Improved Characterization Model for Granular Bases

ROBERT P. ELLIOTT AND LOURDESNATHAN DAVID

Laboratory resilient modulus tests were conducted on granular materials at stress states exceeding the materials' static shear strengths. The test results show that, above the static strength, the modulus decreases with increasing stress levels. These data were used to develop a characterization model that is a modification of the commonly used *k*-theta-*n* model. The modification consists of the addition of a stress ratio (stress/strength) parameter. The stress ratio model was used in the finite element program ILLI-PAVE to analyze typical flexible pavement sections. The analysis results are compared with similar analyses using the Mohr-Coulomb stress adjustment model normally used with ILLI-PAVE. The comparison shows that similar stress and strain patterns are predicted by both models but that the stresses predicted in the granular base by the stress ratio model appear to be more realistic. Also, the stress ratio model provides a means for analyzing the structural effects of granular materials having different shear strength characteristics

In recent years, pavement design research has emphasized the development of mechanistic analysis procedures. The objective of the development is to establish a rational method of design that is based on load-induced stresses and strains in each pavement layer. Material combinations and thicknesses are selected on the basis of the effect the stresses and strains have on each material's behavior as a part of the pavement system.

Perhaps the most significant weakness in the mechanistic analysis procedures that have been developed to date is the inability to model the behavior of unbound granular layers realistically. The granular base models currently in use typically predict stress states that exceed the strength of the material. For example, tensile radial stresses are frequently predicted at the bottom of the granular layer of a conventional flexible pavement.

This paper presents the results of a study sponsored by the National Science Foundation. The objective of the study was to establish an improved structural characterization model for granular base material. An analysis of laboratory test data has been used to propose a characterization model which is a modification of the model that is currently used by most pavement analysts.

PAVEMENT STRUCTURAL MODELS

Two mathematical models are used in mechanistic analyses to represent the pavement system: the elastic layered theory model and the finite element model. The elastic layered model is used most frequently.

By the elastic layered theory, the pavement system is represented as a series of layers of linear elastic material. Each layer is represented by a single elastic modulus and Poisson's ratio. The single modulus provides a reasonable representation for asphalt concrete and other stabilized materials; however, it is not a good representation for unbound granular layers.

Numerous studies have demonstrated that the elastic behavior of unbound granular materials is stress dependent. That is, the apparent modulus of the granular material changes as the applied stress state changes. The typical behavior is shown by the data plotted in Figure 1. The resilient (elastic) modulus of the materials increases as the stress state (sum of the principal stresses) increases.

This stress dependency can be incorporated into an elastic layered analysis through the use of iterative techniques. An initial modulus is assigned and stresses are calculated. A new modulus is assigned for the next iteration on the basis of the stress state of the current iteration. An obvious limitation to this approach is the fact that a single modulus must still be assigned for the entire layer. The stress state will not be constant throughout the layer. It will be higher directly below the load and decrease as the distance from the load increases. Consequently, the modulus should not be constant throughout the layer.

In this respect, the finite element model provides a superior pavement representation. The finite element model treats the pavement as a series of interconnected elements. Each element can be assigned a different modulus and Poisson's ratio. As a result, the influence of stress variation on the modulus can be represented in both the vertical and horizontal directions.

Nevertheless, as currently used, neither model provides a realistic representation of the stresses and strains within an unbound granular layer. Both pavement models (elastic layered and finite element) frequently predict stress states that exceed the strength of the material. For the finite element model, this problem might be alleviated with an appropriate material characterization model.

ILLI-PAVE (a pavement analysis program provided by the Transportation Facilities Group, Department of Civil Engineering, University of Illinois at Urbana-Champaign) is a finite element model that attempts to compensate for the problem by adjusting the predicted stresses so that they do not violate the Mohr-Coulomb failure envelope. However, the adjusted stresses are used only to calculate the modulus values to be used in the next iteration. As a result, the final stresses in the

Arkansas Highway and Transportation Research Center, Department of Civil Engineering, University of Arkansas, Fayetteville, Ark. 72701.

