Effective Granular Modulus to Model Pavement Responses

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This report presents the results of a research study to further investigate the initial findings of an earlier research project concerning the prediction of pavement deflections. The principal objective of this study was to explore the consistent lack of agreement between field-measured deflections and those computed by using elastic-layered theory coupled with nonlinear dynamic modulus tests. During several periods of the year, surface deflections were measured with the Thumper testing vehicles on the same three Maryland flexible pavement sections that were previously studied. These field deflections were predicted mathematically for a large number of specific test conditions. Although these predicted deflections failed to match the measured values, a consistent trend in the ratio of the corresponding deflections was detected. As suggested in a previous study, an adjustment factor was applied to the granular base modulus to cause the deflection ratio to approach one. Linear log-log relationships were derived between this factor and increasing measured deflection values. From this analysis, it was surmised that current laboratory methods of granular material characterization appear to be inadequate for modeling in situ behavior, regardless of the measuring device. Based on the findings of recent seismic research, further analysis was made to determine whether a relationship exists between the adjustment factor and the induced shear strain in the granular layer. A clear curvilinear plot was produced, which indicated that the adjustment to the granular modulus is definitely related to the shear strain that develops in response to the surface loading. As a result, a procedure was presented for correcting for the effective in situ granular base modulus.

With the development of theory to model layered flexible pavement structure, researchers and designers realize the importance of obtaining accurate estimates of the actual field conditions. Laboratory testing of core samples taken from in-service highway pavements to estimate in situ strength characteristics is time consuming, destructive, and expensive. In contrast, surface deflection measurements are recognized as a valuable tool for obtaining quantitative information about a pavement structure because of its simplicity and nondestructive nature.

Currently, a large amount of research work that uses elastic-layered theory is involved in the determination of the in situ moduli of some or all of the layers that constitute a pavement system. The accuracy of these models is dependent on the manner in which the material properties are obtained and entered into the program. Adjustments to the models have been suggested (1-3) to incorporate the effects of test load frequency, temperature, and stress dependency on material behavior. Further improvement is advocated in the characterization of the granular base course material (4). Because of the large scatter that accompanies laboratory testing of remolded specimens, a better method is needed for evaluating the strength of this layer.

STUDY OBJECTIVE

This study (5) was initiated to further research results of a previous study (6) that observed a consistent trend in the analysis of deflections measured with a road rater and a Benkelman beam. The same three Maryland state highway sections were tested by measuring surface deflections by using the Federal Highway Administration (FHWA) pavement testing device called "Thumper." Measurements were made at three frequencies, four load magnitudes, and five times during the year to increase the data base obtained by using the other two deflection devices.

ANALYSIS PROCEDURE

The testing was conducted on field test sections of US-1, MD-97, and Interstate 695. At the time the data were taken, US-1 displayed extensive surface cracking, MD-97 had some minor surface cracking especially in the wheelpath, and I-695 was completely intact. For each of these sections, layer thicknesses and material characterizations were previously established (7) and are presented in Figure 1 and Table 1, respectively. The moduli of the asphalt-stabilized layers were obtained from Shell nomographs developed for these particular mix designs and are a function of pavement temperature and load frequency. The temperature within each asphalt layer for each Thumper test date was calculated from surface measurements and relationships developed by Southgate (8). As shown in Table 1, the moduli of the lower layers were determined in the laboratory

Figure 1. Average cross-sections of Maryland pavements.

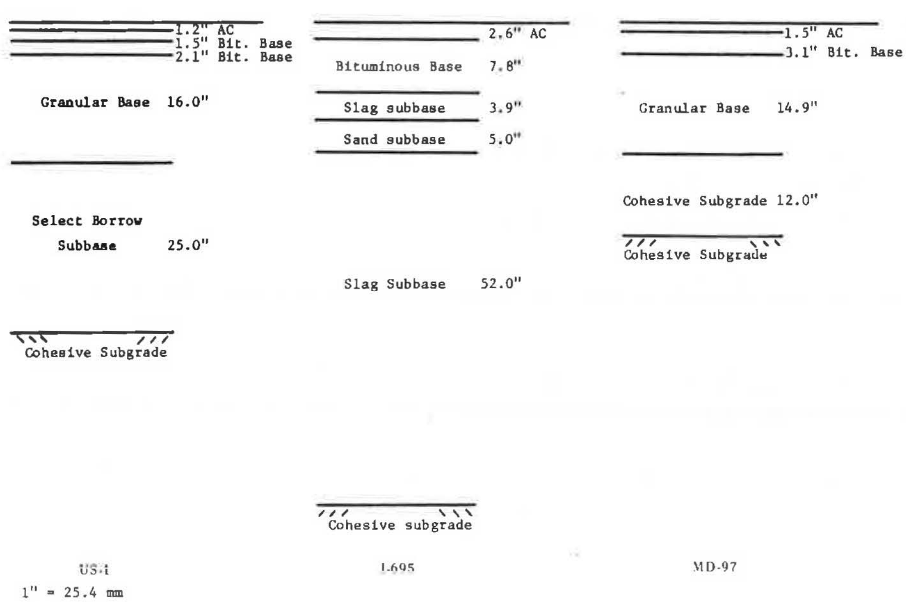


Figure 3. Deflection ratio versus measured deflection.

