MEPDG Work Plan Task No. 5:

Characterization of Unbound Materials (Soils/Aggregates) for Mechanistic-Empirical Pavement Design Guide

Final Report
February 2009

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16. Abstract The resilient modulus (MR) input parameters in the Mechanistic-Empirical Pavement Design Guide (MEPDG) program have a significant effect on the projected pavement performance. The MEPDG program uses three different levels of inputs depending on the desired level of accuracy. The primary objective of this research was to develop a laboratory testing program utilizing the Iowa DOT servo-hydraulic machine system for evaluating typical Iowa unbound materials and to establish a database of input values for MEPDG analysis. This was achieved by carrying out a detailed laboratory testing program designed in accordance with the AASHTO T307 resilient modulus test protocol using common Iowa unbound materials. The program included laboratory tests to characterize basic physical properties of the unbound materials, specimen preparation and repeated load triaxial tests to determine the resilient modulus. The MEPDG resilient modulus input parameter library for Iowa typical unbound pavement materials was established from the repeated load triaxial MR test results. This library includes the non-linear, stress-dependent resilient modulus model coefficients values for level 1 analysis, the unbound material properties values correlated to resilient modulus for level 2 analysis, and the typical resilient modulus values for level 3 analysis. The resilient modulus input parameters library can be utilized when designing low volume roads in the absence of any basic soil testing. Based on the results of this study, the use of level 2 analysis for MEPDG resilient modulus input is recommended since the repeated load triaxial test for level 1 analysis is complicated, time consuming, expensive, and requires sophisticated equipment and skilled operators.			
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MEPDG WORK PLAN TASK NO. 5: CHARACTERIZATION OF UNBOUND MATERIALS (SOILS/AGGREGATES) FOR MECHANISTIC-EMPIRICAL PAVEMENT DESIGN GUIDE

Final Report
February 2009

Principal Investigator
Halil Ceylan
Associate Professor
Institute for Transportation, Iowa State University

Co-Principal Investigator
Kasthurirangan Gopalakrishnan
Research Assistant Professor
Institute for Transportation, Iowa State University

Post-Doctoral Research Assistant
Sunghwan Kim

Authors
Halil Ceylan, Kasthurirangan Gopalakrishnan, and Sunghwan Kim

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A report from
Center for Transportation Research and Education
Iowa State University
2711 South Loop Drive, Suite 4700
Ames, IA 50010-8664
Phone: 515-294-8103
Fax: 515-294-0467
www.intrans.iastate.edu

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EXECUTIVE SUMMARY

The resilient modulus (M_R) properties of unbound materials are required by the Mechanistic-Empirical Pavement Design Guide (MEPDG) program as the material inputs for pavement design. Three different levels of inputs depending on the desired level of accuracy are available for resilient modulus of unbound materials in the Design Guide. Level 1 analysis requires coefficient (K_1, K_2, and K_3) values of NCHRP 1-28A proposed resilient modulus model determined using the M_R data obtained from laboratory test through statistical analysis. The M_R values were determined through the repeated triaxial loading test in accordance with AASHTO T307 and NCHRP 1-28A test protocols. The input parameters for level 2 analysis include the M_R correlated unbound material properties such as CBR, R-value, AASHTO layer coefficient, DCP, etc. Level 3 analysis requires the typical M_R values of local soil.

The Iowa DOT was equipped with a servo-hydraulic machine (known as Nottingham Asphalt Tester) for testing asphalt paving materials in 2003. The Iowa DOT has also attempted to update this system for testing unbound pavement geomaterials. However, a detailed laboratory test program for using the Iowa DOT servo-hydraulic machine system for resilient modulus testing has not yet been developed. Little information is available about the M_R properties of unbound materials in Iowa.

This research project was conducted to characterize typical Iowa unbound materials using the Iowa DOT servo-hydraulic machine system and establish a database of MEPDG input values for three analysis levels. A laboratory test program using the Iowa DOT servo-hydraulic machine system was designed to fabricate test specimen and conduct repeated triaxial loading test in accordance with AASHTO T307 procedure. The M_R database was developed for one type of aggregate and three types of soil categorized as select soil, class 10 (suitable), and unsuitable soil as per Iowa DOT specifications. Statistical analyses on the M_R test results were performed to determine the resilient modulus model coefficient values for level 1 analysis. The results are summarized as follows:

- The average K_1, K_2, and K_3 of select soil are 736, 0.301, and -1.948, respectively;
- The average K_1, K_2, and K_3 of class 10 (suitable) soil are 613, 0.245, and -1.823, respectively;
- The average K_1, K_2, and K_3 of unsuitable soil are 609, 0.244, and -1.869, respectively;
- The K_1, K_2, and K_3 of aggregate with 10 % moisture contents are 1081, 0.585, and -0.103, respectively.

The following unbound materials properties required in level 2 analysis were calculated using the M_R correlation equations provided in the MEPDG:

- The average CBR, R-value, AASHTO layer coefficient, and DCP values of select soil are 7%, 13, 0.04 and 56 in/blow, respectively;
- The average CBR, R-value, AASHTO layer coefficient, and DCP values of class 10

(suitable) soil are 6%, 11, 0.03 and 64 in/blow, respectively;

- The average CBR, R-value, AASHTO layer coefficient, and DCP values of unsuitable soil are 5%, 11, 0.03 and 53 in/blow, respectively;
- The CBR, R-value, AASHTO layer coefficient, and DCP values of aggregate with 10 % moisture content are 44.3%, 50, 0.13 and 5.4 in/blow, respectively.

Typical representative M_R values identified in this study for Level 3 analysis are about 10,000 psi for select soil, 7,500 psi for class 10 (suitable), 8,000 psi for unsuitable soil, and 35,000 psi for the unbound aggregate. However, these values can vary not only under different stress and moisture conditions but also from original soil sampling location.

Based on the research results, the following are the main findings:

- The Iowa DOT servo-hydraulic equipment can be applied to a laboratory M_R test protocol (AASHTO T307) to determine the resilient modulus of unbound materials.
- The resilient modulus database developed for the investigated Iowa unbound materials can be utilized to estimate the MEPDG input parameters values for level 3 analysis.

Based on the results of this research, the following recommendations are made:

- The MEPDG input parameter database developed in this study can be used when designing low volume roads in the absence of any basic soil testing.
- Level 2 analysis is recommended with the use of M_R values in MEPDG because the repeated load triaxial test for level 1 is complicated, time consuming, expensive, and requires sophisticated equipment and skilled operators.
- Further research is needed to expand the M_R database to accommodate a variety of Iowa unbound materials.
- Further research is needed to develop correlations between the physical properties of Iowa soils and the corresponding MR values. Such correlations would greatly help design engineers to quickly determine the MR value of an Iowa soil based on the physical properties of the soil. Development of such correlations would also lead to great economic savings for the Iowa DOT.

INTRODUCTION

The Mechanistic-Empirical Pavement Design Guide (MEPDG) considers traffic, structural features, materials, construction, and climate far more than ever before. It uses a hierarchical approach to determine design inputs. Depending on the desired level of accuracy of input parameter, three levels of input are provided from Level 1 (highest level of accuracy) to level 3 (lowest level of accuracy). Depending on the criticality of the project and the available resources, the designer has the flexibility to choose any one of the input levels for the design as well as use a mix of levels.

The material parameters required for unbound granular materials, subgrade, and bedrock may be classified in one of three major groups: (1) pavement response model material inputs, (2) Enhanced Integrated Climatic Model (EICM) material inputs, and (3) other material inputs. Pavement response model materials input required are resilient modulus, M_R, and Poisson's ratio, μ used for quantifying the stress dependent stiffness of unbound materials under moving wheel loads. Material parameters associated with EICM are those parameters that are required and used by the EICM models to predict the temperature and moisture conditions within a pavement system. These inputs include Atterberg limits, gradation, and saturated hydraulic conductivity. The "other" category of materials properties constitute those associated with special properties required for the design solution. An example of this category is the coefficient of lateral pressure (K).

The resilient modulus input has a significant effect on computed pavement responses and the dynamic modulus of subgrade reaction, k-value, computed internally by the MEPDG. Three different levels of inputs are available for resilient modulus of unbound materials in the Design Guide:

- LEVEL 1 – laboratory testing using standard test methods such as NCHRP 1-28A (NCHRP, 2004b) and AASHTO T307 (1999),
- LEVEL 2 – correlations with other material properties such as CBR, R-value, AASHTO layer coefficient, DCP, etc., and
- LEVEL 3 – typical values based on calibration.

The MEPDG strongly recommends Levels 1 and 2 testing for M_R. A detailed work plan is needed to establish a library of MEPDG input values for typical unbound materials used in Iowa to facilitate the MEPDG implementation process.

BACKGROUND SUMMARY

For unbound materials, the MEPDG uses the AASHTO soils classification as described in AASHTO M145 (1991) or the Unified Soils Classification (USC) definitions as described in ASTM D 2487 (2006). The designer selects the primary unbound material type using one of the classification systems and then provides further input to determine appropriate material properties to be used for design.

The primary input parameter used for pavement design is the resilient modulus (M_R). For Level 1 designs, the M_R values of unbound granular materials, subgrade, and bedrock are determined from triaxial tests in accordance with AASHTO T307 (1999) or NCHRP 1-28A (NCHRP, 2004b). The model for characterizing the nonlinear behavior of unbound materials is described in NCHRP 1-28A (NCHRP, 2004b). The major characteristics associated with unbound materials are related to the fact that moduli of these materials may be highly influenced by the stress state (non-linear) and in-situ moisture content. As a general rule, coarse-grained materials have higher moduli as the state of the confining stress is increased. In contrast clayey materials tend to have reduction in modulus as deviator stress component is increased. Thus, while both categories of unbound materials are stress dependent (non-linear), each behaves differently under the changes of stress states.

While it is expected that resilient modulus testing is to be completed for Level 1 designs, many agencies, including the Iowa DOT are not fully equipped to complete resilient modulus testing. Therefore, for Level 2 designs, correlation equations have been developed with more commonly used testing protocols to estimate the resilient modulus of the unbound materials. However, resilient modulus of the unbound granular and subgrade materials is a required input in any mechanistic-based pavement analysis and design process. With more and more agencies adopting the mechanistic-empirical design concept in their pavement designs, it is anticipated that Iowa DOT may implement the resilient modulus testing protocol considering the benefits that can be derived. In the year 2003, the Iowa DOT was equipped with a servo-hydraulic machine (the HYD – 25 system) manufactured by Cooper Research Technology Ltd (http://www.cooper.co.uk/) for testing asphalt paving materials. For the first time, the Iowa DOT attempted to update this system with the help of Cooper Research Technology Ltd for testing unbound pavement geomaterials.

This report describes the detailed work plan carried out for establishing a library of MEPDG input values for typical unbound materials used across Iowa considering the various factors influencing the M_R values. Other important parameters related to unbound materials considered by the Design Guide include: Atterberg limits (AASHTO T89, 2002; AASHTO T90, 2004), Grain size distribution (AASHTO T27, 2006), and Moisture/density relationship (AASHTO T99, 2004).

OBJECTIVE

The primary objective of this research is to design and implement a laboratory test program for evaluating the unbound materials commonly used in Iowa using the Iowa DOT servo-hydraulic machine system and establish a database of MEPDG input values for three analysis levels.

REVIEW OF UNBOUND MATERIALS CHARACTERIZATION IN THE MEPDG

The material parameters required for unbound granular materials, subgrade, and bedrock may be classified in one of four major group presented in Figure 1.

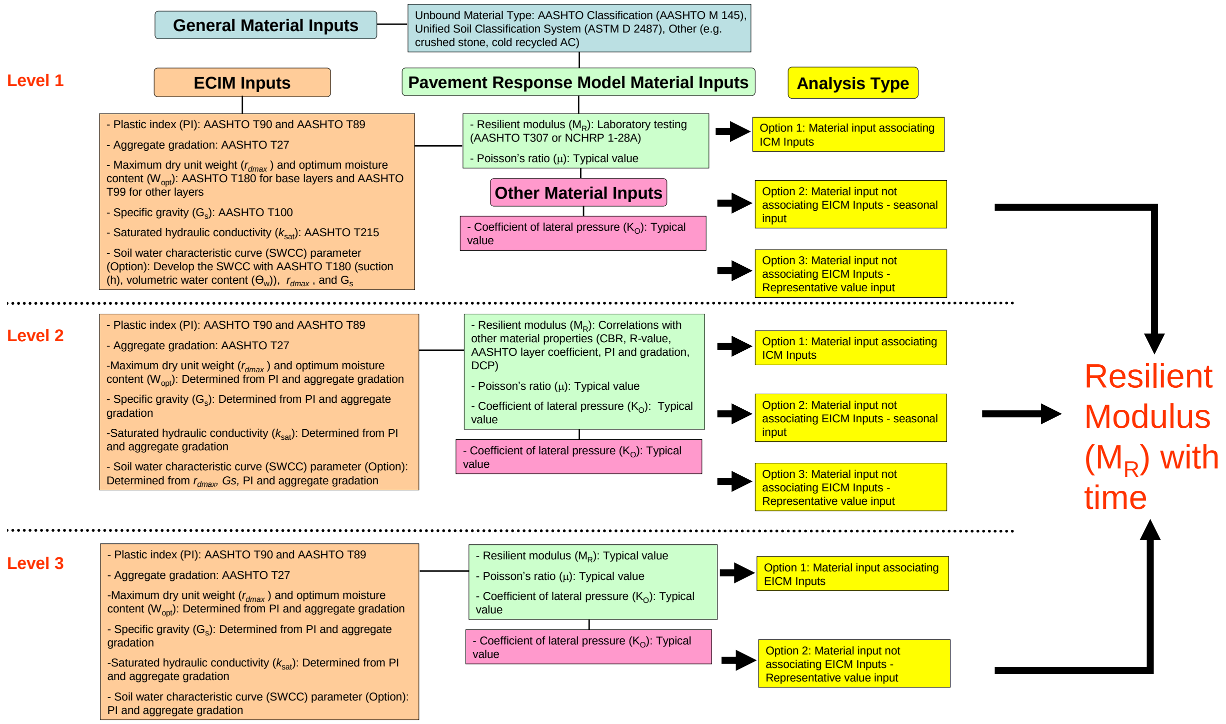


Figure 1. Pictorial representation of material parameters required for unbound materials in MEPDG

The general materials inputs required are the descriptions of unbound granular and subgrade materials using standard AASHTO M145 (1991) and USC definitions (ASTM D 2487, 2006). Unbound materials are categorized by grain size distribution, liquid limit and plasticity index value.

The required pavement response model material inputs include resilient modulus (M_R) and Poisson's ratio (μ) parameters used for quantifying the stress dependent stiffness of unbound materials under moving loads. Resilient modulus is defined as the ratio of the repeated deviator axial stress to the recoverable axial strain. It is used to characterize layer behavior when subjected to stresses. Unbound materials display stress-dependent properties (i.e., granular materials generally are "stress hardening" and show an increase in modulus with an increase in stress while fine-grained soils generally are "stress softening" and display a modulus decrease with increased stress). The MEPDG offers two types of pavement response analysis, the linear elastic analysis (LEA) and the 2-D Finite Element Analysis (FEA). The LEA assumes a constant representative resilient modulus (M_R) for each layer, whereas the FEA employs a stress-dependent resilient modulus for the Level 1 design. According to the NCHRP 1-47A project report (2004a), the FEA needs further calibration before it can be implemented.

The other materials input properties constitute those associated with special properties required for the design solution. An example of this category is the coefficient of lateral pressure (K).

Input parameters associated with EICM are those parameters that are required by the EICM models to predict the temperature and moisture conditions within a pavement system. Key inputs include gradation, Atterberg limits, and hydraulic conductivity.

The MEPDG offers three types of analysis options for level 1 and 2 and two types of analysis options for level 3 to predict resilient modulus with time history. The main difference in these analysis options stem from the analysis procedure that adapts the materials inputs with the inclusion or exclusion of EICM inputs.