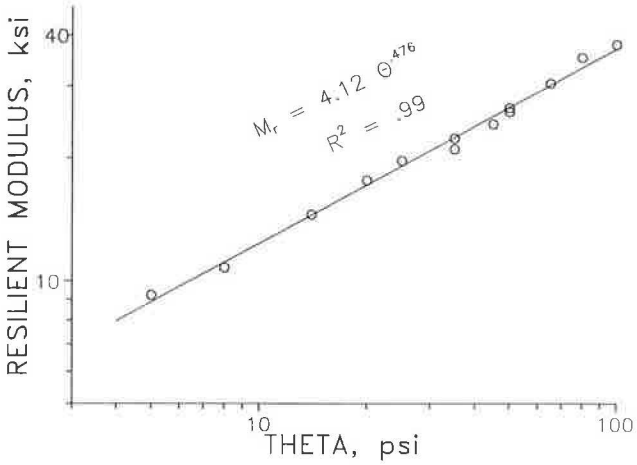

FIGURE 1 Typical stress dependency relationship for a granular base material.

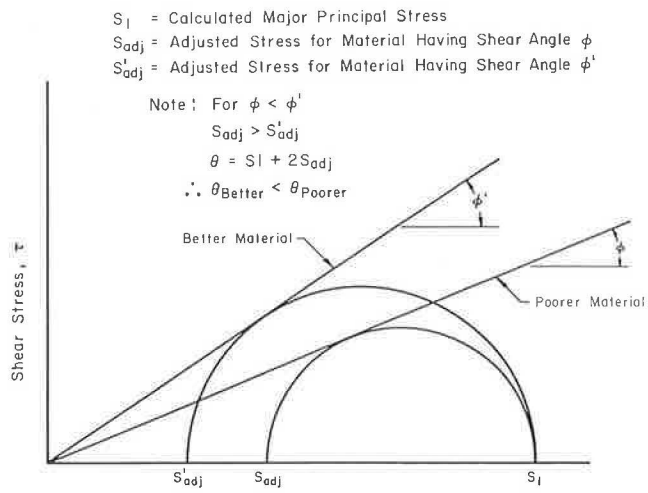

FIGURE 2 Mohr-Coulomb stress adjustment used in ILLI-PAVE (*5*).

granular layer continue to be questionable and frequently exceed the material strength.

GRANULAR LAYER CHARACTERIZATION MODELS

The characterization model most commonly used for unbound granular materials is based on data such as that shown in Figure 1. The resilient modulus is determined using cylindrical specimens in a triaxial cell. The specimen is subjected to a constant confining pressure. A repeated, dynamic deviator load (stress) is applied vertically, and the vertical resilient or rebound deformation (strain) is measured. The characterization model is

$$M_r = k\theta^n \tag{1}$$

where

M_r = the resilient modulus (deviator stress/resilient strain),
k and n = regression coefficients determined from the laboratory data, and
θ = sum of the principal stresses (deviator stress + 3 * confining pressure).

A more complex model was proposed and used by Brown and Pappin (*1*,*2*). This model is referred to as the contour model. It appears to have some analytical advantages but was not investigated in this study because of the complex laboratory testing required to develop the material parameters that are used.

Uzan (*3*) examined these and other granular characterization models. From his analysis, he suggested use of a modification of Equation 1:

$$M_r = k\theta^n\sigma_d^a \tag{2}$$

where σ_d equals the deviator stress and a equals the regression coefficient determined from laboratory data. This model was suggested to account for trends of decreasing resilient modulus with increasing deviator stress at constant confining pressures.

Both Uzan (*3*) and Brown and Pappin (*1*) reported that use of their models resulted in tensile stresses being predicted for at least some pavement configurations. Brown and Pappin stated that this was due to some inaccuracy in their model and was an indication of a weak pavement. Uzan argued that the tensile stresses were small and were offset by residual compressive stresses induced by compaction during pavement construction.

The finite element program ILLI-PAVE uses the Equation 1 model with its Mohr-Coulomb stress-adjustment procedure. This will be referred to as the Mohr-Coulomb model. Elliott and Thompson (*4*) noted that one problem with the Mohr-Coulomb model was that it did not properly differentiate between poorer and better granular material. As illustrated in Figure 2, for equal predicted stress states, the higher phi angle of the better material will result in a lower adjusted stress. As a result, theta will also be lower and the resilient modulus for the next iteration will be lower.

There is another problem with the Mohr-Coulomb model. The stresses are adjusted but are not redistributed. Consequently, the adjusted stresses are not in equilibrium and true convergence of the iterative approach is not achieved.

LABORATORY TESTING

Three aggregates were tested to develop data to be used in developing an improved characterization model. The tests were conducted in accordance with AASHTO T-274 except that some tests were performed at deviator stresses that exceeded the materials' static shear strengths. The failure-state tests were performed to examine the resilient modulus stress dependency under stress states approaching those predicted by the currently used models.

