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Effect of Stress-Dependent Modulus and Poisson's Ratio on Rutting Prediction in Unbound Pavement Foundations

도로기초의 Rutting 예측에 미치는 응력의존 탄성계수와 포와송비의 영향

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요 지

본 논문은 도로기초 입상재료의 응력의존적인 특성을 고려한 응력의존적 재료 상수의 적용을 통하여 층 변형예측을 수행하는 간편한 방식을 소개한다. 이 방법은 Unbound지반재료에 대하여 회복변형과 영구변형을 구분하여 고려하며 두 변형의 상호작용을 적용하지 않는 방식이다. 그 결과 회복변형 탄성계수와 포와송비를 포함한 해석모형은 상호작용이 고려되지 않아도 현장에서의 도로기초 변형을 예측할 수 있음을 잘 보여주고 있다. 또한 응력의존 탄성계수와 응력의존 포와송 비 모형에서 가장 영향을 많이 미치는 계수를 찾기 위하여 민감도 분석을 실시하였다. 이러한 분석결과를 토대로 응력의존에 의하여 변형 예측시 나타나는 경향을 살펴보았다.

Abstract

This paper will present a simple approach for predicting layer deformation of unbound pavement materials with stress-dependent material properties. The approach is based on an uncoupled formulation in which the resilient and deformation response of unbound materials are considered separately. As a result, an uncoupled approach incorporating a resilient stiffness and Poisson's ratio model is able to simulate field measured deformation in pavement foundations. In addition, a sensitivity analysis is conducted to identify the significant factors in the stress-dependent modulus and Poison's ratio model. The predicted trends of deformation from this analysis are presented and discussed.

Keywords : Finite element analysis, Layer deformation, Pavement foundations, Stress-Dependent Modulus

1. Introduction

When pavement materials are subjected to repetitive loadings, both elastic and plastic strains are developed. Plastic strains are unrecoverable and manifest themselves in surface ruts, which represent the accumulated deformation in the underlying layers. For timely and cost-effective maintenance of road infrastructure, the prediction of permanent deformation is very important matter.

In general, the understanding and prediction of permanent deformation of unbound pavement geomaterials has lagged far behind than in the area of resilient responses. From the permanent deformation behavior and models perspective, it is obvious that some models are less satisfactory in cases when a soil is near failure. Consequently, the more elaborate models or approaches can improve the prediction of permanent deformation in unbound pavement materials. However, this may lead to more difficulties in quantifying model parameters for practical applications. Therefore, the model and approach should be reasonable and simple to use. For this, a simplified uncoupled formulation is presented to predict deformations on conventional flexible

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pavements under repeated loadings. In addition, a sensitivity analysis is conducted to identify the significant factors in the stress-dependent modulus and Poison's ratio model of unbound geomaterials.

2. Permanent Deformation on Unbound Pavement Materials

For practical purposes, deformation or rutting has been indirectly considered through the use of empirical or semi-empirical relationships based on limiting the vertical compressive strain at the top of the pavement subgrade. This approach implies that no rutting occurs within the pavement layers above the subgrade. However, serious rutting can occur within the unbound layers including subgrades in case of the thin asphalt pavements. This may be mainly due to consolidation and lateral movement in component pavement layers. An earlier survey conducted by the American Association of State Highway and Transportation Officials Joint Task Force on Rutting indicated that 32 states in US identified base or subbase distress as a major cause of rutting (AASHTO 1995). In addition, from the various studies of field test, about 70 percent of permanent deformation occurred within the base and subgrade layers in conventional flexible pavements (Kenis and Wang 1997). Especially, deformation in the subgrade will be much severe on thin pavements. There are several factors that affect the permanent deformation of unbound pavement materials (Maree 1978; Lekarp 1997). These are stress condition and number of stress applications, rate of stress application, compaction, grading, plasticity of fines, geological origin of materials, strength of materials, particle shape or form, surface texture, moisture, and temperature.