Resilient Modulus (M_R)

Level 1 Analysis – Laboratory Testing

Level 1 resilient modulus values for unbound granular materials, subgrade, and bedrock are determined from repeated load triaxial tests on prepared representative samples. The repeated load triaxial test consists of applying a cyclic load on a cylindrical specimen under constant confining pressure (σ_3 or σ_c) and measuring the axial recoverable strain (ε_r). The resilient modulus determined from the repeated load triaxial test is defined as the ratio of the repeated axial cyclic (resilient) stress to the recoverable (resilient) axial strain:

$$M_R = \frac{\sigma_{\mathrm{cyclic}}}{\varepsilon_{\mathrm{r}}} \tag{1}$$

where M_R is the resilient modulus, σ_{cyclic} (or $\sigma_{\mathrm{deviator}}$) is the cyclic (deviator) stress, and ε_r is the resilient (recoverable) strain in the vertical direction. Figure 2 depicts a graphical representation of the definition of resilient modulus from a repeated load triaxial test.

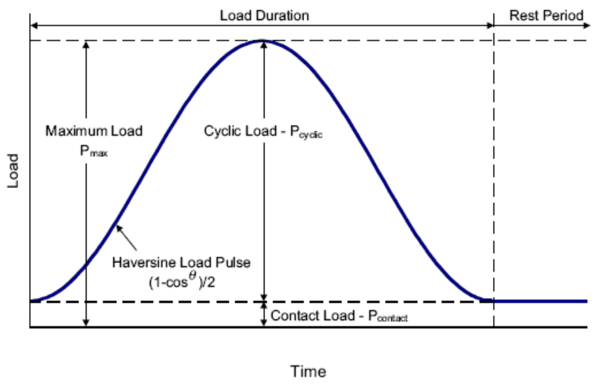


Figure 2. Definition of Resilient Modulus Terms (NCHRP, 2004b)

The system consists of a loading frame with a crosshead mounted hydraulic actuator. A load cell is attached to the actuator to measure the applied load. The soil sample is housed in a triaxial cell where confining pressure is applied. As the actuator applies the repeated load, sample deformation is measured by a set of Linear Variable Differential Transducers (LVDT's). A data acquisitions system records all data during testing.

AASHTO provided standard test procedures for determination of resilient modulus using the repeated load triaxial test, which include AASHTO T 292 "*Interim Method of Test for Resilient Modulus of Subgrade Soils and Untreated Base/Subbase*", AASHTO T 294 "*Standard Method of Test for Resilient Modulus of Unbound Granular Base/Subbase Materials and Subgrade Soil-SHRP Protocol P46*" and AASHTO T 307 (previous AASHTO TP46) "*Determining the Resilient Modulus of Soils and Aggregate Materials*". The comparisons of these test procedures are discussed by Ping et al. (2003) and Kim and Siddiki (2005). The AASHTO T 307 improved with time is the current protocol for determination of resilient modulus of soils and aggregate materials. Detailed background and discussion on AASHTO T 307 is presented by Groeger et al. (2003).

NCHRP Project 1-28 A (NCHRP, 2004b) was conducted to harmonize existing AASHTO methods with those developed in NCHRP Project 1-28. The final product of NCHRP Project 1-28 A is "*Harmonized test methods for laboratory determination of resilient modulus for flexible pavement design*" The test procedures of AASHTO T307 and NCHRP 1-28A are similar except some difference including material classification methods for test producers, load cell and LVDT location, and loading test sequence. Especially, AASHTO T 307 requires the use of a load cell and deformation devices (LVDTs) mounted outside the triaxial chamber where NCHRP 1-28A require the use of a load cell and clamp-mounted deformation devices inside the triaxial chamber. Figures 3 and 4 show the schematics of triaxial chamber according to AASHTO T 307 and NCHRPA 1-28 A requirements, respectively. The MEPDG recommends M_R to be obtained from the repeated triaxial testing following AASHTO T 307 (1999) or resilient modulus testing following NCHPR 1-28 A (NCHRP, 2004b).

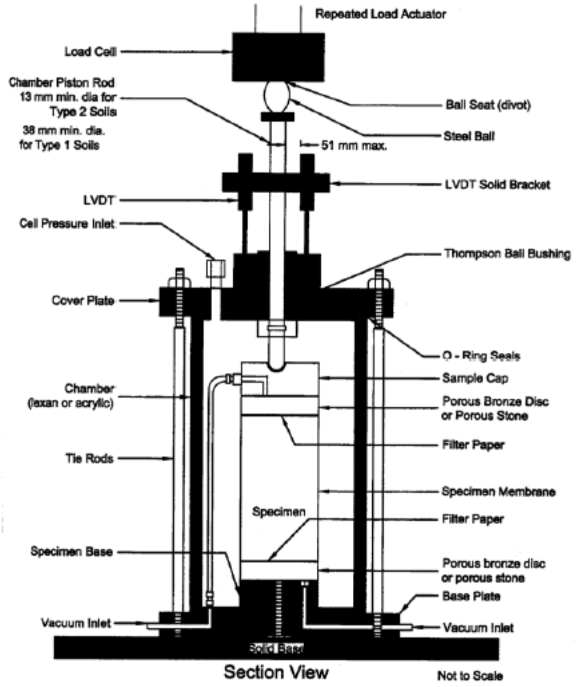


Figure 3. Schematic of a triaxial test chamber according to AASHTO T 307 (1999)

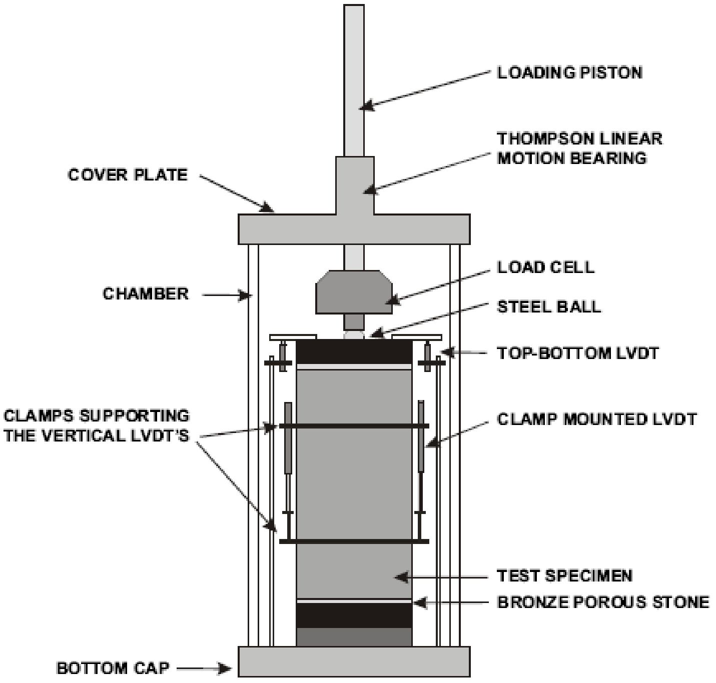


Figure 4. Schematic of a triaxial test chamber according to NCHRP 1-28A (2004b)

For M-E design, resilient moduli at different stress conditions are estimated using a generalized constitutive model from laboratory measured M_R data. Many researchers have proposed numerous predictive models to capture the resilient behavior of unbound materials. Simple resilient modulus models, such as the K-θ (Hicks and Monismith, 1971), Uzan (1985), and the Universal models (Uzan et al., 1992), consider the effects of stress dependency for modeling the nonlinear behavior of base/subbase aggregates. These resilient modulus models are as follows:

K_{GB}-θ Model (Hicks and Monismith, 1971): $M_R = K_{GB}\,\theta^n$ (1)

Uzan Model (Uzan, 1985): $M_R = K_1\,\mathrm{P_a}\left(\theta/P_a\right)^{K_2}\left(\sigma_d/P_a\right)^{K_3}$ (2)

Universal Model (Uzan et al., 1992): $M_R = K_1\,\mathrm{P_a}\left(\theta/P_a\right)^{K_2}\left(\tau_{oct}/P_a\right)^{K_3}$ (3)

where $\sigma = \sigma_1 + \sigma_2 + \sigma_3 = \sigma_1 + 2\sigma_3$ = bulk stress, $\sigma_d = \sigma_1 - \sigma_3$ = deviator stress, τ_{oct} = octahedral shear stress $= \sqrt{2/3} \times \sigma_d$ in triaxial conditions, P_a is the atmospheric pressure or unit reference pressure (101.3 kPa or 14.7 psi) used in the models to make the stresses non-dimensional, and K_{GB}, n, and K_1 to K_3 are multiple regression constants obtained from repeated load triaxial test data on granular materials.

Figure 5 shows for two different sized granular materials, crushed stone and sand, typical nonlinear resilient modulus characterizations obtained from AASHTO T307 test results using the K-θ and Uzan type models. The simpler K- θ model often adequately captures the overall stress dependency (bulk stress effects) of unbound aggregate behavior under compression type field loading conditions. The Uzan (1985) model considers additionally the effects of deviator stresses and handles very well the modulus increase with increasing shear stresses even for extension type field loading conditions. A more recent universal model (Uzan et al. 1992) also accounts for the stress dependency of the resilient behavior as power functions of the 3-D stress states.

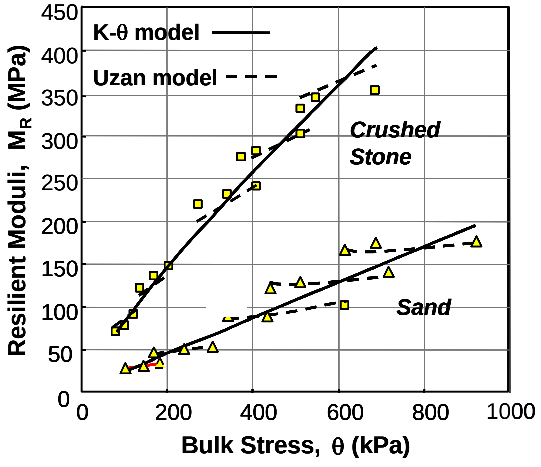


Figure 5. Typical nonlinear modulus characterization of unbound aggregate material

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. As a result, the most important parameter affecting the resilient modulus becomes the vertical deviator stress on top of the subgrade due to the applied wheel load. The bilinear or arithmetic model (Thompson and Elliot, 1985) is the most commonly used resilient modulus model for subgrade soils expressed by the modulus-deviator stress relationship given in Figure 6. As indicated by Thompson and Elliot (1985), the value of the resilient modulus at the breakpoint in the bilinear curve, E_{Ri}, (see Figure 6) can be used to classify fine-grained soils as being soft, medium or stiff.

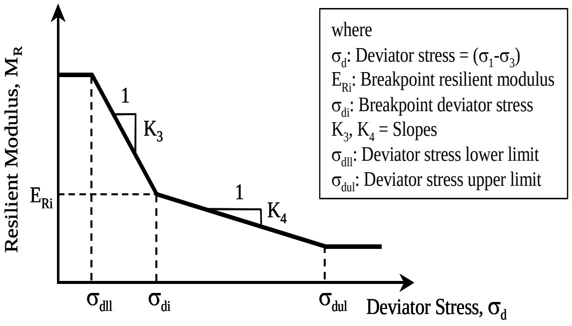


Figure 6. Stress dependency of fine-grained soils characterized by bilinear model (Thompson & Elliott, 1985)

In the MEPDG, resilient modulus for unbound granular materials and subgrade is predicted using a similar model to the equation (3), as shown below in equation (4):

MEPDG Model (NCHRP., 2004): $$M_R = K_1 P_a \left(\theta/P_a\right)^{K_2} \left(\tau_{oct}/P_a + 1\right)^{K_3} \qquad (4)$$

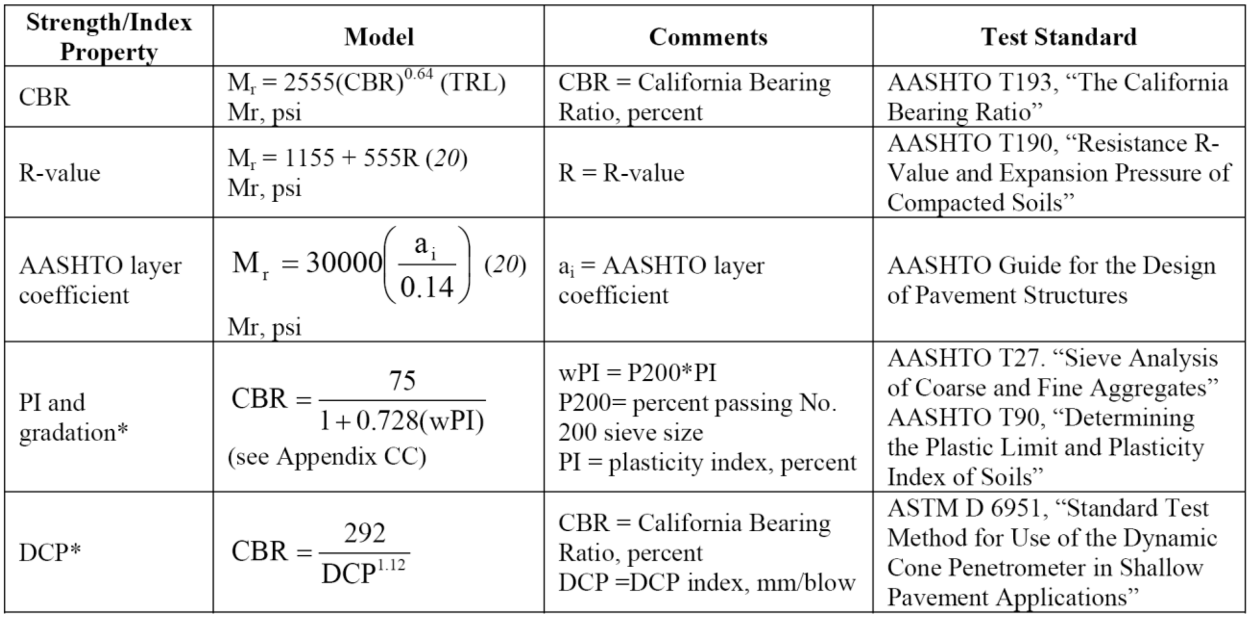
Coefficient K_1 is proportional to Young's modulus. Thus, the values for K_1 should be positive since M_R can never be negative. Increasing the bulk stress, θ, should produce a stiffening or hardening of the material, which results in a higher M_R. Therefore, the exponent K_2 , of the bulk stress term for the above constitutive equation should also be positive. Coefficient K_3 is the exponent of the octahedral shear stress term. The values for K_3 should be negative since increasing the shear stress will produce a softening of the material (i.e., a lower M_R).

Note that the input data required is not the actual M_R test data but rather the coefficients K_1, K_2, and K_3. Coefficient K_1, K_2, and K_3 must therefore be determined outside the Design Guide software.

Level 2 Analysis – Correlations with Other Material Properties

Level 2 analysis can be selected when laboratory M_R test is not available. The value of resilient modulus can be obtained using typical correlations between resilient modulus and physical soil properties (gradation and Atterberg limits) or between resilient modulus and strength properties (i.e., CBR, R-value, AASHTO layer coefficient). The following correlations listed in Table 1 are suggested in the MEPDG.