The failure state tests were conducted in such a manner that a new test specimen was required for each confining pressure in which tests were performed beyond failure. After the tests at the standard confining pressure and deviator stress

combinations were complete, the test was continued at a constant confining pressure with the deviator stress being increased. Testing continued at higher and higher deviator stresses until a significant accumulation of permanent deformation made further testing meaningless.

For two of the aggregates, failure-state testing was performed at only one level of confining pressure (Figures 3 and 4). The third aggregate was tested in failure states at three confining pressures (Figure 5). (The nonfailure results shown on Figures 3, 4, and 5 that have theta values greater than those of failure tests represent tests at higher confining pressures.) No specific effort was made to examine the repeatability of the failure-state tests. However, the consistency of results obtained for the aggregate tested at three confining pressures suggests a reasonable degree of repeatability.

Regression equations conforming to Equation 1 were developed using only the nonfailure data. These equations are shown on the figures. By observing the data points and the R^2 values, it can be seen that Equation 1 provides a good representation of the behavior at stresses below failure.

However, at stresses exceeding failure, the resilient modulus decreases as the deviator stress (and, therefore, theta) increases. This behavior contrasts with the effect of the Mohr-Coulomb adjustment model. As illustrated in Figure 2, the stress adjustment increases theta, which in turn increases the modulus.

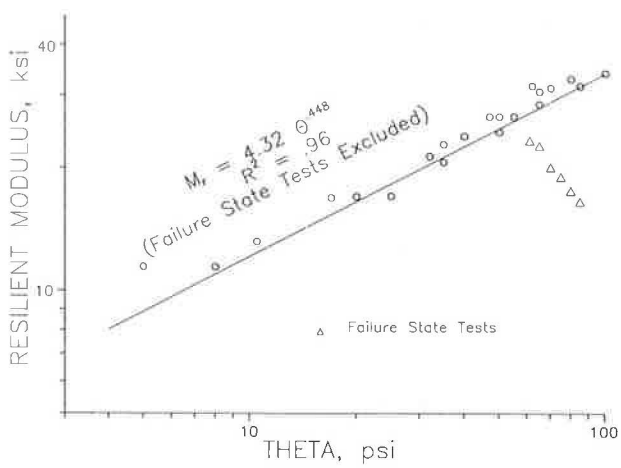

FIGURE 3 Resilient modulus test results for a crushed stone.

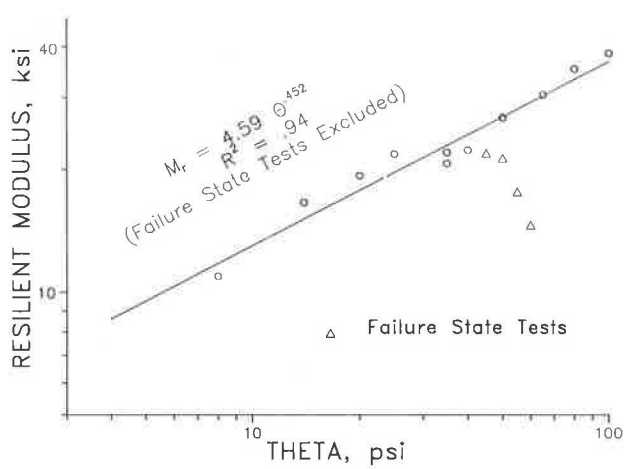

FIGURE 4 Resilient modulus test results for a low fines gravel.

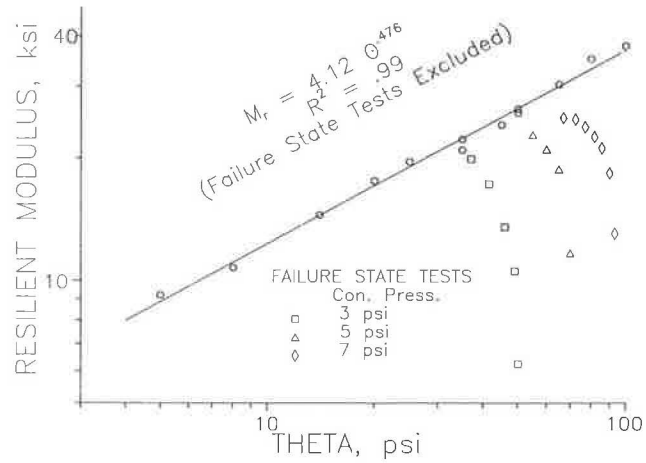

FIGURE 5 Resilient modulus test results for a dense-graded gravel.

