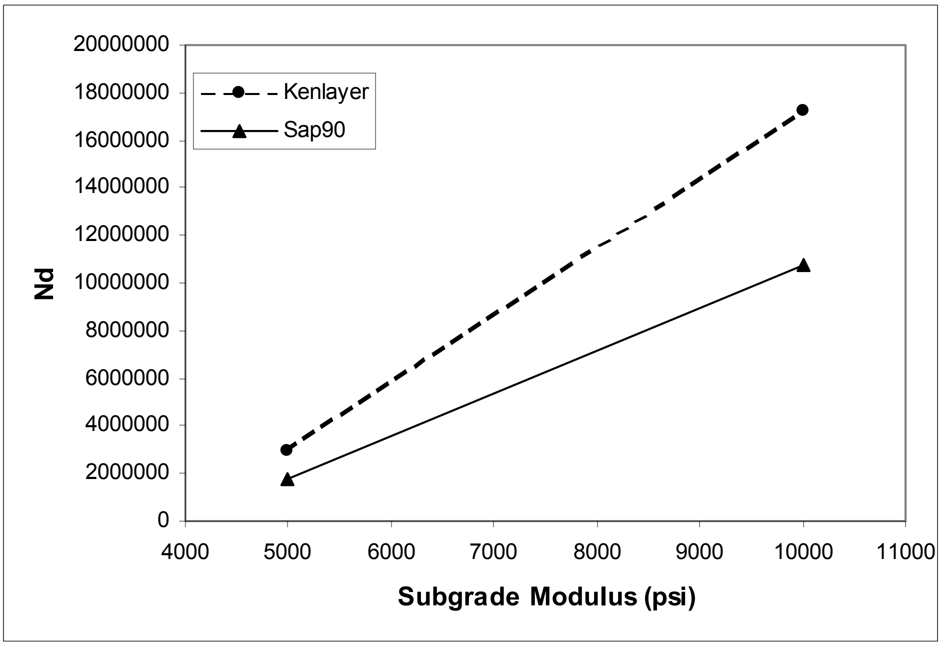


Figure 9.9 Variation of Nd with increasing subgrade modulus values for the pavements having 16" crushed stone base and A.C. modulus of 500000 psi

CHAPTER 10

CONCLUSIONS AND RECOMMENDATIONS

10.1 Conclusions

Research results have shown that unbound granular materials exhibit non-linear stress dependent resilient behavior. Without considering stress dependent behavior of such materials, the pavement responses obtained from structural analysis will be influenced by the selected constant modulus values for the layer(s) composed of unbound materials. In general, constant modulus values are estimated from rough correlations based on standart static loading tests. Because these correlations are very rough, the pavement responses obtained from structural analysis will not be adequately precise. In order to have more precise pavement responses and corresponding pavement lives, it is essential to incorporate stress dependent behavior of unbound granular layers in pavement analysis and design processes.

In this study, three different approaches are used to obtain critical pavement responses. In the first one, the simplest approach, the pavement system is solved by layered elastic theory taking constant modulus values for unbound granular layers.

For the second one, KENLAYER computer program is used. Although this program is also based on the linear elastic theory, it has the capability to divide unbound granular layer into a number of sub-layers. By this means, the stress dependent modulus values can be iterated for each sublayer through successive runs to obtain converged modulus values. Thus, more precise pavement responses are released. The limitation of layered elastic solution is that it does not allow modulus iteration in horizontal direction. The last approach utilizes the use of finite element method in order to apply modulus iteration both in vertical and horizontal directions. For this purpose SAP90 finite element computer program is used.

The pavement responses for 24 different pavement systems are solved by applying three approaches outlined above. The comparison of the results obtained from these analyses yields the following conclusions:

1) Using layered elastic theory requires the selection of modulus values for unbound granular layers. Stress dependent behavior of granular materials constituting these layers can not be incorporated directly in structural analysis. The selection process for modulus values vary depending on the governing recommendations of the pavement design method used. In general, the modulus values are selected according to the correlations based on standart static loading tests and experience. For this reason, the results obtained are subject to variation. In the present work, the modulus values of granular layers are selected by using famous CBR relation. The results show that simple layered elastic solution underestimates critical pavement responses. Tensile strains at the bottom of A.C.

layer come out to be 13 to 21 % smaller and compressive strains on top of subgrade come out to be 10 to 29 % smaller when compared to results obtained by finite element model depending on section properties. Hence the pavement lives are overestimated.

2) The results show that KENLAYER's simplified approximation technique gives higher critical responses compared to linear elastic theory but it still underestimates the critical responses when compared to finite element model. It is observed that this iterative solution predicts 1 to 6 % smaller tensile strains at the bottom of the A.C. layer and 5 to 13 % smaller compressive strains on top of the subgrade compared to SAP90 results depending on section properties. Although this approach gives more approximate results (closer to SAP90 solution) compared to linear elastic theory, it has still some deficincies. Because KENLAYER is based on layered-elastic theory, user can define only one elastic modulus value for each sublayer and it is assumed to be constant in radial direction. Obviously, this approach is not adequate to represent the stress dependent behavior of granular materials exhibiting modulus variation throughout the layer. In order to obtain more precise results, variation of modulus values in radial direction should also be taken into account in addition to variation in vertical direction.

3) The analysis by modelling the pavement system using finite element method, especially when stress dependent unbound granular layers are present, releases higher critical responses, hence lower pavement lives. It is believed that the results obtained by the use of finite element method are more realistic, because

the stress dependent behavior can be modelled in more representative manner. Although the finite element method is quite complex compared to linear elastic solution, if an "analytical-emprical" method is to be adopted in flexible pavement design phase for the pavements having unbound granular layers, non-linear stress-strain behavior of these materials should be taken into account accurately in the solution technique for more precise results.

10.2 Recommendations for Further Study

Although finite element method seems to be the best solution technique for modelling this complex mechanistic behavior of unbound granular materials, it is quite complex and time consuming procedure compared to linear elastic theory. Axisymmetric solid of revolution model used in this study is a two dimensional specialization of a three dimensional system and it can only be applied to the flexible pavement having a circular single wheel load. Any introduction of additional loads results in distortion of the system symmetry and axisymmetric model can not be applied anymore. Generating finite element models of such pavement systems having multiple loads like dual or dual tandem wheels is quite complicated and requires three dimensional modelling. Hence, because of its simplicity, linear elastic theory is still the most popular solution technique used in the analysis of flexible pavement systems by engineers. Structural analysis of pavements with multiple wheel loads can easily be conducted by applying superposition principle in elastic solutions. By using a method of successive approximation, similar to the approach adopted in KENLAYER computer program, the precision of layered elastic solution will be improved. But as mentioned earlier, application of such techniques in elastic layered theory will not improve the results completely to match with the results of finite element solution adopted in this study. In order to get more precise results from linear elastic theory, the simplified modulus iteration technique needs to be calibrated. The calibration process will require adjustments on iterated modulus values of granular sub-layers after each run until convergence is reached. For this purpose a series of representative pavement systems with the same input models should be solved by iterative technique for both layered elastic theory and finite element method simultenously. Calibration methodology should be developed based on the comperative evaluation of the results from both solutions.

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APPENDIX A

RESULTS OF COMPUTER ANALYSES BY LINEAR ELASTIC SYSTEM, KENLAYER AND SAP90

A.1 General

Results of analyses related to flexible pavement systems used in this study are presented in this section. Input parameters used in the analysis of the pavement system and calculated responses with predicted lives by using three different solution techniques are tabulated in two different tables. Predicted lives are calculated by using previously defined equations 1.1 and 1.2. Constants f_1, f_2, f_3, f_4 and f_5 are selected as the same values that Asphalt Institute used which are 0.0795, 3.29, 0.854, 1.365E-9 and 4.477 respectively [A.I., 1982]. In addition to these tables, a figure showing the variations of converged resilient modulus values within the granular base layer for three different solution techniques is also plotted for each pavement system.

Table A.1 Input parameters used in the analysis of the pavement system "p01"

p01	h (inches)	Modulus (psi)	Unit Weight (pcf)	Poisson's Ratio	k0	Model Parameters	
						k1	k2
A.C.	4	300000	139.97	0.35	0.54	-	-
Granular Base	12	k-Q model	133.06	0.40	0.67	7210	0.45
Subgrade	semi-inf.	5000	125.00	0.45	0.82	-	-

Table A.2 Calculated responses and predicted lives for the pavement "p01"

p01	Fatigue of A.C.		Permanent deformation of subgrade	
	Tensile Strain (A.C.)	Life (Nf)	Compressive Strain (Subgrade)	Life (Nd)
Linear-elastic	0.00027480	867911	-0.00047250	1056418
KENLAYER	0.00031400	559682	-0.00055710	505347
SAP90	0.00033432	455343	-0.00062080	311235

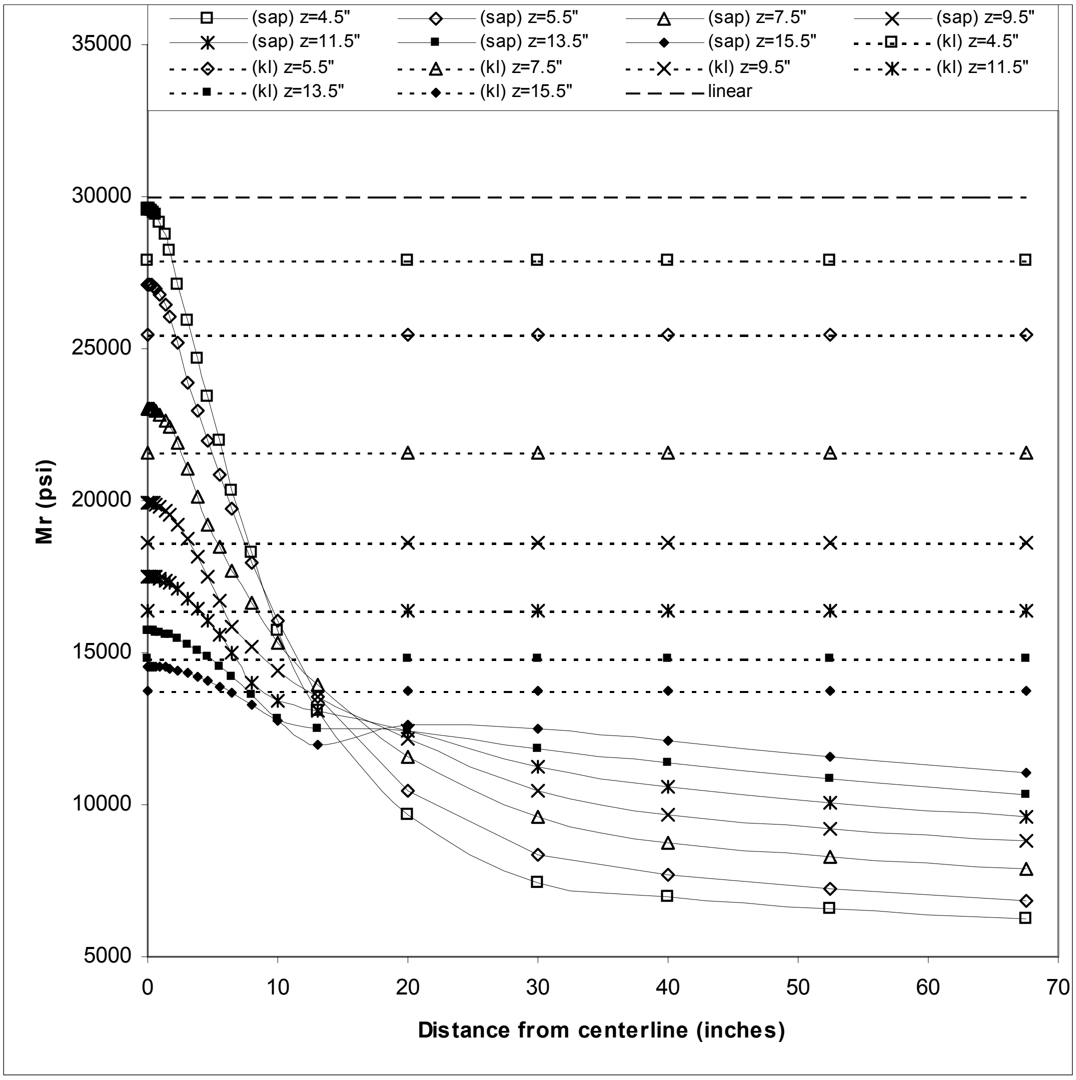

Figure A.1 Converged modulus values within the granular layer for "p01"

Table A.3 Input parameters used in the analysis of the pavement system "p02"

p02	h (inches)	Modulus (psi)	Unit Weight (pcf)	Poisson's Ratio	k0	Model Parameters	
						k1	k2
A.C.	4	500000	139.97	0.35	0.54	-	-
Granular Base	12	k-Q model	133.06	0.40	0.67	7210	0.45
Subgrade	semi-inf.	5000	125.00	0.45	0.82	-	-

Table A.4 Calculated responses and predicted lives for the pavement "p02"

p02	Fatigue of A.C.		Permanent deformation of subgrade	
	Tensile Strain (A.C.)	Life (Nf)	Compressive Strain (Subgrade)	Life (Nd)
Linear-elastic	0.00021210	1315414	-0.00041900	1809175
KENLAYER	0.00024860	780158	-0.00049450	861688
SAP90	0.00026033	670349	-0.00053660	597705

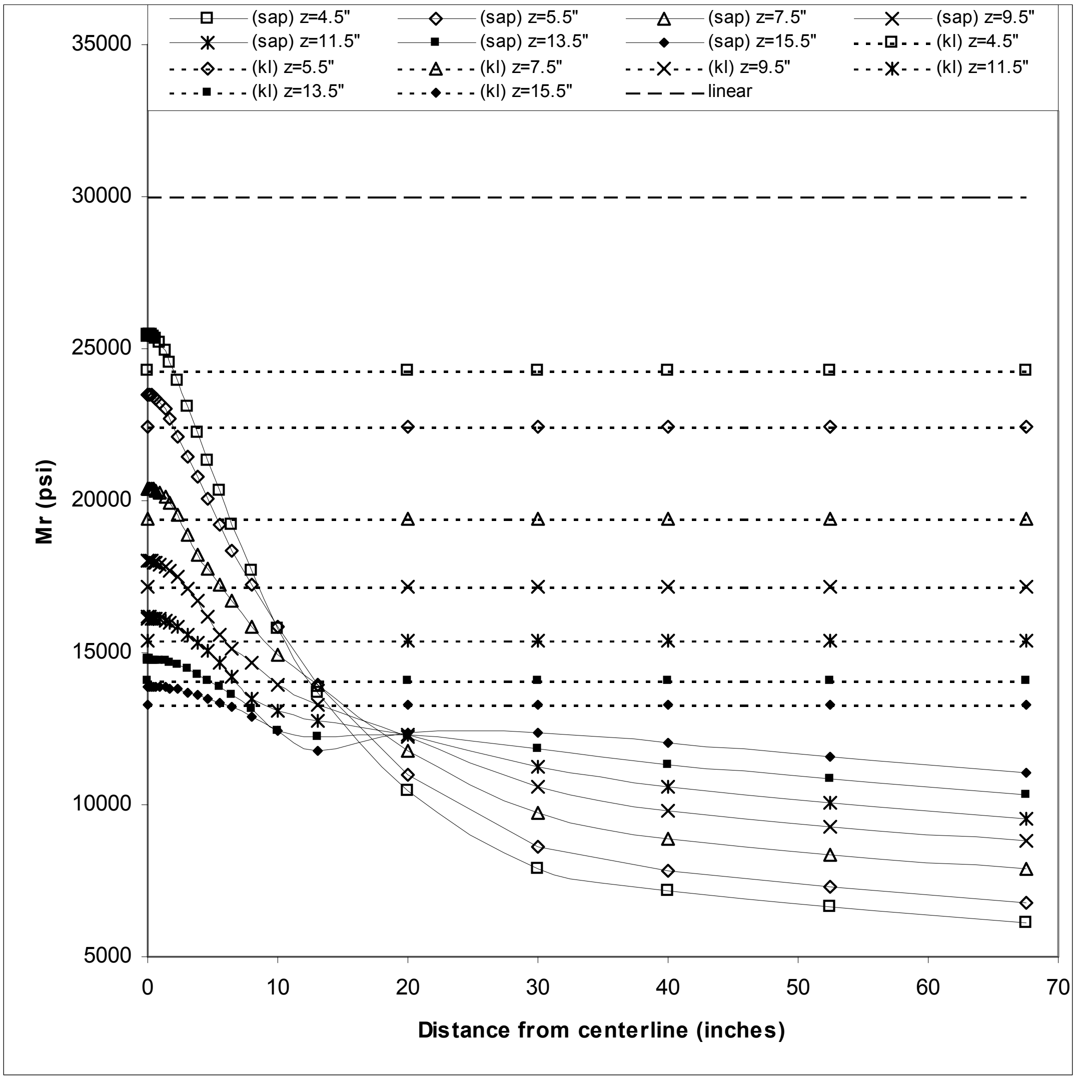

Figure A.2 Converged modulus values within the granular layer for "p02"

Table A.5 Input parameters used in the analysis of the pavement system "p03"

p03	h (inches)	Modulus (psi)	Unit Weight (pcf)	Poisson's Ratio	k0	Model Parameters	
						k1	k2
A.C.	4	700000	139.97	0.35	0.54	-	-
Granular Base	12	k-Q model	133.06	0.40	0.67	7210	0.45
Subgrade	semi-inf.	5000	125.00	0.45	0.82	-	-

Table A.6 Calculated responses and predicted lives for the pavement "p03"

p03	Fatigue of A.C.		Permanent deformation of subgrade	
	Tensile Strain (A.C.)	Life (Nf)	Compressive Strain (Subgrade)	Life (Nd)
Linear-elastic	0.00017530	1847334	-0.00038240	2723956
KENLAYER	0.00020690	1070868	-0.00044880	1330124
SAP90	0.00021367	963202	-0.00047460	1035651