Table 1. Models relating material index and strength properties to MR (NCHRP, 2004)

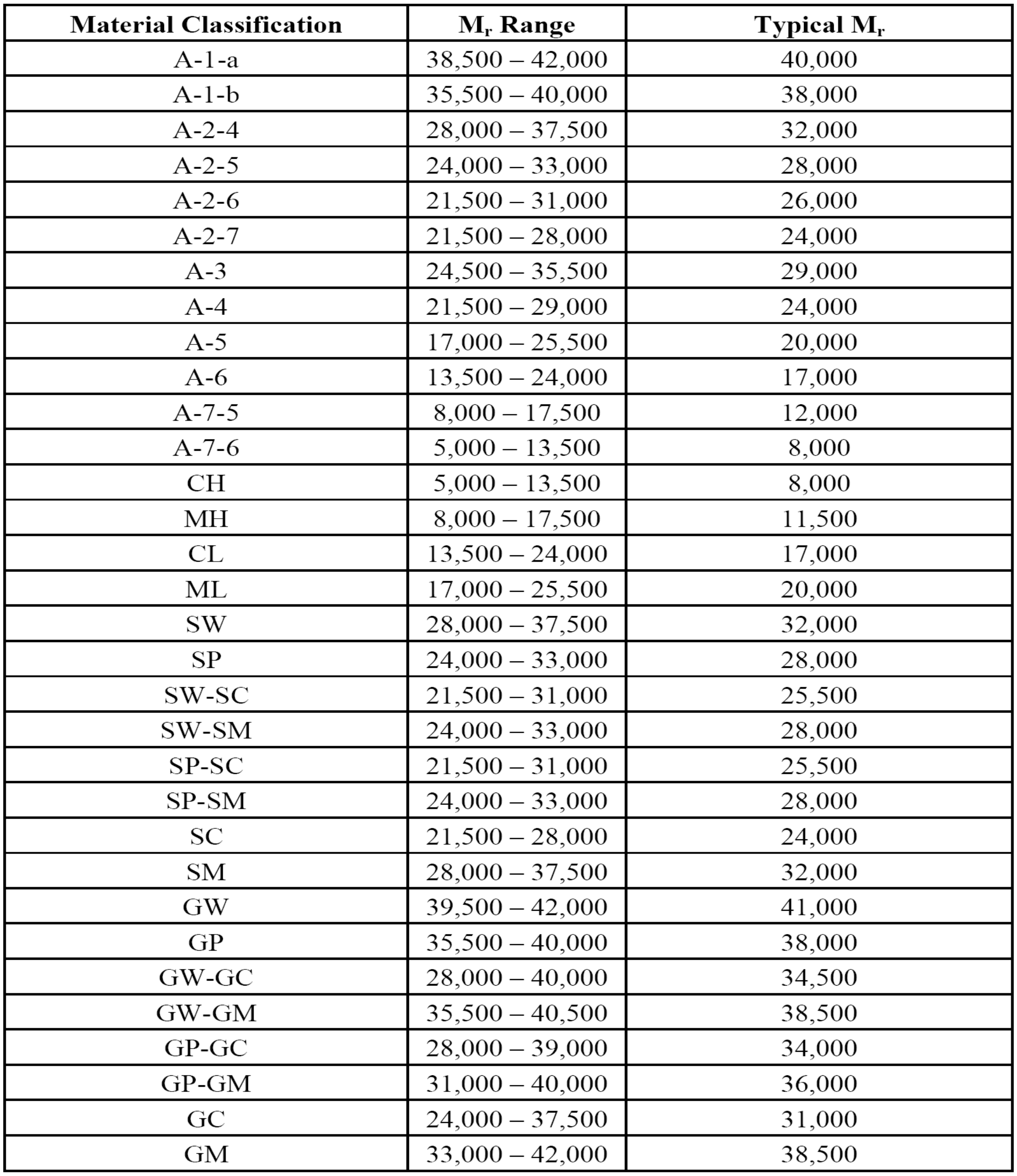


Strength/Index Property	Model	Comments	Test Standard
CBR	$M_r = 2555(CBR)^{0.64}$ (TRL) Mr, psi	CBR = California Bearing Ratio, percent	AASHTO T193, "The California Bearing Ratio"
R-value	$M_r = 1155 + 555R$ (*20*) Mr, psi	R = R-value	AASHTO T190, "Resistance R-Value and Expansion Pressure of Compacted Soils"
AASHTO layer coefficient	$M_r = 30000\left(\frac{a_i}{0.14}\right)$ (*20*) Mr, psi	a_i = AASHTO layer coefficient	AASHTO Guide for the Design of Pavement Structures
PI and gradation*	$CBR = \frac{75}{1 + 0.728(wPI)}$ (see Appendix CC)	wPI = P200*PI P200= percent passing No. 200 sieve size PI = plasticity index, percent	AASHTO T27. "Sieve Analysis of Coarse and Fine Aggregates" AASHTO T90, "Determining the Plastic Limit and Plasticity Index of Soils"
DCP*	$CBR = \frac{292}{DCP^{1.12}}$	CBR = California Bearing Ratio, percent DCP =DCP index, mm/blow	ASTM D 6951, "Standard Test Method for Use of the Dynamic Cone Penetrometer in Shallow Pavement Applications"

Level 3 Analysis – Typical Values

For input Level 3, typical the M_R values presented in Table 2 are recommended. Note that for level 3 only a typical representative M_R value is required at optimum moisture content. The M_R values used in calibration were those recommended in Table 2 and adjusted for the effect of bedrock and other conditions that influence the pavement foundation strength.

Table 2. Typical resilient modulus values for unbound granular and subgrade materials (NCHRP, 2004)



Material Classification	M_r Range	Typical M_r
A-1-a	38,500 – 42,000	40,000
A-1-b	35,500 – 40,000	38,000
A-2-4	28,000 – 37,500	32,000
A-2-5	24,000 – 33,000	28,000
A-2-6	21,500 – 31,000	26,000
A-2-7	21,500 – 28,000	24,000
A-3	24,500 – 35,500	29,000
A-4	21,500 – 29,000	24,000
A-5	17,000 – 25,500	20,000
A-6	13,500 – 24,000	17,000
A-7-5	8,000 – 17,500	12,000
A-7-6	5,000 – 13,500	8,000
CH	5,000 – 13,500	8,000
MH	8,000 – 17,500	11,500
CL	13,500 – 24,000	17,000
ML	17,000 – 25,500	20,000
SW	28,000 – 37,500	32,000
SP	24,000 – 33,000	28,000
SW-SC	21,500 – 31,000	25,500
SW-SM	24,000 – 33,000	28,000
SP-SC	21,500 – 31,000	25,500
SP-SM	24,000 – 33,000	28,000
SC	21,500 – 28,000	24,000
SM	28,000 – 37,500	32,000
GW	39,500 – 42,000	41,000
GP	35,500 – 40,000	38,000
GW-GC	28,000 – 40,000	34,500
GW-GM	35,500 – 40,500	38,500
GP-GC	28,000 – 39,000	34,000
GP-GM	31,000 – 40,000	36,000
GC	24,000 – 37,500	31,000
GM	33,000 – 42,000	38,500

Environmental Effect on Resilient Modulus (MR) in MEPDG

Moisture and temperature are two key factors that significantly affect the changing in-situ resilient modulus with time. Effects of these factors on resilient modulus are considered in the MEPDG through a sophisticated climate modeling tool called the Enhanced Integrated Climatic Model (EICM). The EICM consist of three components:

- The Climatic-Materials-Structural Model (CMS Model).
- The CRREL Frost Heave and Thaw Settlement Model (CRREL Model).
- The Infiltration and Drainage Model (ID Model).

The EICM deals with all environmental factors and provides soil moisture, suction, and temperature as a function of time, at any location in the unbound layers from which the composite environmental adjustment factor (F_{env}) can be determined. The resilient modulus at any time or position is then expressed as follows:

$$M_R = F_{env} \times M_{Ropt} \tag{5}$$

Where, F_{env} is an environmental adjustment factor and M_{Ropt} is the resilient modulus at optimum conditions (maximum dry density and optimum moisture content) and at any state of stress. It is obvious in equation 5 that the variation of the modulus with stress and the variation of the modulus with environmental factors (moisture, density, and freeze/thaw conditions) are assumed independent.

The F_{env} is a composite factor, which could in general represent a weighted average of the factors appropriate for various possible conditions:

- Frozen: frozen material – F_F (factor for frozen materials)
- Recovering: thawed material that is recovering to its state before freezing occurred – F_R (factor for recovering materials)
- Unfrozen/fully recovered/normal: for materials that were never frozen or are fully recovered – F_U (factor for unfrozen material)

F_{env} is calculated for all three cases at two levels - at each nodal point and for each layer.

Resilient Modulus as Function of Soil Moisture

Moisture content is one of important factors affecting resilient behavior of soils. Generally, for a given soil with the same dry density, the higher the moisture content, the lower the resilient modulus. The EICM adapted the soil-water characteristic curve (SWCC) suggested by Fredlund and Xing (1999) to define the degree of moisture-saturated soil condition. The SWCC is generally used in unsaturated soil mechanics and defined as variation of water storage capacity within the macro-and micro-pores of a soil, with respect to suction. This relationship is generally plotted as variation of water content (gravimetric, volumetric, or degree of saturation) with soil suction. The SWCC is used to calculate the degree of saturation in equilibrium, S_{equil} as given by:

$$S_{equil} = C(h) \times \frac{1}{\left[\ln \left[EXP(1) + (\frac{h}{a_f})^{b_f} \right] \right]^{C_f}}, \quad C(h) = 1 - \frac{\ln(1 + \frac{h}{h_r})}{\ln(1 + \frac{1.45 - 10^5}{h_r})} \qquad (6)$$

Where, h = distance from the point in question to ground water table (psi) and a_f, b_f, c_f, and h_r = input parameters obtained from regression analyses. The MEPDG employ a predictive equation incorporating F_{env} within the EICM to predict changes in modulus due to changes in moisture. The resilient modulus as a function of soil moisture in the MEPDG is as follows:

$$\log \frac{M_r}{M_{r_{opt}}} = a + \frac{b - a1}{1 + EXP(\ln \frac{-b}{n} + k_m (S - S_{opt}))} \qquad (7)$$

Where, $M_R/M_{R_{opt}}$ = resilient modulus ratio; M_R is the resilient modulus at a given time and $M_{R_{opt}}$ is the resilient modulus at the optimum moisture content; a = minimum of log ($M_R/M_{R_{opt}}$); b = maximum of log ($M_R/M_{R_{opt}}$); k_m = regression parameter; (S – S_{opt}) = variation in degree of saturation expressed in decimal.

The MEPDG suggests that the modulus ratio, $M_R/M_{R_{opt}}$, is in the range of 2 to 0.5 for coarse-grained soils, while it is between 2.5 to 0.5 for fine-grained soils. This means that the fine-grained soils are more influenced by the moisture content than the coarse-grained soils. Generally, the degree of saturation of subgrades (especially for fine-grained subgrades) increases with time, the resilient modulus will decrease over the design period due to the increase in moisture content and reach the minimum resilient modulus.

Resilient Modulus as Frozen/ Thawed Unbound Materials

Resilient modulus of unbound material has significant variations under freezing/thawing condition. In the development of MEPDG (NCHRP, 2004a), a significant number of literatures were studied to obtain values of resilient modulus of unbound materials for different conditions as follows:

- $M_{Rfrz} = M_{Rmax} = M_R$ for frozen material
- M_{Runfrz} = the normal M_R for unfrozen material
- $M_{Rmin} = M_R$ just after thawing

The modulus reduction factor, termed RF, is also used to adjust the M_{Runfrz} or M_{Ropt} to $M_{Rmin.}$ Since some of the data from the literature produced RF values based on M_{Runfrz} as a reference and some were based on M_{Ropt} as a reference, it adopted a conservative interpretation of using the smaller of M_{Runfrz} and M_{Ropt} as a reference. Recovering materials experience a rise in modulus with time, from M_{Rmin} to M_{Runfrz}, which can be tracked using a recovery ratio (RR) that ranges from 0 to 1.

EXPERIMENTAL METHODLOGY

A detailed research plan was developed to collect unbound pavement geomaterials and design an experimental test program in consultation with the Iowa DOT and the project's Technical Advisory Committee (TAC). The collected soil samples were subjected to different tests to determine their physical properties, compaction characteristics, and resilient modulus. The physical and compaction properties were characterized using the Geotechnical Research Laboratory at the Iowa State University and repeated load triaxial tests were carried out at the Materials Testing Laboratory at the Iowa DOT.

Materials

A total of three soil types commonly found and used in Iowa were sampled and tested for this study with the consultation of Iowa DOT engineers. The three soil types were obtained from a new construction site (see Figure 7) near US-20 highway in Calhoun County (STA. 706 to STA.712, Project Number NHSX-20-3(102)- -3H-13). Following Iowa DOT specifications (2008), the collected soils were categorized as select, class 10 or suitable soil, and unsuitable soil. The select soil in Figure 8 meets the criteria for subgrade treatments. The class 10 or suitable soil in Figure 9 is the excavated soil including all normal earth materials such as loam, silt, clay, sand, and gravel and is suitable for the construction of embankments. The unsuitable soil in Figure 10 can be used in the work only as specified in Iowa DOT specifications or should be removed.

In addition to these three types of soil materials, one type of aggregate material (see Figure 11) provided by Iowa DOT engineers was also tested to determine resilient modulus.

Figure 7. New construction site for US-20 in Calhoun County

Figure 8. Select soil

Figure 9. Class 10 or suitable soil

Figure 10. Unsuitable soil

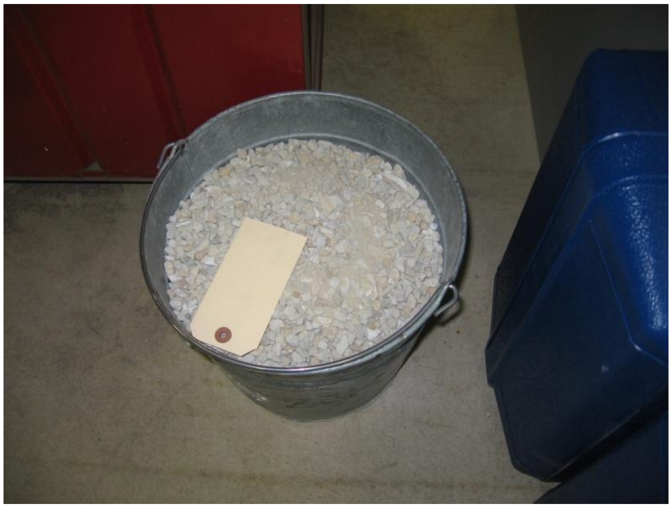


Figure 11. Aggregate sample

Laboratory Testing Program

An experimental test plan was formulated as shown in Figure 12. A total of three soil types and one aggregate type were tested. Especially, each soil type was tested three times to consider the effect of moisture content on resilient modulus: OMC (Optimum Moisture Content), OMC+4%, OMC-4%. One aggregate type with 10 % moisture content was also tested.

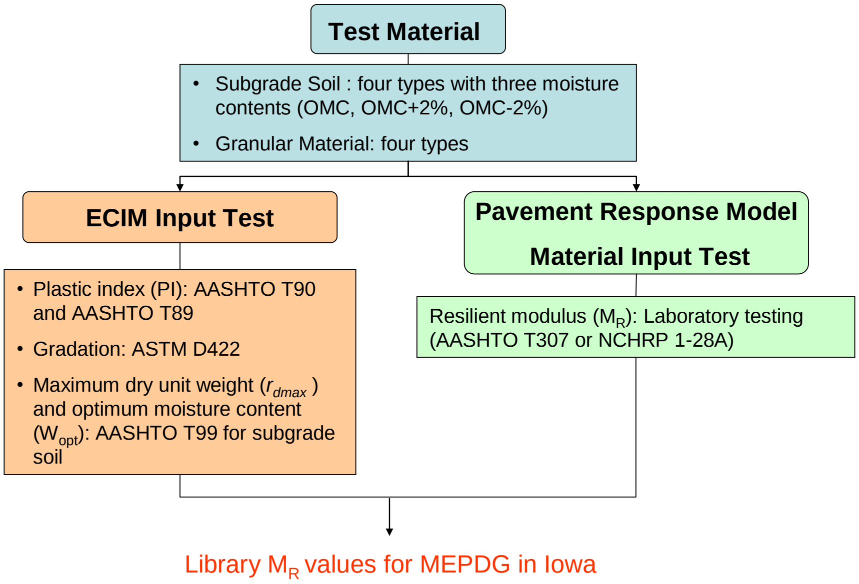


Figure 12. Experimental tests plan

Physical Properties and Compaction Characteristics

The collected soils were subjected to standard laboratory tests to determine their physical properties and compaction characteristics as required ECIM unbound material input parameters for use with the Design Guide. Standard laboratory tests included the following: grain size distribution (sieve and hydrometer analyses) according to ASTM D 442 (2006), Atterberg limits (liquid limit, LL and plastic limit, PL) according to AASHTO T89 (2002) and T90 (2004), and Moisture/density relationship according to AASHTO T 99 (2004). In order to obtain quality test results, most tests were conducted twice.