The level of stress is one of the most important factors in the development of permanent deformation in pavements. Repetitive or cyclic loading may develop permanent deformation in unbound materials, subgrade soils causing more rapid deformation than monotonic loading. Several studies found that the permanent axial strain increases with decreasing confining pressure, and increasing deviatoric stress (Shackel 1973). An increase in stress rotation also increases the permanent deformation (Momoya et al. 2005). Barksdale (1972) has reported that the accumulated plastic strain of base materials increased with an increase in the deviatoric stress or with a reduction in the confining pressure. The effect of the deviatoric stress in the accumulation of plastic strains was also found to be more pronounced for clay soils than granular materials (Shackel 1973; Li and Selig 1996). In addition, the accumulated permanent deformation is increased substantially with higher moisture contents primarily due to the loss of cohesion, particularly at moisture contents above optimum. There is also some interaction between the moisture content and the applied stress level. At high levels of deviatoric stress, an increase in moisture content will accumulate the development of permanent deformation more than at low levels of deviatoric stress.

3. Resilient Response Modeling

The strain resulting from traffic load on a typical pavement should be nearly completely recoverable and proportional to the applied load. Although there is some permanent deformation related to each load application, this strain is normally small and causes only long term deterioration of the pavement structure. The deformation can therefore be considered as elastic and this elastic or resilient modulus, M_r, is defined as the ratio of the repeated deviatoric stress to the recoverable part of the axial strain resulting from repeated load tests as described in Figure 1 and Equation 1.

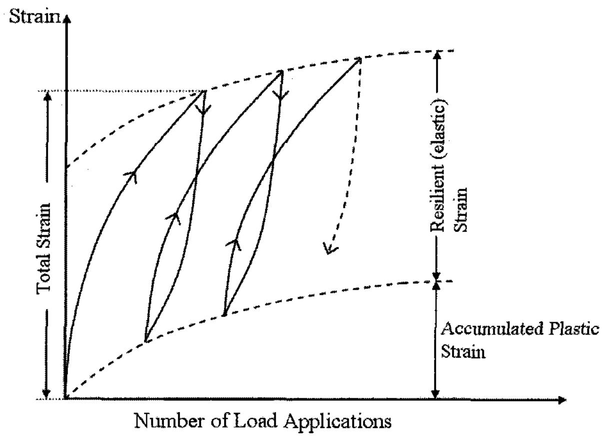

Fig. 1. Typical Resilient Response from Repeated Load Applications

$$M_r = \frac{\sigma_d}{\varepsilon_r} \tag{1}$$

where:

σ_d = the repeated deviatoric stress, and

ε_r = the recoverable strains obtained from repeated load triaxial test.

Typically, the behavior of unbound pavement geomaterials is non-linear and stress-sensitive. In order to simulate this, the stress-dependent stiffness is calculated using nonlinear Universal Soil Model (Uzan 1992) which can consider the effect of octahedral shear stress with the confining stress simultaneously as shown by Equation 2.

$$M_r = K_1 P_a \left(\frac{I_1}{P_a}\right)^{K_2} \left(\frac{\tau_{oct}}{P_a}\right)^{K_3} \tag{2}$$

where:

M_r = resilient modulus for vertical direction,

P_a = atmospheric pressure,

I_1 = bulk stress,

τ_{oct} = octahedral shear stress, and

K_i = material constants (i=1, 3).

Depending on the level of stress, the bulk stress term considers the hardening response associated with higher modulus, while the octahedral shear stress term considers the softening response. In addition, Poisson's ratio of unbound geomaterials is also known to be stress-sensitive and should be considered simultaneously. For this, a relationship between Poisson's ratio and the resilient modulus can be established based on a thermodynamic constraint (Lade and Nelson 1987; Liu 1993). This relationship is established using the resilient property parameters as expressed in Equation 2 and the thermodynamic constraints to derive an expression that relates the state of stress and the rate of change of Poisson's ratio with the changing stress state as follows in Equation 3.

$$\frac{2}{3}\frac{\partial \nu}{\partial J_2} + \frac{1}{I_1}\frac{\partial \nu}{\partial I_1} = \nu \left[\frac{1}{3}\frac{K_3'}{J_2} + \frac{K_2}{I_1^2}\right] + \left[-\frac{1}{6}\frac{K_3'}{J_2} + \frac{K_2}{I_1^2}\right] \tag{3}$$

where:

ν = Poisson's ratio,

$K_3' = K_3/2$,

K_i = material parameters,

I_1 = normalized first stress invariant, and

J_2 = normalized second invariant of the deviatoric stress.