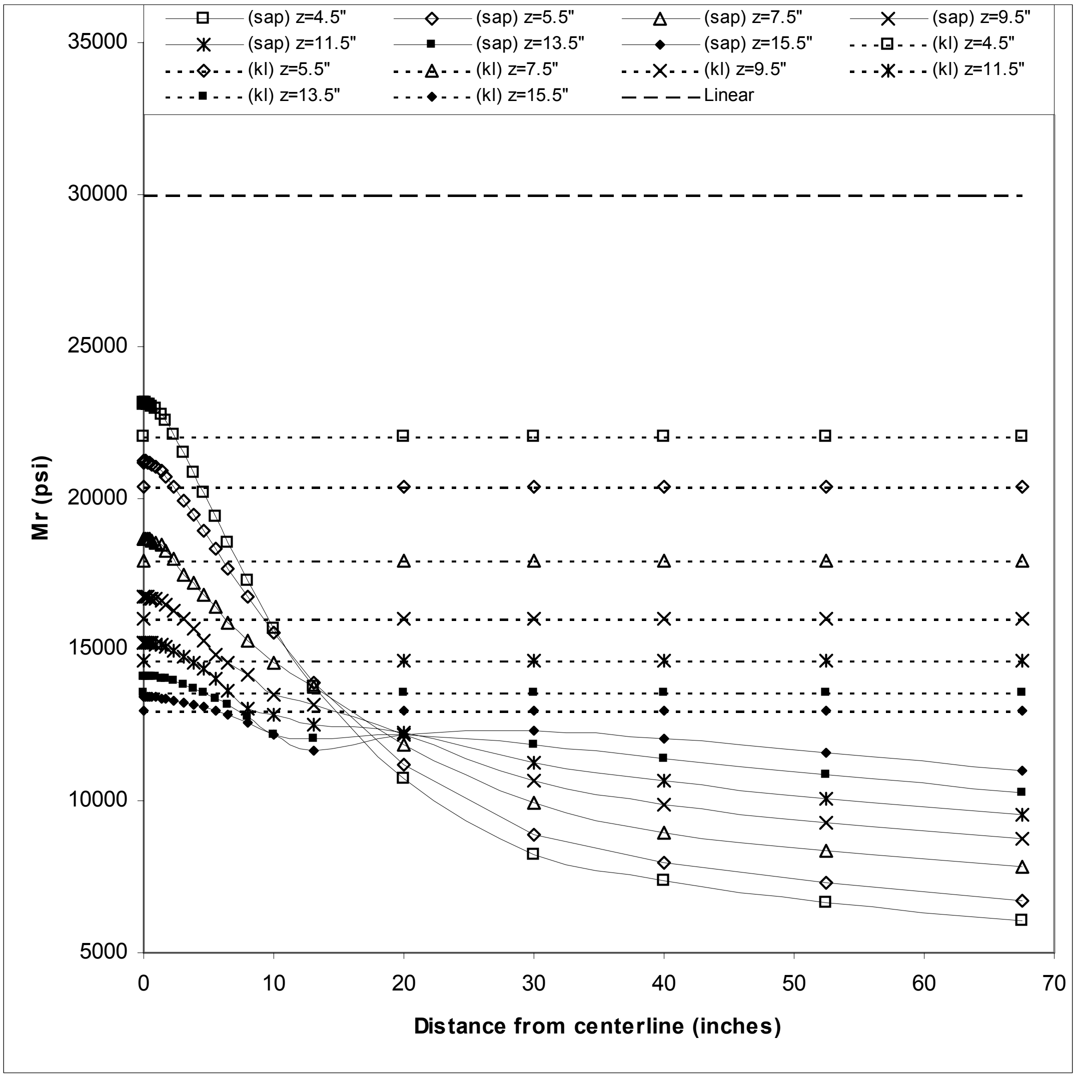

Figure A.3 Converged modulus values within the granular layer for "p03"

Table A.7 Input parameters used in the analysis of the pavement system "p04"

p04	h (inches)	Modulus (psi)	Unit Weight (pcf)	Poisson's Ratio	k0	Model Parameters	
						k1	k2
A.C.	4	300000	139.97	0.35	0.54	-	-
Granular Base	12	k-Q model	133.06	0.40	0.67	7210	0.45
Subgrade	semi-inf.	10000	125.00	0.45	0.82	-	-

Table A.8 Calculated responses and predicted lives for the pavement "p04"

p04	Fatigue of A.C.		Permanent deformation of subgrade	
	Tensile Strain (A.C.)	Life (Nf)	Compressive Strain (Subgrade)	Life (Nd)
Linear-elastic	0.00027080	910806	-0.00035120	3987357
KENLAYER	0.00030050	646743	-0.00038070	2778837
SAP90	0.00031411	559057	-0.00041840	1820819

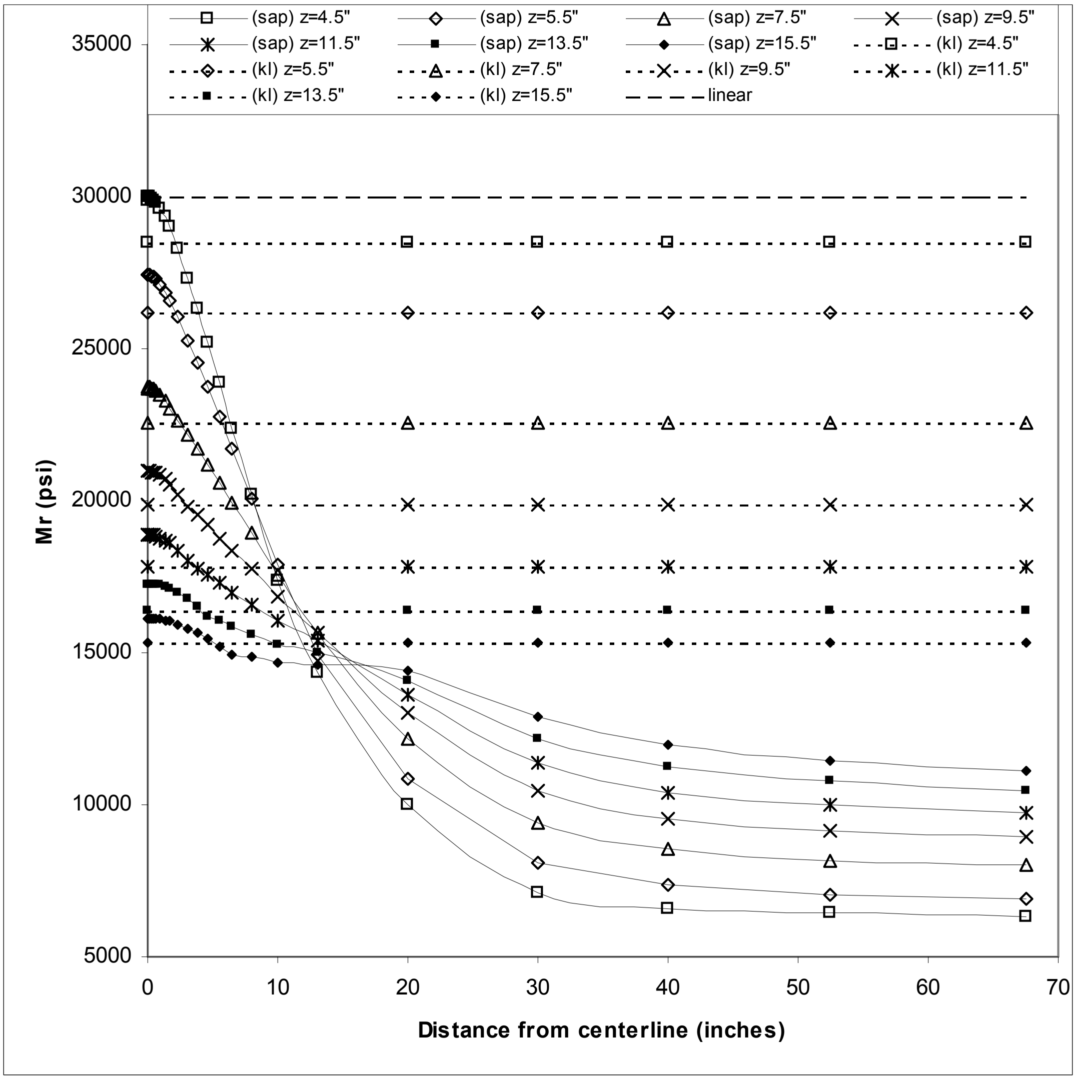

Figure A.4 Converged modulus values within the granular layer for "p04"

Table A.9 Input parameters used in the analysis of the pavement system "p05"

p05	h (inches)	Modulus (psi)	Unit Weight (pcf)	Poisson's Ratio	k0	Model Parameters	
						k1	k2
A.C.	4	500000	139.97	0.35	0.54	-	-
Granular Base	12	k-Q model	133.06	0.40	0.67	7210	0.45
Subgrade	semi-inf.	10000	125.00	0.45	0.82	-	-

Table A.10 Calculated responses and predicted lives for the pavement "p05"

p05	Fatigue of A.C.		Permanent deformation of subgrade	
	Tensile Strain (A.C.)	Life (Nf)	Compressive Strain (Subgrade)	Life (Nd)
Linear-elastic	0.00020670	1431894	-0.00031080	6891205
KENLAYER	0.00023490	940104	-0.00033560	4886836
SAP90	0.00024094	864794	-0.00035920	3604889

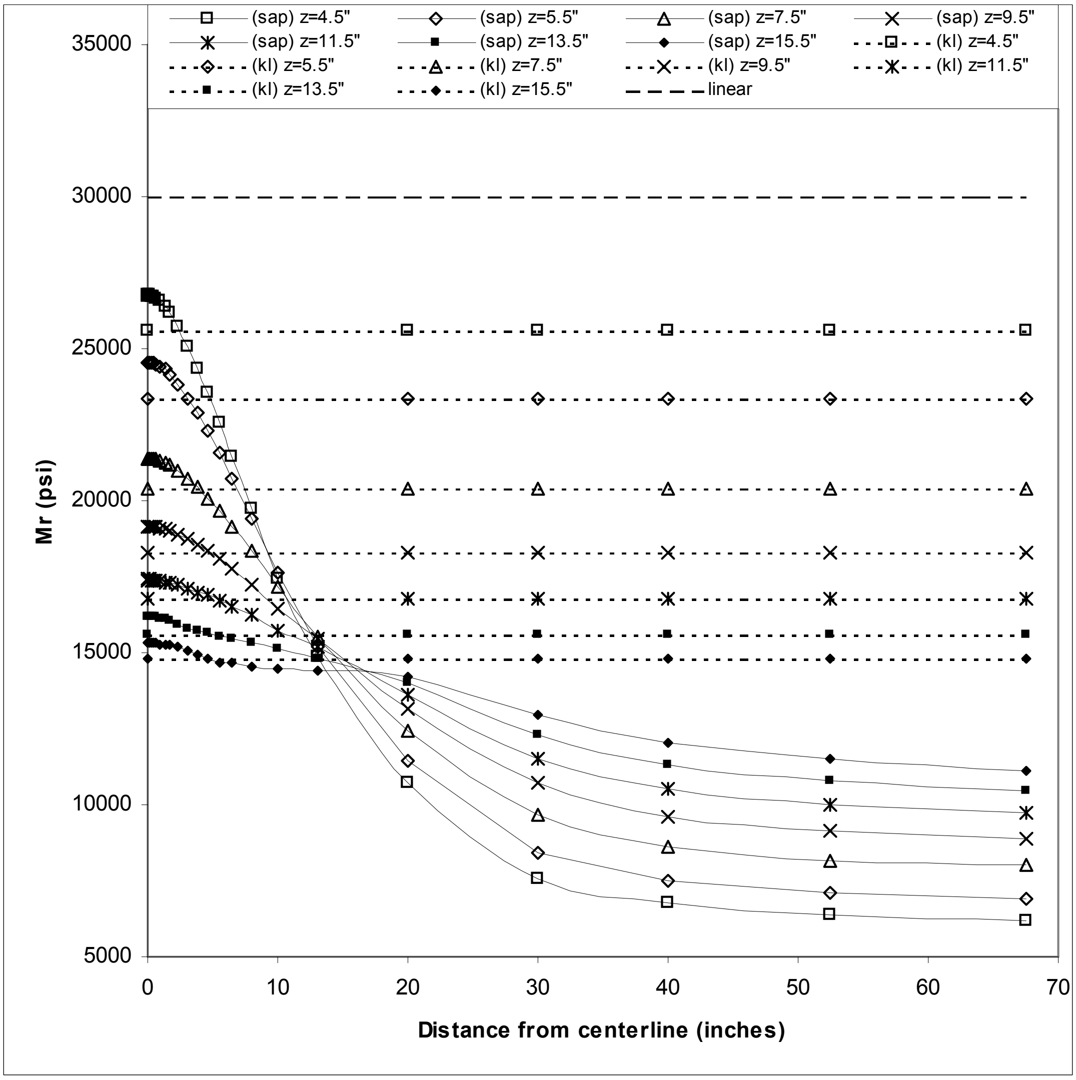

Figure A.5 Converged modulus values within the granular layer for "p05"

Table A.11 Input parameters used in the analysis of the pavement system "p06"

p06	h (inches)	Modulus (psi)	Unit Weight (pcf)	Poisson's Ratio	k0	Model Parameters	
						k1	k2
A.C.	4	700000	139.97	0.35	0.54	-	-
Granular Base	12	k-Q model	133.06	0.40	0.67	7210	0.45
Subgrade	semi-inf.	10000	125.00	0.45	0.82	-	-

Table A.12 Calculated responses and predicted lives for the pavement "p06"

p06	Fatigue of A.C.		Permanent deformation of subgrade	
	Tensile Strain (A.C.)	Life (Nf)	Compressive Strain (Subgrade)	Life (Nd)
Linear-elastic	0.00016970	2055581	-0.00028310	10466413
KENLAYER	0.00019360	1332506	-0.00030290	7733139
SAP90	0.00019650	1268923	-0.00032120	5947009

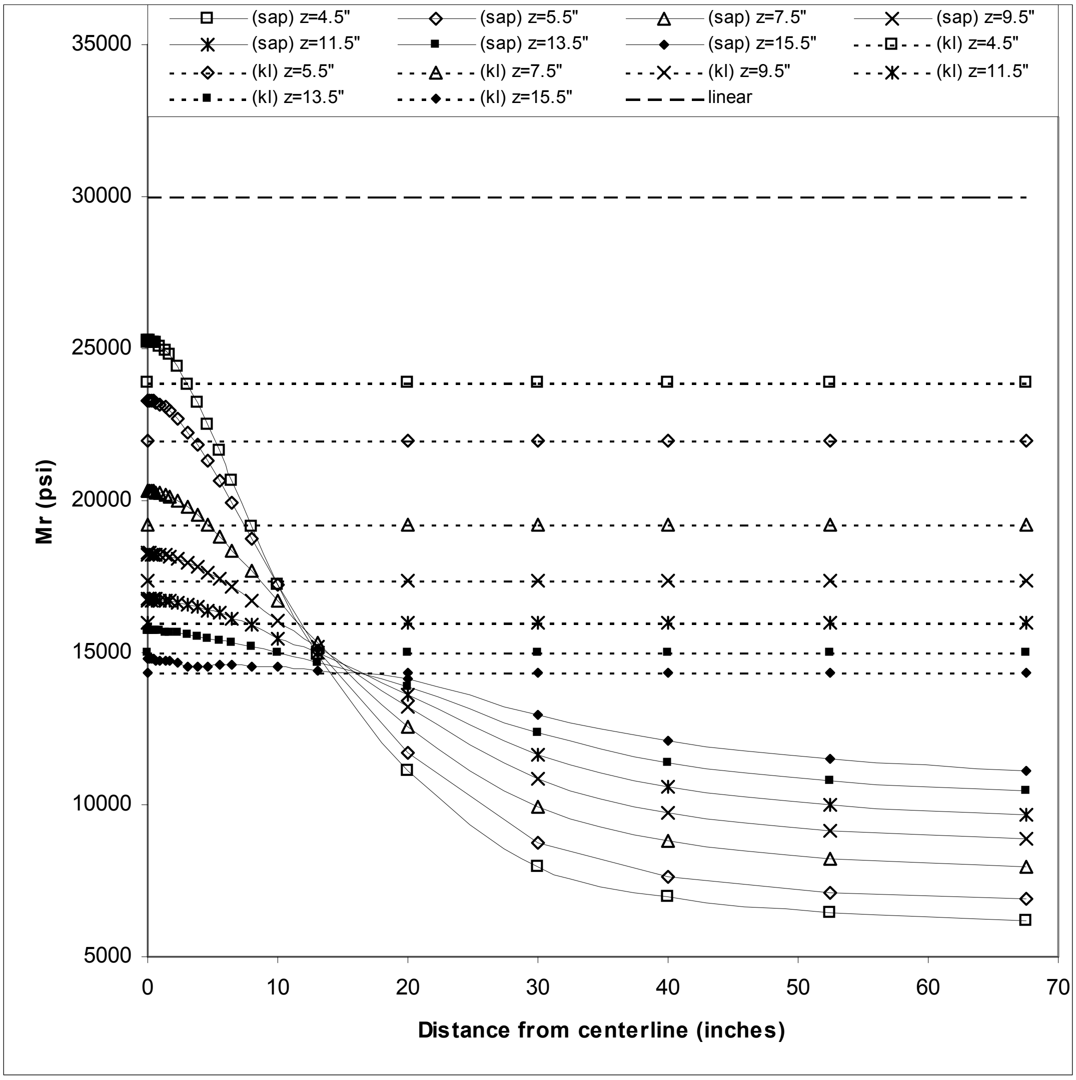

Figure A.6 Converged modulus values within the granular layer for "p06"

Table A.13 Input parameters used in the analysis of the pavement system "p07"

p07	h (inches)	Modulus (psi)	Unit Weight (pcf)	Poisson's Ratio	k0	Model Parameters	
						k1	k2
A.C.	4	300000	139.97	0.35	0.54	-	-
Granular Base	12	k-Q model	133.06	0.40	0.67	4480	0.53
Subgrade	semi-inf.	5000	125.00	0.45	0.82	-	-

Table A.14 Calculated responses and predicted lives for the pavement "p07"

p07	Fatigue of A.C.		Permanent deformation of subgrade	
	Tensile Strain (A.C.)	Life (Nf)	Compressive Strain (Subgrade)	Life (Nd)
Linear-elastic	0.00030060	646035	-0.00050710	769890
KENLAYER	0.00036270	348280	-0.00060180	357705
SAP90	0.00038054	297392	-0.00066440	229676