Repeated Load Triaxial Test

Repeated load triaxial tests were conducted to determine the resilient modulus of the investigated soils as required pavement response model material input parameter, following AASHTO T 307 (1999). Figure 13 shows the resilient modulus test flowchart in accordance with the procedure described in AASHTO T 307 (1999) protocol.

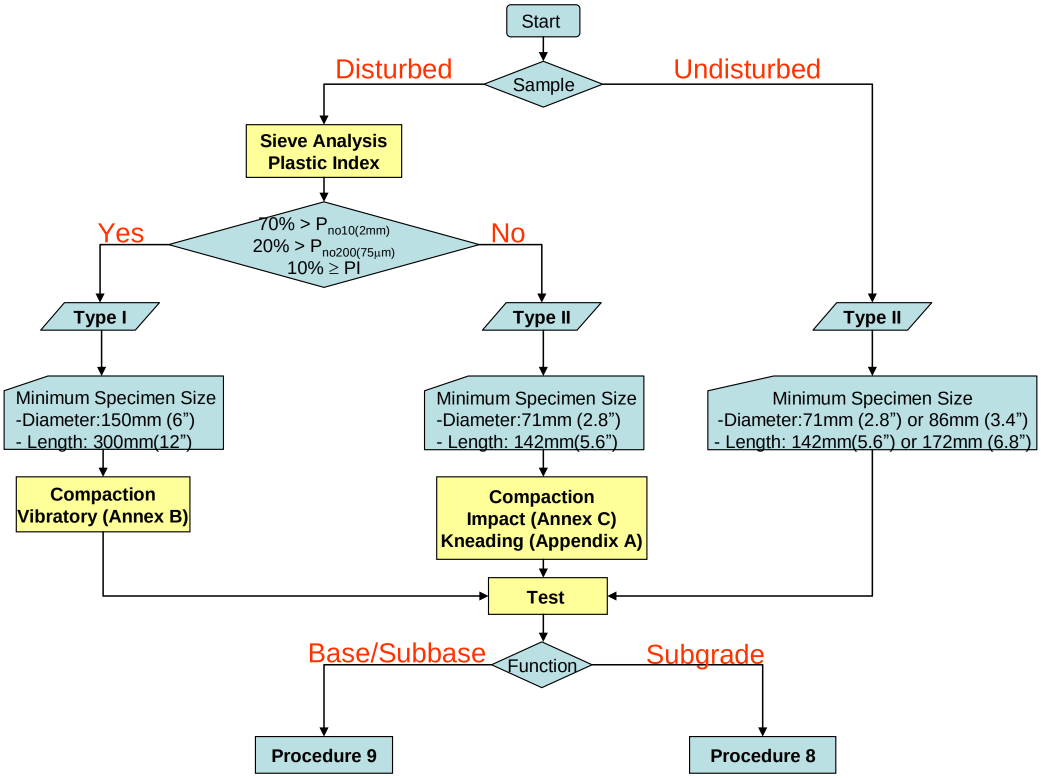
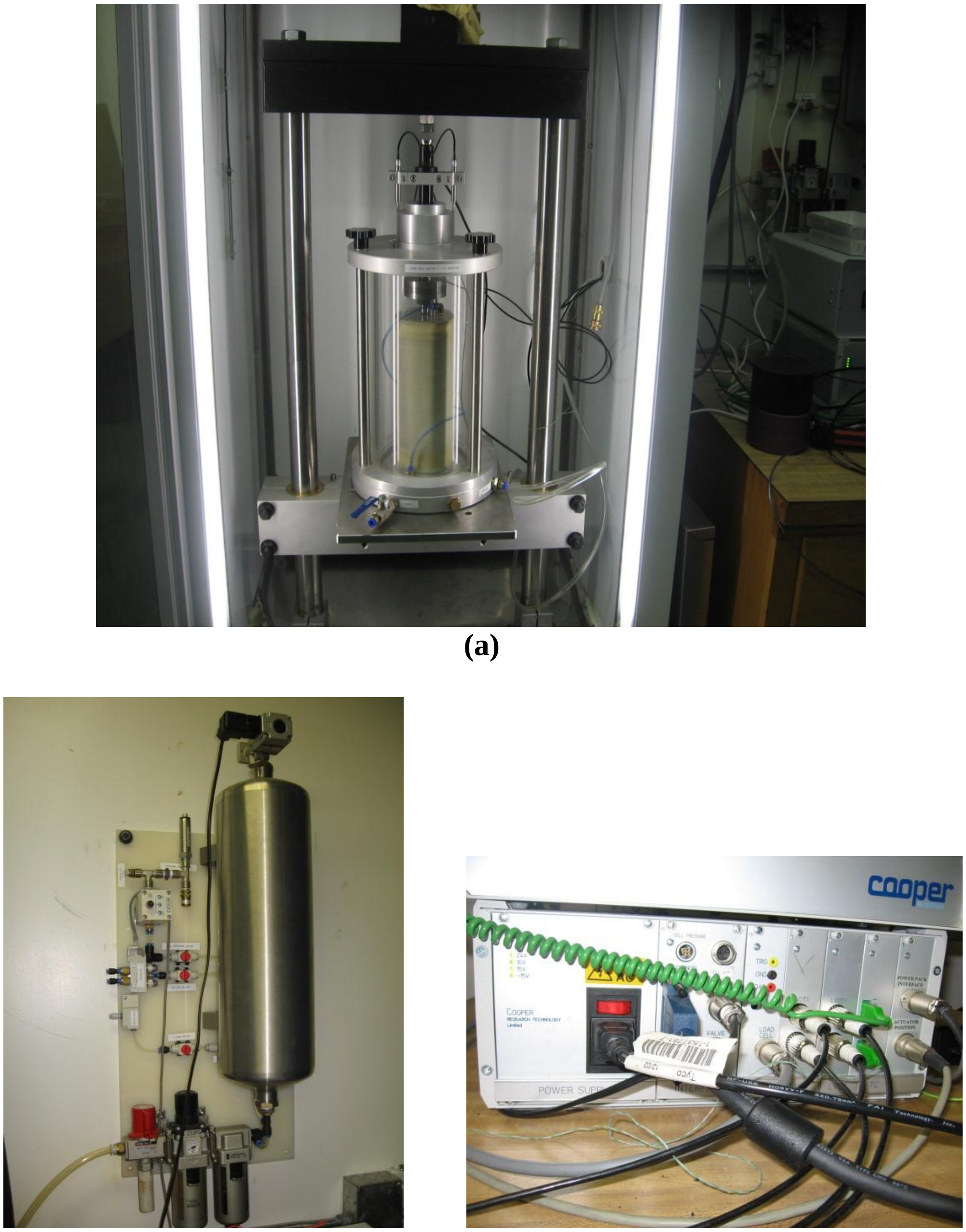


Figure 13. AASHTO T307 resilient modulus test method flowchart

<u>Dynamic Load Test System</u>

The HYD – 25 repeated load triaxial test system with temperature controlled cabinet at the Iowa DOT was utilized for resilient modulus testing of unbound material as suggested by Iowa DOT. The HYD-25 manufactured by Cooper Research Technology, Ltd is a servo-hydraulic machine designed for testing a range of asphalt paving materials, subgrade soils and granular subbase materials including strength test, rutting, fatigue, and modulus tests. The Iowa DOT purchased the HYD-25 system in 2003 for asphalt paving material tests and has attempted to update this system with the support of Cooper Research Technology, Ltd for testing unbound pavement geomaterials. The use of HYD-25 system in this study was also intended to verify the capacity of this system for unbound material resilient modulus testing in accordance with AASHTO T307, which has never been done before.

The system utilizes a sophisticated control and data acquisition system with 16-bit digital servo-control to digitally generate control waveforms so that materials are tested under conditions that are simulative of those applied by static or moving vehicles. The main user interface is a user-friendly Windows software written in LabView that allows user-designed test routines that can include multiple wave types and methods of data acquisition. Temperature controlled cabinet can cycle temperature in a range of -10ºC to +60ºC with ±0.2ºC. The system has two triaxial cells for 100 mm (3.9 in) and 150 mm (5.9 in) specimens of unbound materials. Figure 14 shows pictures of the dynamic materials test system used in this study.



(a)

(b) (c)

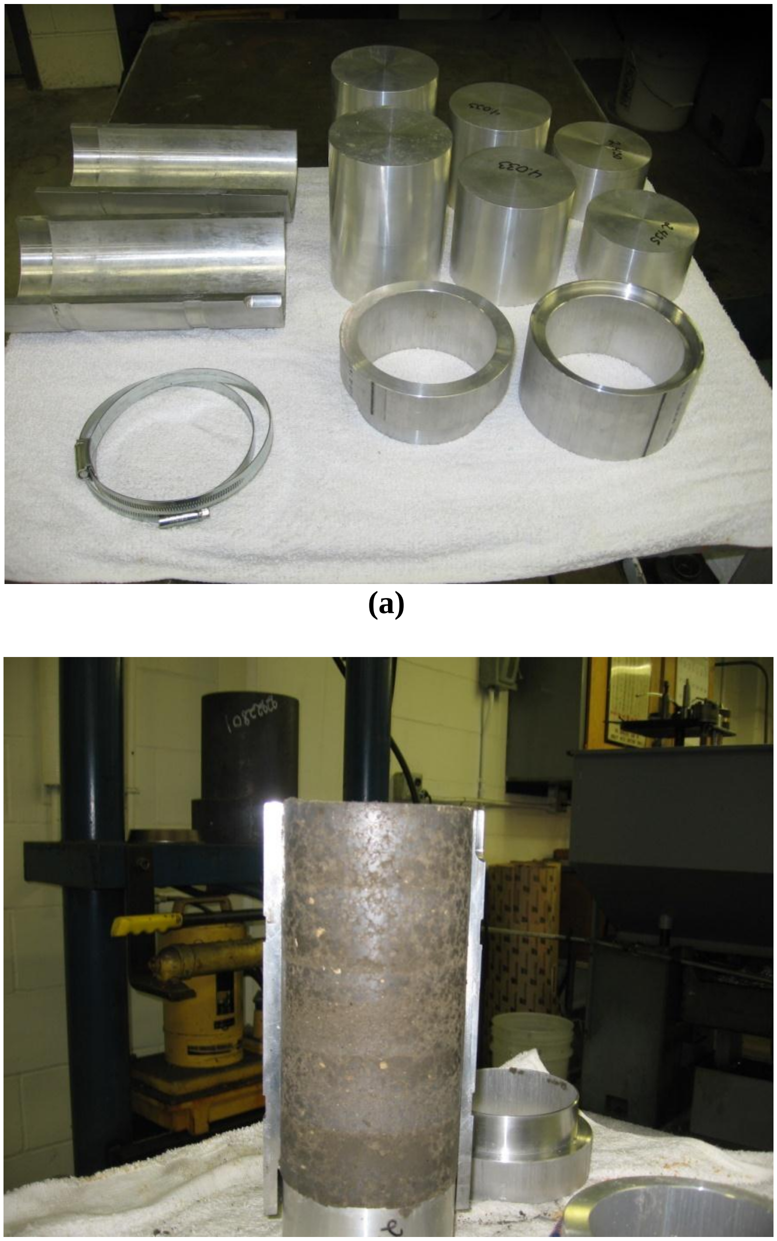
Figure 14. The dynamic materials test system at Iowa DOT: (a) Triaxial cell in HYD-25 with temperature controlled cabinet, (b) Control panel, (c) Data acquisition system

Specimen Preparation

Based on soil characterization results, the unbound materials could be categorized as Type 1 (aggregate) or Type 2 (soil) to fabricate samples and apply loading test sequence in accordance with AASHTO T307 (See Figure 13). Type 1 unbound material is classified as all materials which meet the criteria of less than 70% passing the No. 10 sieve (2.00 mm) and less than 20% passing the No. 200 sieve (75-μm), and which have a plasticity index of 10 or less. These materials are compacted in a 6.0 in. diameter mold. Type 2 soils include all material that does not meet the criteria for Type 1. All soils investigated in this study were categorized as Type 2 and the one type of aggregate considered in this study was categorized as Type 1.

Type 2 soil samples are prepared in 2.8-in. diameter mold (minimum size) with five-lift static compaction. Since the HYD – 25 system in Iowa DOT has a triaxial cell of 100 mm (3.9 in) diameter for Type 2 soil, specially designed mold apparatuses, as shown in Figure 15, were fabricated and used to prepare soil specimens by static compaction with five layers of equal thickness. For each soil type, compacted soil specimens were prepared at three different moisture content combinations, namely: OMC, OMC-4 on the dry side, and OMC+4 on the wet side. After a soil specimen was compacted with specified moisture content, it was placed in a membrane and mounted on the base of the triaxial cell. Porous stones were placed at the top and bottom of the specimen. The triaxial cell was sealed and mounted on the base of the dynamic materials test system frame. All connections were tightened and checked. Cell pressure, LVTD's, load cell, and all other required setup were connected and checked.

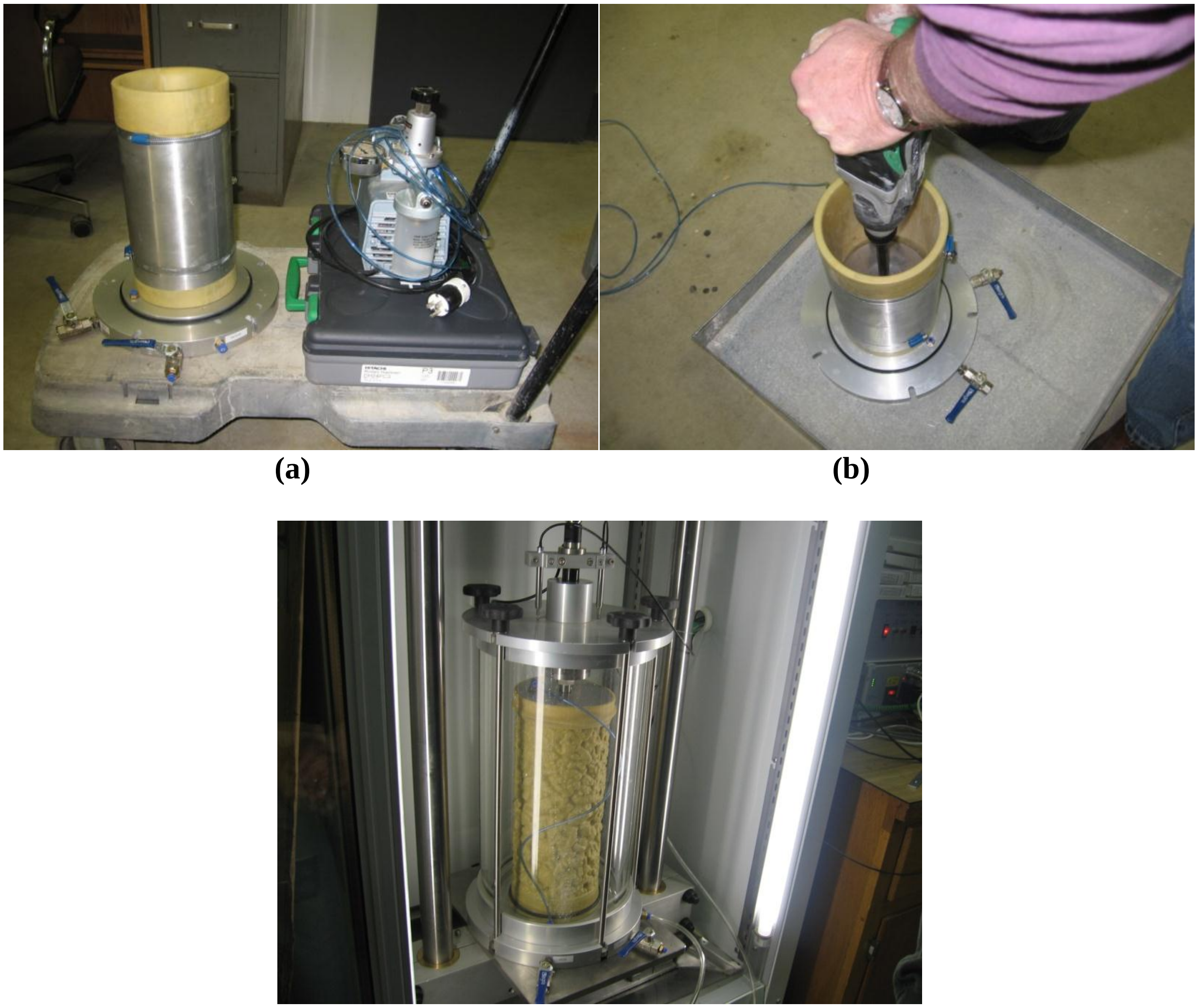
Type 1 aggregate sample is prepared in a 6-in. diameter mold (minimum size) with vibratory compaction. Compacted aggregate specimens with 10% moisture content were prepared. The membrane is fitted inside the mold by applying vacuum. The required amount of aggregate and water are mixed and compacted by vibratory compaction with five layers of equal thickness. The vacuum was maintained throughout the compaction procedure. After compaction, the membrane was sealed to the top and bottom platens with rubber "O" rings and checked. The triaxial cell was sealed and mounted on the base of the dynamic materials test system frame. All connections were tightened and checked. Cell pressure, LVTD's, load cell, and all other required setup were connected and checked. Figure 16 presents Type 1 aggregate sample preparation for the resilient modulus test.