MODEL DEVELOPMENT

The data displayed in Figures 3, 4, and 5 were studied to develop a new characterization model. Two facts were noted. First, the Equation 1 model provided an excellent representation of the data below failure. Second, above failure, there appeared to be a need to incorporate a failure term. These facts suggested that the general form of Equation 1 should be modified by incorporating a failure term. The failure term should have little or no impact until failure is approached.

Several models were investigated. The one found to provide the best fit modifies Equation 1 by adding a stress/strength ratio as the failure term. The model selected is

$$M_r = k\theta^n/10^A \tag{3}$$

where

$A = mR^3$,
m = regression coefficient determined from laboratory data, and
R = stress/strength ratio (deviator stress divided by the failure deviator stress).

The failure deviator stress is determined on the basis of the confining pressure and the static triaxial shear test.

This model (Equation 3) is referred to hereafter as the stress ratio model. Analysis of all the data shown in Figure 5 using the stress ratio model produced the regression equation shown in Figure 6. The plots of the regression equation at the three confining pressures for which failure-state tests were conducted show a good fit between the model and the test results.

Analyses were also performed on the data for the other two aggregates. These produced similar regression equations. However, because the other aggregates were tested at only one confining pressure, the results are not as meaningful and are not shown.

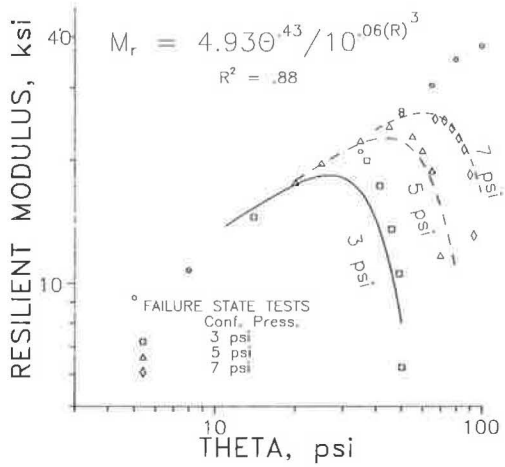

FIGURE 6 Plot of stress ratio model versus test results for a dense-graded gravel.

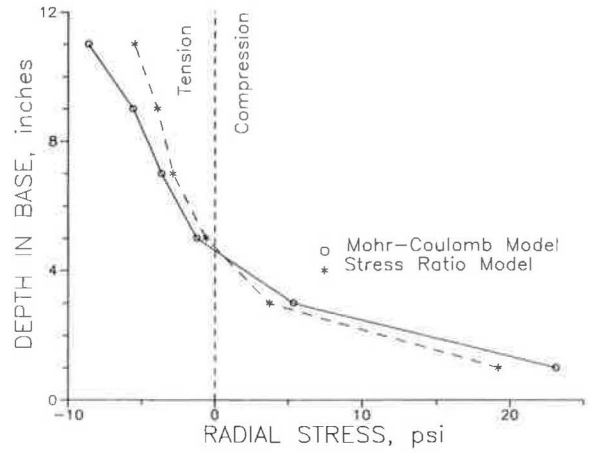

FIGURE 7 Comparison of predicted radial stresses in the base for the 1-in. (25-mm) surface pavement.

MODEL COMPARISON

A comparison of the stress ratio model and the Mohr-Coulomb model was developed using ILLI-PAVE. This required creating a modified version of ILLI-PAVE that incorporated the stress ratio model in lieu of the Mohr-Coulomb model.

Three pavement sections were analyzed using the two models. The sections were identical except for the thickness of the asphalt surfacing. Each section had a 12-in. (305-mm) granular layer. The surfacing thicknesses were 1 in. (25 mm), 3 in. (76 mm), and 6 in. (152 mm). A modulus of 500,000 psi (3447 Mpa) was used for the asphalt concrete; and the subgrade was represented as having a breakpoint resilient modulus of 6,000 psi (41.4 MPa).

The material parameters determined for the aggregate tested most extensively in the study were used for the granular layer. For the Mohr-Coulomb model, the phi angle (48.6 degrees) determined by the triaxial shear strength test was used for the stress adjustment, and the stress dependency was characterized using the regression equation developed from the below failure data and shown on Figure 5. The stress ratio model used the regression equation developed from all the data and shown on Figure 6.