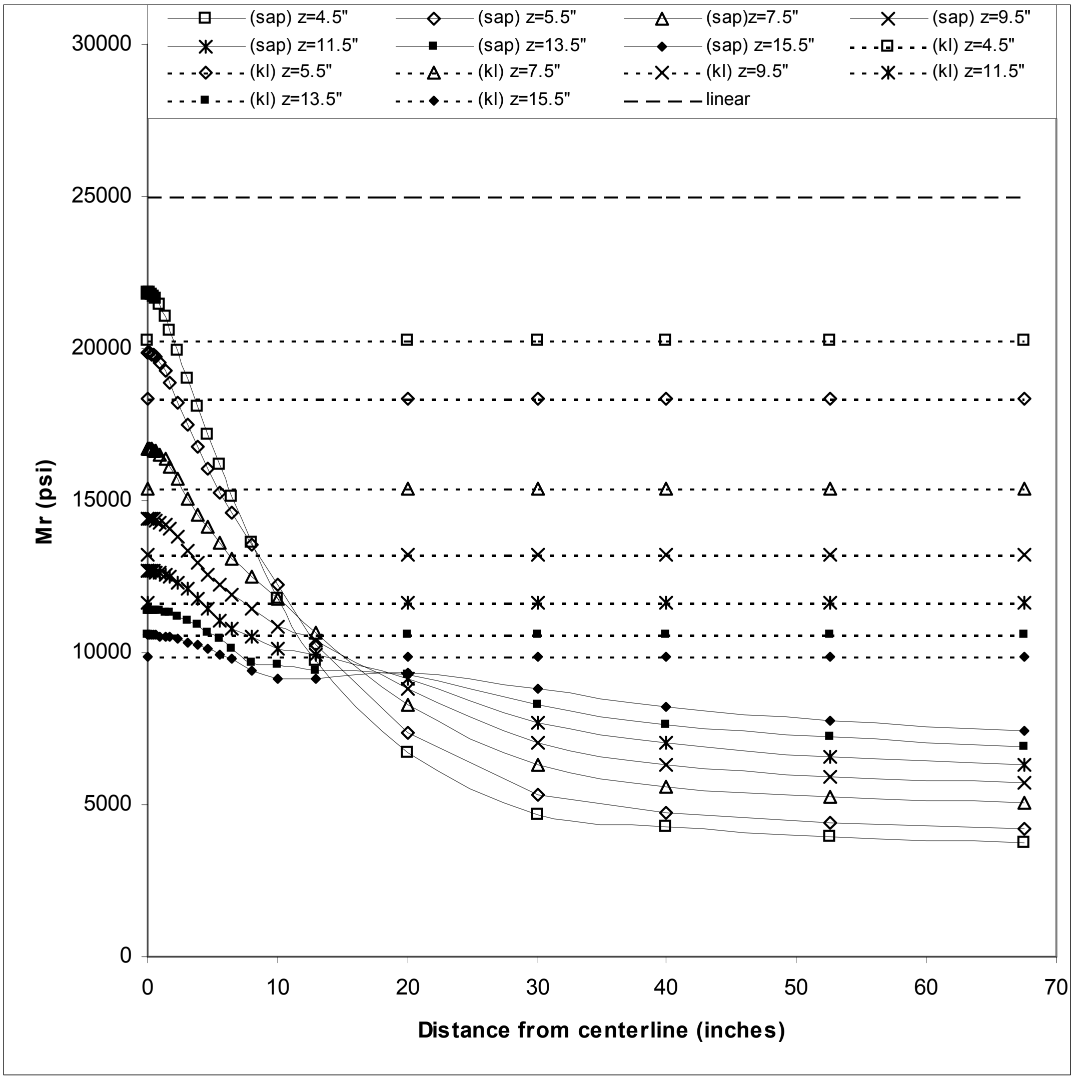

Figure A.7 Converged modulus values within the granular layer for "p07"

Table A.15 Input parameters used in the analysis of the pavement system "p08"

p08	h (inches)	Modulus (psi)	Unit Weight (pcf)	Poisson's Ratio	k0	Model Parameters	
						k1	k2
A.C.	4	500000	139.97	0.35	0.54	-	-
Granular Base	12	k-Q model	133.06	0.40	0.67	4480	0.53
Subgrade	semi-inf.	5000	125.00	0.45	0.82	-	-

Table A.16 Calculated responses and predicted lives for the pavement "p08"

p08	Fatigue of A.C.		Permanent deformation of subgrade	
	Tensile Strain (A.C.)	Life (Nf)	Compressive Strain (Subgrade)	Life (Nd)
Linear-elastic	0.00022820	1034005	-0.00044590	1369293
KENLAYER	0.00027890	534387	-0.00052290	671077
SAP90	0.00028645	489441	-0.00055760	503322

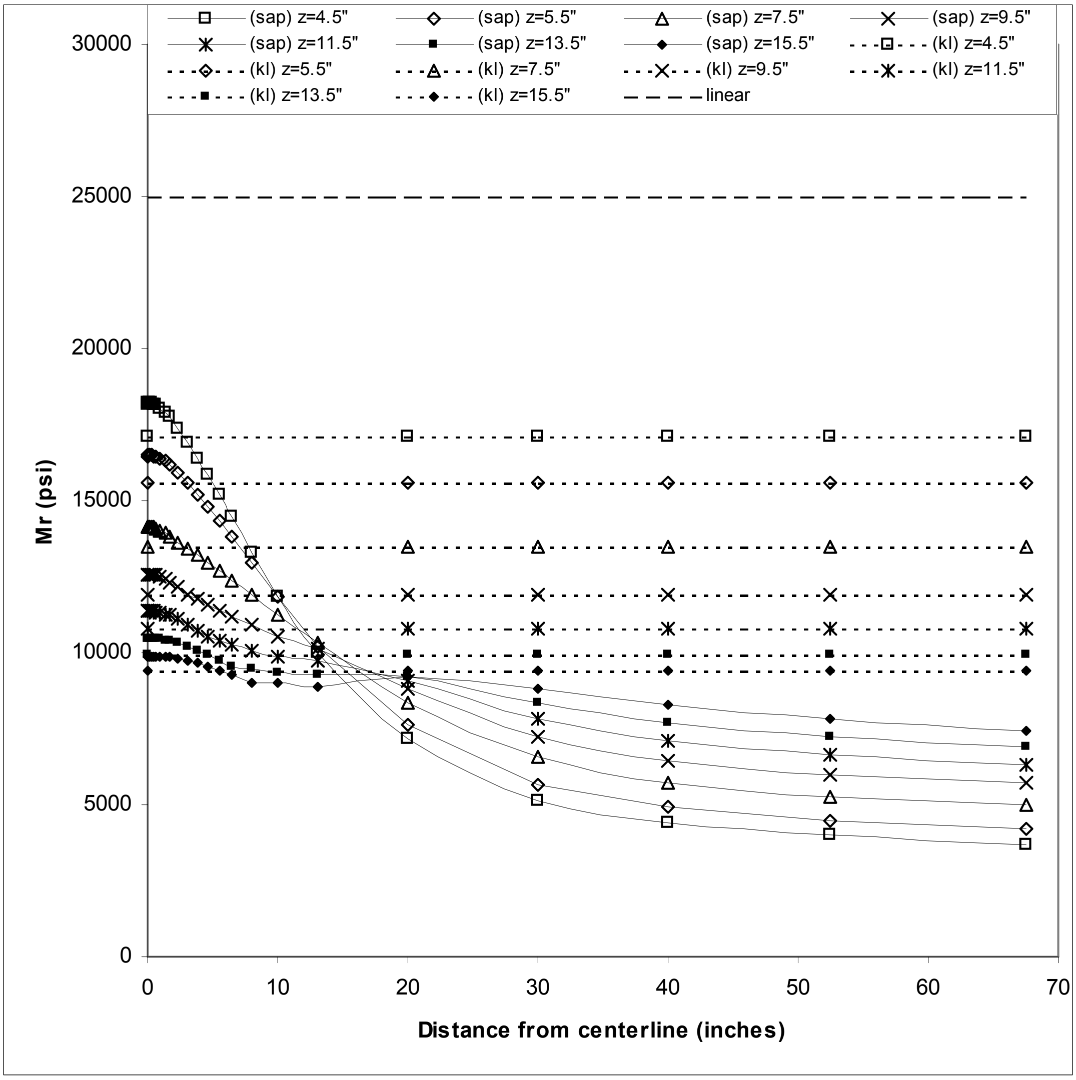

Figure A.8 Converged modulus values within the granular layer for "p08"

Table A.17 Input parameters used in the analysis of the pavement system "p09"

p09	h (inches)	Modulus (psi)	Unit Weight (pcf)	Poisson's Ratio	k0	Model Parameters	
						k1	k2
A.C.	4	700000	139.97	0.35	0.54	-	-
Granular Base	12	k-Q model	133.06	0.40	0.67	4480	0.53
Subgrade	semi-inf.	5000	125.00	0.45	0.82	-	-

Table A.18 Calculated responses and predicted lives for the pavement "p09"

p09	Fatigue of A.C.		Permanent deformation of subgrade	
	Tensile Strain (A.C.)	Life (Nf)	Compressive Strain (Subgrade)	Life (Nd)
Linear-elastic	0.00018680	1498849	-0.00040440	2120504
KENLAYER	0.00022740	784779	-0.00046560	1128336
SAP90	0.00023116	743543	-0.00049120	887910

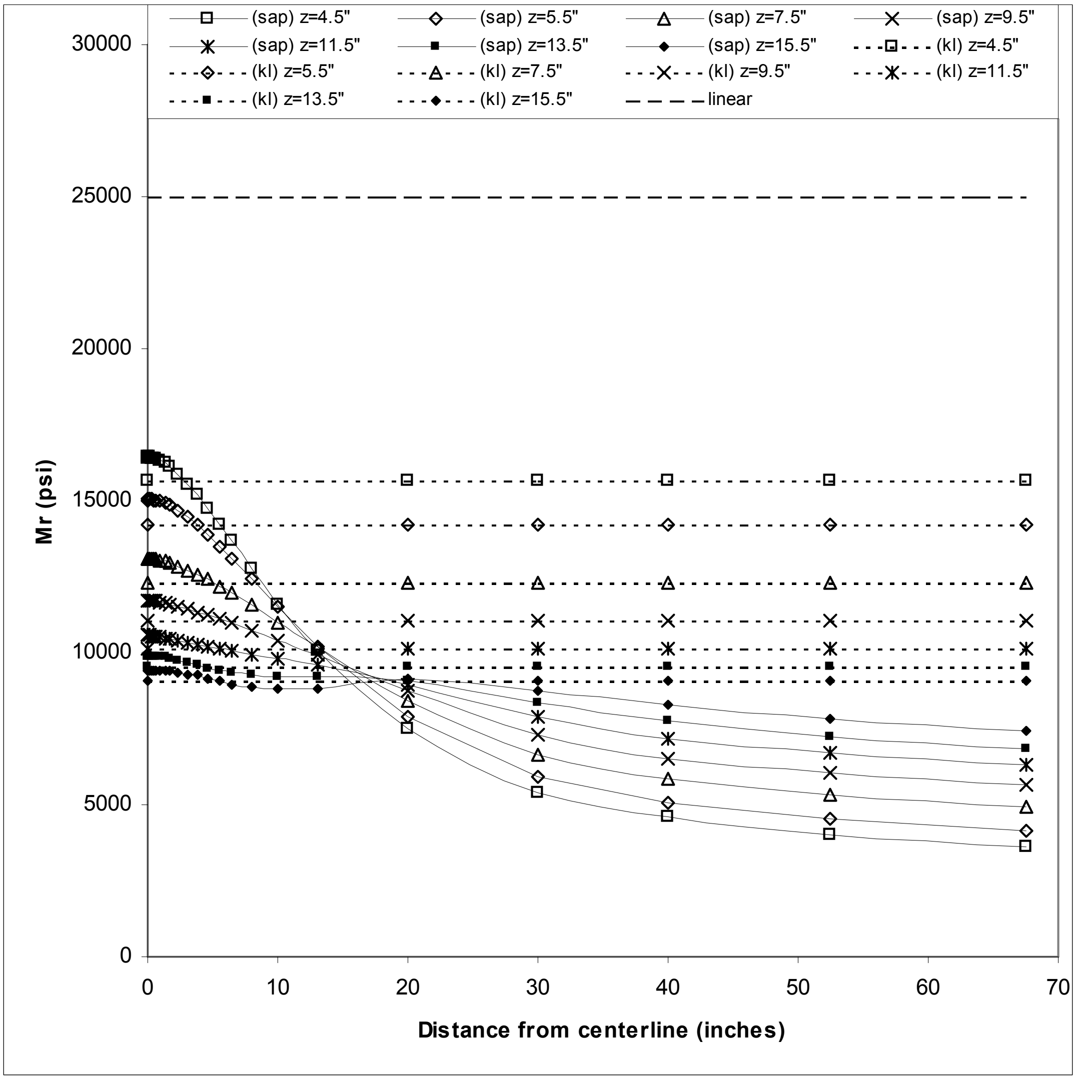

Figure A.9 Converged modulus values within the granular layer for "p09"

Table A.19 Input parameters used in the analysis of the pavement system "p10"

p10	h (inches)	Modulus (psi)	Unit Weight (pcf)	Poisson's Ratio	k0	Model Parameters	
						k1	k2
A.C.	4	300000	139.97	0.35	0.54	-	-
Granular Base	12	k-Q model	133.06	0.40	0.67	4480	0.53
Subgrade	semi-inf.	10000	125.00	0.45	0.82	-	-

Table A.20 Calculated responses and predicted lives for the pavement "p10"

p10	Fatigue of A.C.		Permanent deformation of subgrade	
	Tensile Strain (A.C.)	Life (Nf)	Compressive Strain (Subgrade)	Life (Nd)
Linear-elastic	0.00029490	688034	-0.00036900	3195624
KENLAYER	0.00034260	420136	-0.00039500	2355958
SAP90	0.00035030	390504	-0.00043330	1556789

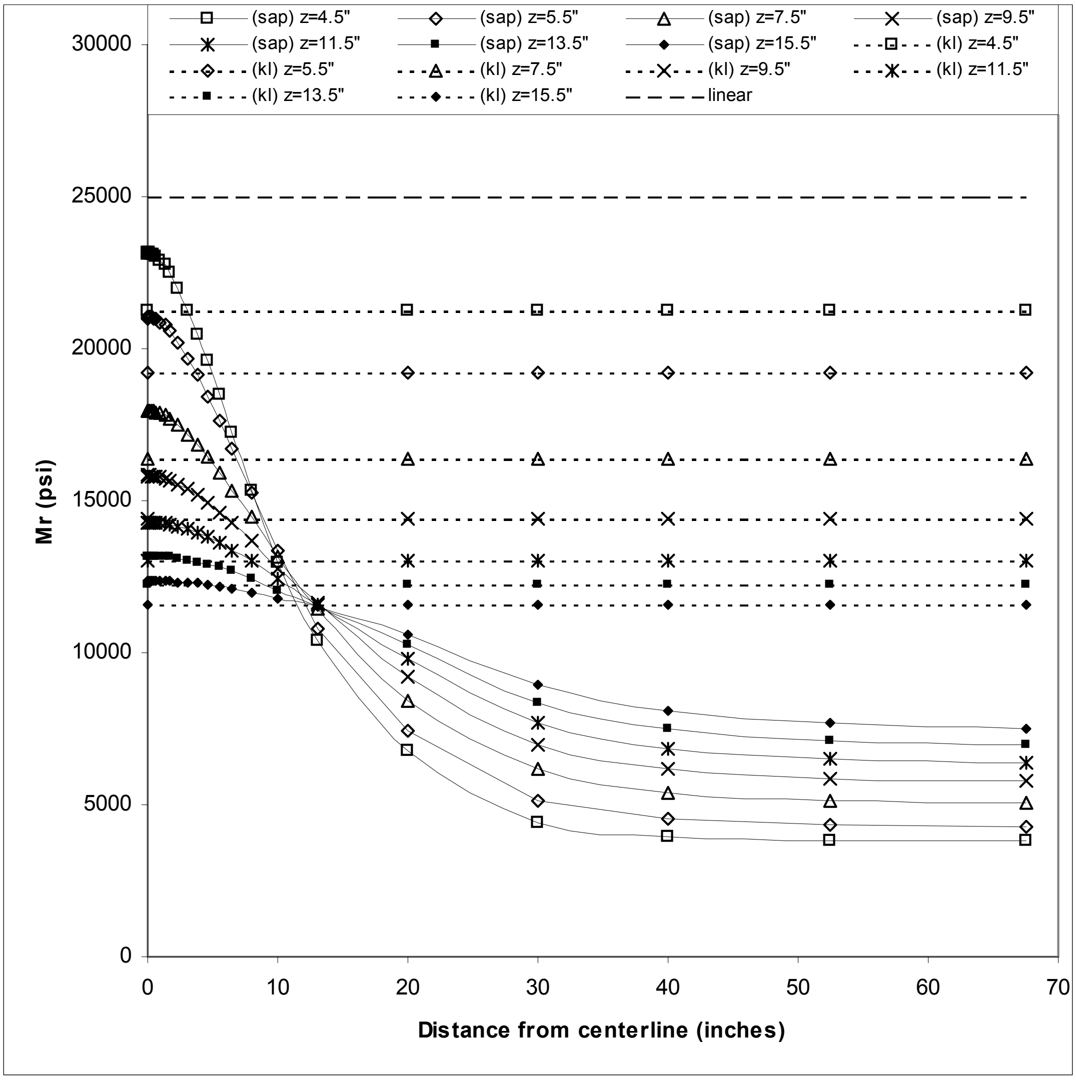

Figure A.10 Converged modulus values within the granular layer for "p10"

Table A.21 Input parameters used in the analysis of the pavement system "p11"

p11	h (inches)	Modulus (psi)	Unit Weight (pcf)	Poisson's Ratio	k0	Model Parameters	
						k1	k2
A.C.	4	500000	139.97	0.35	0.54	-	-
Granular Base	12	k-Q model	133.06	0.40	0.67	4480	0.53
Subgrade	semi-inf.	10000	125.00	0.45	0.82	-	-

Table A.22 Calculated responses and predicted lives for the pavement "p11"

p11	Fatigue of A.C.		Permanent deformation of subgrade	
	Tensile Strain (A.C.)	Life (Nf)	Compressive Strain (Subgrade)	Life (Nd)
Linear-elastic	0.00022150	1140517	-0.00032380	5736186
KENLAYER	0.00025810	689602	-0.00034130	4531912
SAP90	0.00026218	654929	-0.00036840	3218991