The stress-dependent Poisson's ratio can be determined using Equation 3. However, this analytical solution can be indeterminate for certain combinations of I_1 and I_2 conditions. Therefore, it can be solved numerically by simple substitutions of partial terms based on the backward difference method. These partial terms are shown in Equations 4 and 5.

$$\frac{\partial \nu}{\partial J_2} = \frac{\nu_j^i - \nu_{j-1}^i}{k} \tag{4}$$

$$\frac{\partial \nu}{\partial I_1} = \frac{\nu_j^i - \nu_{j-1}^i}{l} \tag{5}$$

where:

l, k = step sizes for increasing I_1 and J_2, and

i, j = counter for I_1 and J_2.

By setting Equations 4 and 5 into Equation 3 and performing some algebraic manipulation, the iterative formula for estimating the Poisson's ratio for a given stress condition can be expressed as Equation 6.

$$\nu_j^i = \frac{\left[\left(\frac{2}{3k}\right)\times \nu_{j-1}^i + \left(\frac{1}{lI_1}\right)\times \nu_{j-1}^i - \frac{k_3'}{3J_2} + \frac{k_2}{I_1^2}\right]}{\left[\frac{2}{3k} + \frac{1}{lI_1} - 2\frac{k_3'}{3J_2} - \frac{k_2}{I_1^2}\right]} \tag{6}$$

Equation 6 is solved by choosing a step size for increasing I_1 and J_2 and then increasing I_1 and J_2 from a fixed boundary condition for which the Poisson's ratio is known. Varying Poisson's ratio values are estimated iteratively until the specified convergence during each load increment is accomplished. More detailed information regarding resilient dilatancy approach can be found in elsewhere (Park and Lytton 2004).

4. Algorithm of Predicting Layer Deformation

Deformation in conventional flexible pavements is the direct result of the passage of loads over the pavement surface and the strain induced by the loads. This induced strain can be simplified as two components, the resilient strain and the permanent strain. It is suggested that the resilient strain remains fairly constant during the major part of the pavement's life, except for at a low number of load repetitions where the material undergoes conditioning and near failure (Uzan et al. 1988). Therefore, it can also be assumed that the elastic strain is constant throughout the pavement performance life and the plastic strain per load application is assumed to decrease with the number of load applications.

For the deformation calculation, uncoupled analysis by the simple layer strain approach is adopted with a finite element program. In this approach, the nonlinear stress-dependent finite element analysis is made using an incremental loading and an iterative solution technique for each load increment. From the results of stress-dependent finite element analysis, deformation at each layer is calculated by summing the products of the permanent strains and the corresponding difference in depths between the layers as described in the earlier paper by Park (2005).

The layer deformation is calculated by multiplying vertical strains at the center of each element by the layer thickness and by the plastic model properties of each layer. The VESYS model is used (Kenis and Wang 1997). This model states that the ratio of vertical plastic strain per cycle to the resilient strain is an exponential function of the number of load cycles as shown in below.

$$\frac{1}{\varepsilon_r}\frac{d\varepsilon_p}{dN} = \mu N^{-\alpha} \qquad (7)$$

where:

ε_p = permanent deformation,

ε_r = elastic or/ resilient deformation,

N = the number of load applications,

μ = parameter representing the constant of proportionality of strains, and

α = parameter indicating the rate of decrease.

Then, the total permanent deformation is calculated by Equation 8.

$$\delta_a(N) = \sum_{i=1}^{n}\left[\frac{\mu_i N^{1-\alpha_i}}{1-\alpha_i}\int_{d_{i-1}}^{d}\varepsilon_c(z)\,dz\right] \qquad (8)$$

where:

$\varepsilon_c(z)$ = compressive strain at depth z,

d_i = the depths of each layer in the pavement, and

$\delta_a(N)$ = the total permanent deformation.

5. Determination of Layer Deformation Parameters

In order to evaluate deformation parameters under traffic loading, the repeated-load-permanent deformation test is necessary to conduct in the laboratory. Currently, the laboratory study of permanent deformation is less advanced than the resilient modulus test, and there is no standard test procedure for determining the permanent deformation of unbound materials. However, the VESYS procedure (Kenis 1978) has commonly been used for the repeated load-permanent deformation tests.