(a)

(b)

Figure 15. Type 2 (soil) sample preparation for resilient modulus test: (a) Specially designed mold apparatuses for static compaction, (b) Compacted soil sample



(a) **(b)**

(c)

Figure 16. Type 1 (aggregate) sample preparation for resilient modulus test: (a) Mold and vibratory compaction apparatus, (b) Vibratory compaction, (c) Compacted sample inside the triaxial cell

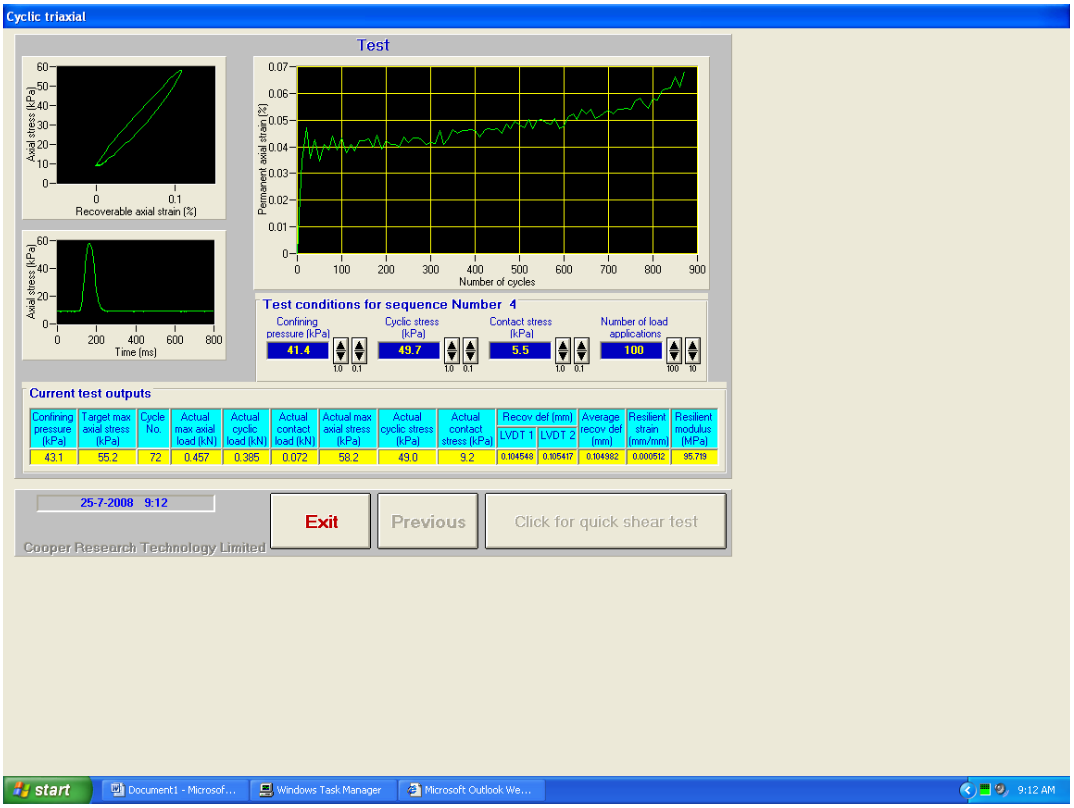
<u>Specimen Testing</u>

The software that controls the dynamic materials test system was programmed to apply repeated loads according to the test sequences specified by AASHTO T 307 based on the material type. Figure 17 shows screenshot of the software used to control and run the repeated load triaxial test.

The soil specimen was conditioned by applying 500 to 1,000 repetitions of a specified cyclic load at a certain confining pressure. Conditioning eliminates the effects of specimen disturbance from compaction and specimen preparation procedures and minimizes the imperfect contacts between end platens and the specimen. The specimen is then subjected to different deviator stress and confining stress sequences as per AASHTO T 307 test procedure. The stress sequence is selected to cover the expected in-service range that a base (aggregate) or subgrade (soil) material would experience due to traffic loading.

A different cyclic loading test sequence was applied on the Type 2 specimen following the AASHTO T 307 specifications to investigate resilient modulus under zero- confining pressure. The loading conditions used in these test sequences were same as those specified by AASHTO T 307 except that a zero-confining pressure was used. After the repeated load triaxial test was completed, compressive loading with a specific confining pressure (27.6 kPa for Type 2 soil and 34.5 kPa for Type 1 aggregate) in accordance with AASHTO T307 (referred to as quick shear test) was applied on the test specimens. Figure 18 shows screenshot of the software used to control and run the quick shear test.

It was very difficult to apply the exact specified loading, especially contact loading, on the soil specimen in a repeated load configuration. This was in part due to the controls of the equipment as well as stiffness of soil specimens. The applied loads and measured displacements were continuously monitored during the test to ensure that the applied loads were close to the specified loads. If there were significant differences between the applied and the specified loads, then test was stopped and test sample was discharged.



Test conditions for sequence Number 4

Confining pressure (kPa): 41.4
Cyclic stress (kPa): 49.7
Contact stress (kPa): 5.5
Number of load applications: 100

Current test outputs

Confining pressure (kPa)	Target max axial stress (kPa)	Cycle No.	Actual max axial load (kN)	Actual cyclic load (kN)	Actual contact load (kN)	Actual max axial stress (kPa)	Actual cyclic stress (kPa)	Actual contact stress (kPa)	Recov def (mm)		Average recov def (mm)	Resilient strain (mm/mm)	Resilient modulus (MPa)
									LVDT 1	LVDT 2			
43.1	55.2	72	0.457	0.385	0.072	58.2	49.0	9.2	0.104548	0.105417	0.104982	0.000512	95.719

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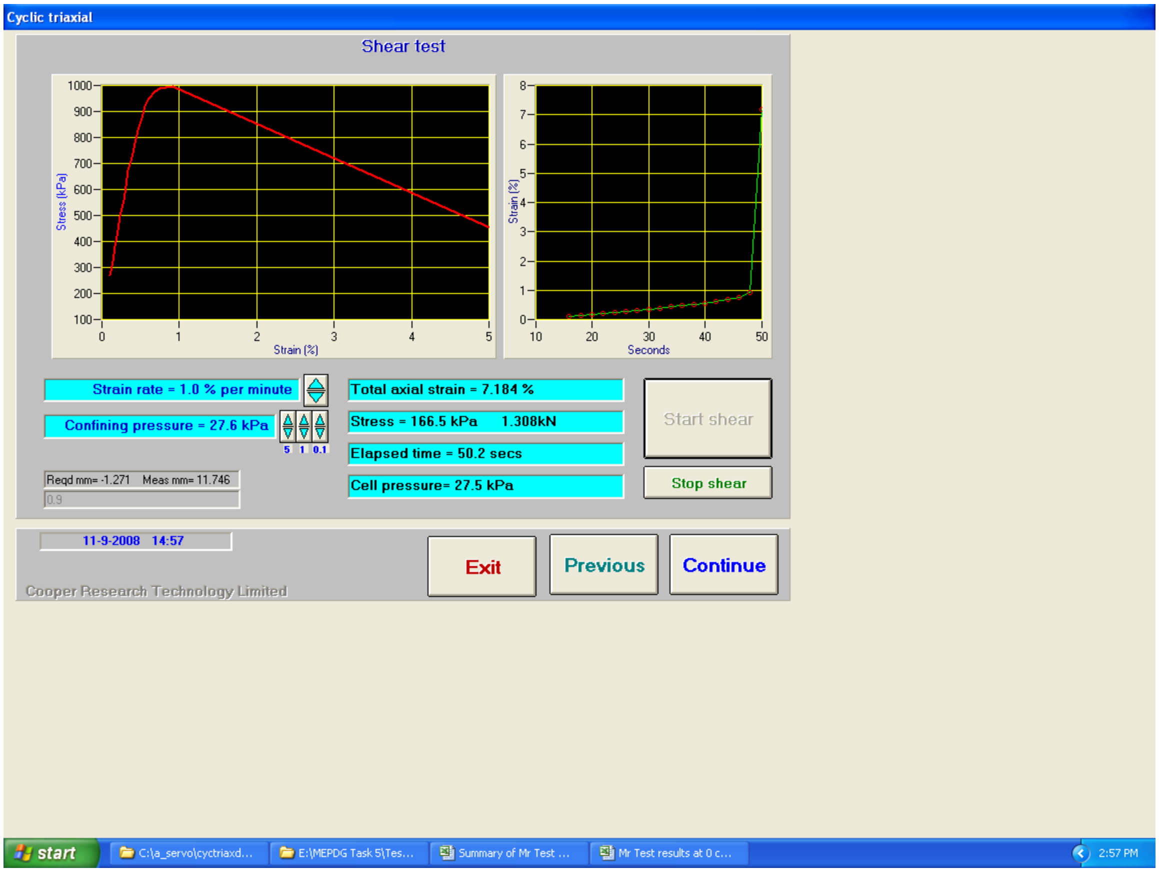
Figure 17. Screenshot of the software used for the resilient modulus test



Strain rate = 1.0 % per minute

Confining pressure = 27.6 kPa

Reqd mm= -1.271 Meas mm= 11.746

0.9

Total axial strain = 7.184 %

Stress = 166.5 kPa 1.308kN

Elapsed time = 50.2 secs

Cell pressure= 27.5 kPa

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Figure 18. Screenshot of the software used for the quick shear test

TEST RESULTS

Grain Size Distribution and Plasticity Characteristics

Grain size analysis of the test soils was conducted in general accordance with ASTM D422 (2007). Particle size distributions for all three soil types are displayed in Figure 19. The percentages of gravel, sand, silt, and clay found in each soil type are summarized in Table 3. Atterberg limits were determined in general accordance with AASHTO T89 (2002) and AASHTO T90 (2004). Atterberg limits test results are provided in Table 3. The suitable soil has the lowest liquid limit (LL) and plasticity index (PI) while the unsuitable soil has the highest LL and PI. The LL and PI values of class 10 soil are between those of the suitable and the unsuitable soils.

The soils were classified in general accordance with ASTM D2487 (2006) and AASHTO M145 (1991). The Unified Soil Classification System (USCS) and AASHTO classification symbols as well as the USCS group names and AASHTO group index values are provided in Table 3. The select soil consists of 43% of fine materials (passing sieve #200) with a plasticity index $PI = 12$, which was classified as lean clay (CL) according to the USCS and clayey soil (A-6) according to the AASHTO soil classification with a group index $GI = 4$. The class10 or suitable soil consists of 51.9% passing sieve #200 with plasticity index *PI* = 23.3, which was classified as sandy lean clay (CL) according to USCS and clayey soil (A-6) according to the AASHTO soil classification with *GI* = 8. The unsuitable soil consists of 58.4% passing sieve #200 with plasticity index *PI* = 34.2, which was classified as sandy fat clay (CH) according to USC and clayey soil (A-6) according to the AASHTO soil classification with *GI* = 16.

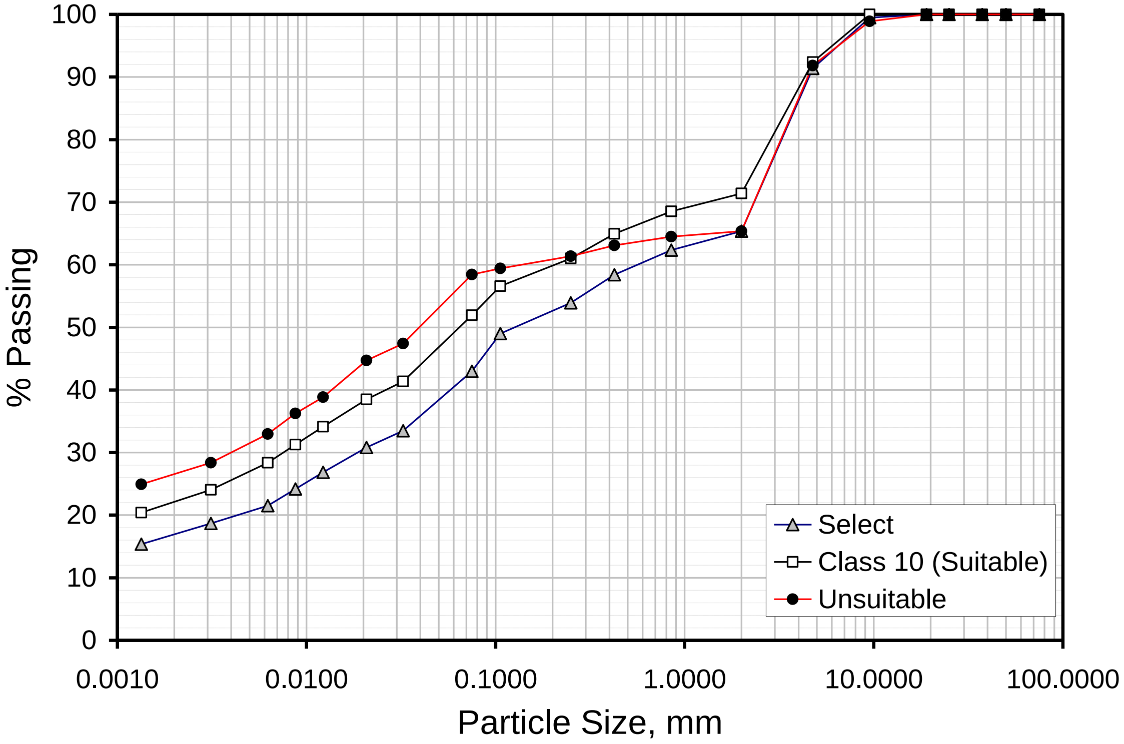

Figure 19. Soil particle size distribution

Table 3. Summary of soil physical properties

Property	Select[a]	Class 10 (Suitable[b])	Unsuitable[c]
% Gravel	8.6	7.6	8.2
% Sand	48.4	40.4	33.4
% Silt and Clay	43.0	51.9	58.4
LL (%)	34.8	39.3	50.5
PL (%)	15.6	16.0	16.3
PI (%)	19.1	23.3	34.2
UCS Group Symbol	SC	CL	CH
UCS Group Name	Clayey sand	Sandy lean clay	Sandy fat clay
AASHTO (Group Index)	A-6 (4)	A-6(8)	A-7-6(16)

[a] Select cohesive soil: 45% ≥ % Silt and Clay, 10%< PI, A-6 or A-7-6 soils of glacial origin, [b] Suitable soil: 30%>PI, [c] Unsuitable soil: soil not meeting select and suitable requirements (Iowa DOT, 2008).

Moisture-Density Relationships

Moisture-density relationships for each soil were determined in general accordance with AASHTO T 99 (2004). A wide range of maximum densities and optimum moisture contents were determined. Results for all three soils are shown in Figure 20. Table 4 summarizes the optimum moisture contents and maximum dry densities. The select soil has the lowest optimum moisture content (15.7%) and highest maximum dry density (110.6 pcf) while the unsuitable soil has the highest optimum moisture content (20.4%) and lowest maximum dry density (100.9 pcf). The class 10 (suitable) soil falls in between select and unsuitable soils with an optimum moisture content of 17.7% and maximum dry density of 105.7 pcf.