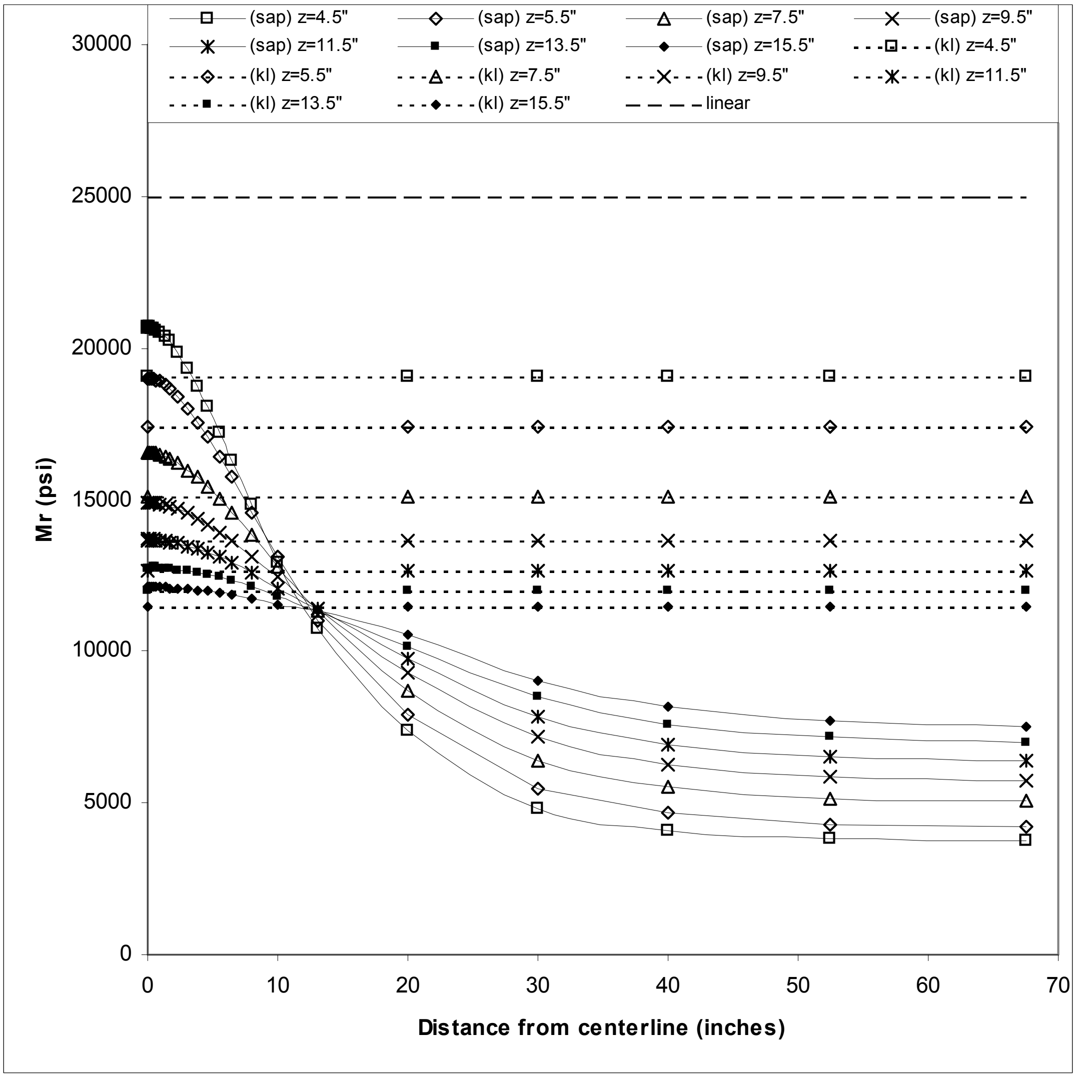

Figure A.11 Converged modulus values within the granular layer for "p11"

Table A.23 Input parameters used in the analysis of the pavement system "p12"

p12	h (inches)	Modulus (psi)	Unit Weight (pcf)	Poisson's Ratio	k0	Model Parameters	
						k1	k2
A.C.	4	700000	139.97	0.35	0.54	-	-
Granular Base	12	k-Q model	133.06	0.40	0.67	4480	0.53
Subgrade	semi-inf.	10000	125.00	0.45	0.82	-	-

Table A.24 Calculated responses and predicted lives for the pavement "p12"

p12	Fatigue of A.C.		Permanent deformation of subgrade	
	Tensile Strain (A.C.)	Life (Nf)	Compressive Strain (Subgrade)	Life (Nd)
Linear-elastic	0.00018010	1690237	-0.00029310	8959893
KENLAYER	0.00020860	1042423	-0.00030430	7575125
SAP90	0.00021166	993700	-0.00032640	5534434

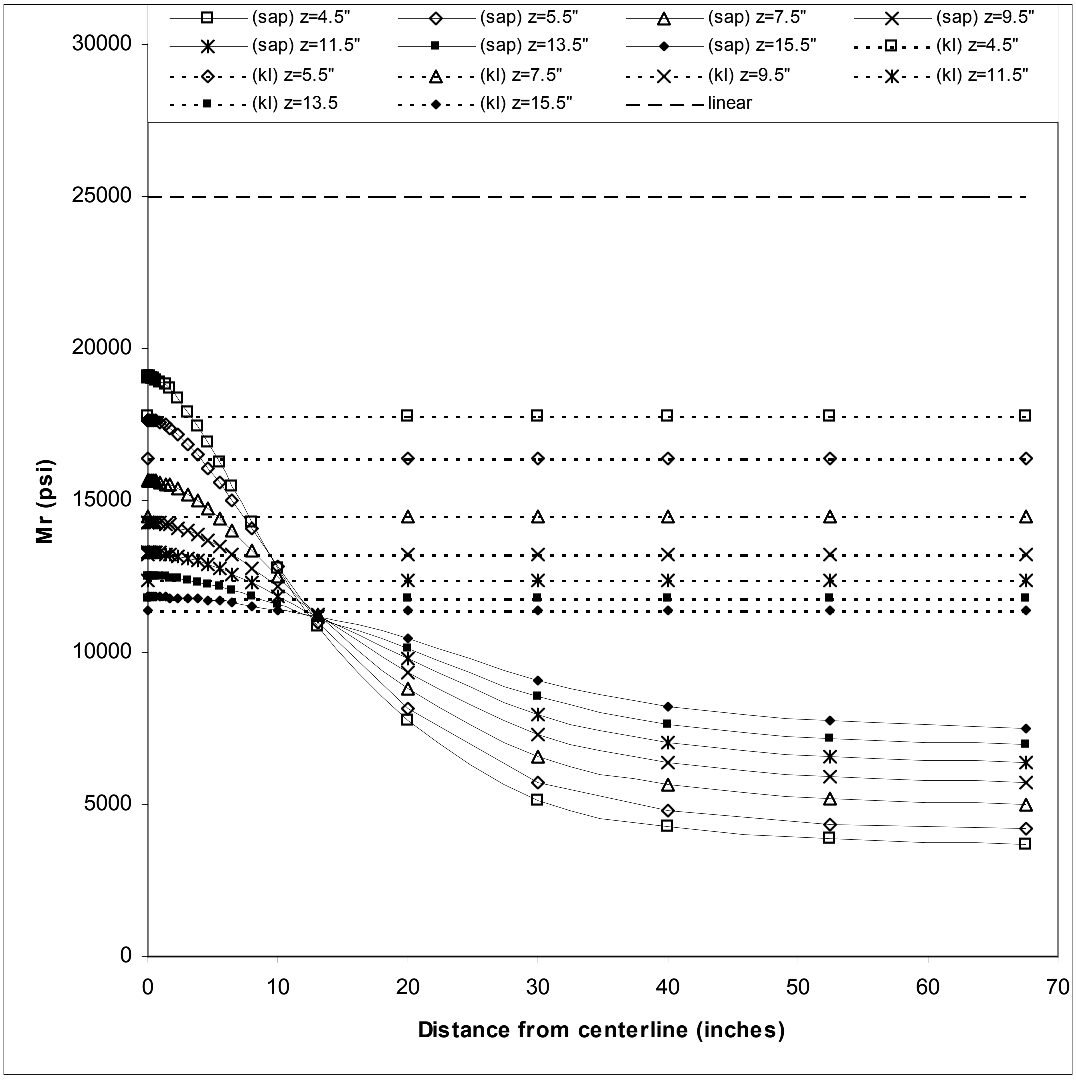

Figure A.12 Converged modulus values within the granular layer for "p12"

Table A.25 Input parameters used in the analysis of the pavement system "p13"

p13	h (inches)	Modulus (psi)	Unit Weight (pcf)	Poisson's Ratio	k0	Model Parameters	
						k1	k2
A.C.	4	300000	139.97	0.35	0.54	-	-
Granular Base	16	k-Q model	133.06	0.40	0.67	7210	0.45
Subgrade	semi-inf.	5000	125.00	0.45	0.82	-	-

Table A.26 Calculated responses and predicted lives for the pavement "p13"

p13	Fatigue of A.C.		Permanent deformation of subgrade	
	Tensile Strain (A.C.)	Life (Nf)	Compressive Strain (Subgrade)	Life (Nd)
Linear-elastic	0.00026710	952978	-0.00033570	4880322
KENLAYER	0.00030440	619879	-0.00041030	1987363
SAP90	0.00032152	517739	-0.00047200	1061437

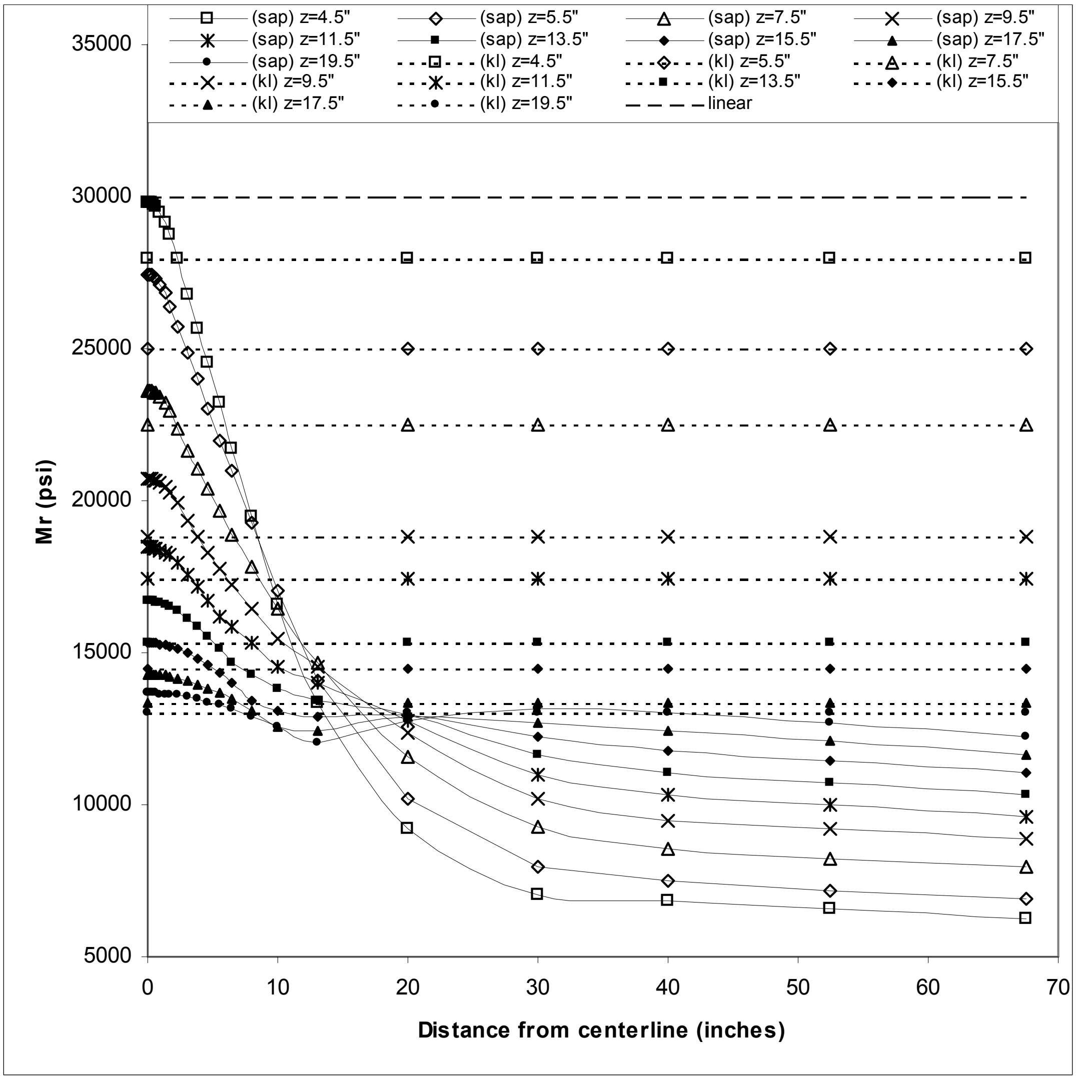

Figure A.13 Converged modulus values within the granular layer for "p13"

Table A.27 Input parameters used in the analysis of the pavement system "p14"

p14	h (inches)	Modulus (psi)	Unit Weight (pcf)	Poisson's Ratio	k0	Model Parameters	
						k1	k2
A.C.	4	500000	139.97	0.35	0.54	-	-
Granular Base	16	k-Q model	133.06	0.40	0.67	7210	0.45
Subgrade	semi-inf.	5000	125.00	0.45	0.82	-	-

Table A.28 Calculated responses and predicted lives for the pavement "p14"

p14	Fatigue of A.C.		Permanent deformation of subgrade	
	Tensile Strain (A.C.)	Life (Nf)	Compressive Strain (Subgrade)	Life (Nd)
Linear-elastic	0.00020470	1478439	-0.00030570	7421043
KENLAYER	0.00024110	862884	-0.00037600	2937762
SAP90	0.00025033	762549	-0.00041980	1793790

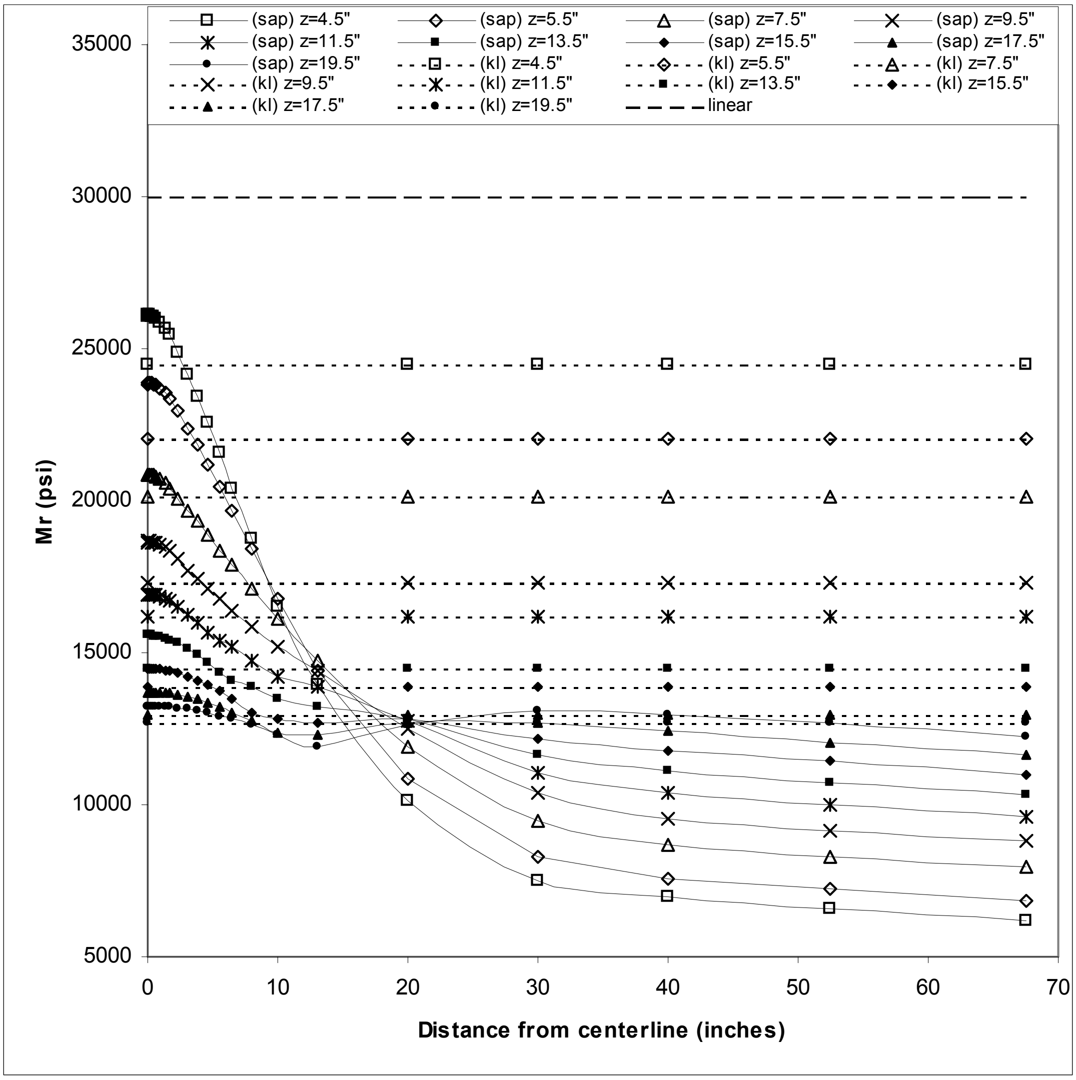

Figure A.14 Converged modulus values within the granular layer for "p14"

Table A.29 Input parameters used in the analysis of the pavement system "p15"

p15	h (inches)	Modulus (psi)	Unit Weight (pcf)	Poisson's Ratio	k0	Model Parameters	
						k1	k2
A.C.	4	700000	139.97	0.35	0.54	-	-
Granular Base	16	k-Q model	133.06	0.40	0.67	7210	0.45
Subgrade	semi-inf.	5000	125.00	0.45	0.82	-	-

Table A.30 Calculated responses and predicted lives for the pavement "p15"

p15	Fatigue of A.C.		Permanent deformation of subgrade	
	Tensile Strain (A.C.)	Life (Nf)	Compressive Strain (Subgrade)	Life (Nd)
Linear-elastic	0.00016860	2100035	-0.00028460	10221697
KENLAYER	0.00020030	1191400	-0.00034870	4116947
SAP90	0.00020576	1090512	-0.00038180	2743173

