Geomaterial Characterizations of Full Scale Pavement Test Sections for Mechanistic Analysis and Design

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ABSTRACT

Resilient modulus is a key input property of pavement foundation geomaterials, i.e., subgrade soil and base/subbase unbound aggregate, for the mechanistic-empirical design of flexible pavements. Recent research at the University of Illinois has focused on the development of a mechanistic model for the response analysis of geogrid reinforced flexible pavements. This model utilized the finite element approach and considered the nonlinear, stress dependent pavement foundation behavior in a similar way to the level I analysis approach in the 2002 Pavement Design Guide. To validate the response model as well as to develop pavement distress models, nine full-scale flexible pavement test sections, geogrid reinforced and unreinforced, were recently constructed. To quantify the effectiveness of geogrid reinforcement on low volume flexible pavements, the fine-grained subgrade soils were carefully constructed and maintained at California Bearing Ratio (CBR) values 4% or lower throughout the test sections. A complete suite of laboratory and field tests were performed to characterize the pavement geomaterials for mechanistic analysis of the test section response. This required both monitoring of the pavement layer properties during construction and also development of modulus characterization models from multiple regression analyses of the laboratory test data.

INTRODUCTION

Under the repeated application of moving traffic loads, most of the deformations are recoverable and thus considered elastic. It has been customary to use resilient modulus (M_R) for the elastic stiffness of the pavement materials defined as the repeatedly applied wheel load stress divided by the recoverable strain determined after shakedown of the material. Repeated load triaxial tests are commonly employed to evaluate the resilient properties of pavement foundation geomaterials, i.e., fine-grained subgrade soils and unbound aggregate materials.

The resilient modulus is also the key input property for pavement geomaterials in the mechanistic-empirical pavement design approach. The recently developed 2002 Design Guide methodology, a product of the National Cooperative Highway Research Program (NCHRP) 1-37A (2004) project, requires conducting repeated load triaxial tests to determine the resilient modulus properties and characterize subgrade soil and granular base aggregate behavior. The 2002 Design Guide Level 1 flexible pavement analysis utilizes the finite element (FE) model, which requires the nonlinear resilient modulus geomaterial model parameters obtained from regression analyses of the test data.

Current ongoing research at the University of Illinois has focused on the development of a mechanistic model for the analysis of geogrid granular base reinforced pavements (Kwon et al., 2005). This model, which utilizes the FE approach, considers the nonlinear stress-dependent pavement foundation to predict the critical pavement responses. To validate/calibrate the mechanistic response model, instrumented full-scale flexible pavement test sections, geogrid reinforced and unreinforced, were recently designed and constructed (Al-Qadi et al., 2006). Test section variables examined in full-scale test studies consist of hot mix asphalt and granular base layer thicknesses, type and location of geogrid within the base course. Pavement geomaterial layer properties as well as nonlinear resilient modulus models developed for characterizing layer stiffnesses are presented to provide a methodology on how to collect key geomaterial input data for mechanistic pavement analysis through proper laboratory and field testing, perform material characterizations, and control field soil properties during pavement construction.

RESILIENT MODULUS MODELS USED IN MECHANISTIC ANALYSIS

Base/subbase unbound aggregate

Resilient modulus models, such as the Uzan model (1985), Witczak-Uzan Universal model (1992) and 2002 Design Guide model (NCHRP 1-37A, 2004) consider the effects of stress dependency for modeling the nonlinear behavior of base/subbase aggregates and are generally suitable for FE programming and practical design use. These models handle very well the modulus or stiffness increase with increasing stresses in an unbound aggregate layer. Uzan model considers the effects of bulk and deviator stresses in axisymmetric analysis and the Witczak-Uzan Universal model and 2002 Design Guide model (2004) include an octahedral shear stress component instead of deviator stress, which makes also applicable to three-dimensional FE analysis. These modulus models for the unbound base/subbase aggregate are expressed as follows:

$$\mathrm{M_R} = \mathrm{K_1} \left(\frac{\theta}{\mathrm{P_0}}\right)^{\mathrm{K_2}} \left(\frac{\sigma_\mathrm{d}}{\mathrm{P_0}}\right)^{\mathrm{K_3}} \tag{1}$$