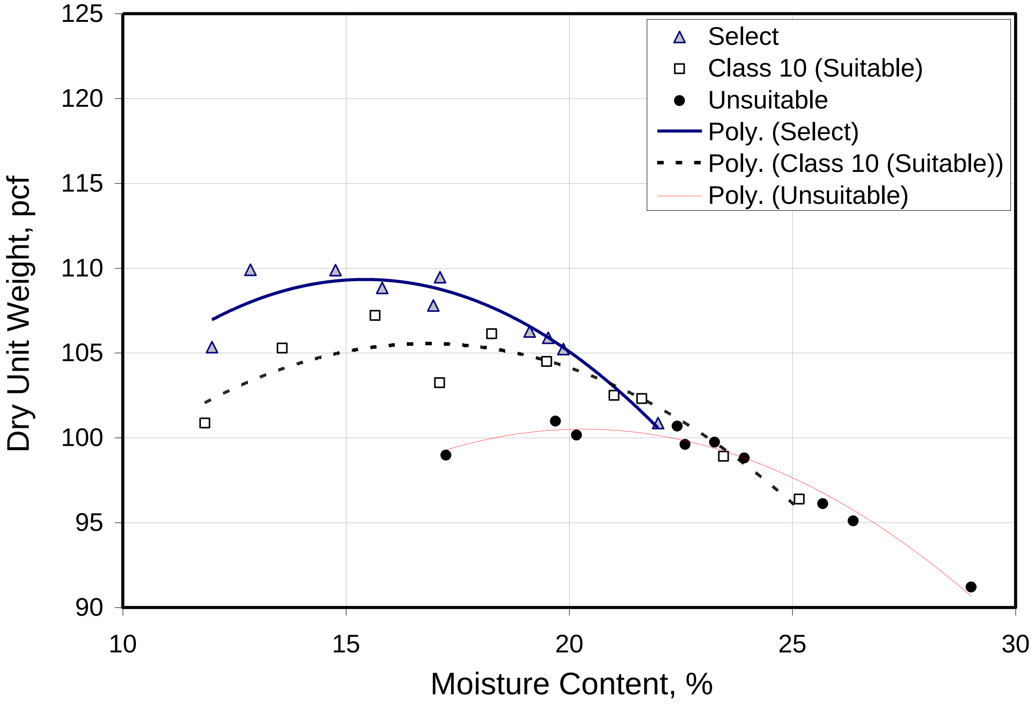

Figure 20. Moisture-density relationships of soils used in this study

Table 4. Summary of soil optimum moisture contents and maximum dry unit weights

Property	Select[a]	Class 10 (Suitable[b])	Unsuitable[c]
Optimum Moisture Content (%)	15.7	17.7	20.4
Maximum Dry Unit Weight (pcf)	110.6	105.7	100.9

[a] Select cohesive soil: maximum dry unit weight (AASHTO T 99) ≥ 110 pcf ,[b] Suitable soil: maximum dry unit weight (AASHTO T 99) ≥ 95 pcf , [c] Unsuitable soil: soil not meeting select and suitable requirements (Iowa DOT, 2008).

Resilient Modulus of Soils

Typical results from repeated load triaxial test on the investigated soils as per AASHTO T307 specified test sequence for subgrade soil are shown in Table 5. The test was conducted on select soil specimens at OMC. Table 5 presents the mean resilient modulus values, standard deviation (SD), and coefficient of variation (CV) for the 15 test sequences conducted according to AASHTO T 307. The mean resilient modulus values, Standard Deviation (SD) and Coefficient of Variation (CV) summarized in Table 5 are obtained from the last five load cycles of each test sequence. The CV values presented in Table 5 range between 0.3 % and 1.5% indicating fairly consistent test results during each test sequence.

Table 5. Typical results from repeated load triaxial tests conducted according to AASHTO T307 specified testing sequence for subgrade soil

		Resilient Modulus, M_r (psi)		
Confining Stress, $s_{c\ \text{or}}\ s_3$ (psi)	Deviator Stress, $s_{d\ \text{or}}\ s_{\text{cyclic}}$ (psi)	Mean	SD	CV (%)
6.0	1.8	13,068	198	1.5
6.0	3.6	11,985	52	0.4
6.0	5.4	10,836	113	1.0
6.0	7.2	9,919	49	0.5
6.0	9.0	9,289	29	0.3
4.0	1.8	12,007	41	0.3
4.0	3.6	10,602	159	1.5
4.0	5.4	9,644	49	0.5
4.0	7.2	9,059	52	0.6
4.0	9.0	8,720	33	0.4
2.0	1.8	10,124	122	1.2
2.0	3.6	9,244	133	1.4
2.0	5.4	8,552	61	0.7
2.0	7.2	8,180	41	0.5
2.0	9.0	7,956	29	0.4

The resilient modulus of soil is dependent on stress condition such as bulk stress, deviator stress, and confining stress. The effects of bulk stress (overall stress) on resilient modulus values are illustrated in Figures 21 to 23. These figures indicate that the resilient modulus of soils increases with increasing bulk stress. These results are consistent with the results displayed in Figure 5 illustrating typical soil behavior under repeated loads. The effects of deviator stress on resilient modulus are illustrated in Figures 24 to 26 and the effects of confining stress on resilient modulus are illustrated in Figures 27 to 29. Predictive linear equations and R^2 based on regression analysis are also provided in these figures to show the trends of effects and the strength of these trends. A positive slope value in the linear equation indicates increase in resilient modulus with the increase of stress and negative slope value indicates decrease in resilient modulus with the decrease in stress. Higher R^2 value indicates a stronger trend.

As shown in these figures, in general, the resilient modulus decrease with the increase in deviator stress (stress-softening behavior) and decrease in confining stress. These results reflect a typical stress dependent behavior of soil under compression type field loading conditions. Moreover, the select soil specimens with lower moisture contents exhibited relatively higher resilient modulus values compared to the other specimens.