Stresses and strains were determined for a standard 9,000-pound (40-kN) wheel load and an 80-psi (552-kPa) contact pressure. Five analysis iterations were specified so that both the final analysis results and the program convergence could be compared.

The radial stresses predicted by the two models are shown in Figures 7, 8, and 9 for the 1-in. (25-mm), 3-in. (76-mm), and 6-in. (152-mm) surface pavements, respectively. The stress patterns predicted by the models are seen to be similar, with both models predicting tensile stresses at the bottom of the base for the 1-in. (25-mm) and 3-in. (76-mm) surface pavements. However, the tensile stresses are lower with the stress ratio model.

Program convergence and the base course modulus values used are compared in Figure 10 for the 6-in. (152-mm) surface pavement. Both models converged in fewer than five iterations, with the stress ratio model converging in three iterations and the Mohr-Coulomb model converging in four. The modulus values used were similar to the stress ratio model, using

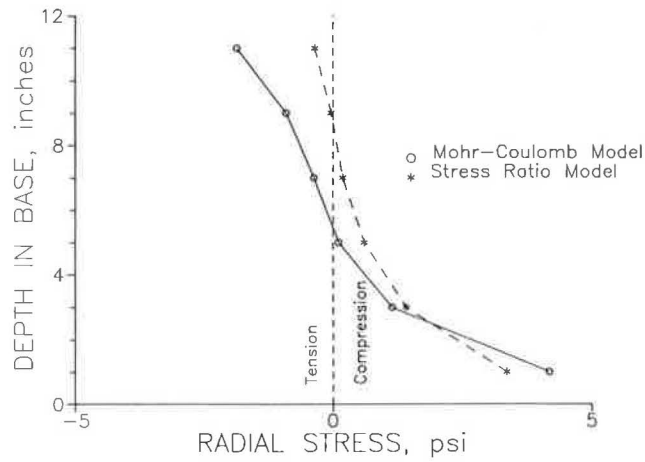

FIGURE 8 Comparison of predicted radial stresses in the base for the 3-in. (76-mm) surface pavement.

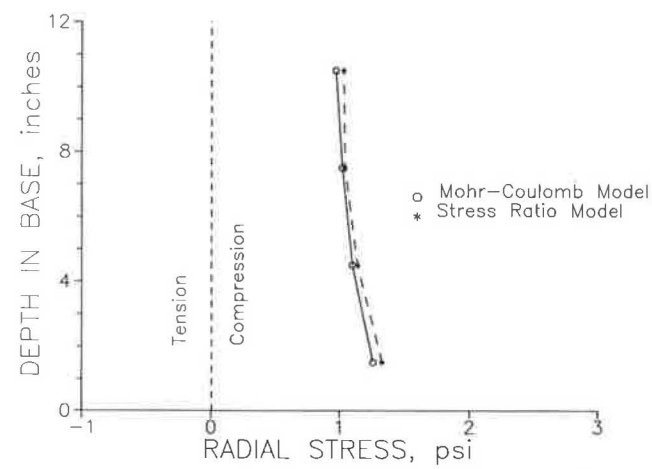

FIGURE 9 Comparison of predicted radial stresses in the base for the 6-in. (152-mm) surface pavement.

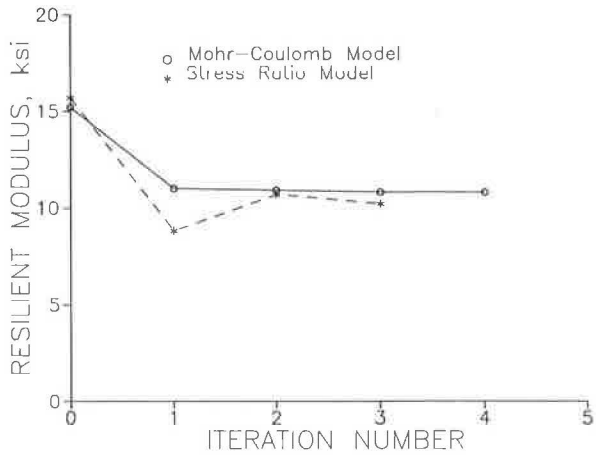

FIGURE 10 Comparison of convergence and resilient modulus values used for the 6-in. (152-mm) surface pavement.

slightly lower values. Similar patterns of modulus values were noted for the other surface thicknesses; however, neither model converged in fewer than five iterations.