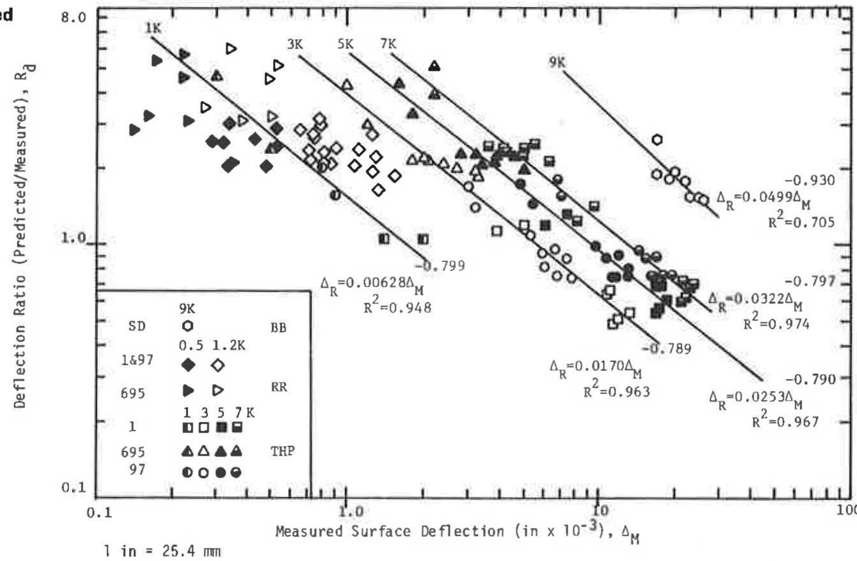
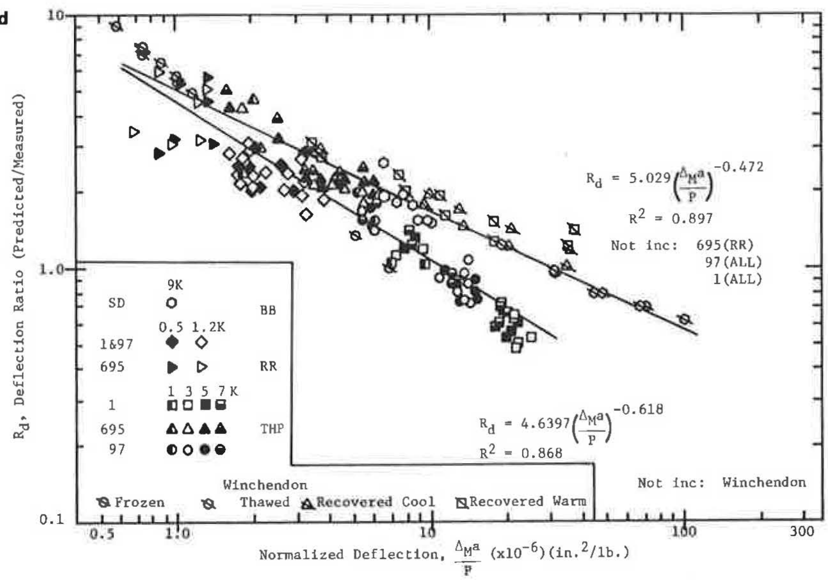


Figure 4. Deflection ratio versus normal measured deflection.



shown in Figure 4. In view of all the possible sources of error, the amount of scatter is extremely small. These data show that some consistent and rational cause appears to be responsible for the lack of agreement between measured and calculated deflections.

Data for the Winchendon test section appear to fall slightly out of line with the rest of points plotted in Figure 4. Although analysis of these data is still in progress, this deviation may be partly explained by a closer examination of the individual data points. MD-97 and especially US-1 had considerable surface cracking that was not taken into account in the characterization of the modulus of this layer. If the original asphalt concrete moduli for these sections were reduced to reflect the loss of structural integrity due to cracking, the predicted or computed deflection would increase and, in turn, increase the deflection ratio. This revision could conceivably cause the MD-97 and US-1 data to align more closely with the I-695, San Diego road test, and Winchendon data; however, further research must be conducted before conclusive results can be reached.

Granular Modulus Adjustment

Past research (4,11) has shown deficiencies in current methods for evaluation of granular material in the laboratory. In this study, because of these uncertainties in remolding and compacting granular material for modulus testing in the laboratory and the suggestions of other research results (6,12), the granular base modulus was modified to produce agreement between measured and computed deflections. Assuming that the multilayer elastic computer model is satisfactory and the modular inputs of the other layers are appropriate, the revised pavement layer system is believed to be compatible with field behavior.

The procedure used for adjusting the modulus of the granular layer was the same as that reported by D'Amato and Witczak (6). The resilient modulus equation obtained from dynamic laboratory testing is of the form

$$M_R = k_1 \theta^{k_2} \quad (1)$$

where k_1 and k_2 are laboratory-derived regres-

Figure 5. K_1-factor versus measured surface deflection for thumper data points only.