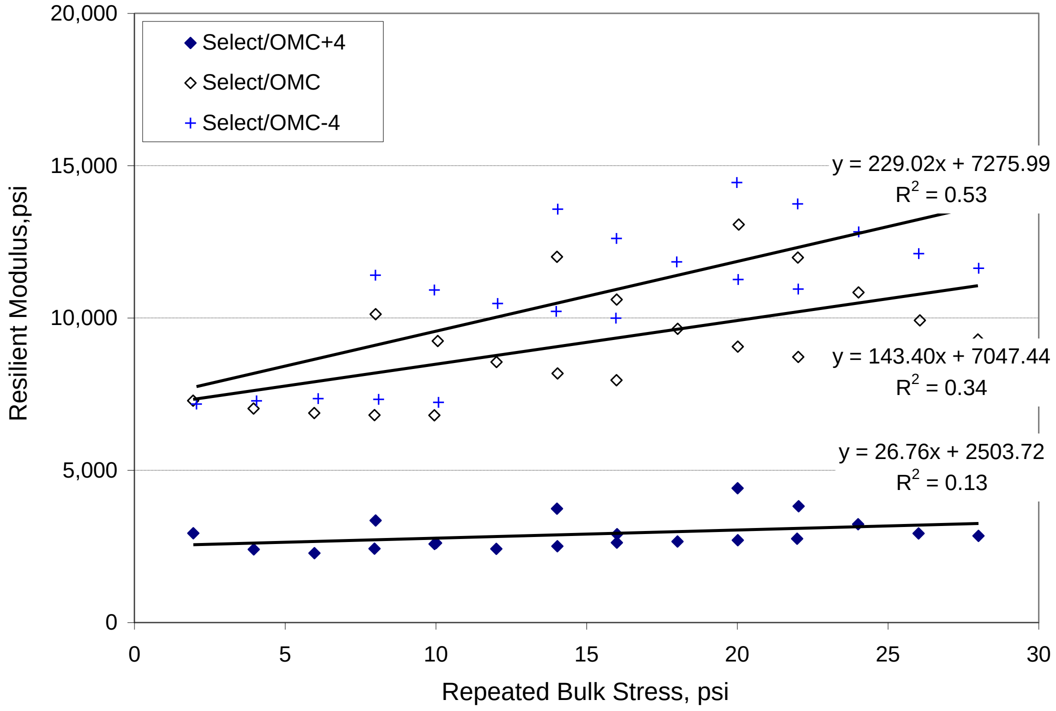

Figure 21. Resilient modulus versus bulk stress for select soils

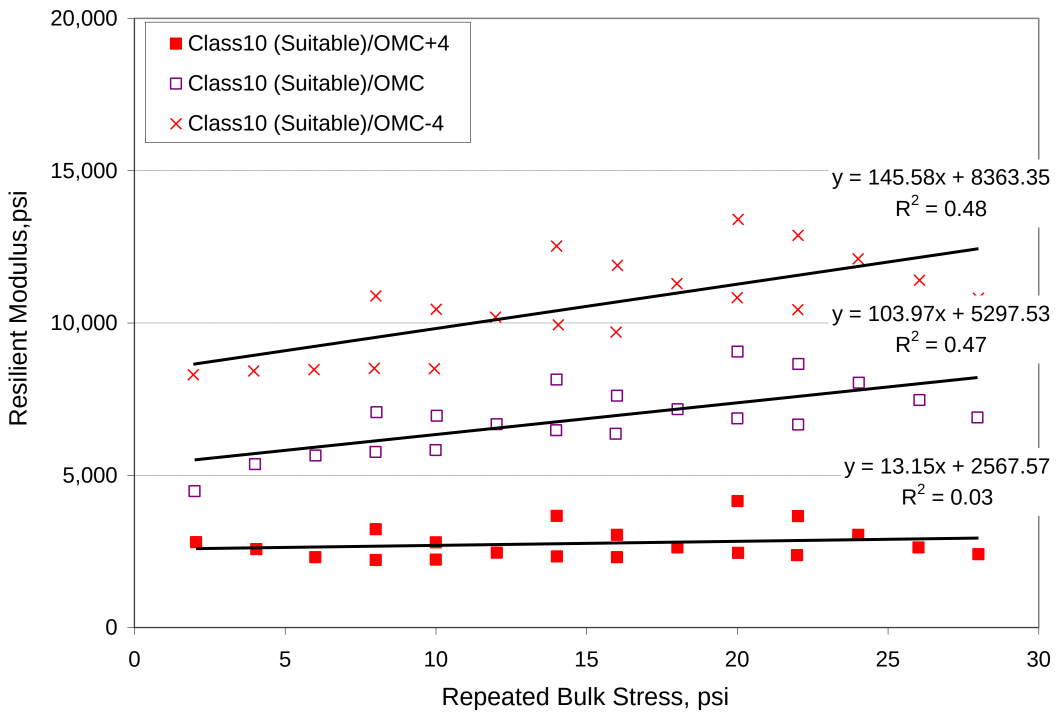

Figure 22. Resilient modulus versus bulk stress for class 10 (suitable) soils

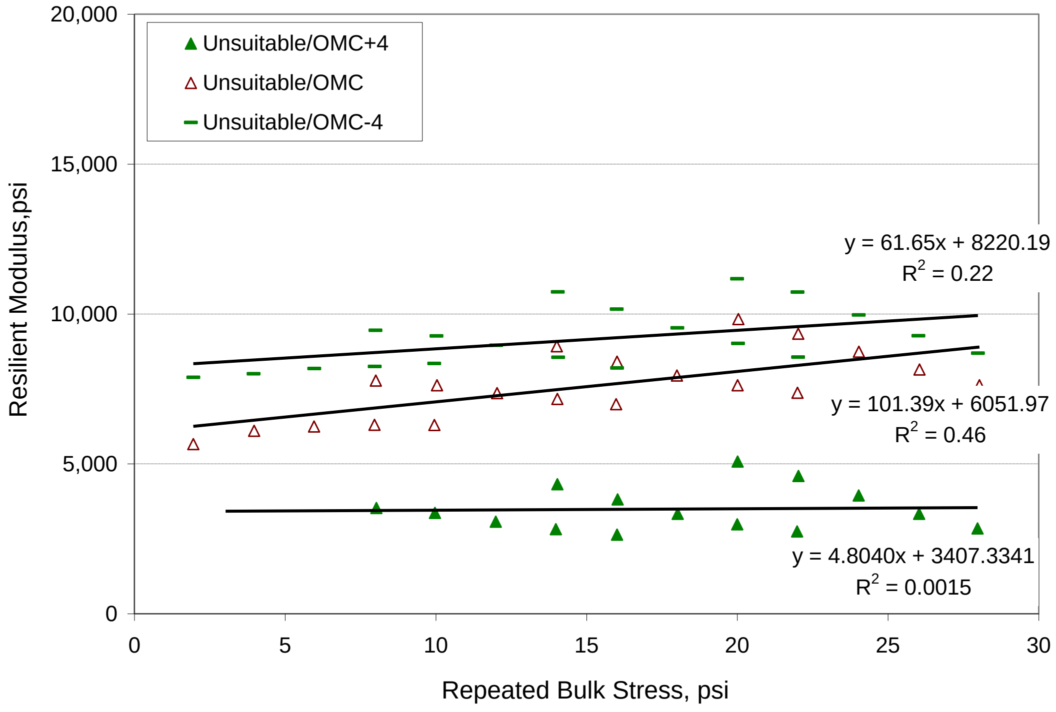

Figure 23. Resilient modulus versus bulk stress for unsuitable soils

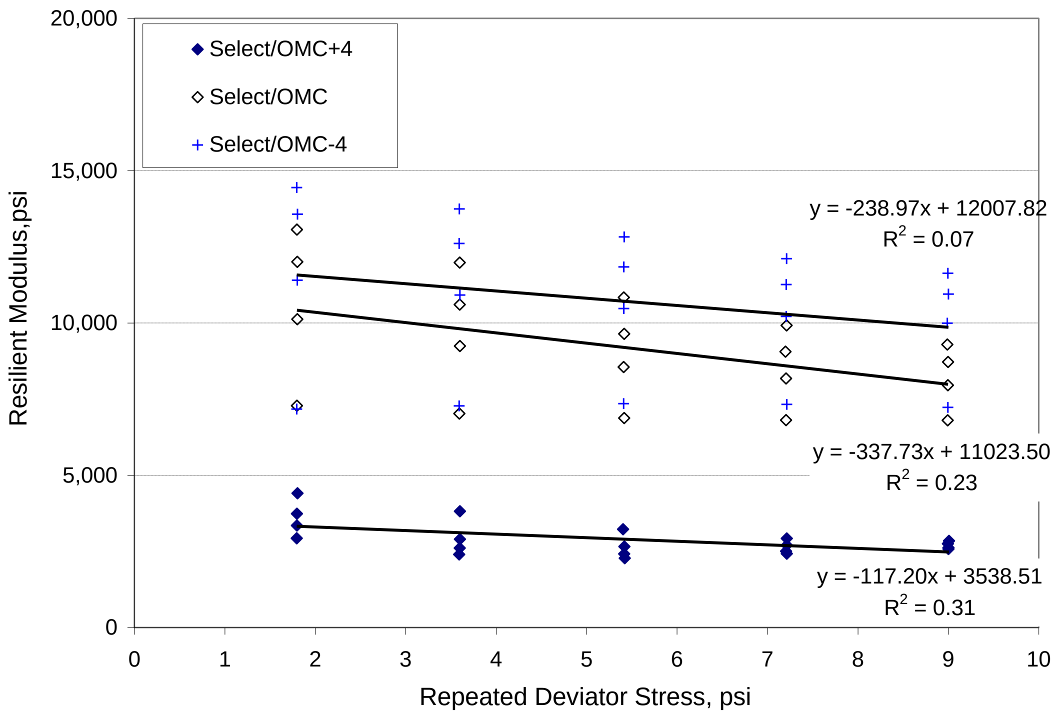

Figure 24. Resilient modulus versus deviator stress for select soils

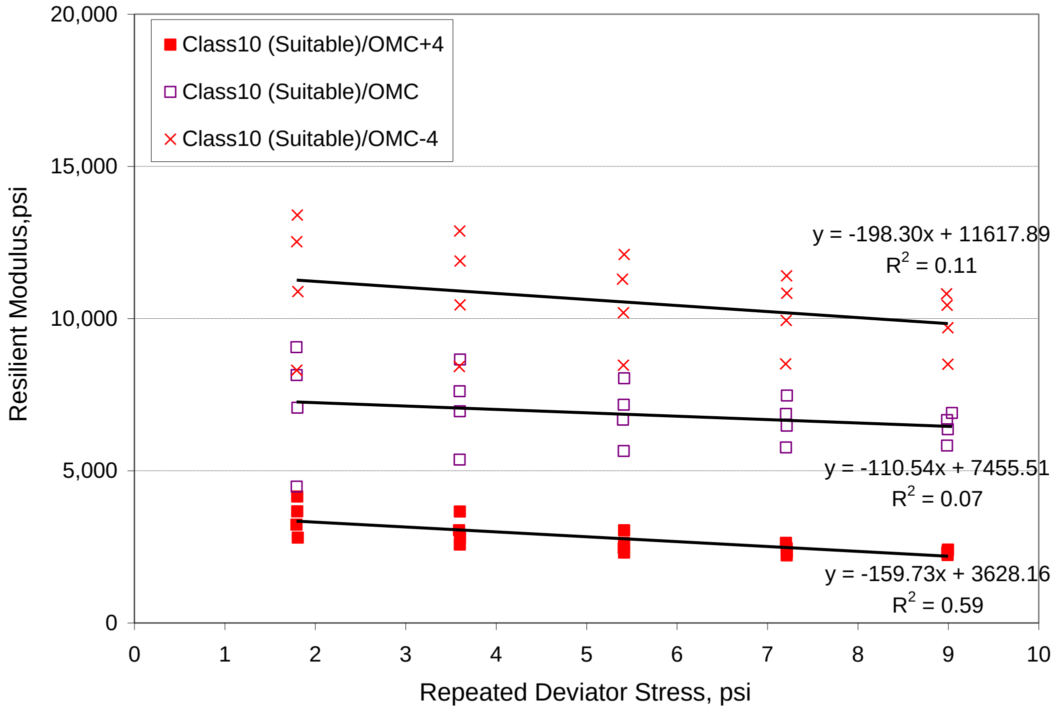

Figure 25. Resilient modulus versus deviator stress for class 10 (suitable) soils

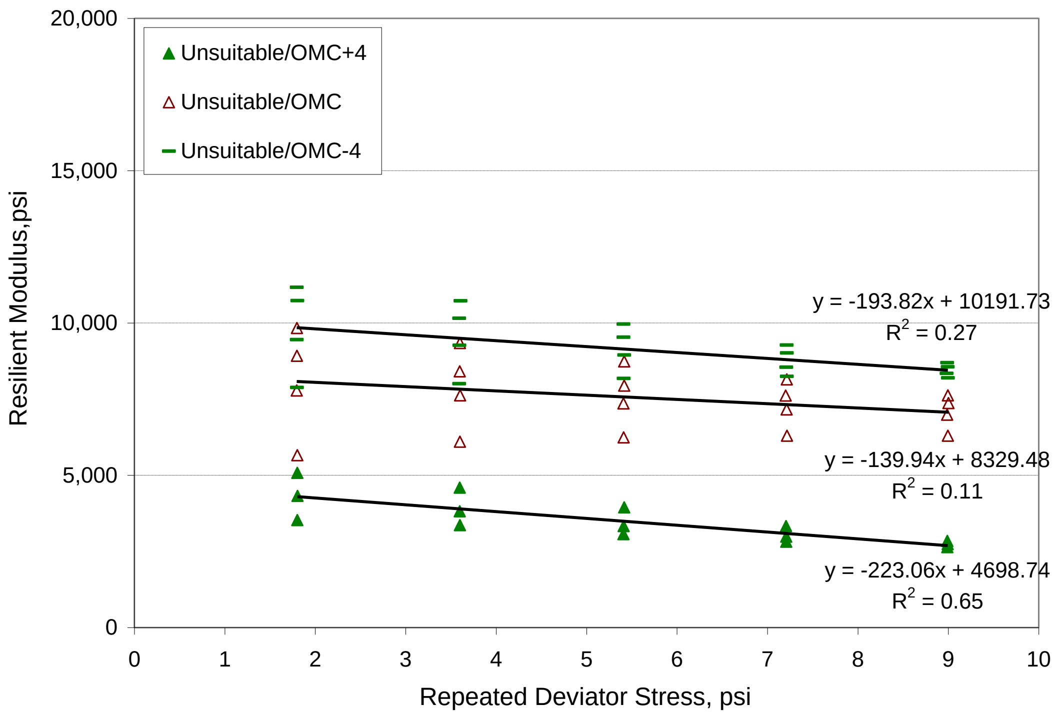

Figure 26. Resilient modulus versus deviator stress for unsuitable soils

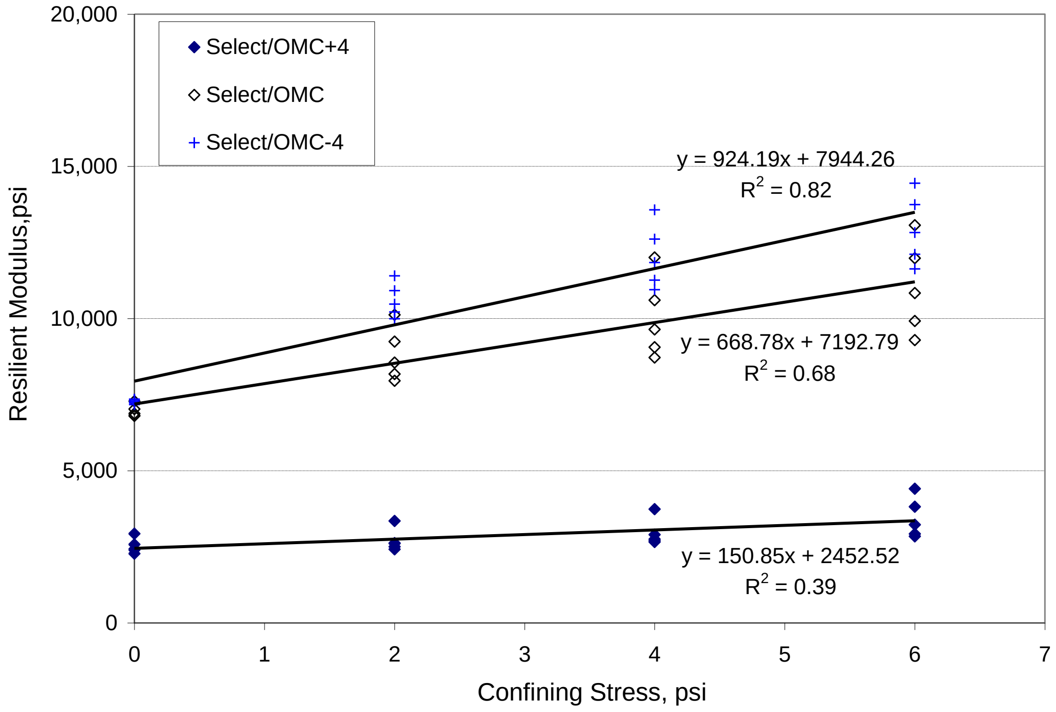

Figure 27. Resilient modulus versus confining stress for select soils

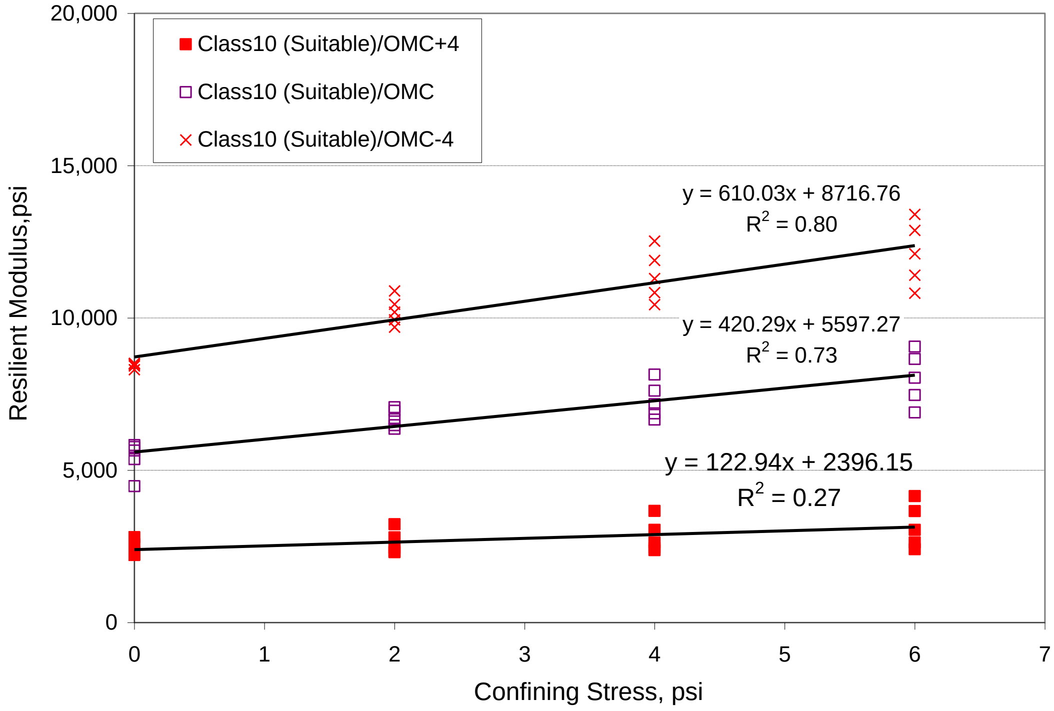

Figure 28. Resilient modulus versus confining stress for class 10 (suitable) soils

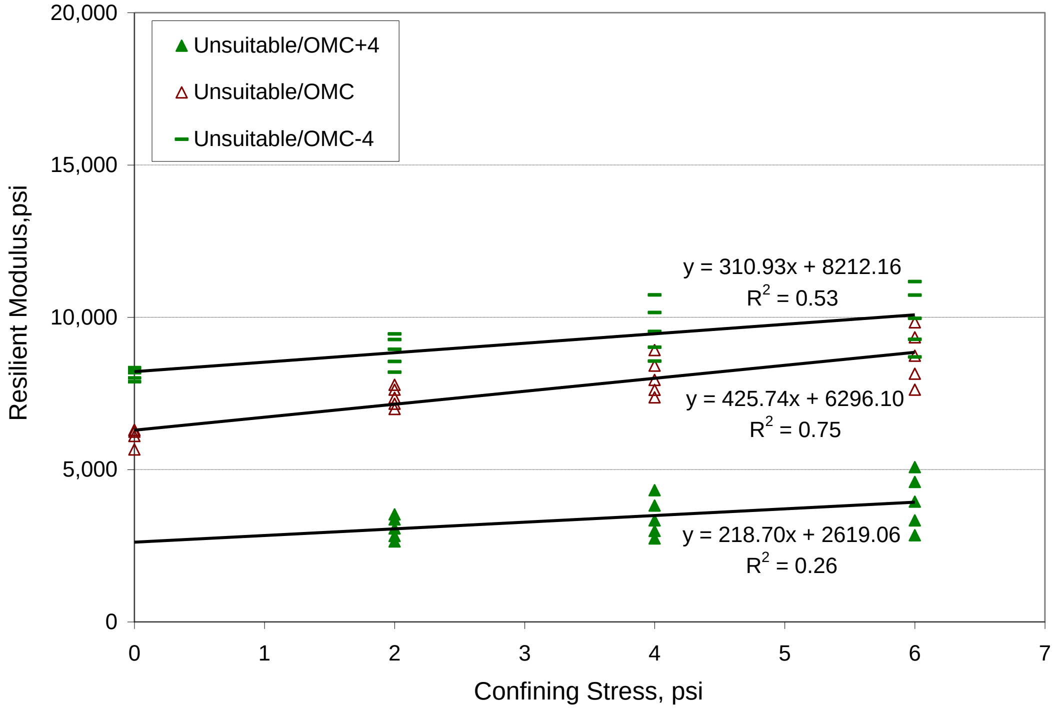

Figure 29. Resilient modulus versus confining stress for unsuitable soils

The average resilient modulus values of tested soil specimens are presented in Figure 30 to illustrate the effects of soil types and moisture contents on the resilient modulus values. The test sequences of AASHTO T 307 do not include those under zero-confining stress conditions. However, this study adopted the test sequences under zero-confining stress conditions after the completion of the standard test sequences according to AASHTO T 307. Two data sets were used for the calculation of average resilient modulus as follows: one from the M_R results of the standard 15 stress combinations without zero-confining stress conditions (i.e., standard 15 load sequences according to AASHTO T 307) and the other from M_R results of the 20 stress combination with zero-confining stress conditions (i.e., standard 15 load sequences followed by 5 load sequences under zero-confining stress conditions).

As seen in Figure 30, the M_R values range from 2,905 to 11,865 psi for select soils, from 2,765 to 11,249 psi for class 10 (suitable) soils, and from 3,495 to 9,483 psi for unsuitable soils under different moisture content conditions. For the same type of soil, specimens with lower moisture contents exhibit higher resilient modulus values compared to those with relatively higher moisture contents. The effect of increased soil moisture content on reducing the resilient modulus is significant. For all the investigated soils, the resilient modulus of soil compacted at OMC-4 were higher compared to those compacted to OMC, as expected. Similarly, resilient modulus of soil specimens compacted at OMC+4 were relatively lower compared to soils compacted to OMC. The soil compacted at moisture content less than the optimum exhibited hardening and showed higher values of resilient modulus with the increase of the overall stress.

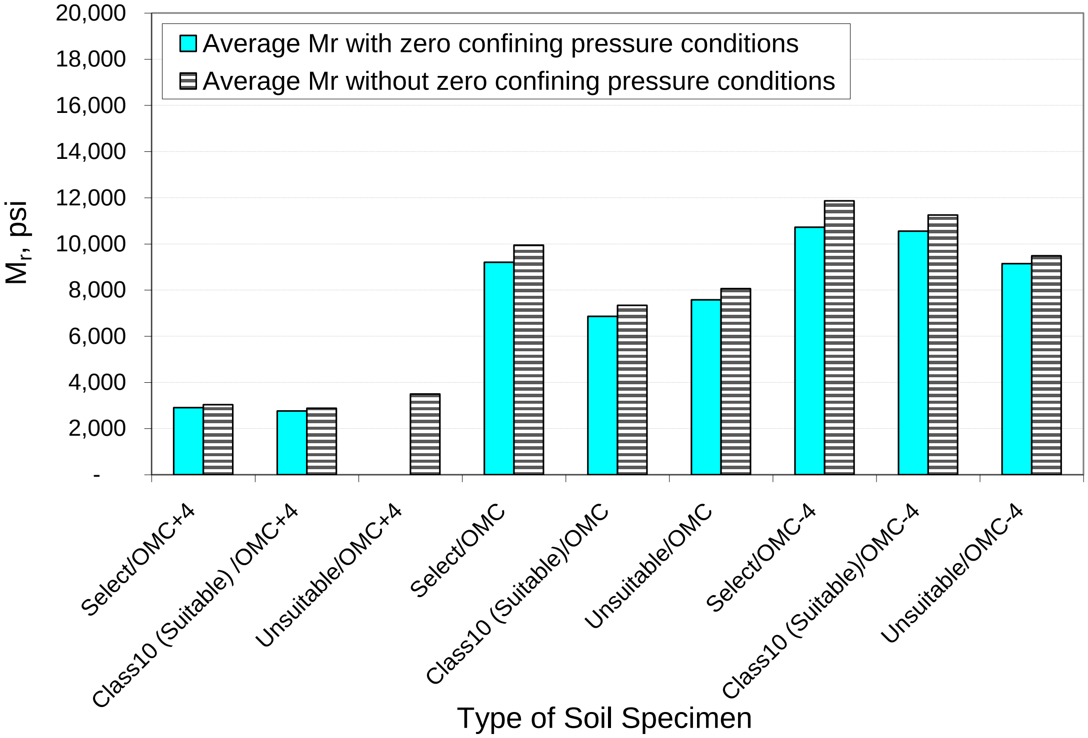

Figure 30. The average resilient modulus of tested soil specimens

At the completion of resilient modulus testing, specimens were subjected to compressive loading under a specific confining pressure (27.6 kPa) in accordance with AASHTO T307 (commonly known as quick shear test) until either: (1) the load values decrease with increasing strains, (2) five percent strain is reached, or (3) the capacity of the load cell is reached. The failure of specimen in this study occurred under the first case. Figure 31 presents the results of quick shear tests conducted after the determination of resilient modulus. Similar to observations made from resilient modulus test results, the maximum strength values of the suitable soils and the soils with low moisture content (OMC-4) are higher than those of the others.