$$\mathrm{M_R} = \mathrm{K_1} \cdot \mathrm{P_a} \cdot \left(\frac{\theta}{\mathrm{P_a}}\right)^{\mathrm{K_2}} \cdot \left(\frac{\tau_\mathrm{oct}}{\mathrm{P_a}}\right)^{\mathrm{K_3}} \tag{2}$$

$$\mathrm{M_R} = \mathrm{K_1} \cdot \mathrm{P_a} \cdot \left(\frac{\theta}{\mathrm{P_a}}\right)^{\mathrm{K_2}} \cdot \left(\frac{\tau_\mathrm{oct}}{\mathrm{P_a}} + 1\right)^{\mathrm{K_3}} \tag{3}$$

where P_o = the unit pressure of 1 kPa, P_a = atmospheric pressure (100 kPa), K_1 to K_3 = multiple regression parameters, $\sigma_d = \sigma_1 - \sigma_3$ = deviator stress, θ = bulk stress = $\sigma_1 + \sigma_2 + \sigma_3$, τ_{oct} = octahedral shear stress = $\frac{1}{3}\sqrt{(\sigma_1-\sigma_2)^2+(\sigma_1-\sigma_3)^2+(\sigma_2-\sigma_3)^2} = \frac{\sqrt{2}}{3}(\sigma_1-\sigma_3)$ for cylindrical specimens in triaxial tests, σ_1 = major principal stress, σ_2 = intermediate principal stress, and σ_3 = minor principal stress/confining pressure.

Resilient modulus model for subgrade soil

The resilient modulus of fine-grained subgrade soils is also dependent upon the stress state. Typically, soil modulus decreases in proportion to the increasing stress levels thus exhibiting stress-softening type behavior. The constitutive relationships are primarily established between the resilient modulus and the deviator stress for fine-grained subgrade soils. The bilinear or arithmetic model is the most commonly used resilient modulus model for subgrade soils (Thompson and Elliott, 1985). The bilinear soil model used in the developed mechanistic model is expressed as follows:

$$\mathrm{M_R} = \mathrm{K_1} + \mathrm{K_3} \times (\mathrm{K_2} - \sigma_\mathrm{d}) \text{ When } \sigma_\mathrm{d} \leq \mathrm{K_2} \tag{4}$$

$$\mathrm{M_R} = \mathrm{K_1} - \mathrm{K_4} \times (\sigma_\mathrm{d} - \mathrm{K_2}) \text{ When } \sigma_\mathrm{d} \geq \mathrm{K_2} \tag{5}$$

where K_1 to K_4 = material constants obtained from repeated load triaxial test data and $\sigma_d = \sigma_1 - \sigma_3$ = deviator stress.

In addition to the bilinear model, the 2002 Design Guide model (NCHRP 1-37A, 2004) is also used in the mechanistic analysis to characterize subgrade soils.

GEOMATERIAL CHARACTERIZATION

Characterization of Subgrade Soil

Soil Classification and Index Properties

To construct the instrumented full-scale flexible pavement test sections, initial soil sampling was performed using a hand auger to collect soil samples from a depth of 1.5 m. A total of 36 bags of soil samples were collected from the nine test section locations. Atterberg limit tests (ASTM D 4318) indicated that the subgrade soils had an average liquid limit (LL) of 21 and an average plasticity limit (PL) of 16 and an average plasticity index (PI) of 5. The results of visual soil classification performed on the bag samples gave predominant soil types as brown clayey silt and brown silty clay. Light brown well-graded sand with clay and brown clay sand were also found. The subgrade soil had a specific gravity of 2.72 and was classified as ML-CL using the dual classification following the Unified Soil Classification System.