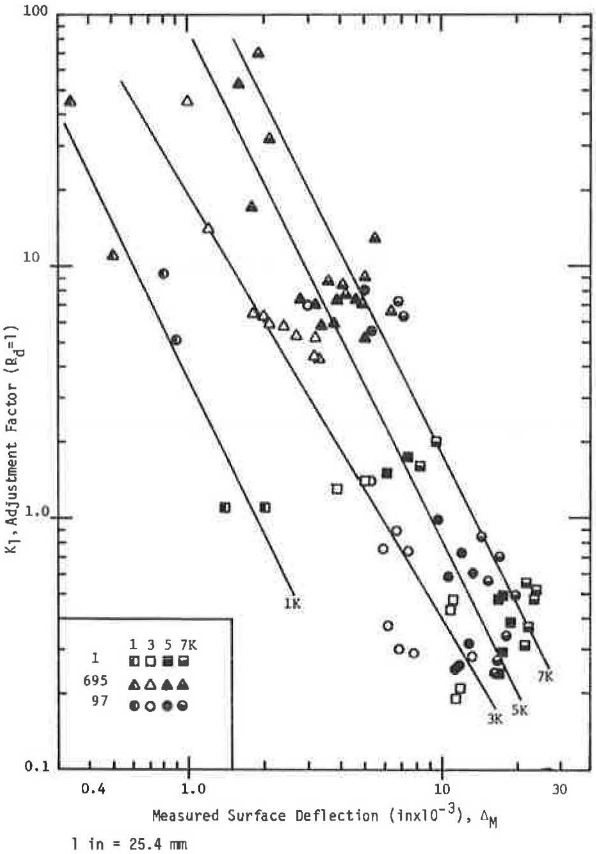
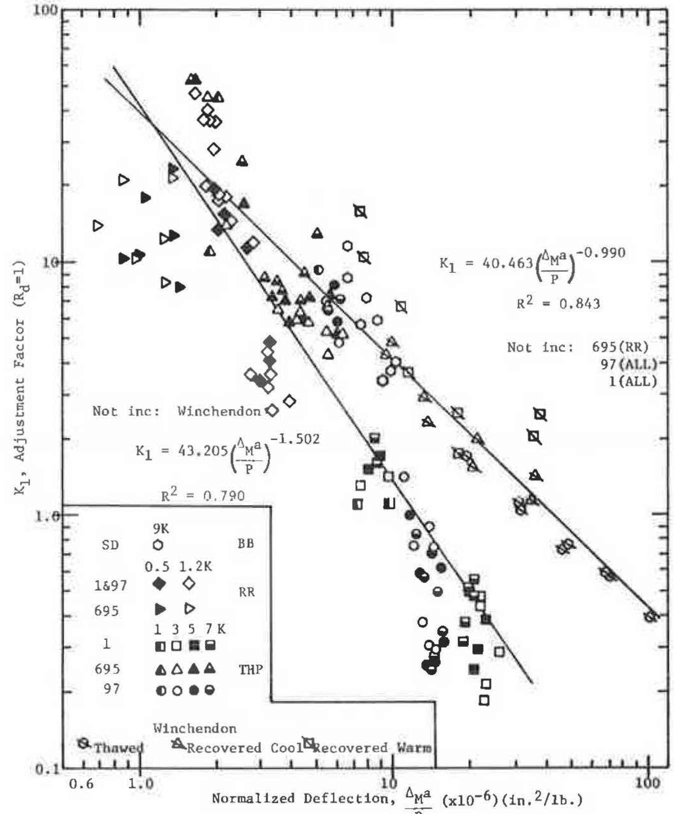


Figure 6. K_1-factor versus normal measured deflection.



sion constants and θ represents the first stress invariant (bulk stress). In this study, the computed surface deflections were made to equate to the measured values ($R_d = 1$). The resulting equation used in this approach was

$$M_R = K_1 k_1 \theta^{k_2} \quad (2)$$

where K_1 is an empirical adjustment factor.

In the iterative procedure of the modified program, the combined coefficient K_1k_1 is entered into the program and changed repeatedly until the center deflections match those measured in the field.

A plot of the calculated K_1-values at a deflection ratio equal to one ($R_d = 1$) versus the deflections measured by using Thumper is shown in Figure 5. Although there is scatter in the data, a trend of decreasing K_1 with increasing surface deflection is clearly visible for each load magnitude. As before, the K_1-factor versus deflection data was made normal to eliminate the variables of load and surface contact and this is plotted in Figure 6 along with the results of the previous D'Amato and Witczak study. Again, the scatter is more pronounced with the I-695 road-rater data. The additional data from Winchendon continue to appear isolated when compared with the other data. However, if the US-1 and MD-97 data are revised to incorporate a reduced surface modulus as described previously, the entire data set may provide a good correlation. With a lower asphalt surface modulus, the K_1-factor necessary to obtain the same field-measured deflection would increase, which would cause all data points to tend to coincide along a unique relationship. Although this hypothesis is speculative, certain problems are unavoidable in the use of original material properties to model pavement responses with elastic layer theory when the existing surface is severely cracked.