Each load cycle consisted of a 0.1-second loading time and a 0.9-second rest period. Initially, specimen is subjected to 200 cycles of preconditioning at vertical loads that were 10 percent of the deviatoric stress. The accumulated vertical and radial deformations are recorded throughout the test. Figure 2 provides a conceptual illustration of the data from a repeated load-permanent deformation test. In addition, the full deformation data covering the loading and unloading portions of a given

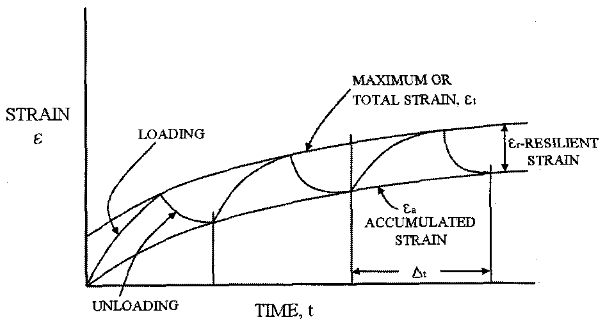

Fig. 2. Accumulated Strains due to Repeated-Load Deformation Test

cycle are recorded for the 199th, 200th, and 201st load cycles to determine the resilient strain at the 200th repetition. This quantity is needed to characterize the parameters, α and μ, of the VESYS rutting model.

The parameters, α and μ, of the VESYS rutting model can be determined using a simple relationship between the logarithm of the accumulated strain and the logarithm of the number of load cycles. This relationship between permanent strain and the repeated loads is assumed to be linear over a range of load applications. Two parameters are estimated using the y-intercept and the strain slope. Then, the corresponding rutting parameters can be estimated. If the α value is equal to zero, the rutting on unbound materials under repetitive loadings will be a constant rate. When the temperature increases and α will decrease, then the rutting potential becomes greater. In the case of a thin pavement with a clay subgrade, α will be negative when the clay warms up. Such a pavement will be subjected to more rutting.

6. Model Validation with Field Measurement

In order to validate the approach for layer deformation prediction, field measurement results from a full-scale loading test studies by Chen and Hugo (2001) and Zhou and Scullion (2002) were used. Based on the parameters in Table 1, the layer deformation on pavement foundations of each test was predicted and compared with the results from the literature. The equivalent of 8 years of traffic was applied. It is assumed that the traffic is equal for all seasons and the initial set of resilient moduli for each season was used at the given traffic periods. The comparisons of layer deformation between the field measurements and the predictions are shown in Figures 3 through 5.

From Figure 3, it was found that the predicted rutting at the base and subgrade layers agrees well with the field measurements although predictions overestimate at an

Table 1. Moduli and rutting parameters for test sites (Chen and Hugo 2001; Zhou and Scullion 2002)

Site	Layer	Moduli (GPa)	α	μ
281N	AC	2.00	0.73	0.46
	Base	0.26	0.75	0.21
	Subgrade	0.06	0.75	0.02
281S	AC	4.01	0.74	0.21
	Base	0.26	0.73	0.07
	Subgrade	0.06	0.75	0.02
F5	AC	2.35	0.74	0.31
	Base	0.26	0.75	0.28
	Subgrade	0.06	0.75	0.02