Moisture Density and CBR Tests (ASTM D 1883 and AASHTO T-193-81)

Standard Proctor tests (AASHTO D698) were conducted to define moisture-density relationship. CBR tests were also performed on both soaked (standard) and unsoaked CBR test samples to define moisture-CBR curves. Considering the fact that both unsoaked and soaked CBR tests gave almost the same results for the wet of optimum moisture contents (OMCs), Figure 1 shows the subgrade soil standard Proctor moisture-density and unsoaked CBR results. A maximum dry density (γ_{dmax}) of 19.3 was obtained with an OMC of 11.2%. The dry density and the moisture content values are also shown in Figure 1 corresponding to a soil CBR of 4, which was the maximum soil CBR allowed in the test strip subgrade.

Correlation between Dynamic Cone Penetrometer (DCP) and CBR

Dynamic Cone Penetrometer (DCP) tests were routinely conducted in the field before and during construction at each pavement test section location. The following correlation, given by Equation 6, between the DCP penetration rates and the laboratory determined CBR values was validated for all soil groups collected from the pavement test strip:

$$\text{Log (CBR)} = 2.61\text{-}1.26 \text{ Log (PR)} \qquad (6)$$

where CBR = California bearing ratio, PR = penetration rate (inches/blow) of DCP. Accordingly, the DCP based evaluation of the test strip soil CBR values ranged from 5 to 28% before the top subgrade soils were prepared for pavement construction.

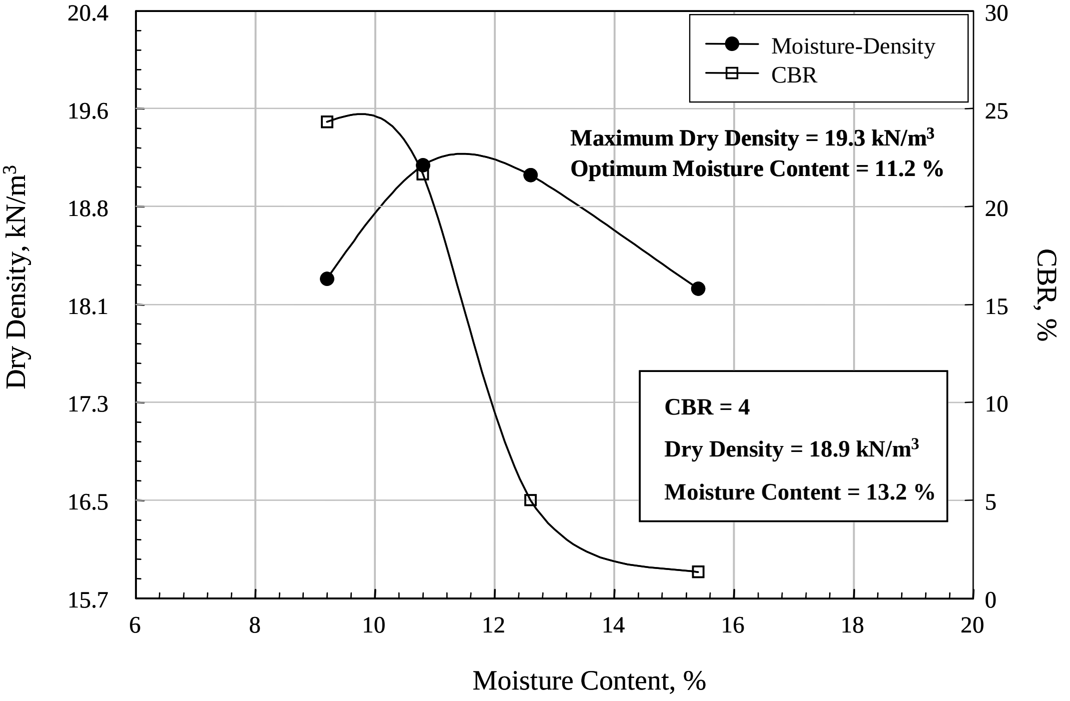

Figure1. Moisture-Density-CBR Relationship for the Subgrade Soils

As-Constructed Subgrade Properties

The 30.5-cm prepared subgrade layer was built in three lifts using a sheepsfoot roller compactor. The compaction effort was monitored with nuclear density gauge and DCP measurements taken from each pavement test section. As-built density of each subgrade lift obtained using the nuclear gauge satisfied a minimum relative density of 97%. This percentage was calculated based on the 18.94 kN/m^3 dry density at the target CBR of 4 as indicated in Figure 1 from the laboratory standard Proctor and CBR tests. The amount of water added to each pavement test section soil fill was determined accordingly to maintain the subgrade CBR of 4 or below. Figure 2 shows the subgrade CBR profile with depth for a typical pavement test section constructed. The CBR values were obtained from DCP penetrations using Equation 6.