Effective Base Modulus

The final iteration of the computer program analysis provided the final modulus for each sublayer at a deflection ratio of one ($R_d = 1$). The resulting moduli represent the effective response of the lower layers. These lower moduli of the sublayers were averaged together into one composite granular base modulus (E_B) and one composite subgrade modulus.

In Figure 7, the average granular base modulus was plotted against the measured deflection. The trend of increasing base modulus with decreasing surface deflection is intuitively correct; however, a lot of scatter is shown in these data. This scatter is expected because the surface deflection can result from varying amounts of displacement in the other layers as well. Again, definitive bands of data for each load magnitude demonstrate the linear elastic behavior of the material. These individual bands were blended together by using the same normalization process described earlier. A plot of these data along with the additional Winchendon data is shown in Figure 8. This extreme range of effective material moduli presented in Figure 8, for even the same pavement section, is not just an indication of the need to incorporate stress-dependent effects. It illustrates the necessity for further examination of the in situ characterization of granular material.

Once again, the Winchendon data plot above the data from US-1 and MD-97 in the lower portion of the figure. As before, if the cracking in the surface of these pavements was considered, by reducing the moduli of the existing material, the effective base

Figure 7. Average effective granular base modulus versus measured surface deflection.

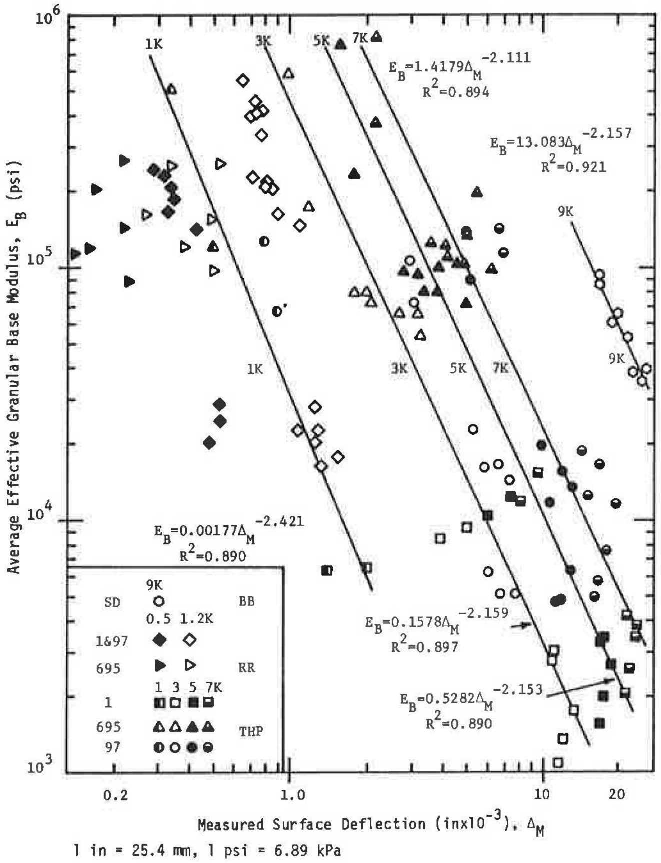
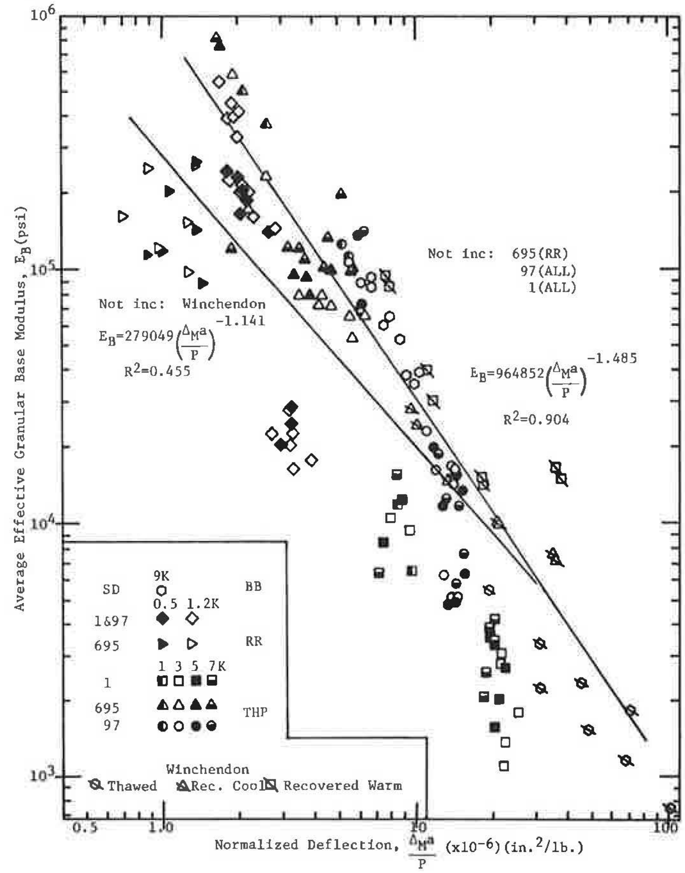


Figure 8. Base modulus versus normal measured deflection.



modulus necessary to produce the same deflection would certainly increase.