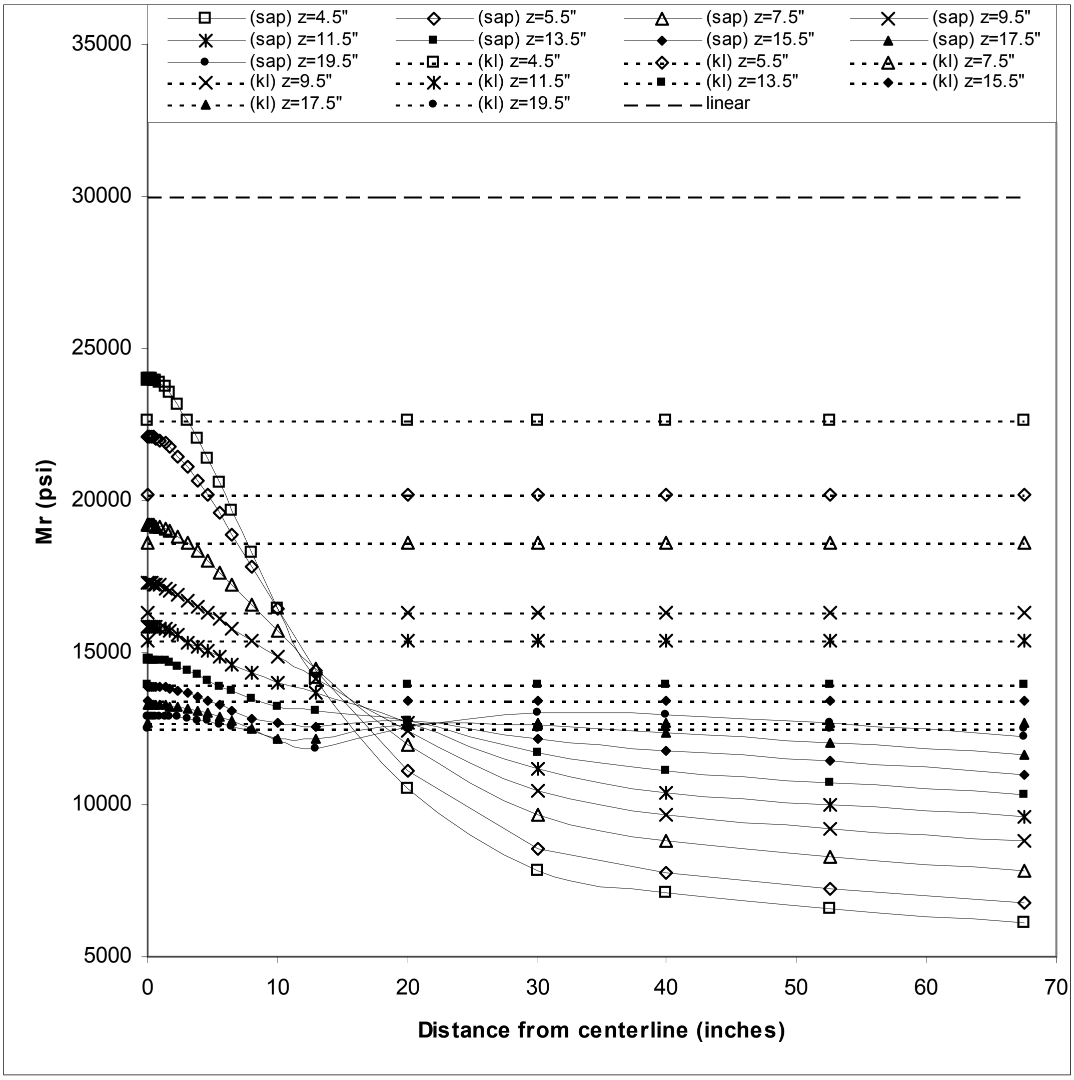

Figure A.15 Converged modulus values within the granular layer for "p15"

Table A.31 Input parameters used in the analysisof the pavement system "p16"

p16	h (inches)	Modulus (psi)	Unit Weight (pcf)	Poisson's Ratio	k0	Model Parameters	
						k1	k2
A.C.	4	300000	139.97	0.35	0.54	-	-
Granular Base	16	k-Q model	133.06	0.40	0.67	7210	0.45
Subgrade	semi-inf.	10000	125.00	0.45	0.82	-	-

Table A.32 Calculated responses and predicted lives for the pavement "p16"

p16	Fatigue of A.C.		Permanent deformation of subgrade	
	Tensile Strain (A.C.)	Life (Nf)	Compressive Strain (Subgrade)	Life (Nd)
Linear-elastic	0.00026620	963619	-0.00025070	18035106
KENLAYER	0.00029670	674396	-0.00027880	11208743
SAP90	0.00030727	601023	-0.00031610	6388787

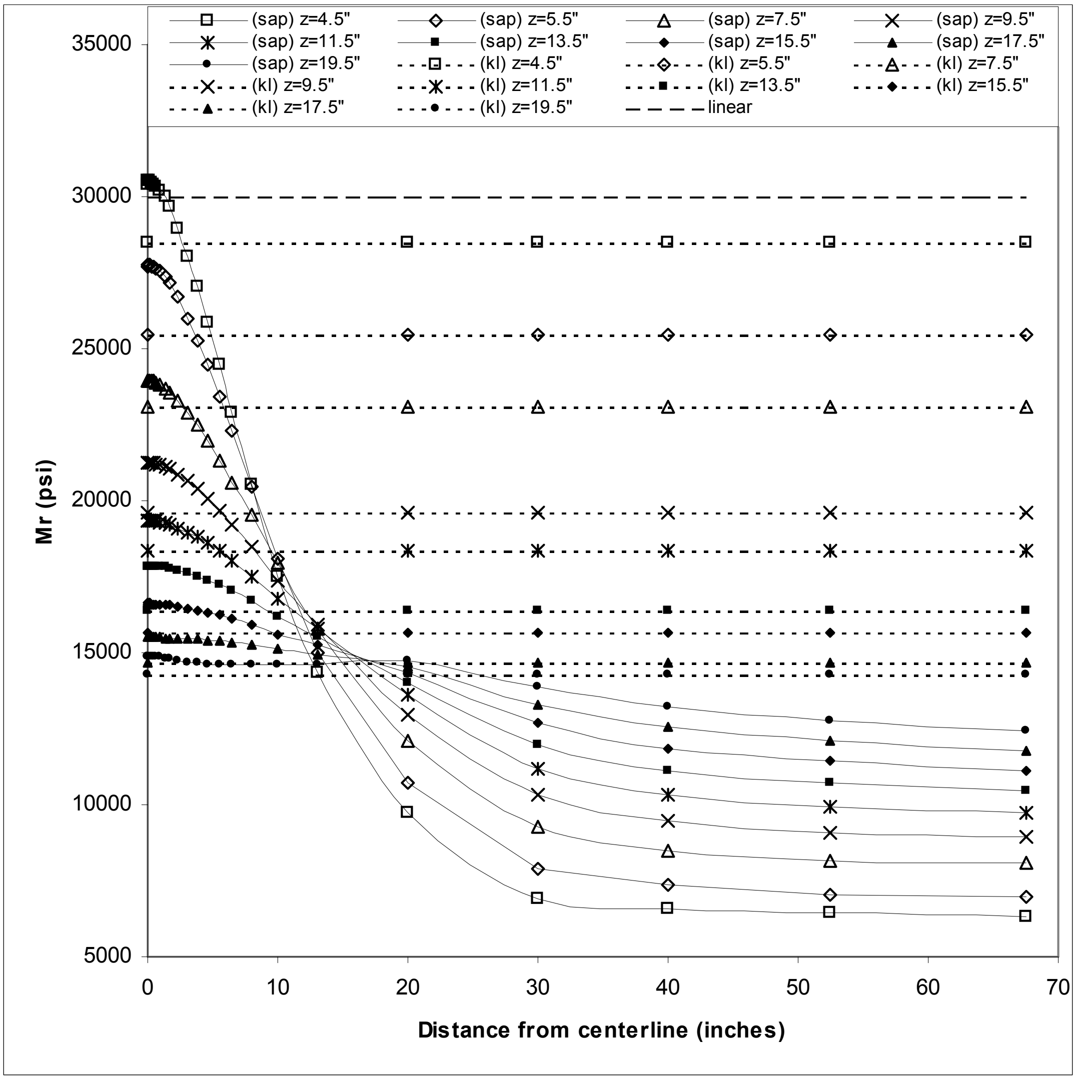

Figure A.16 Converged modulus values within the granular layer for "p16"

Table A.33 Input parameters used in the analysis of the pavement system "p17"

p17	h (inches)	Modulus (psi)	Unit Weight (pcf)	Poisson's Ratio	k0	Model Parameters	
						k1	k2
A.C.	4	500000	139.97	0.35	0.54	-	-
Granular Base	16	k-Q model	133.06	0.40	0.67	7210	0.45
Subgrade	semi-inf.	10000	125.00	0.45	0.82	-	-

Table A.34 Calculated responses and predicted lives for the pavement "p17"

p17	Fatigue of A.C.		Permanent deformation of subgrade	
	Tensile Strain (A.C.)	Life (Nf)	Compressive Strain (Subgrade)	Life (Nd)
Linear-elastic	0.00020240	1534435	-0.00022790	27638299
KENLAYER	0.00023140	987702	-0.00025320	17251452
SAP90	0.00023604	925288	-0.00028120	10786762

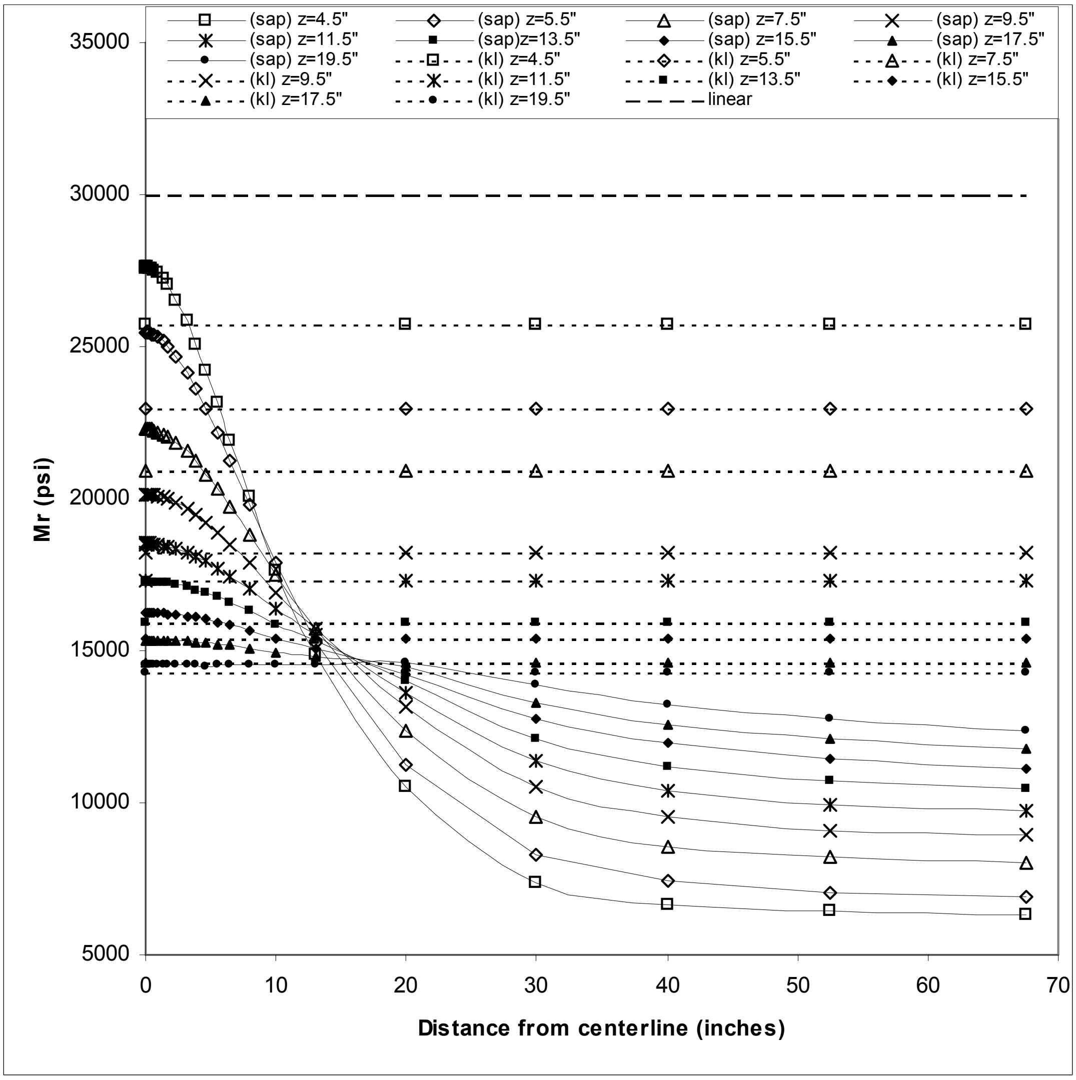

Figure A.17 Converged modulus values within the granular layer for "p17"

Table A.35 Input parameters used in the analysis of the pavement system "p18"

p18	h (inches)	Modulus (psi)	Unit Weight (pcf)	Poisson's Ratio	k0	Model Parameters	
						k1	k2
A.C.	4	700000	139.97	0.35	0.54	-	-
Granular Base	16	k-Q model	133.06	0.40	0.67	7210	0.45
Subgrade	semi-inf.	10000	125.00	0.45	0.82	-	-

Table A.36 Calculated responses and predicted lives for the pavement "p18"

p18	Fatigue of A.C.		Permanent deformation of subgrade	
	Tensile Strain (A.C.)	Life (Nf)	Compressive Strain (Subgrade)	Life (Nd)
Linear-elastic	0.00016580	2218987	-0.00021180	38367380
KENLAYER	0.00019000	1417387	-0.00023340	24839631
SAP90	0.00019339	1337354	-0.00025640	16308224

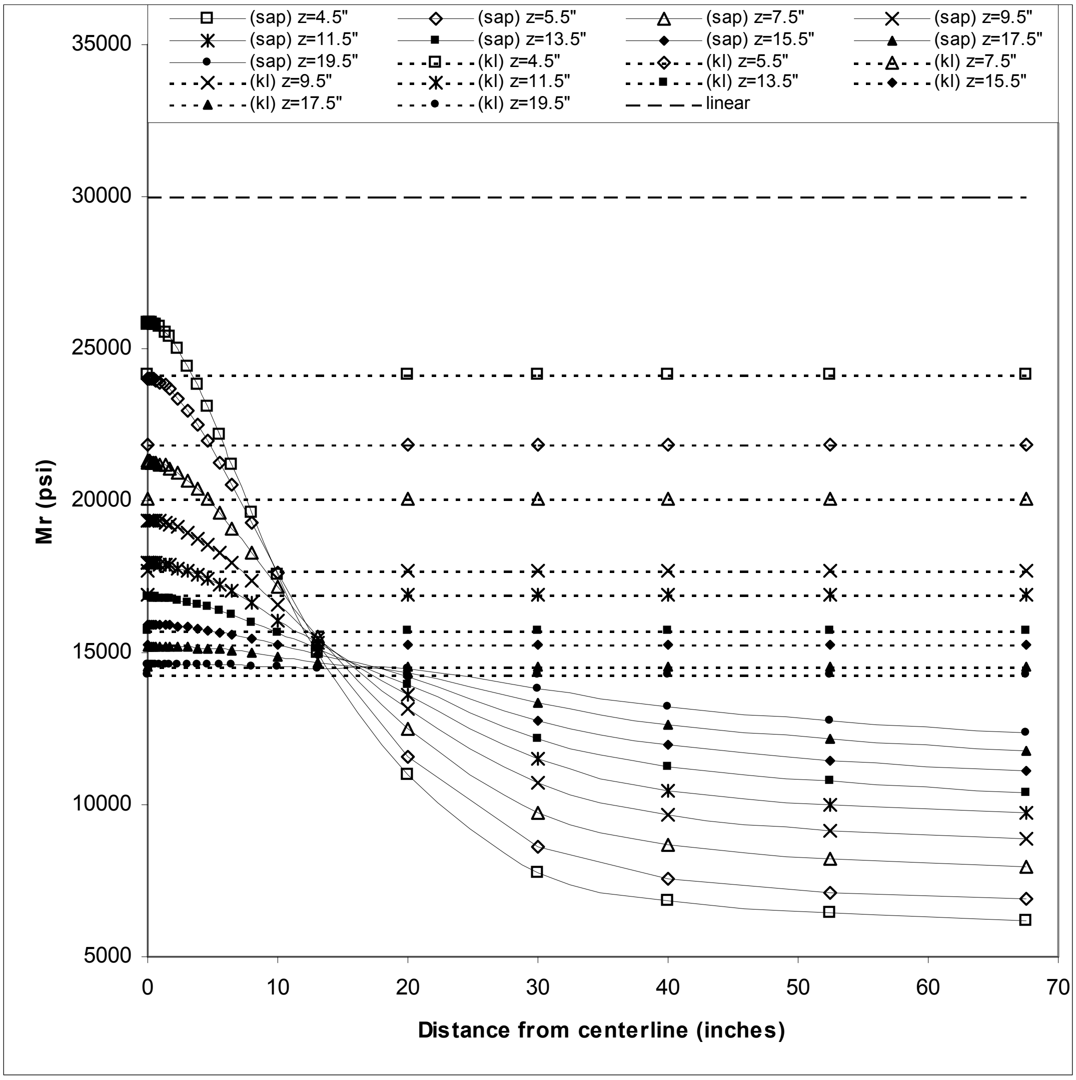

Figure A.18 Converged modulus values within the granular layer for "p18"

Table A.37 Input parameters used in the analysis of the pavement system "p19"

p19	h (inches)	Modulus (psi)	Unit Weight (pcf)	Poisson's Ratio	k0	Model Parameters	
						k1	k2
A.C.	4	300000	139.97	0.35	0.54	-	-
Granular Base	16	k-Q model	133.06	0.40	0.67	4480	0.53
Subgrade	semi-inf.	5000	125.00	0.45	0.82	-	-

Table A.38 Calculated responses and predicted lives for the pavement "p19"

p19	Fatigue of A.C.		Permanent deformation of subgrade	
	Tensile Strain (A.C.)	Life (Nf)	Compressive Strain (Subgrade)	Life (Nd)
Linear-elastic	0.00029230	708375	-0.00036410	3392717
KENLAYER	0.00035470	374798	-0.00045060	1306500
SAP90	0.00036888	329444	-0.00051060	746543