Characterization of Base Aggregate

A crushed limestone, designated as dense graded CA-6 aggregate by Illinois Department of Transportation, was used as the base course material. The gradation curve of the CA-6 crushed aggregate is shown in Figure 3 with the maximum allowed 12% fines passing No. 200 sieve. Modified Proctor (AASHTO T180) moisture-density tests conducted on the CA-6 material gave a maximum dry density of 22.5 kN/m^3 corresponding to an OMC of 6.5% (see Figure 4). The compaction effort was monitored with a nuclear gauge to maintain a minimum 95% relative compaction in the field.

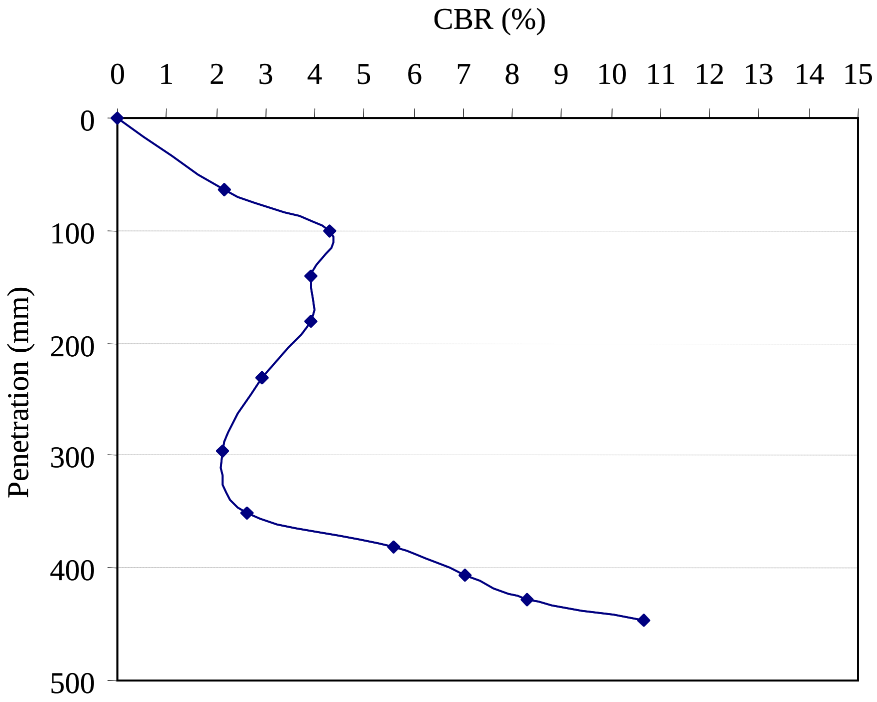

Figure 2. Prepared Subgrade CBR Profile with Depth of a Typical Pavement Test Section