Associated Shear Strain

The modulus of granular material is a function of density, gradation, degree of saturation, angularity of the particles, and stress state (13). As such, duplication in the laboratory of the actual particle structure that exists in the field is impossible. Recent studies, directed toward development of better understanding of soil response under dynamic loading conditions, have indicated that the shear modulus (G) of a granular soil is dependent on both the level of shear strain and stress state. Ideal relationships have been developed that show that the shear modulus of a granular soil decreases with increasing shear strain (12), as shown in Figure 9, according to the equation:

$$G = 1000K_2(\sigma_m')^{0.5} \tag{3}$$

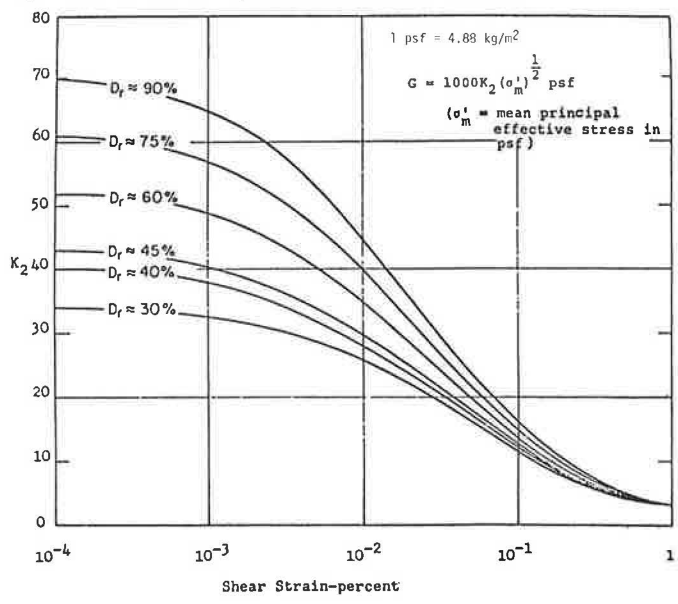
In this expression the K_2-value has been related to magnitude of the shear strain.

This equation is similar to the modified resilient modulus equation (Equation 2) if the elastic modulus (E) is substituted into the equation along with a typical Poisson ratio:

$$E = 2800K_2(\sigma_m')^{0.5} \tag{4}$$

By using the Chevron N-layer program to compute the principal strains at the middle of the adjusted granular base layer beneath the center of loading and the following Mohr circle of strain relationship, D'Amato and Witczak examined the hypothesis (6)

Figure 9. Shear modulus of granular soil related to shear strain.



$$\gamma_{MAX} = \epsilon_1 - \epsilon_2 \tag{5}$$

where ϵ_1 and ϵ_2 are the principal strains. They found separate linear relationships for the road-rater and Benkelman beam data. The effect of shear strain also appeared to diminish when the strain was large and the slope of the Benkelman beam data was considerably flatter. This corresponded conceptually with the change in slope of the ideal curves of Figure 9 (12).

The shear strain hypothesis was extended further by including the data determined from measurements of Thumper deflection. Plots of all the data for the three devices revealed a unique family of curves for each pavement section, depending on the magnitude of test load, as shown in Figures 10-12. These plots show that the K_1-factor appears to be a function of pavement structure, test load, and developed shear strain. The shear strain developed in the I-695 section was relatively low, as expected in a very stiff pavement that produced higher values for K_1. In the US-1 section, the induced shear strain was much higher. This is not only a result of a thinner cross section, but, the high strain in the granular layer is probably a consequence of a severely cracked surface course, which was not distributing the load. The MD-97 section, which is even thinner, falls in between the other two pavements with respect to shear strain and K_1-values. The San Diego road test data, plotted on Figure 10, had the highest shear strains and unusually high K_1-factors for these corresponding strains; this is partly explained by the heavy [9000-lb (40-kN)] load, applied through a flexible tire to very thin test sections.

Unfortunately, shear strain data for the Winchendon test sections are not available at this time. For all the sections analyzed, one general characteristic could be found: The deflection increased naturally with load and, consequently, the maximum shear strain also increased.

The in situ modulus of the granular layer [designated as $K_1 \times M_R$(laboratory)] can vary significantly from the original laboratory resilient modulus as shown in the figures. This variation may be caused by differences in the shear strain, which is mobilized under the triaxial simulation devices, from that induced in the field. Slight differences in shear strain may mean large differences between the two moduli (K_1), especially when measured de-

Figure 10. K1-factor versus maximum shear strain for US-1 and San Diego data.