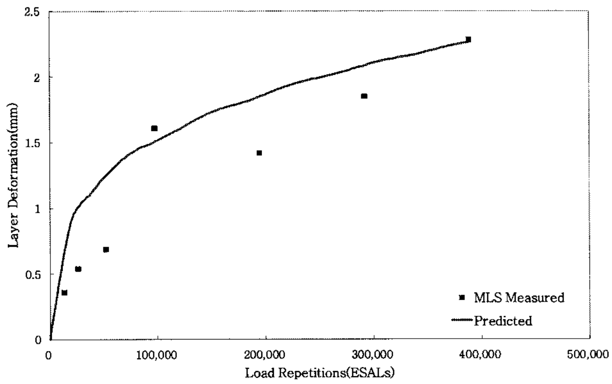

Fig. 3. Measured and Predicted Base and Subgrade Deformation in Site 281N

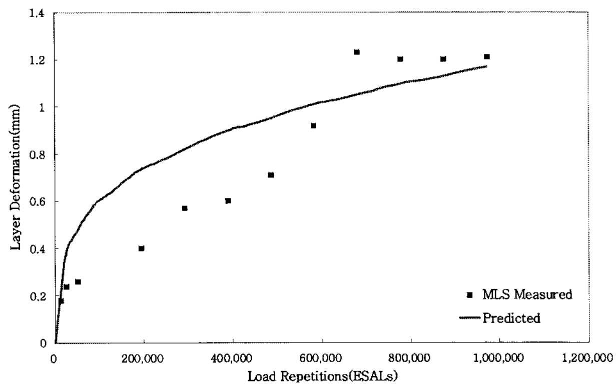

Fig. 4. Measured and Predicted Base and Subgrade Deformation in Site 281S

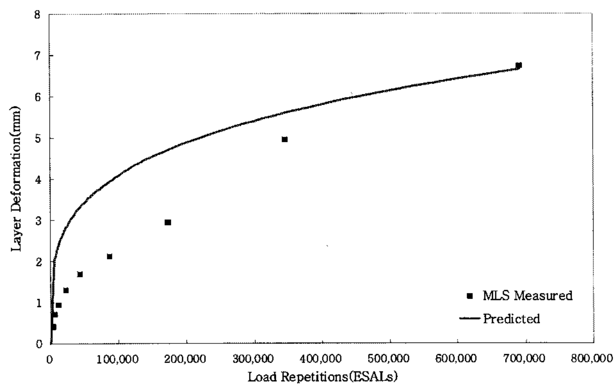

Fig. 5. Measured and Predicted Base and Subgrade Deformation in Site F5

early stage of trafficking. Figure 4 shows the comparison of the rutting for 281S1 test site. Still, the deformation at the base and subgrade layers is predicted fairly well. The comparisons of the F5 field measurements and predicted base and subgrade layer rutting are presented in Figure 5. It is found from these comparisons that predicted layer rutting on pavement foundations matches the field measurements results fairly well.

7. Effect of Stress Sensitivity on Deformation

A sensitivity analysis was conducted to identify the factors that have a significant influence on the development of layer permanent deformation in pavement foundations. For this purpose, each of the K1 to K3 resilient parameters was varied one at a time from its assumed base value, while the other parameters were held at their corresponding base values. The change in the predicted layer deformation due to a change in a given parameter was evaluated using the uncoupled finite element analysis program. Because of the unavailability of some of the material properties, typical values for the VESYS rutting parameters, α and μ, are assumed for each layer in the analyses and were kept the same. To model the pavement response under the standard 80 kN single axle load, a single wheel load of 40.0 kN was applied over a circular area with a radius of 136 mm, which corresponds to a surface pressure of 689 kPa. Table 2 shows the base value used in the sensitivity analysis for the stress-dependent parameters respectively. Each parameter is determined from results of the laboratory study by Titus-Glover and Fernando (1995). In addition, each parameter was varied ±30 percent from its base value except for the surface layer, k3, and the subgade, k2, which were fixed at zero.

The results of predicted deformation from the variation in the resilient material properties are shown in Figures 6 through 12. These figures illustrate the layer deformation development on pavement foundations to changes in the resilient material parameters. Note that the base and subgrade k3 is negative, and an increase of 30 percent of the k3 means less negative and vice versa. In addition, the predicted layer rutting is summarized in Table 3.

Predicted deformation is most sensitive to the parameter k1. Figures 6, 8, and 11 show that the predicted deformation changes significantly whenever k1 for a given

Table 2. Base Levels of Resilient and Deformation Parameters Used in Sensitivity Analysis

Layer	Thickness (mm)	K_1	K_2	K_3	α	μ
AC Surface	100	50,000	0.1	0.0	0.60	0.75
Granular Base	200	700	0.6	−0.3	0.84	0.53
Subgrade	2,300	400	0.0	−0.3	0.81	0.08

Table 3. Predicted Total and Layer Deformation to Changes in Resilient Parameters