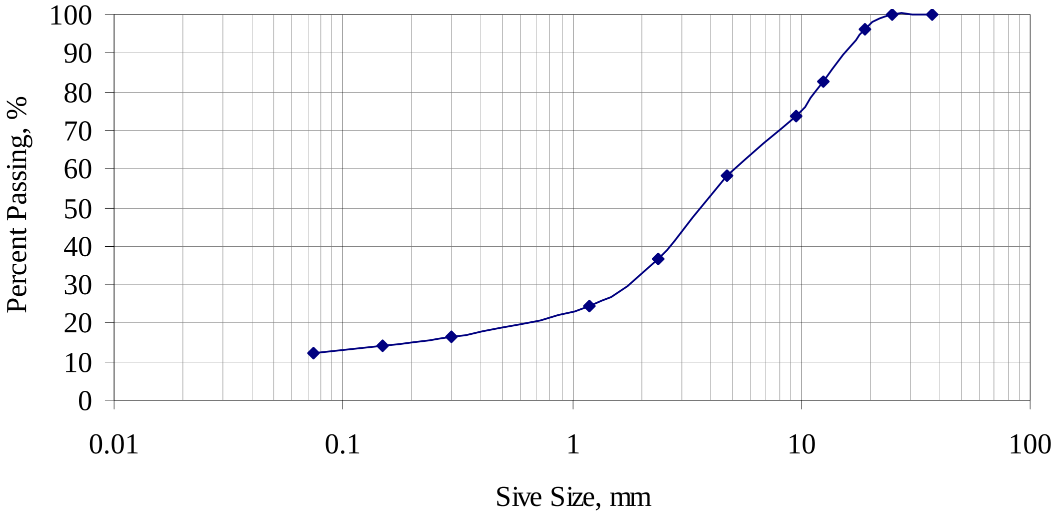

Figure 3. Gradation Curve for the CA-6 Unbound Aggregate Base

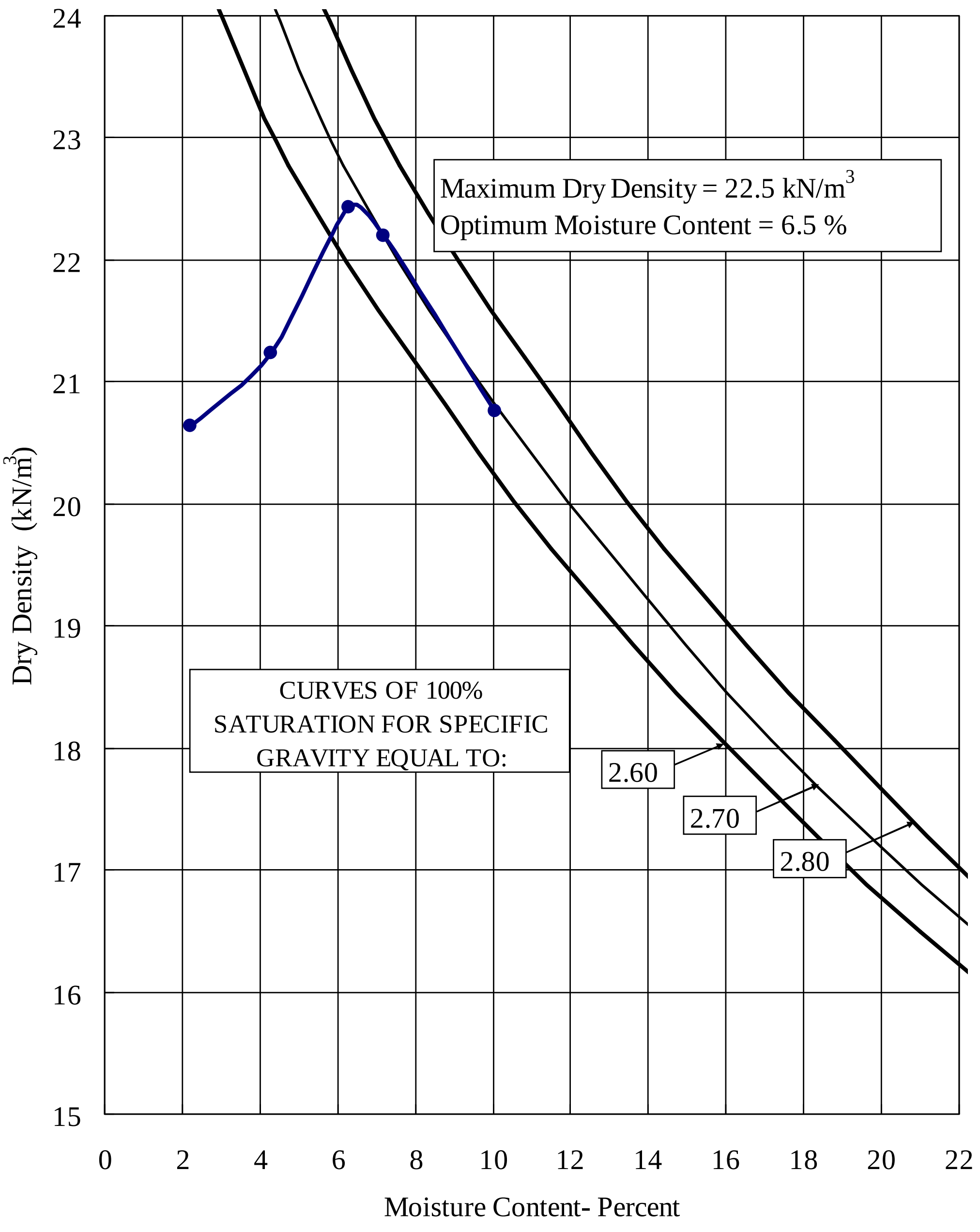

Figure 4. Modified Proctor Moisture-Density Results for the CA-6 Base Aggregate

REPEATED LOAD TRIAXIAL TEST RESULTS

Fine-grained Subgrade Soils

A series of repeated load triaxial tests were conducted next to determine resilient modulus properties of the subgrade soil at OMC and on the wet of optimum conditions corresponding to the target CBR of 4 and below. The soil samples were compacted to prepare cylindrical test specimens 5.1 cm in diameter by 10.2 cm high. Using pneumatic type repeated load triaxial equipment, the specimens were first conditioned by applying 200 load pulses at 41.4 kPa deviator stress. A haversine load pulse was used with load duration of 0.1 seconds and rest period of 0.9 seconds similar to the AASHTO T307. No confining pressure was applied on the specimens. Realistically, confining pressures acting on top of pavement subgrades are generally very low. Accordingly, the unconfined conditions on the test specimens simulated possibly the worst loading conditions in the field. After conditioning, the specimens were subjected to pulsed deviator stress levels of 13.8, 27.6, 41.4, 55.2, 68.9, 82.7, 96.5, and 110.3 kPa, respectively. Each stress level was applied 100 times and the resilient modulus was calculated based on the last 5 cycles.

Table 1 lists the applied deviator stresses and the measured resilient modulus properties. The resilient modulus and deviator stress relationships are shown in Figure 5. The resilient moduli generally decreased with the increasing deviator stresses, which is in accordance with the stress-softening behavior of fine-grained soils characterized by Thompson and Elliott (1985) using the bilinear approximation model.