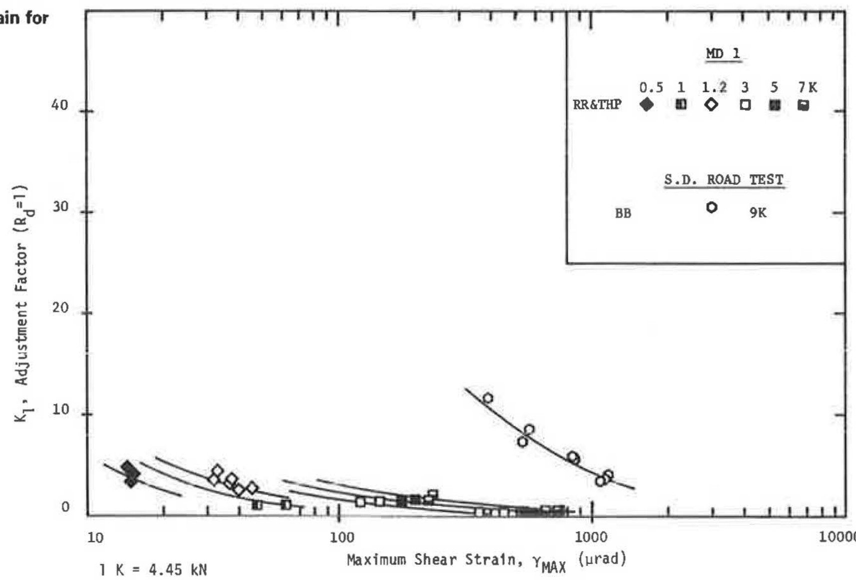


Figure 11. K1-factor versus maximum shear strain for I-695 data.

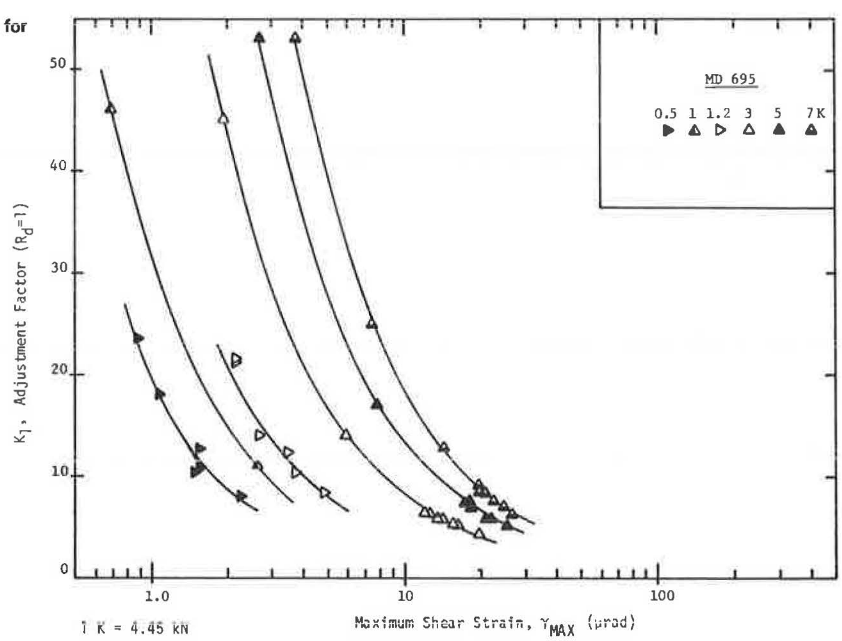


Figure 12. K_1-factor versus maximum shear strain for MD-97 data.

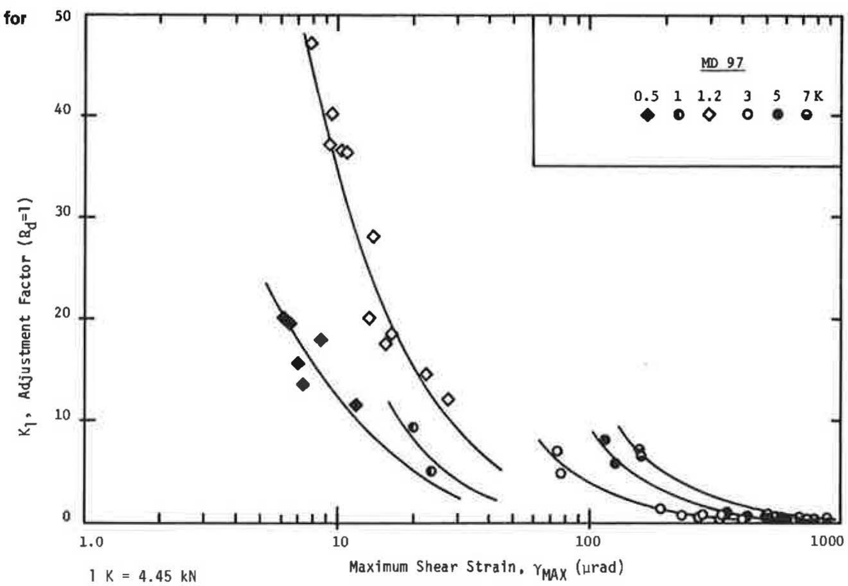
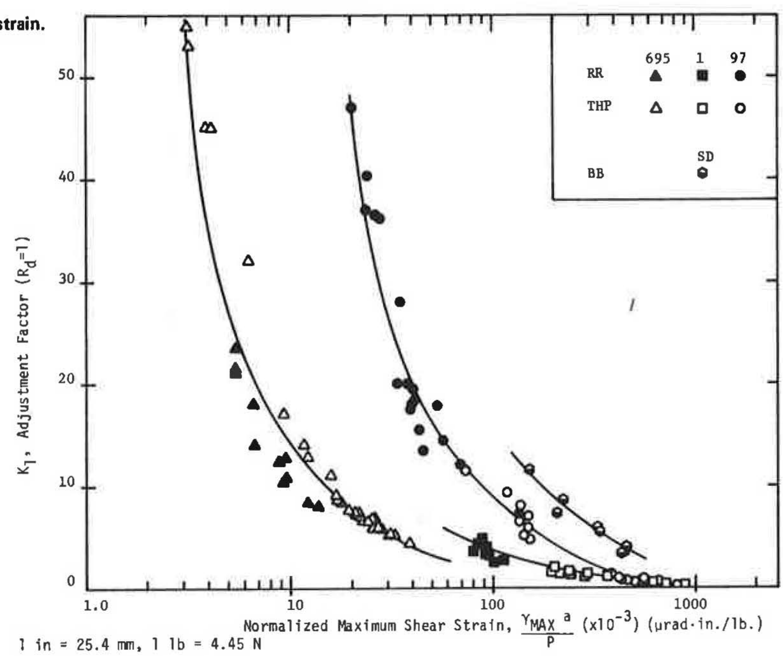