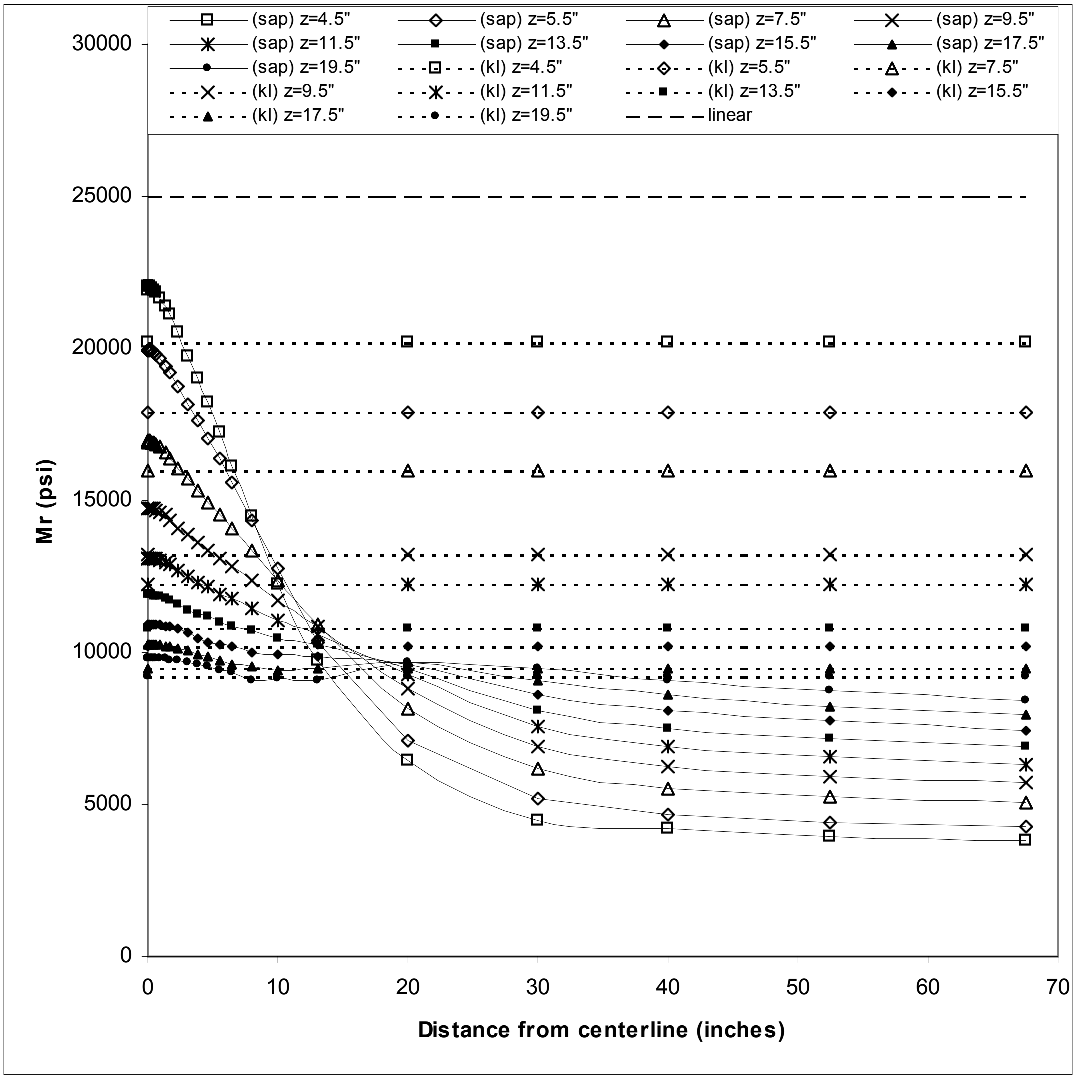

Figure A.19 Converged modulus values within the granular layer for "p19"

Table A.39 Input parameters used in the analysis of the pavement system "p20"

p20	h (inches)	Modulus (psi)	Unit Weight (pcf)	Poisson's Ratio	k0	Model Parameters	
						k1	k2
A.C.	4	500000	139.97	0.35	0.54	-	-
Granular Base	16	k-Q model	133.06	0.40	0.67	4480	0.53
Subgrade	semi-inf.	5000	125.00	0.45	0.82	-	-

Table A.40 Calculated responses and predicted lives for the pavement "p20"

p20	Fatigue of A.C.		Permanent deformation of subgrade	
	Tensile Strain (A.C.)	Life (Nf)	Compressive Strain (Subgrade)	Life (Nd)
Linear-elastic	0.00022070	1154175	-0.00032930	5319545
KENLAYER	0.00027270	575410	-0.00040520	2101825
SAP90	0.00027755	542992	-0.00044440	1390107

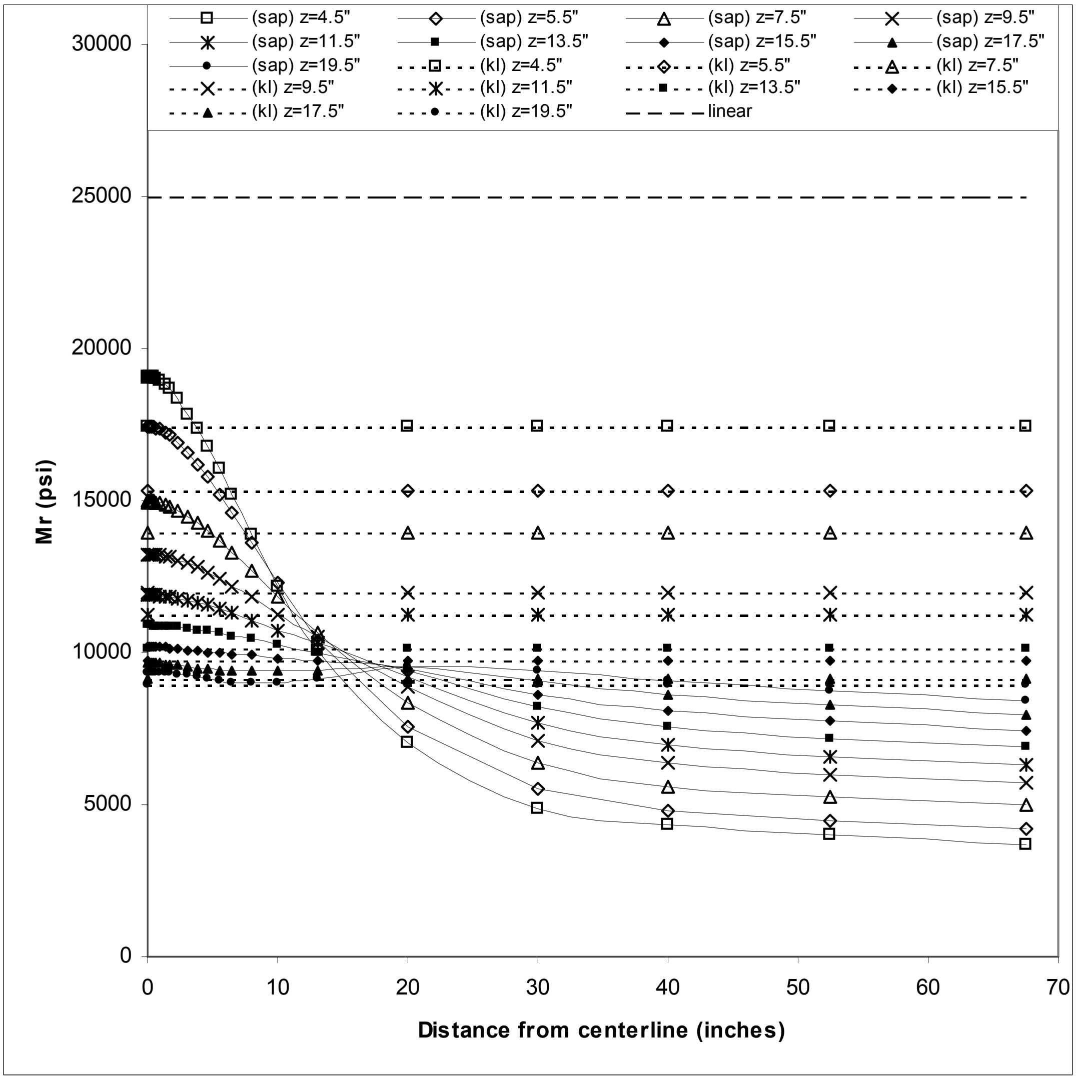

Figure A.20 Converged modulus values within the granular layer for "p20"

Table A.41 Input parameters used in the analysis of the pavement system "p21"

p21	h (inches)	Modulus (psi)	Unit Weight (pcf)	Poisson's Ratio	k0	Model Parameters	
						k1	k2
A.C.	4	700000	139.97	0.35	0.54	-	-
Granular Base	16	k-Q model	133.06	0.40	0.67	4480	0.53
Subgrade	semi-inf.	5000	125.00	0.45	0.82	-	-

Table A.42 Calculated responses and predicted lives for the pavement "p21"

p21	Fatigue of A.C.		Permanent deformation of subgrade	
	Tensile Strain (A.C.)	Life (Nf)	Compressive Strain (Subgrade)	Life (Nd)
Linear-elastic	0.00018020	1687153	-0.00030490	7508615
KENLAYER	0.00022170	853137	-0.00036940	3180161
SAP90	0.00022441	819725	-0.00040220	2172929

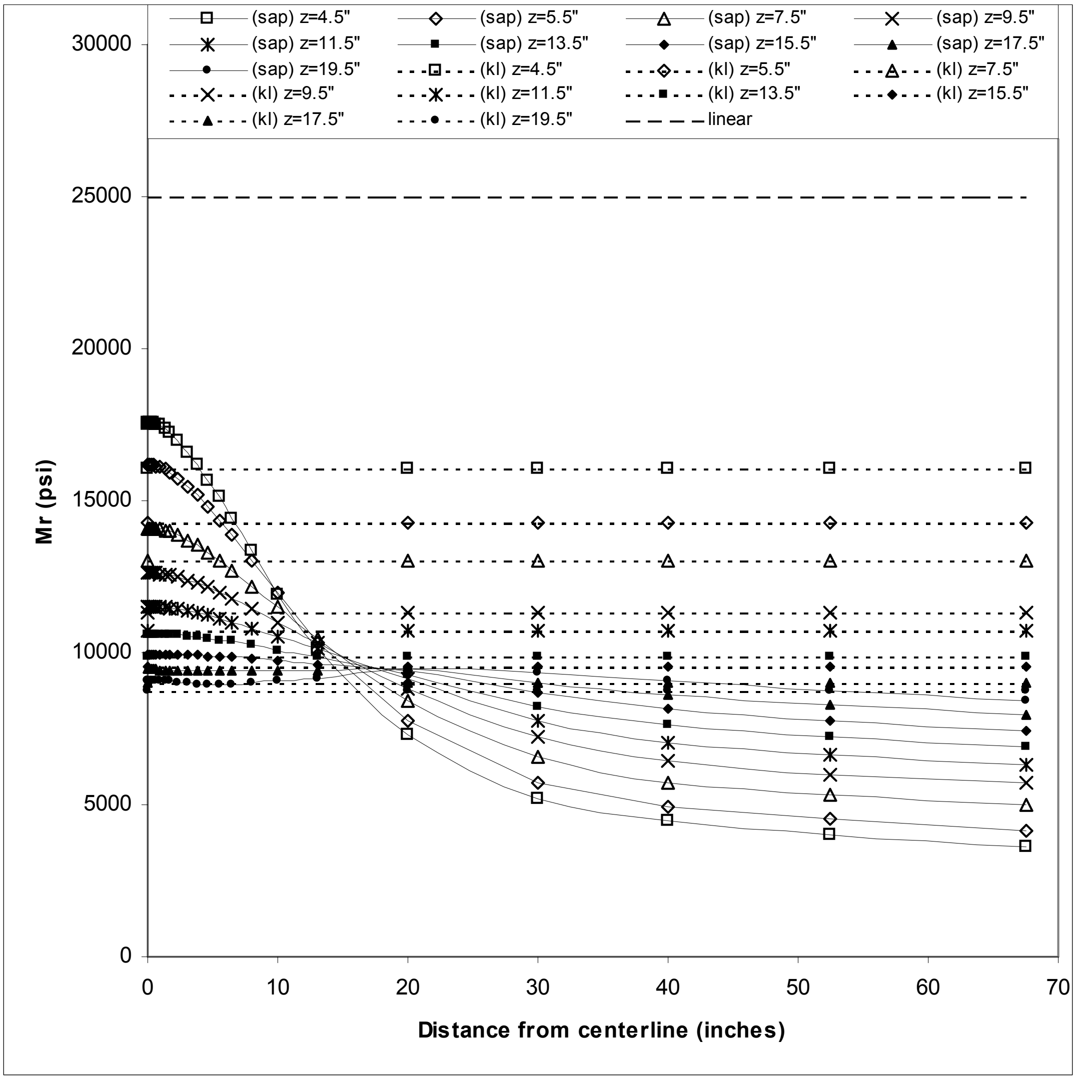

Figure A.21 Converged modulus values within the granular layer for "p21"

Table A.43 Input parameters used in the analysis of the pavement system "p22"

p22	h (inches)	Modulus (psi)	Unit Weight (pcf)	Poisson's Ratio	k0	Model Parameters	
						k1	k2
A.C.	4	300000	139.97	0.35	0.54	-	-
Granular Base	16	k-Q model	133.06	0.40	0.67	4480	0.53
Subgrade	semi-inf.	10000	125.00	0.45	0.82	-	-

Table A.44 Calculated responses and predicted lives for the pavement "p22"

p22	Fatigue of A.C.		Permanent deformation of subgrade	
	Tensile Strain (A.C.)	Life (Nf)	Compressive Strain (Subgrade)	Life (Nd)
Linear-elastic	0.00029040	723738	-0.00026610	13810416
KENLAYER	0.00033980	431633	-0.00029320	8946220
SAP90	0.00034677	403761	-0.00033420	4979157

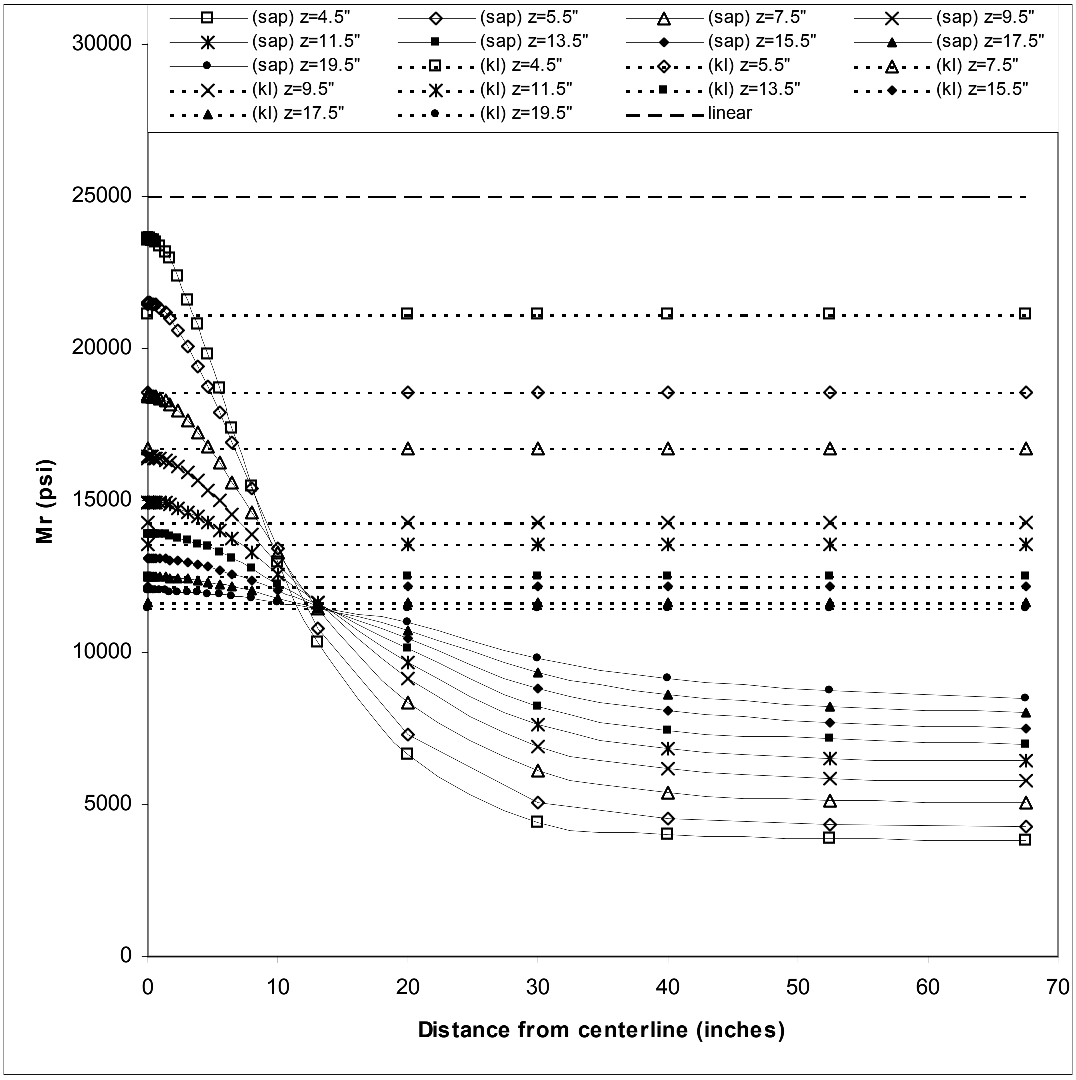

Figure A.22 Converged modulus values within the granular layer for "p22"

Table A.45 Input parameters used in the analysis of the pavement system "p23"

p23	h (inches)	Modulus (psi)	Unit Weight (pcf)	Poisson's Ratio	k0	Model Parameters	
						k1	k2
A.C.	4	500000	139.97	0.35	0.54	-	-
Granular Base	16	k-Q model	133.06	0.40	0.67	4480	0.53
Subgrade	semi-inf.	10000	125.00	0.45	0.82	-	-

Table A.46 Calculated responses and predicted lives for the pavement "p23"

p23	Fatigue of A.C.		Permanent deformation of subgrade	
	Tensile Strain (A.C.)	Life (Nf)	Compressive Strain (Subgrade)	Life (Nd)
Linear-elastic	0.00021750	1210989	-0.00024020	21842750
KENLAYER	0.00025570	711127	-0.00026150	14931790
SAP90	0.00026019	671536	-0.00029240	9056324