Multiple regression analyses were also conducted using the test data to characterize the nonlinear modulus behavior by the 2002 Design Guide model (NCHRP 1-37A, 2004). Table 2 summarizes the 2002 Design Guide nonlinear modulus model parameters (K_i) and the high correlation coefficients, R^2, which indicate an overall reasonably good fit. These resilient modulus model parameters are the subgrade soil inputs needed for the 2002 Design Guide Level 1 flexible pavement mechanistic analysis and design.

Table 1. Soil Resilient Modulus Test Results Obtained at Four Moisture Contents

Optimum water content = 11.2% Maximum dry density = 19.3 kN/ m^3		Achieved water content = 13% Dry density = 19.0 kN/ m^3		Achieved water content = 14% Dry density = 18.5 kN/ m^3		Achieved water content = 15% Dry density = 18.4 kN/ m^3	
Deviator Stress (kPa)	Resilient Modulus (MPa)	Deviator Stress (kPa)	Resilient Modulus (MPa)	Deviator Stress (kPa)	Resilient Modulus (MPa)	Deviator Stress (kPa)	Resilient Modulus (MPa)
7	60.3	6	45.0	6	32.3	6	27.0
12	51.3	20	29.8	20	21.2	20	14.9
29	45.2	33	26.0	32	17.6	46	9.8
48	43.4	47	25.4	46	17.4	55	10.9
63	47.1	60	26.0	60	17.2	63	12.0
89	46.8	79	26.1	79	17.9	77	13.0
100	44.0	96	28.4	93	16.1	91	12.8
118	40.7	110	29.3	104	14.2	104	13.3

Base Aggregate

Repeated load triaxial tests were conducted on the CA-6 aggregate material to determine its resilient modulus properties following the 15 AASHTO T307 stress states. The specimens were compacted at the field moisture content and dry density of 5.0 % and