Figure 13. K_1-factor versus normal maximum shear strain.

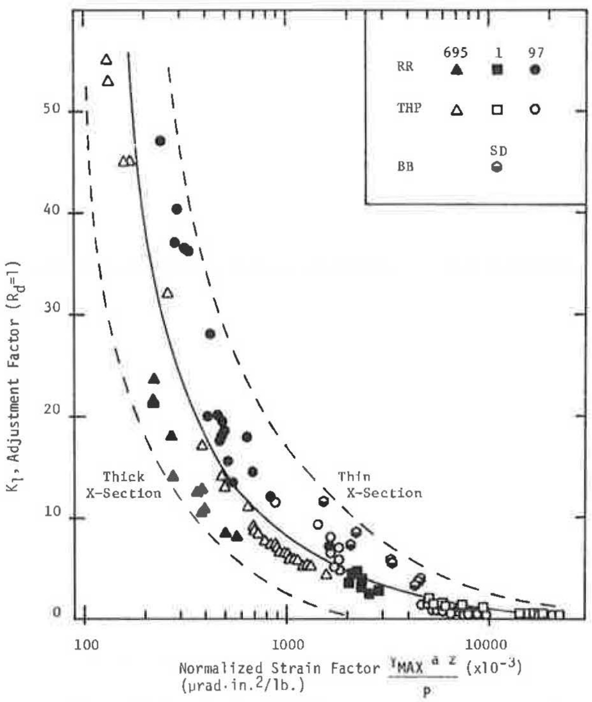


flections or shear strains are relatively low. Granular materials, when recompacted in the laboratory to field density and moisture conditions, will probably not construct the same fabric or particle structure that exists in the pavement. Since the modulus of this layer is affected by so many variables, the values determined in the laboratory may not be completely accurate.

The amount of shear strain development in the granular layer, which apparently influences the magnitude of adjustment (K_1) required for the laboratory modulus, is naturally dependent on the structural characteristics of each particular pavement section. Close examination of Figures 10-12 shows that the shape of the curves are the same; however, each set of curves, for each pavement, appears to be shifted along the horizontal shear-strain axis. This idea is better illustrated in Figure 13; all the data have been normalized, as before, for test load and contact surface, and are shown in one plot. Here, four separate curves can be distinguished for the four different pavement sections that were used to produce the data. Again, the curvilinear trend of decreasing K_1 with increasing shear strain is shown; however, in this figure, a convergence of the curves at the high shear strains is clearly presented. This convergence closely resembles that shown in Figure 9, developed from the dynamic studies. Similarly, at the low end of the shear-strain scale, the curves are expected to flatten out when the deflections and shear strain become very small, although no data exist to verify such an extrapolation.

The separation of the data according to pavement structure can be partly compensated by accounting for the thickness of the granular base layer. When a load is imposed on the pavement surface, the shear strain will obviously vary with depth regardless of the type of material. In this study, the average depth of the granular layer or the approximate mid-

Figure 14. K_1-factor versus normal maximum shear strain times average base depth.



1 in = 25.4 mm, 1 lb = 4.45 N

point of the granular layer was simply figured into the normalized expression of maximum shear strain, as shown in Figure 14.

The spread of the data is greatly reduced; however, the scatter is still rather extensive, especially for logarithmic scales. This scatter has a clearly defined basis in the fact that the points blend from an extremely stiff pavement to a relatively weak pavement in going from left to right (outside to inside) across the band of data. For example, at a K_1 equal to 6, the normalized shear-strain expression is 1100, 1800, and 3300 for sections I-695, MD-97, and the San Diego test road, respectively. The stronger pavement naturally experiences the lesser shear strain. This grading aspect holds true at every level of K_1. From this analysis, there appears to be some basis for the K_1 modification of the granular layer modulus and this basis seems to be connected to the shear strain mobilized in this layer.