COMPARISON OF GRANULAR MATERIALS

Because of the problems in modeling the behavior of granular materials, mechanistic analyses to date have not been able to examine the relative influence of aggregate bases of different quality. The stress ratio model provides an approach that makes such examinations possible.

To demonstrate this, the 3-in. (76-mm) surface pavement was also analyzed assuming a weaker base material. For this analysis, a base shear strength phi angle of 40 degrees was used. This changed both the stress adjustment of the Mohr-Coulomb model and the failure deviator stress in the stress ratio model. All other parameters in the characterization models were left unchanged so that the phi angle effect could be demonstrated.

The pavement response parameters most commonly used in mechanistic pavement analysis are surface deflection at the center of loading, radial strain at the bottom of the asphalt, and vertical strain at the top of the subgrade. The influence of changes in base course phi angle is shown by the results of the analyses displayed in Table 1.

In general, a pavement that exhibits a lower surface deflection, a lower asphalt radial strain, and a lower subgrade vertical strain is a better (i.e., longer expected service life) pavement. Using these criteria, Table 1 shows that the Mohr-Coulomb model ranks the pavements incorrectly by predicting lower deflection and asphalt strain for the pavement with the weaker base course (lower phi angle). With the stress ratio model, the pavements are ranked correctly, because the pavement with the weaker base is predicted to have higher deflection and higher asphalt strain.

Except for the relative rankings, the differences in predicted pavement response are not significant for practical engineering purposes with either model. However, the fact that the stress ratio model ranks the pavements in the proper order is important and encouraging.

CONCLUSIONS

On the basis of the testing and analyses reported in this paper, the following conclusions have been made, relative to the structural characterization of granular base materials.

1. The *k*-theta-*n* model (Equation 1) provides a good representation of the laboratory stress-dependent behavior of granular material as long as the stress conditions are less than failure, as determined by the static triaxial test.
2. The stress ratio model (Equation 3) provides a good representation of the laboratory stress-dependent behavior of granular material both below and above static failure stresses.
3. The stress, strain, and deflections predicted using the stress ratio model in the ILLI-PAVE finite element program are similar to those predicted using the Mohr-Coulomb model. However, the predicted tensile stresses in the granular base are lower, appearing to be more realistic.
4. The stress ratio model provides a means for analyzing the structural effects of granular materials having different shear strength characteristics.
5. Although additional testing and analysis are needed, the stress ratio model appears to offer a significant improvement in the ability to analyze the structural behavior of granular base flexible pavements.

ACKNOWLEDGMENTS

This research was part of a study, Development of an Improved Structural Model for Granular Pavement Layers, sponsored by the National Science Foundation. The study was conducted by the Arkansas Highway and Transportation Research Center at the University of Arkansas, Fayetteville.

TABLE 1 COMPARISON OF STRESS RATIO AND MOHR-COULOMB MODELS IN EVALUATING EFFECT OF GRANULAR BASE SHEAR STRENGTH

	Effect of Phi Angle (°) by Structural Model			
	Mohr-Coulomb		Stress Ratio	
Pavement Response Parameter	40.0	48.6	40.0	48.6
Surface deflection (in.)	.0304	.0307	.0318	.0315
AC radial strain	.000371	.000380	.000414	.000408
Subgrade vertical strain	.000855	.000857	.000816	.000814

REFERENCES

1. S. F. Brown and J. W. Pappin. Analysis of Pavements with Granular Bases. In *Transportation Research Record 810*, TRB, National Research Council, Washington, D.C., 1981.
2. S. F. Brown and J. W. Pappin. Modeling of Granular Materials in Pavements. In *Transportation Research Record 1022*, TRB, National Research Council, Washington, D.C., 1985.
3. J. Uzan. Characterization of Granular Material. In *Transportation Research Record 1022*, TRB, National Research Council, Washington, D.C., 1985.
4. R. P. Elliott and M. R. Thompson. *Mechanistic Design Concepts for Conventional Flexible Pavements*. Transportation Engineering Series No. 42, University of Illinois at Urbana-Champaign, 1985.

The opinions, findings, and conclusions expressed in this paper are those of the author and not necessarily those of the National Science Foundation.

Publication of this paper sponsored by Committee on Strength and Deformation Characteristics of Pavements.