21.6 kN/m^3, respectively. To obtain the model parameters K_1, K_2 and K_3 of the different characterization models (see Equations 1, 2, and 3), the resilient modulus models were expressed in logarithmic relationships to transform the power functions into linear expressions having three separate terms. Multiple linear regression analyses were then performed to determine the model parameters and develop the resilient modulus prediction models given in Equations 1 through 3. Table 3 summarizes the parameters (K_i) of the different nonlinear resilient modulus models and the very high correlation coefficients, R^2. Figure 6 shows graphically the increasing resilient moduli with the increasing deviator stresses at each of the five confining pressure levels (21, 35, 69, 103, 138 kPa) applied following the AASHTO T307. The predicted resilient moduli from all three models matched very well with the measured resilient moduli.

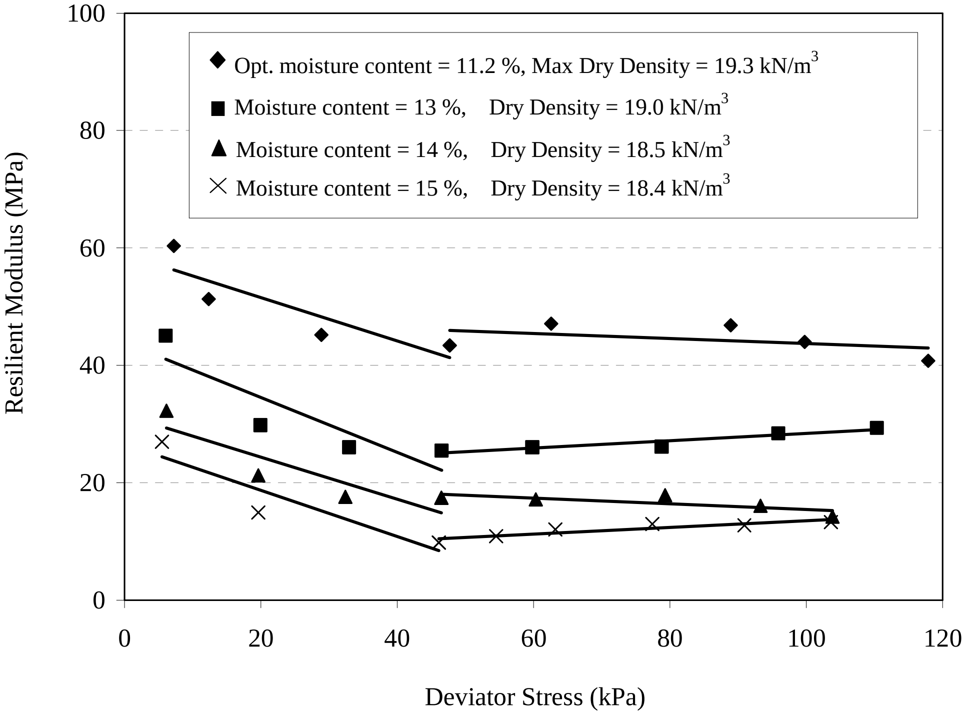

Figure 5. Soil Resilient Moduli Characterized by the Bilinear Model

Table 2. 2002 Design Guide Model Parameters for Characterizing Soil Resilient Moduli

2002 Design Guide model parameters	Optimum water content = 11.2% Maximum dry density = 19.3 kN/ m^3	Achieved water content = 13% Dry density = 19.0 kN/ m^3	Achieved water content = 14% Dry density = 18.5 kN/ m^3	Achieved water content = 15% Dry density = 18.4 kN/ m^3
K_1	0.312	0.088	0.096	0.022
K_2	-0.220	-0.542	-0.409	-0.812
K_3	0.468	1.667	0.698	2.560
R^2	0.81	0.99	0.94	0.94

Table 3. Base Aggregate Resilient Modulus Model Parameters

Resilient modulus model		Uzan (1985)	Witczak-Uzan Universal (1992)	2002 Design Guide
Model parameters	K_1	3.826 (MPa)	0.665	0.101
	K_2	0.849	0.849	0.791
	K_3	-0.196	-0.196	-0.478
R^2	-	0.997	0.997	0.990