PROCEDURE FOR ESTIMATING SUBGRADE MODULUS

The most-important potential for testing pavement deflection is the possibility of evaluating the modulus of the subgrade without having to drill cores and take samples back to the laboratory. Subgrade response is extremely variable in the field and poses the most problems when designing the proper thickness of pavement overlay. This section presents a tentative procedure for obtaining an approximation of the subgrade modulus by using elastic layer theory and one of the relationships developed in this study.

The procedure is based on the premise that accurate information is available on the materials that were used in the construction of the upper layers of the existing pavement. The moduli of the asphalt surface layers are assumed to be known or obtainable from laboratory mix testing results. In addition, it is presumed that the coefficients of resilient modulus testing, performed on the base course materials, are accessible or can be approximated from experience.

Initially, the procedure requires the average field-measured deflection response (Δ_M) at the center of the applied test load. For these measurements, the temperature, test frequency, magnitude of the load, and time of day should be recorded. The asphalt surfacing moduli are adjusted for field conditions as a function of the test temperature and frequency.

In addition to deflection, the method employs the relationship shown in Figure 6. In the absence of further research regarding the effect of surface cracking on the US-1 and MD-97 data, a relationship closer to that found in the Winchendon data may be more accurate for preliminary use. The solution for subgrade modulus involves the following steps:

1. Compute the normalized deflection $[\Delta_M a/P(\times 10^{-6})]$,
2. Determine the K_1-adjustment factor by using Figure 6,
3. Use elastic layered theory and the modified resilient modulus relationship for the granular material ($K_1 k_1 \theta^{k_2}$) to calculate the predicted deflection (Δ_p), and
4. Repeat this solution of Δ_p for various assumed subgrade modulus values until $\Delta_p = \Delta_M$.

Although the solution is based on purely empirical relationships, evidence is substantial that a rational explanation exists in the behavior of granular material. As discussed previously, the characterization of this material in the laboratory by using remolded specimens is highly questionable. In Figure 13, the curves that relate the computed maximum shear strain to the adjustment factor (K_1) necessary for matching deflections suggest that differences in shear strain development between laboratory and field situations are responsible.

CONCLUSIONS

In summary, the results presented in this report are preliminary because the data base is limited to only a few different pavement sections. However, based on the results obtained, we can unequivocably state that the type of device used in making the deflection measurements is independent from the relationships described. Further investigation is necessary to substantiate these findings with data obtained from other flexible pavement sections. The following is a list of conclusions reached as a result of this study:

1. The major factor that contributes to the discrepancy between measured and theoretically predicted surface deflections (from a layered-elastic program) lies in the current procedure for characterizing the resilient modulus (M_R) of granular materials in the laboratory.
2. The data produced from this research study with the FHWA Thumper exhibit complete agreement with earlier work, which demonstrates that an adjustment factor (K_1) must be applied to the value of the laboratory-resilient modulus in order to obtain equal measured and predicted deflections (by multilayer-elastic theory); this K_1 adjustment was found to vary linearly with surface deflections on a log-log scale.
3. Evidence is substantial that the in situ effective modulus ($K_1 M_R$) of the granular layer is a function not only of the stress state but also the magnitude of the shear strain induced in that layer by the surface loading. For low levels of shear

strain, the effective in situ modulus is much larger than at higher levels of shear strain.

4. The amount of shear-strain development in the granular layer appears to be related to the overall pavement strength in addition to loading magnitude, which is intuitively correct.

5. Since shear strain cannot be measured easily in the field, a provisional procedure was developed and outlined for estimating the granular base modulus adjustment factor (K_1) directly from field-measured deflection results by using an empirically derived relationship from this study.

6. With the bituminous surface and granular base layers of a conventional asphalt pavement accurately characterized, elastic-layered theory can be used to compute the subgrade modulus by matching surface deflections.

From the results of this study, the possibility of the behavior of granular material being related to mobilized shear strain seems entirely plausible. We recommend that this connection be further investigated over a broader range of pavement sections to incorporate different material types and climate conditions. In recognition of all the possible sources of error that could enter into the production of the data used in this study (e.g., field deflection measurement, laboratory material testing, mathematical manipulation, and existing natural variation), the amount of scatter exhibited in the relationships involving the proposed adjustment factor is simply too small to forego additional exploration.

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Prediction of Subgrade Moduli for Soil that Exhibits Nonlinear Behavior

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The main objective of this report is to develop a simple and accurate procedure to predict an equivalent one-layer subgrade modulus for a soil that exhibits nonlinear behavior in a flexible highway pavement system. The analysis is predicated on developing such a modulus that would yield identical values of either vertical strain or deflection at the top of the subgrade compared with results obtained from a stress-dependent iteration technique that accounts for the stress-dependent (nonlinear) behavior of the subgrade. Use of a modified elastic layered computer program was made to determine equivalent subgrade modulus values for nearly 3900 separate layered pavement problems. By using the results obtained, multiple regression techniques were used to determine predictive equations for the equivalent subgrade modulus values as a function of the nonlinear subgrade and layered pavement properties. Use of partial model regressions techniques allowed predictive equations to be obtained that had correlation coefficients in excess of 0.95 and residual errors less than 10 percent. Both analytical and nomographic solutions are presented to demonstrate the simplicity of the approach. It was found that values of deflection-based equivalent mod-