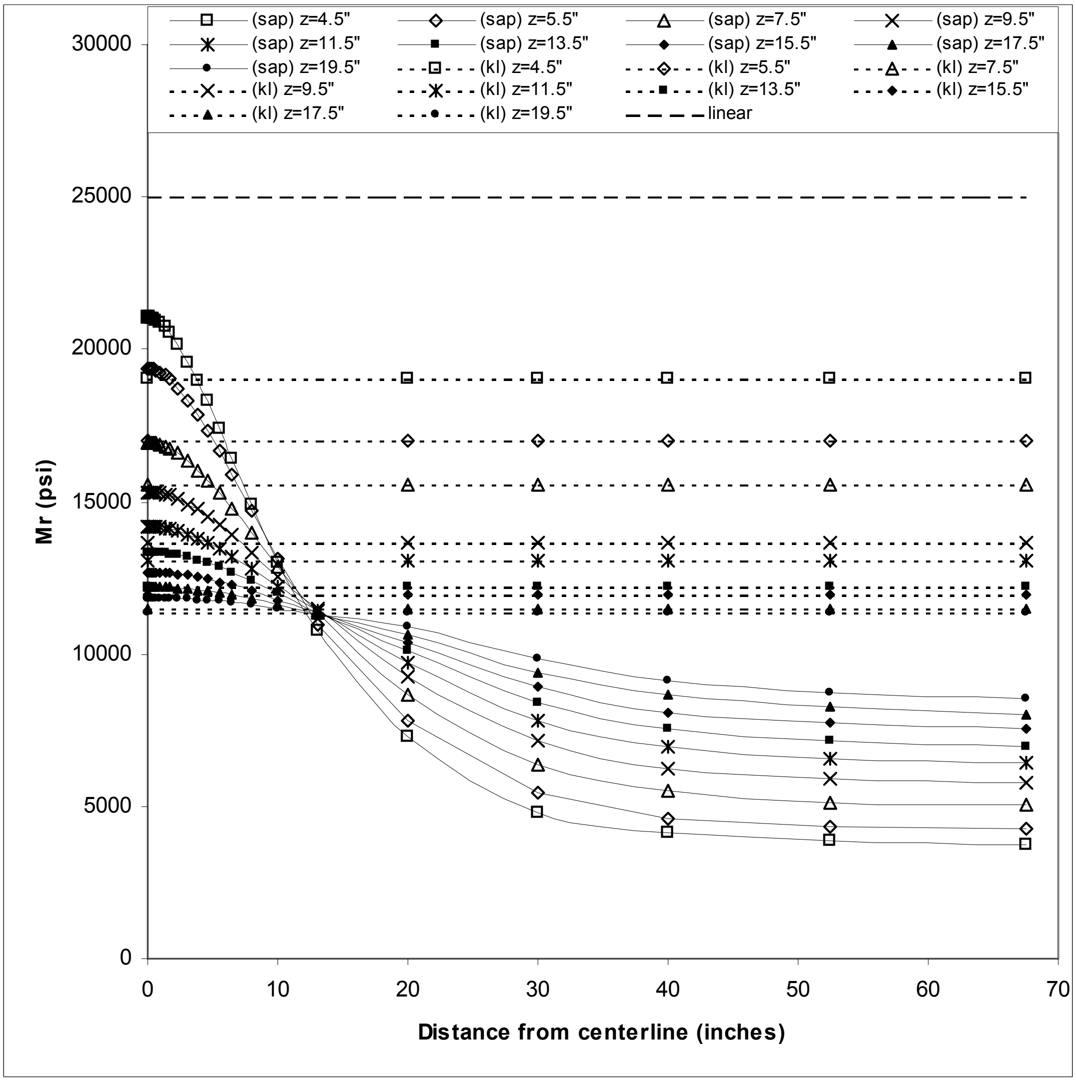

Figure A.23 Converged modulus values within the granular layer for "p23"

Table A.47 Input parameters used in the analysis of the pavement system "p24"

p24	h (inches)	Modulus (psi)	Unit Weight (pcf)	Poisson's Ratio	k0	Model Parameters	
						k1	k2
A.C.	4	700000	139.97	0.35	0.54	-	-
Granular Base	16	k-Q model	133.06	0.40	0.67	4480	0.53
Subgrade	semi-inf.	10000	125.00	0.45	0.82	-	-

Table A.48 Calculated responses and predicted lives for the pavement "p24"

p24	Fatigue of A.C.		Permanent deformation of subgrade	
	Tensile Strain (A.C.)	Life (Nf)	Compressive Strain (Subgrade)	Life (Nd)
Linear-elastic	0.00017660	1802970	-0.00022190	31144862
KENLAYER	0.00020700	1069167	-0.00023840	22590850
SAP90	0.00021033	1014410	-0.00026440	14212423

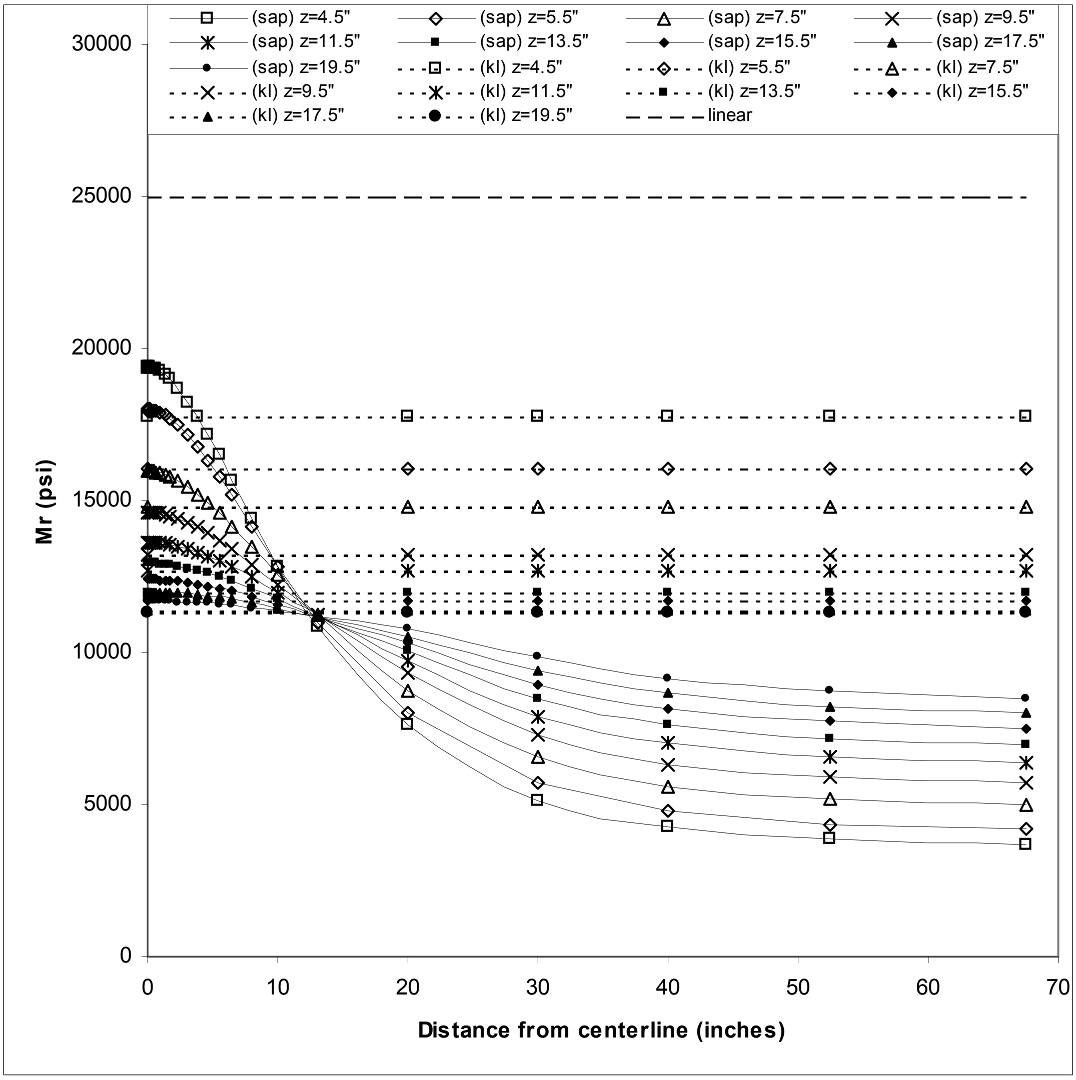

Figure A.24 Converged modulus values within the granular layer for "p24"

APPENDIX B

EXAMPLE INPUT AND OUTPUT FILES OF PROGRAM KENLAYER

B.1 General

As explained earlier, KENLAYER is a computer program written in Visual Basic language in order to solve an elastic multi-layered system under a circular loaded area and its solution principle is based on the Burmister's multi-layered elastic theory similar to other programs using analytical approach. But the superiority of KENLAYER over the other elastic layer programs is its capability of solving systems either linear-elastic, nonlinear-elastic or viscoelastic [*Huang, 2004*]. Non-linear analysis is performed by using a simplified iterative tecnique explained in section 4.3. In order to enter and edit input data, program named LAYERINP is used. This program uses menus and forms for data entry in order to create and edit the data file.

B.2 KENLAYER Input File

After entering all required inputs for flexible pavement system by using the program LAYERINP, KENLAYER writes this data to a file with an extension of LAY. Then program KENLAYER reads required inputs from this data file and performs analysis. In figure B.1, the input file of pavement system "p05" edited by the program LAYERINP is shown.

```
1
Pavement System p05
 2  0  1  1
14  2  0
4  1  1  1  1  1  1  1  1  1  1  1  1  1
0.35  0.4  0.4  0.4  0.4  0.4  0.4  0.4  0.4  0.4  0.4  0.4  0.4  0.45
4  16.001
500000  30000  30000  30000  30000  30000  30000  30000  30000  30000  30000  30000  30000  10000
0
4.231  80
19
0  0.025  0.075  0.125  0.25  0.45  0.65  0.95  1.35  1.75  2.35  3.15  3.8905  4.656  5.5325  6.492  8  10  13
12
2  0  3  0  4  0  5  0  6  0  7  0  8  0  9  0  10  0  11  0  12  0  13  0
4.5  5.5  6.5  7.5  8.5  9.5  10.5  11.5  12.5  13.5  14.5  15.5
0  0  0  0
139.97  133.06  133.06  133.06  133.06  133.06  133.06  133.06  133.06  133.06  133.06  133.06  133.06  125
0.45  0.67
0.45  0.67
0.45  0.67
0.45  0.67
0.45  0.67
0.45  0.67
0.45  0.67
0.45  0.67
0.45  0.67
0.45  0.67
0.45  0.67
0.45  0.67
0  7210
0  7210
0  7210
0  7210
0  7210
0  7210
0  7210
0  7210
0  7210
0  7210
0  7210
0  7210
```

Figure B.1 Input file "p05.LAY" for the analysis of the pavement system "p05"

B.3 KENLAYER Output File

After the analysis, program KENLAYER writes the input parameters and calculated results with an understandable format into a file having an extension of TXT. In figure B.2, generated output file of the pavement system "p05" is shown.

```
NUMBER OF PROBLEMS TO BE SOLVED =  1

TITLE -Pavement System p05

MATL = 2 FOR NONLINEAR ELASTIC LAYERED SYSTEM
NDAMA = 0, SO DAMAGE ANALYSIS WILL NOT BE PERFORMED
NUMBER OF PERIODS PER YEAR (NPY) =  1
NUMBER OF LOAD GROUPS (NLG) =  1
TOLERANCE FOR INTEGRATION (DEL) -- =  0.001
NUMBER OF LAYERS (NL)------------- =  14
NUMBER OF Z COORDINATES (NZ)------ =  2
LIMIT OF INTEGRATION CYCLES (ICL)- =  80
COMPUTING CODE (NSTD)------------- =  9
SYSTEM OF UNITS (NUNIT)------------=  0

Length and displacement in in., stress and modulus in psi
unit weight in pcf, and temperature in F

THICKNESSES OF LAYERS (TH) ARE : 4  1  1  1  1  1  1  1  1  1  1  1  1
POISSON'S RATIOS OF LAYERS (PR) ARE : 0.35  0.4  0.4  0.4  0.4  0.4  0.4  0.4
 0.4  0.4  0.4  0.4  0.4  0.45
VERTICAL COORDINATES OF POINTS (ZC) ARE:  4  16.001
ALL INTERFACES ARE FULLY BONDED

FOR PERIOD NO. 1 LAYER NO. AND MODULUS ARE :    1  5.000E+05   2  3.000E+04
   3  3.000E+04   4  3.000E+04   5  3.000E+04   6  3.000E+04   7  3.000E+04
   8  3.000E+04   9  3.000E+04  10  3.000E+04  11  3.000E+04  12  3.000E+04
  13  3.000E+04  14  1.000E+04

LOAD GROUP NO. 1 HAS 1 CONTACT AREA
CONTACT RADIUS (CR)--------------- =  4.231
CONTACT PRESSURE (CP)------------- =  80
RADIAL COORDINATES OF  19  POINT(S) (RC) ARE :  0  0.025  0.075  0.125  0.25
 0.45  0.65  0.95  1.35  1.75  2.35  3.15  3.8905  4.656  5.5325  6.492  8
 10  13

NUMBER OF NONLINEAR LAYERS (NOLAY)-------------------------- =  12
MAXIMUM NUMBER OF ITERATIONS FOR NONLINEAR ANALYSIS (ITENOL) =  10

LAYER NUMBER (LAYNO) AND SOIL TYPE (NCLAY) ARE:  2  0  3  0  4  0  5  0  6  0
 7  0  8  0  9  0  10  0  11  0  12  0  13  0

Z COORDINATES (ZCNOL) FOR COMPUTING ELASTIC MODULUS ARE:  4.5  5.5  6.5  7.5
 8.5  9.5  10.5  11.5  12.5  13.5  14.5  15.5
R COORDINATE (RCNOL) FOR COMPUTING ELASTIC MODULUS ---------- =  0
X COORDINATE (XPTNOL) FOR COMPUTING ELASTIC MODULUS --------- =  0
Y COORDINATE (YPTNOL) FOR COMPUTING ELASTIC MODULUS --------- =  0
SLOPE OF LOAD DISTRIBUTION (SLD) ---------------------------- =  0
TOLERANCE (DELNOL) FOR NONLINEAR ANALYSIS ------------------- =  0.01
RELAXATION FACTORS (RELAX) FOR NONLINEAR ANALYSIS OF EACH PERIOD ARE: 0.5


UNIT WEIGHT OF LAYERS (GAM) ARE:  139.97  133.06  133.06  133.06  133.06
 133.06  133.06  133.06  133.06  133.06  133.06  133.06  133.06  125
```

```
LAYER NO. =  2     NCLAY =  0     K2 =  0.45     K0 =  0.67
LAYER NO. =  3     NCLAY =  0     K2 =  0.45     K0 =  0.67
LAYER NO. =  4     NCLAY =  0     K2 =  0.45     K0 =  0.67
LAYER NO. =  5     NCLAY =  0     K2 =  0.45     K0 =  0.67
LAYER NO. =  6     NCLAY =  0     K2 =  0.45     K0 =  0.67
LAYER NO. =  7     NCLAY =  0     K2 =  0.45     K0 =  0.67
LAYER NO. =  8     NCLAY =  0     K2 =  0.45     K0 =  0.67
LAYER NO. =  9     NCLAY =  0     K2 =  0.45     K0 =  0.67
LAYER NO. =  10    NCLAY =  0     K2 =  0.45     K0 =  0.67
LAYER NO. =  11    NCLAY =  0     K2 =  0.45     K0 =  0.67
LAYER NO. =  12    NCLAY =  0     K2 =  0.45     K0 =  0.67
LAYER NO. =  13    NCLAY =  0     K2 =  0.45     K0 =  0.67

LAYER NUMBER AND GEOSTATIC STRESS (GEOS) ARE:
   2    0.36251   3    0.43951   4    0.51651   5    0.59351   6    0.67052
   7    0.74752   8    0.82452   9    0.90152  10    0.97852  11    1.05553
  12    1.13253  13    1.20953

FOR PERIOD 1  LAYER NO. =  2  NCLAY =  0  PHI =  0   K1 =  7210
FOR PERIOD 1  LAYER NO. =  3  NCLAY =  0  PHI =  0   K1 =  7210
FOR PERIOD 1  LAYER NO. =  4  NCLAY =  0  PHI =  0   K1 =  7210
FOR PERIOD 1  LAYER NO. =  5  NCLAY =  0  PHI =  0   K1 =  7210
FOR PERIOD 1  LAYER NO. =  6  NCLAY =  0  PHI =  0   K1 =  7210
FOR PERIOD 1  LAYER NO. =  7  NCLAY =  0  PHI =  0   K1 =  7210
FOR PERIOD 1  LAYER NO. =  8  NCLAY =  0  PHI =  0   K1 =  7210
FOR PERIOD 1  LAYER NO. =  9  NCLAY =  0  PHI =  0   K1 =  7210
FOR PERIOD 1  LAYER NO. =  10 NCLAY =  0  PHI =  0   K1 =  7210
FOR PERIOD 1  LAYER NO. =  11 NCLAY =  0  PHI =  0   K1 =  7210
FOR PERIOD 1  LAYER NO. =  12 NCLAY =  0  PHI =  0   K1 =  7210
FOR PERIOD 1  LAYER NO. =  13 NCLAY =  0  PHI =  0   K1 =  7210

FOR LOAD GROUP 1  LAYER NO. AND R COORDINATE FOR COMPUTING MODULUS ARE:
 2  0  3  0  4  0  5  0  6  0  7  0  8  0  9  0  10  0  11  0  12  0  13  0

PERIOD NO.  1   LOAD GROUP NO.  1

AT ITERATION 1 LAYER NO. AND MODULUS ARE :      2  3.000E+04   3  3.000E+04
   4  3.000E+04   5  3.000E+04   6  3.000E+04   7  3.000E+04   8  3.000E+04   9
3.000E+04  10  3.000E+04  11  3.000E+04  12  3.000E+04  13  3.000E+04
AT ITERATION 2 LAYER NO. AND MODULUS ARE :      2  2.995E+04   3  2.858E+04
   4  2.736E+04   5  2.625E+04   6  2.527E+04   7  2.465E+04   8  2.409E+04   9
2.358E+04  10  2.313E+04  11  2.273E+04  12  2.240E+04  13  2.216E+04
AT ITERATION 3 LAYER NO. AND MODULUS ARE :      2  2.882E+04   3  2.680E+04
   4  2.507E+04   5  2.372E+04   6  2.259E+04   7  2.172E+04   8  2.093E+04   9
2.024E+04  10  1.962E+04  11  1.909E+04  12  1.865E+04  13  1.832E+04
AT ITERATION 4 LAYER NO. AND MODULUS ARE :      2  2.762E+04   3  2.536E+04
   4  2.360E+04   5  2.223E+04   6  2.106E+04   7  2.010E+04   8  1.925E+04   9
1.849E+04  10  1.783E+04  11  1.727E+04  12  1.680E+04  13  1.644E+04
AT ITERATION 5 LAYER NO. AND MODULUS ARE :      2  2.671E+04   3  2.441E+04
   4  2.273E+04   5  2.137E+04   6  2.020E+04   7  1.921E+04   8  1.834E+04   9
1.759E+04  10  1.693E+04  11  1.636E+04  12  1.590E+04  13  1.553E+04
AT ITERATION 6 LAYER NO. AND MODULUS ARE :      2  2.613E+04   3  2.385E+04
   4  2.221E+04   5  2.087E+04   6  1.971E+04   7  1.873E+04   8  1.787E+04   9
1.712E+04  10  1.647E+04  11  1.592E+04  12  1.546E+04  13  1.510E+04
AT ITERATION 7 LAYER NO. AND MODULUS ARE :      2  2.579E+04   3  2.354E+04
   4  2.190E+04   5  2.058E+04   6  1.944E+04   7  1.846E+04   8  1.762E+04   9
1.688E+04  10  1.624E+04  11  1.570E+04  12  1.525E+04  13  1.489E+04
AT ITERATION 8 LAYER NO. AND MODULUS ARE :      2  2.559E+04   3  2.337E+04
   4  2.172E+04   5  2.042E+04   6  1.929E+04   7  1.832E+04   8  1.748E+04   9
1.676E+04  10  1.613E+04  11  1.559E+04  12  1.515E+04  13  1.479E+04

LAYER NUMBER AND THREE NORMAL STRESSES INCLUDING GEOSTATIC STRESSES
    2     15.530      0.440      0.440    3     13.225      0.095      0.095
    4     11.390     -0.108     -0.108    5      9.929     -0.219     -0.219
    6      8.757     -0.265     -0.265    7      7.810     -0.278     -0.278
    8      7.040     -0.277     -0.277    9      6.408     -0.272     -0.272
   10      5.891     -0.274     -0.274   11      5.468     -0.292     -0.292
   12      5.128     -0.335     -0.335   13      4.862     -0.414     -0.414
```