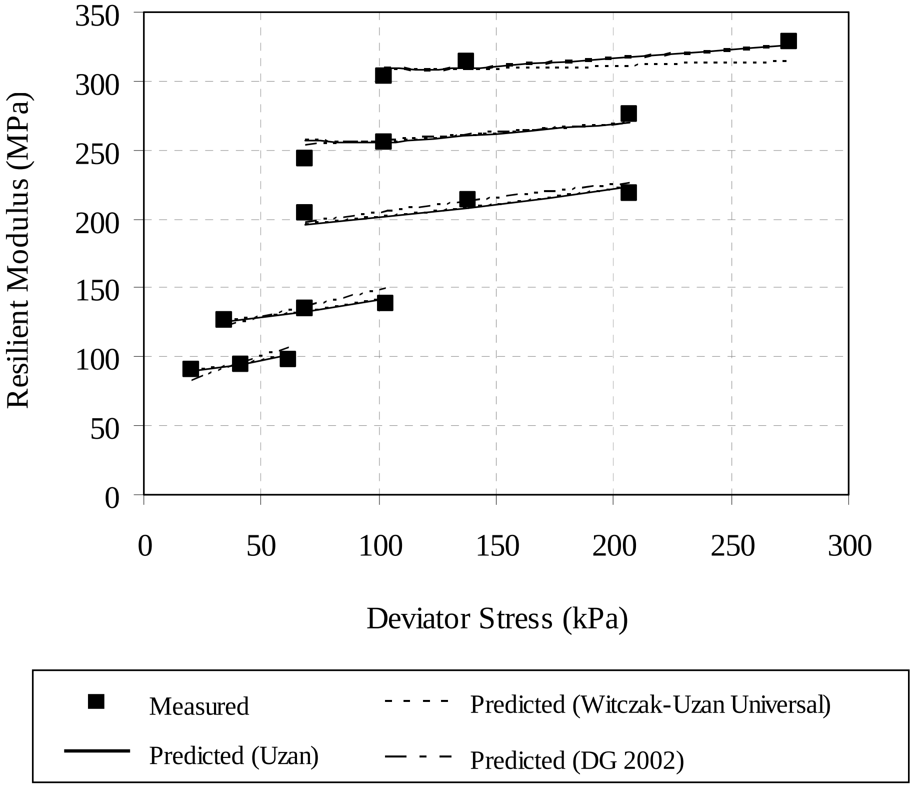

Figure 6. Performances of the CA-6 Base Aggregate Resilient Modulus Models

SUMMARY

This paper was intended to present a methodology on how to collect key geomaterial, i.e., subgrade soil and base unbound aggregate, input data for mechanistic pavement analysis through proper laboratory and field testing, perform material characterizations, and control field soil properties during pavement construction. Full-scale flexible pavement test sections, geogrid reinforced and unreinforced, were recently constructed at the University of Illinois Advanced Transportation Research and Engineering Laboratory (ATREL). To validate a recently developed geogrid reinforced pavement mechanistic response model as well as to develop trafficking pavement distress models for typical low volume roads with no subgrade improvement, the subgrade California Bearing Ratio (CBR) was maintained at 4% or lower throughout the test sections. This brought challenges to the project for constructing and monitoring the high moisture content and low strength properties of the soft subgrade conditions. A series of laboratory and field tests were conducted to characterize the pavement geomaterials before, during and after pavement construction. Compaction efforts were monitored in the field with Dynamic Cone Penetrometer and nuclear density gauge measurements. Repeated load triaxial tests were conducted in the laboratory to determine resilient modulus properties of subgrade soil and base aggregate. Proper modulus characterization models were developed based on the laboratory test data to provide model parameters as key inputs for mechanistic-empirical pavement design procedures, such as the 2002 Design Guide Level 1 flexible pavement analysis, which utilizes the finite element model and requires the nonlinear resilient modulus model parameters obtained from regression analyses of the test data.

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