Change Parameter	Deformationat	K_1 (+30%)	K_1 (−30%)	K_2 (+30%)	K_2 (−30%)	K_3 (+30%)	K_3 (−30%)
AC	Total	12.02	18.86	14.22	13.54	−	−
	AC	4.60	7.46	6.03	5.32	−	−
	Base	5.32	6.89	5.91	5.94	−	−
	Subgrade	2.10	2.52	2.28	2.28	−	−
Base	Total	12.87	17.21	14.70	13.16	14.48	13.34
	AC	5.46	7.04	5.79	5.52	5.76	5.56
	Base	5.46	7.80	6.60	5.40	6.44	5.51
	Subgrade	2.25	2.37	2.31	2.24	2.28	2.27
Subgrade	Total	13.39	14.73	−	−	14.16	13.61
	AC	5.54	5.85	−	−	5.73	5.59
	Base	5.96	5.99	−	−	5.93	5.94
	Subgrade	1.89	2.89	−	−	2.50	2.08

layer is varied. A higher increase in deformation is due to decreasing the AC k1 parameter, as shown in Figure 6. This is mainly due to higher induced strains resulting from a more flexible AC layer brought by a decrease in k1. It is also observed that major deformation occurs at both the AC and base layers. The lower the AC k1 value, the higher the strain in the base layer. This is due to the higher stresses predicted in the base because of the flexible AC surface. In addition, the effect of varying the AC k1 on the predicted deformation at the AC layer gives a higher percent change compared to the corresponding effect on the predicted deformation at the base layer, as shown in Table 3.

Figure 7 shows that predicted deformation is not very sensitive to changes in the AC k2 for the pavement considered. Even though an increase in deformation due to an increase in AC k2 is observed, the effects of the AC k2 on the predicted deformation of the AC layer are relatively smaller compared to the effects of k1. At the base and subgrade layers, the effects of the AC k2 are almost negligible. It would be expected that a higher k2 results in a higher modulus for that layer. However, in the case of the changes in the AC k2, the deformation predicted in the AC layer is slightly greater than that predicted in the case of the lower k2. It seems to indicate that a lower modulus in the AC layer is predicted by an increase in AC k2 because the higher AC k2 results in a lower modulus for base and subgrade layers due to the lower stress conditions for a given base and subgrade. Therefore, the ratio of modulus between the AC and base layer is increased when base k2 was increased by 30 percent. This may affect the stresses and strains in the bottom half of the AC layer and increase the resulting compressive strains.

Figures 8 through 10 show that the changes in the stress dependent behavior of the base layer led to significant changes in the predicted deformation. Figure 8 shows that increasing the base k1 led to a lower deformation in the AC and base layers, reflecting the reduction in the vertical strains in component layers due to the stronger support provided by the stiffer base. The deformations predicted in the AC and subgrade layers are not very sensitive to changes in the base k2 and k3 parameters, as shown in Figures 9 through 10. Only the base layer shows greater changes in deformation to the changes in the base k2, and k3 parameters. Again, this could be explained by the changes in the predicted stiffness ratio due to nonlinear stress dependency. When the base k2 is increased by 30 percent, the predicted deformation at the base is also

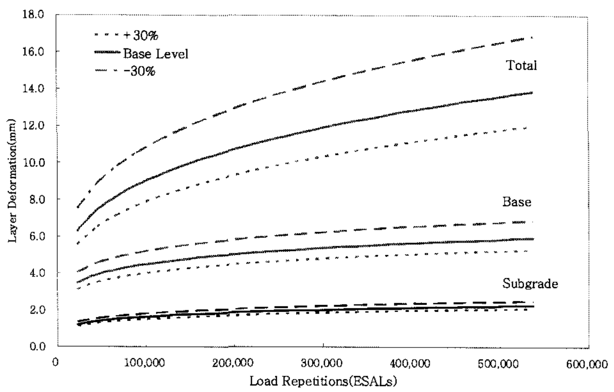

Fig. 6. Predicted Foundation Layer Deformation to Change in k1 Parameter of the AC