LAYER NUMBER AND ADJUSTED THREE NORMAL STRESSES INCLUDING GEOSTATIC
STRESSES FOR COMPUTING ELASTIC MODULUS ARE:

2	15.530	0.440	0.440	3	13.225	0.095	0.095
4	11.390	0.000	0.000	5	9.929	0.000	0.000
6	8.757	0.000	0.000	7	7.810	0.000	0.000
8	7.040	0.000	0.000	9	6.408	0.000	0.000
10	5.891	0.000	0.000	11	5.468	0.000	0.000
12	5.128	0.000	0.000	13	4.862	0.000	0.000

RADIAL COORDINATE	VERTICAL COORDINATE	VERTICAL DISPLACEMENT	VERTICAL STRESS (STRAIN)	RADIAL STRESS (STRAIN)	TANGENTIAL STRESS (STRAIN)	SHEAR STRESS (STRAIN)
0.00000	4.00000	0.01403	16.500	-171.845	-171.845	0.000
(STRAIN)			2.736E-04	-2.349E-04	-2.349E-04	.000E+00
0.00000	16.00100	0.00895	3.514	0.175	0.175	0.000
(STRAIN)			3.356E-04	-1.485E-04	-1.485E-04	.000E+00
0.02500	4.00000	0.01403	16.499	-171.828	-171.829	0.036
(STRAIN)			2.736E-04	-2.349E-04	-2.349E-04	.196E-06
0.02500	16.00100	0.00895	3.514	0.175	0.175	0.003
(STRAIN)			3.356E-04	-1.485E-04	-1.485E-04	.978E-06
0.07500	4.00000	0.01403	16.498	-171.803	-171.814	0.109
(STRAIN)			2.735E-04	-2.349E-04	-2.349E-04	.588E-06
0.07500	16.00100	0.00895	3.513	0.175	0.175	0.010
(STRAIN)			3.356E-04	-1.485E-04	-1.485E-04	.293E-05
0.12500	4.00000	0.01403	16.495	-171.753	-171.784	0.182
(STRAIN)			2.735E-04	-2.348E-04	-2.349E-04	.981E-06
0.12500	16.00100	0.00895	3.513	0.175	0.175	0.017
(STRAIN)			3.356E-04	-1.485E-04	-1.485E-04	.489E-05
0.25000	4.00000	0.01402	16.481	-171.520	-171.644	0.363
(STRAIN)			2.732E-04	-2.344E-04	-2.348E-04	.196E-05
0.25000	16.00100	0.00895	3.513	0.175	0.175	0.034
(STRAIN)			3.355E-04	-1.484E-04	-1.485E-04	.978E-05
0.45000	4.00000	0.01401	16.438	-170.823	-171.227	0.653
(STRAIN)			2.723E-04	-2.333E-04	-2.344E-04	.352E-05
0.45000	16.00100	0.00894	3.511	0.176	0.174	0.061
(STRAIN)			3.353E-04	-1.483E-04	-1.484E-04	.176E-04
0.65000	4.00000	0.01400	16.372	-169.726	-170.570	0.940
(STRAIN)			2.710E-04	-2.315E-04	-2.338E-04	.508E-05
0.65000	16.00100	0.00894	3.507	0.177	0.174	0.088
(STRAIN)			3.349E-04	-1.480E-04	-1.483E-04	.254E-04
0.95000	4.00000	0.01396	16.228	-167.326	-169.132	1.367
(STRAIN)			2.680E-04	-2.276E-04	-2.325E-04	.738E-05
0.95000	16.00100	0.00893	3.500	0.179	0.174	0.128
(STRAIN)			3.341E-04	-1.474E-04	-1.482E-04	.370E-04
1.35000	4.00000	0.01389	15.951	-162.690	-166.362	1.924
(STRAIN)			2.622E-04	-2.201E-04	-2.300E-04	.104E-04
1.35000	16.00100	0.00892	3.487	0.184	0.174	0.181
(STRAIN)			3.326E-04	-1.463E-04	-1.478E-04	.524E-04
1.75000	4.00000	0.01380	15.577	-156.416	-162.607	2.457
(STRAIN)			2.545E-04	-2.099E-04	-2.266E-04	.133E-04
1.75000	16.00100	0.00890	3.469	0.190	0.174	0.233
(STRAIN)			3.305E-04	-1.449E-04	-1.473E-04	.675E-04
2.35000	4.00000	0.01362	14.840	-143.944	-155.142	3.196
(STRAIN)			2.390E-04	-1.897E-04	-2.199E-04	.173E-04
2.35000	16.00100	0.00887	3.434	0.203	0.173	0.309
(STRAIN)			3.265E-04	-1.420E-04	-1.463E-04	.897E-04
3.15000	4.00000	0.01332	13.555	-122.011	-141.911	4.001
(STRAIN)			2.119E-04	-1.542E-04	-2.079E-04	.216E-04
3.15000	16.00100	0.00881	3.372	0.224	0.172	0.406
(STRAIN)			3.194E-04	-1.371E-04	-1.446E-04	.118E-03
3.89050	4.00000	0.01298	12.148	-98.204	-127.159	4.492
(STRAIN)			1.821E-04	-1.159E-04	-1.941E-04	.243E-04
3.89050	16.00100	0.00874	3.301	0.248	0.170	0.490
(STRAIN)			3.113E-04	-1.314E-04	-1.427E-04	.142E-03
4.65600	4.00000	0.01260	10.622	-73.234	-110.874	4.710
(STRAIN)			1.501E-04	-7.629E-05	-1.779E-04	.254E-04
4.65600	16.00100	0.00865	3.216	0.276	0.169	0.571
(STRAIN)			3.015E-04	-1.246E-04	-1.403E-04	.165E-03
5.53250	4.00000	0.01213	8.977	-48.176	-93.032	4.658
(STRAIN)			1.168E-04	-3.751E-05	-1.586E-04	.252E-04
5.53250	16.00100	0.00854	3.104	0.312	0.166	0.653
(STRAIN)			2.889E-04	-1.159E-04	-1.371E-04	.189E-03
6.49200	4.00000	0.01162	7.443	-27.574	-76.203	4.378

```
 (STRAIN)                                 8.753E-05 -7.015E-06 -1.383E-04  .236E-04
  6.49200    16.00100     0.00840          2.969      0.354      0.163      0.730
 (STRAIN)                                 2.736E-04 -1.055E-04 -1.332E-04  .212E-03
  8.00000     4.00000     0.01082          5.606     -7.718    -56.101      3.816
 (STRAIN)                                 5.588E-05  1.991E-05 -1.107E-04  .206E-04
  8.00000    16.00100     0.00814          2.736      0.422      0.157      0.823
 (STRAIN)                                 2.476E-04 -8.802E-05 -1.264E-04  .239E-03
 10.00000     4.00000     0.00983          3.902      5.747    -38.024      3.129
 (STRAIN)                                 3.040E-05  3.538E-05 -8.280E-05  .169E-04
 10.00000    16.00100     0.00776          2.410      0.506      0.149      0.898
 (STRAIN)                                 2.115E-04 -6.449E-05 -1.163E-04  .260E-03
 13.00000     4.00000     0.00850          2.278     13.816    -21.672      2.306
 (STRAIN)                                 1.006E-05  4.121E-05 -5.461E-05  .125E-04
 13.00000    16.00100     0.00714          1.928      0.604      0.134      0.920
 (STRAIN)                                 1.596E-04 -3.241E-05 -1.006E-04  .267E-03
```

Figure B.2 Output file "p05.TXT" generated after the analysis of the pavement system "p05"

APPENDIX C

EXAMPLE INPUT AND OUTPUT FILES OF PROGRAM SAP90

C.1 General

As explained in Chapter 3, another technique used for the structural analysis of flexible pavement system is the finite element method. In this study SAP90 computer program developed at University of California Berkeley is used to generate the finite element models of flexible pavement systems under a single wheel load.

C.2 SAP90 Input File

In order to perform analysis, program requires the input file with no extension. Input file is composed of several data blocks defining the system properties like geometry, materials and loads (see section 6.3). In figure C.1, the input file of pavement system "p05" edited for the program SAP90 is shown. Because this input file is composed of more than 2000 data lines, all of them are not shown for brevity.

```
FINITE ELEMENT SOLUTION OF "p05"
SYSTEM
L=1
C **************************************************
JOINTS
1 X=0 Y=0 Z=0
7 X=0.15 Y=0 Z=0
189 X=0 Y=-0.1 Z=0
195 X=0.15 Y=-0.1 Z=0 Q=1,7,189,195,1,47
C **************************************************
236 X=0 Y=-0.15 Z=0
242 X=0.15 Y=-0.15 Z=0
471 X=0 Y=-0.40 Z=0
477 X=0.15 Y=-0.40 Z=0 Q=236,242,471,477,1,47
C **************************************************
518 X=0 Y=-0.50 Z=0
524 X=0.15 Y=-0.50 Z=0
753 X=0 Y=-1 Z=0
759 X=0.15 Y=-1 Z=0 Q=518,524,753,759,1,47
C **************************************************
24 X=3.8905   Y=0  Z=0
25 X=4.231   Y=0  Z=0
26 X=4.656   Y=0  Z=0
27 X=5.081   Y=0  Z=0
28 X=5.5325   Y=0  Z=0
29 X=5.984   Y=0  Z=0
30 X=6.492   Y=0  Z=0
.......

C **************************************************
C **************************************************
RESTRAINTS
1 5217 R=0,0,1,1,1,1
1 5124 47 R=1,0,1,1,1,1
5171 5217 R=1,1,1,1,1,1
.......

C **************************************************
C **************************************************
ASOLID
NM=278 ETYPE=0 MAXN=1
1
E=      500000  U=0.35
2
E=      26940   U=0.40
3
E=      26998   U=0.40
4
E=      27005   U=0.40
5
E=      26959   U=0.40
6
E=      26940   U=0.40
7
E=      26895   U=0.40
8
E=      26790   U=0.40
9
E=      26620   U=0.40

.......
```

```
C **************************************************
1 JN=5171,5172,5173,5124,5125,5126,5077,5078,5079 M=278 G=23,30 LP=1
944 JN=1317,1318,1319,1270,1271,1272,1223,1224,1225 M=2  LP=1
945 JN=1319,1320,1321,1272,1273,1274,1225,1226,1227 M=3  LP=1
946 JN=1321,1322,1323,1274,1275,1276,1227,1228,1229 M=4  LP=1
947 JN=1323,1324,1325,1276,1277,1278,1229,1230,1231 M=5  LP=1
948 JN=1325,1326,1327,1278,1279,1280,1231,1232,1233 M=6  LP=1
949 JN=1327,1328,1329,1280,1281,1282,1233,1234,1235 M=7  LP=1
950 JN=1329,1330,1331,1282,1283,1284,1235,1236,1237 M=8  LP=1
951 JN=1331,1332,1333,1284,1285,1286,1237,1238,1239 M=9  LP=1
.......
C **************************************************
C **************************************************
LOADS
1 L=1 F=0,-0.00276,0,0,0,0
2 L=1 F=0,-0.0668,0,0,0,0
3 L=1 F=0,-0.0664,0,0,0,0
4 L=1 F=0,-0.2004,0,0,0,0
5 L=1 F=0,-0.1328,0,0,0,0
6 L=1 F=0,-0.3340,0,0,0,0
7 L=1 F=0,-0.5408,0,0,0,0
8 L=1 F=0,-2.6680,0,0,0,0
9 L=1 F=0,-1.8648,0,0,0,0
10 L=1 F=0,-4.8024,0,0,0,0
11 L=1 F=0,-2.9304,0,0,0,0
12 L=1 F=0,-6.9368,0,0,0,0
13 L=1 F=0,-6.1336,0,0,0,0
14 L=1 F=0,-20.2616,0,0,0,0
15 L=1 F=0,-12.2728,0,0,0,0
16 L=1 F=0,-28.7928,0,0,0,0
17 L=1 F=0,-16.5416,0,0,0,0
18 L=1 F=0,-37.324,0,0,0,0
19 L=1 F=0,-31.7328,0,0,0,0
20 L=1 F=0,-100.2792,0,0,0,0
21 L=1 F=0,-58.6520,0,0,0,0
22 L=1 F=0,-134.4168,0,0,0,0
23 L=1 F=0,-69.8960,0,0,0,0
24 L=1 F=0,-141.3030,0,0,0,0
25 L=1 F=0,-37.9020,0,0,0,0
C **************************************************
```

Figure C.1 Input file for the analysis of the pavement system "p05" by SAP90

C.3 Sap90 Output Files

After the axisymmetric solid analysis of flexible pavement system, SAP90 produce several output files. The most important ones are the files with exstensions of F5F and SOL. The file having an extension of SOL gives the radial and axial displacement values for each nodal point in the finite element mesh. In the output file with an extension of F5F, normal and principal stresses for the joints of the each element are given. In figures C.2 and C.3, generated SOL and F5F files for the pavement system "p05" are shown respectively. For brevity, all of the lines are not shown.

```
                                                        PROGRAM:SAP90/FILE:P05.SOL
 FINITE ELEMENT SOLUTION OF "p05"

 J O I N T   D I S P L A C E M E N T S

 LOAD CONDITION    1 -  DISPLACEMENTS "U" AND ROTATIONS "R"

 JOINT        U(X)        U(Y)
     1     .000000    -.019277
     2    -.000006    -.019275
     3    -.000011    -.019275
     4    -.000017    -.019274
     5    -.000023    -.019274
     6    -.000028    -.019274
     7    -.000034    -.019274
     8    -.000056    -.019270
     9    -.000079    -.019265
    10    -.000101    -.019259
    11    -.000124    -.019251
    12    -.000146    -.019242
    13    -.000168    -.019232
    14    -.000213    -.019206
    15    -.000256    -.019174
    16    -.000300    -.019136
    17    -.000342    -.019093
    18    -.000384    -.019043
    19    -.000426    -.018989
    20    -.000506    -.018860
    21    -.000581    -.018708
    22    -.000653    -.018532
    23    -.000719    -.018329
    24    -.000774    -.018133
    25    -.000821    -.017885
    26    -.000854    -.017582
    27    -.000879    -.017324
    28    -.000904    -.017060
    29    -.000924    -.016803
    30    -.000941    -.016518
    31    -.000952    -.016238
    32    -.000962    -.015695
    33    -.000958    -.015169
    34    -.000943    -.014660
    35    -.000920    -.014171
    36    -.000860    -.013255
    37    -.000790    -.012426
    38    -.000621    -.010704
    39    -.000463    -.009422
    40    -.000351    -.008485
    41    -.000258    -.007798
    42    -.000197    -.007296
    43    -.000149    -.006921
```

Figure C.2 Generated output file p05.SOL

PROGRAM:SAP90/FILE:P05.F5F

FINITE ELEMENT SOLUTION OF "p05"

A S O L I D   E L E M E N T   S T R E S S E S

```
ELEMENT ID      1 ----------------------------
LOAD COND       1 ----------------------------
JOINT        S11       S22       S33       S12    S(MAX)    S(MIN)     ANGLE
 5171       -.20      -.25      -.20       .00      -.20      -.25       .00
 5172       -.21      -.26      -.21       .00      -.21      -.26       .03
 5173       -.21      -.27      -.21       .00      -.21      -.27       .07
 5124       -.14      -.30      -.14       .00      -.14      -.30       .00
 5125       -.14      -.30      -.14       .00      -.14      -.30       .01
 5126       -.13      -.29      -.13       .00      -.13      -.29       .01
 5077       -.08      -.35      -.08       .00      -.08      -.35       .00
 5078       -.07      -.33      -.07       .00      -.07      -.33       .00
 5079       -.05      -.32      -.05       .00      -.05      -.32       .00

ELEMENT ID      2 ----------------------------
LOAD COND       1 ----------------------------
JOINT        S11       S22       S33       S12    S(MAX)    S(MIN)     ANGLE
 5173       -.21      -.26      -.21       .00      -.21      -.26       .06
 5174       -.21      -.26      -.21       .00      -.21      -.26       .10
 5175       -.21      -.26      -.21       .00      -.21      -.26       .13
 5126       -.14      -.30      -.14       .00      -.14      -.30       .01
 5127       -.13      -.30      -.13       .00      -.13      -.30       .02
 5128       -.13      -.29      -.13       .00      -.13      -.29       .02
 5079       -.07      -.33      -.06       .00      -.07      -.33       .00
 5080       -.06      -.33      -.06       .00      -.06      -.33       .00
 5081       -.05      -.32      -.06       .00      -.05      -.32       .00

ELEMENT ID      3 ----------------------------
LOAD COND       1 ----------------------------
JOINT        S11       S22       S33       S12    S(MAX)    S(MIN)     ANGLE
 5175       -.21      -.26      -.21       .00      -.21      -.26       .13
 5176       -.21      -.26      -.21       .00      -.21      -.26       .16
 5177       -.21      -.26      -.21       .00      -.21      -.26       .19
 5128       -.14      -.30      -.14       .00      -.14      -.30       .02
 5129       -.13      -.30      -.13       .00      -.13      -.30       .03
 5130       -.13      -.29      -.13       .00      -.13      -.29       .03
 5081       -.06      -.33      -.06       .00      -.06      -.33       .00
 5082       -.06      -.33      -.06       .00      -.06      -.33       .00
 5083       -.06      -.32      -.06       .00      -.06      -.32       .00
```

Figure C.3 Generated output file p05.F5F