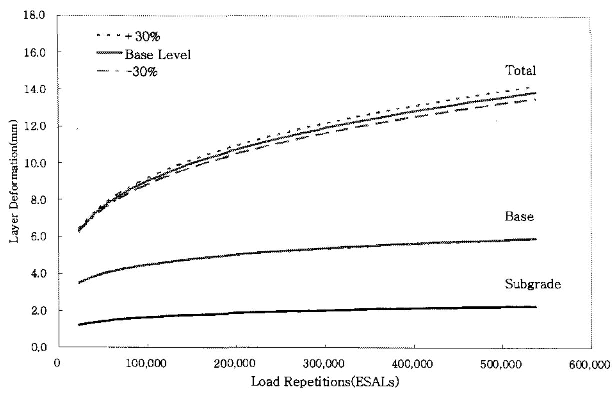

Fig. 7. Predicted Foundation Layer Deformation to Change in k2 Parameter of the AC

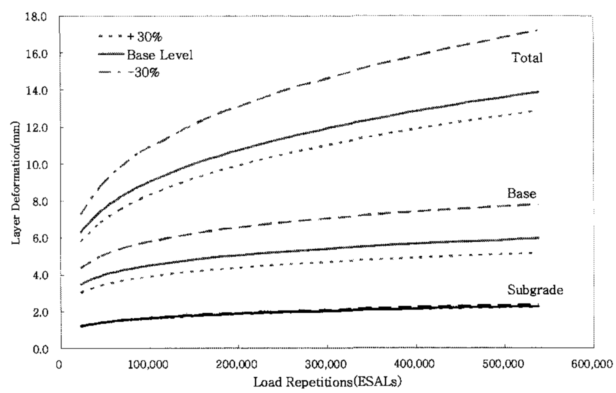

Fig. 8. Predicted Foundation Layer Deformation to Change in k1 Parameter of the Base

increased owing to the corresponding change in ratio of modulus between layers. Figure 10 shows that the less negative k3 which is increased by 30 percent have a greater predicted deformation. The effects of the base k3 parameter may be explained by the changes in the predicted base stiffness. Since the predicted values of the first stress invariant and the octahedral shear stress at the subgrade are less than atmospheric pressure, the stiffness of the base decreased when the base k3 is increased by 30 percent.

Figure 11 shows that the subgrade k1 increases the predicted deformation only in the subgrade layer. However, the predicted deformation in the AC and base layers are not sensitive to changes in the subgrade k1. Note that the subgrade k3 is negative and the trends are the same as the base k3 but have a lesser impact compared to the effects of base k3, as shown in Figure 12.

From the results, the variations of the deformation predicted in the AC and the base layers are far greater than that of the subgrade. The greatest increase in deformation is observed when the base k1 is decreased. Even when the base k2 and k3 were changed, minor changes are observed in the AC and base layers. As can be seen in Table 2, the parameters which relate to the nonlinear behavior, such as k2 and k3, have a relatively smaller effect on the predicted deformation than did the k1 parameter. The deformation predicted in the subgrade shows a lower change in most of the k1 to k3 parameters. For the base and subgrade layers, the high modulus ratio between the base and subgrade is seen as important because the vertical stresses and strains are major factors in deformation prediction. In some cases, the deformation is not very sensitive to changes in parameters due to the minor changes of the vertical compressive stresses. The effects of stress dependency on deformation prediction are affected by the applied load and pavement geometry due to the effects of the nonlinear parameters (k2 and k3). It is also noted that the boundary effects of the stress

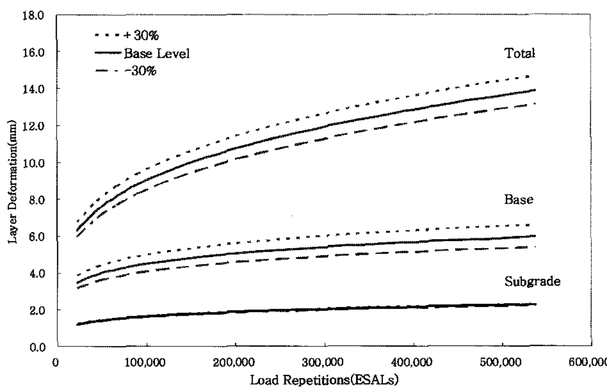

Fig. 9. Predicted Foundation Layer Deformation to Change in k2 Parameter of the Base

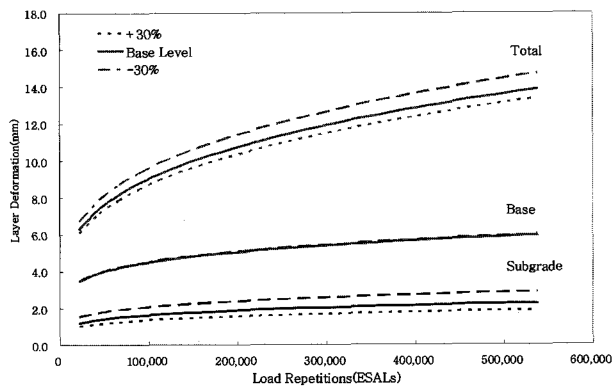

Fig. 11. Predicted Foundation Layer Deformation to Change in k1 Parameter of the Subgrade

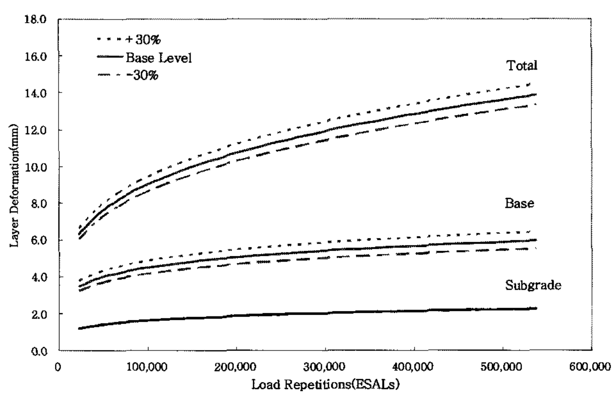

Fig. 10. Predicted Foundation Layer Deformation to Change in k3 Parameter of the Base

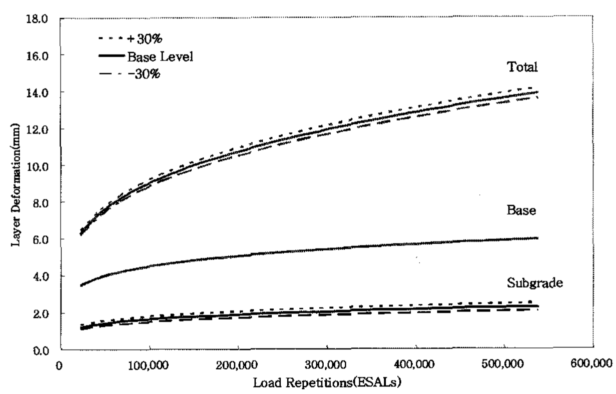

Fig. 12. Predicted Foundation Layer Deformation to Change in k3 Parameter of the Subgrade

condition for the k2 and k3 terms used in stress dependent calculations may affect the deformation prediction and interact with pavement geometry.

As these results illustrate, it is apparent that both the stress dependent modulus and the Poisson's ratio vary considerably within the layers. This may significantly change the predicted deformation of unbound foundation layers. For a detailed study of the stress dependent behaviors on deformation, it is recognized that actual measurements from large-scale testing or in-field testing are needed.

8. Conclusions

A simplified layer deformation analysis on pavement foundation has been presented and discussed in which the layer strain method is incorporated in a nonlinear stress-dependent finite element analysis. Based on the analysis, the proposed approach adequately predicted the observed deformation on foundation layers. In addition, the following observations are noted.

(1) Predicted deformation is most sensitive to the parameter k1. The effect of the higher k1 is to increase the predicted deformation.

(2) Largest Changes in predicted deformation occurred when AC k1 was varied. Variations in base k2 and k3 parameters result in significant changes of the predicted deformation in base as well.

(3) Because of the effects of the nonlinear characteristics of pavement materials, deformations are affected by the applied load, pavement geometry, and stress dependent parameters.

(4) Good foundation support will mobilize resilient modulus and Poisson's ratio in unbound layers and reduce deformation in upper layers due to a lesser bending effect.

Although results indicated that it could predict deformation well, there is still a need to calibrate predicted deformation with the observed deformation data in fields. In particular, better estimation on deformation during the early stages of traffic loadings and more full-scale trials are necessary to verify whether the results of the predictions are proved in practice.

Acknowledgements

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