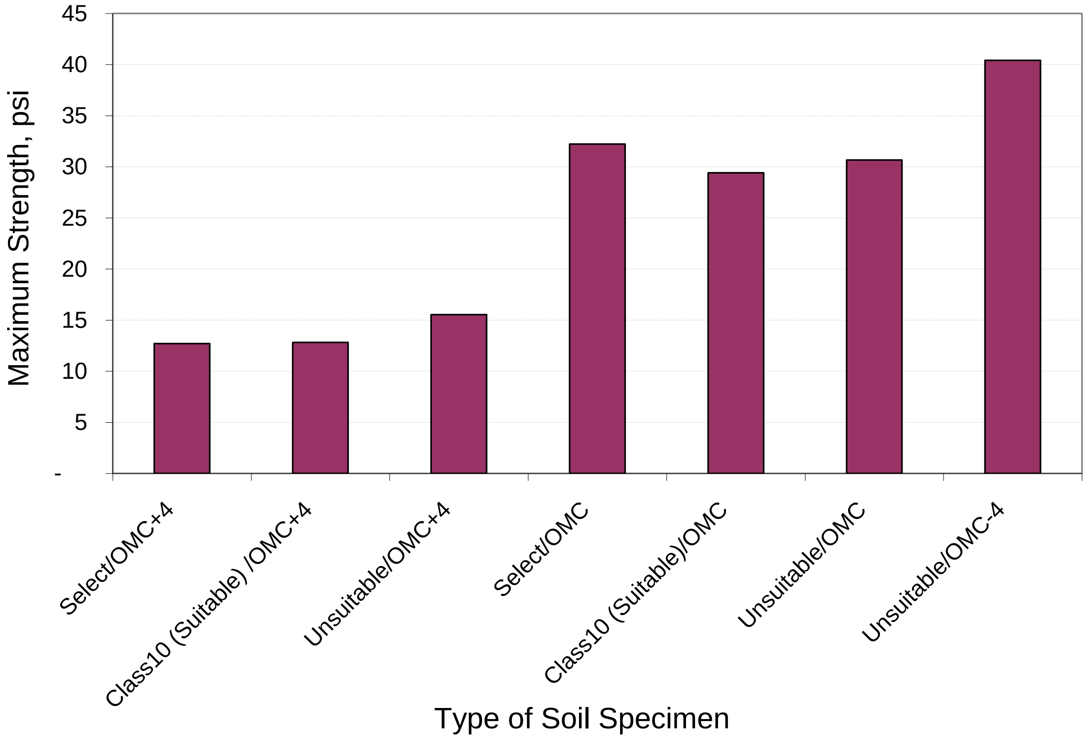

Figure 31. Quick shear test results

Resilient Modulus of Aggregate

Typical results from repeated load triaxial tests conducted on the aggregate specimen according to testing sequence specified for base/subbase aggregates in AASHTO T307 are shown in Table 6. The tests were conducted on aggregate specimen with 10% moisture contents. Similar to Table 5, Table 6 presents the mean resilient modulus values, standard deviation (SD), and coefficient of variation (CV) for the 15 test sequences conducted according to AASHTO T 307. The coefficient of variation values for the test results presented in Table 6 range between 0.2% and 1.7% indicating fairly consistent test results during each test sequence.

Table 6. Typical results for the repeated load triaxial tests conducted according to testing sequence for base/subbase aggregate in AASHTO T 307

Confining Stress, $\sigma_{c\ \text{or}}\ \sigma_3$ (psi)	Deviator Stress, $\sigma_{d\ \text{or}}\ \sigma_{cyclic}$ (psi)	Resilient Modulus, M_r (psi)		
		Mean	SD	CV (%)
3.0	2.7	13,793	181	1.3
3.0	5.4	15,501	176	1.1
3.0	8.1	17,179	132	0.8
5.0	4.5	19,067	331	1.7
5.0	9.0	21,483	218	1.0
5.0	13.5	23,227	92	0.4
10.0	9.0	28,842	135	0.5
10.0	18.0	31,825	146	0.5
10.0	27.0	33,224	79	0.2
15.0	9.0	32,797	190	0.6
15.0	13.5	34,002	201	0.6
15.0	27.0	38,375	208	0.5
20.0	13.5	39,028	448	1.1
20.0	18.0	40,644	196	0.5
20.0	36.0	44,940	143	0.3

The resilient modulus of unbound aggregate layer is also dependent on stress condition. The effects of stress condition on aggregate resilient modulus values are illustrated in Figures 32 to 34. Similar to resilient modulus of soil, resilient modulus of aggregate increases with increasing overall stress (bulk stress) and confining stress but at a higher slope. These results are also consistent with the results displayed in Figure 5 showing typical behavior of unbound material under repeated loads. The resilient modulus of soils decrease with the increase in deviator stress (stress-softening behavior) as shown in Figure 24 to 26 while the resilient modulus of aggregate increase with the increase in deviator stress (stress-hardening behavior) as shown in Figure 33.

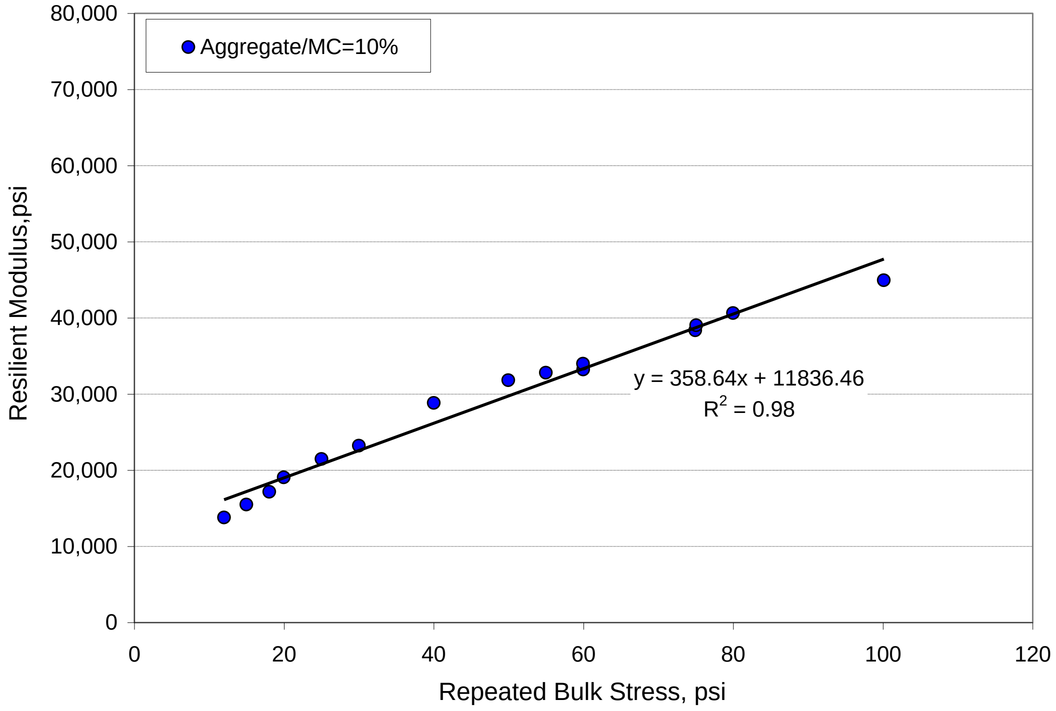

Figure 32. Resilient modulus versus bulk stress for aggregate

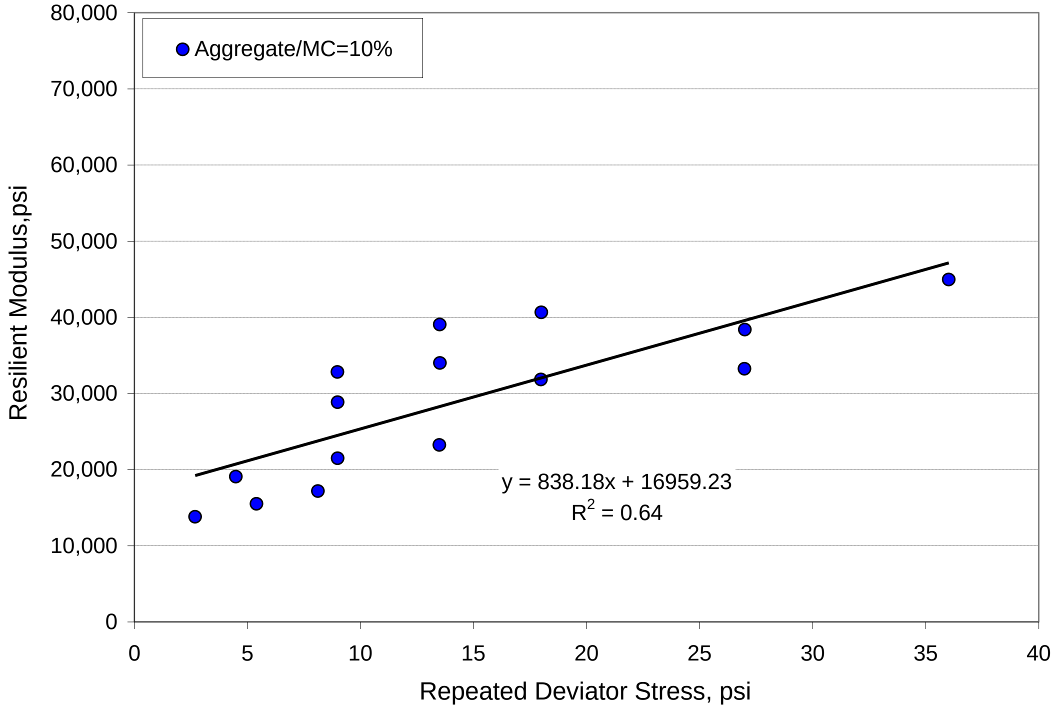

Figure 33. Resilient modulus versus deviator stress for aggregate

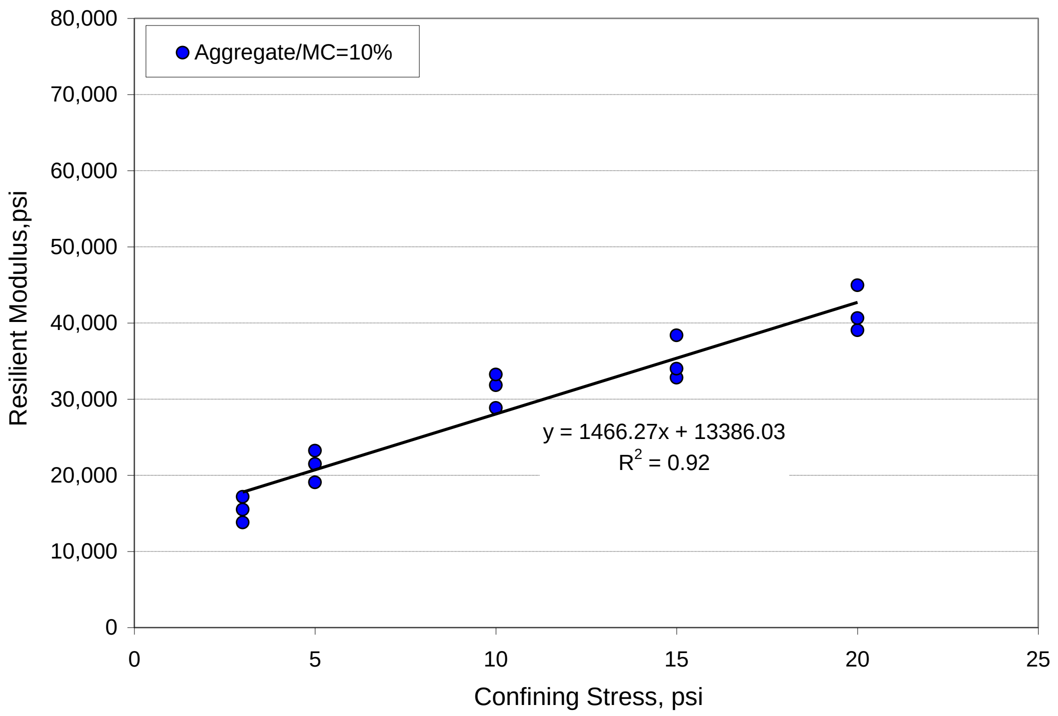

Figure 34. Resilient modulus versus confining stress for aggregate

Table 7 summarizes the average resilient modulus and the results of quick shear tests for the aggregate specimen. The standard test sequences as per AASHTO T 307 were applied on the aggregate specimen (no-zero confining stress condition).

Table 7. Average resilient modulus and the quick shear test results for aggregate specimen with 10% moisture content

Average resilient modulus (psi)	Maximum compressive/shear strength (psi)
28,928	49

EVALUATION OF THE RESILIENT MODULUS VALUES USING THE RESILIENT MODULUS (M_R) - STRENGTH (Q) RELATIONSHIPS

Correlations between the resilient modulus (M_R) and the compressive/shear strength (Q) of soils have been studied and reported by previous researchers. The measured resilient modulus values in this study were evaluated using some of the commonly referred M_R–Q correlations in Table 8.

Table 8. MR–Q correlations used in this study

No.	M_R–Q correlation	Reference
1	$M_R(psi) = 1500CBR = \frac{1500Q_U(psi)}{4.5}$	Heukelom and Klomp (1962), Crovetti (2002)
2	$M_R(at\ \sigma_D\ of\ 6psi)(ksi) = 0.86 + 0.317Q_U(psi)$	Thompson and Robnett (1979)
3	$M_R(at\ \sigma_D\ of\ 6psi)(ksi) = -1.287 + 0.219Q_U(psi)$	Bejarano and Thompson (1999)
4	$M_R(at\ \sigma_D\ of\ 6psi)(ksi) = -9.23 + 0.7067Q_U(psi)$	Gopalakrishnan and Thompson (2007)

The value of M_R in some M_R–Q correlation equations is the value of M_R at the 6 psi of deviator stress (σ_D). However, the repeated loading test sequences in AASHTO T 307 do not include the 6 psi of deviator stress condition. Two measured M_R values at different conditions in Table 9 were considered to compare closely to the M_R values calculated from M_R–Q correlation in this study. As seen in Table 7, average values of M_R at standard 15 load sequences are a little higher than those at 5.4 psi and 7.2 psi deviator stress conditions. The average values of M_R at standard 15 load sequences were selected as the representative measured values to compare with M_R values predicted from correlation equations since these values were averaged from M_R data under a variety of different stress conditions (the 15 stress combination).

Table 9. M_R values suggested for using in M_R–Q correlation equation

Sample I.D	Average of M_R at standard 15 load sequences specified in AASHTO T307	Average of M_R at 5.4 psi and 7.2 psi deviator stress conditions
Select/OMC+4	3,033	2,643
Select/OMC	9,946	8,734
Select/OMC-4	11,865	10,425
Class10 (Suitable)/OMC+4	2,878	2,507
Class10(Suitable)/OMC	7,340	6,762
Class10(Suitable)/OMC-4	11,249	10,343
Unsuitable/OMC+4	3,494	3,247
Unsuitable/OMC	8,057	7,440
Unsuitable/OMC-4	9,483	8,964

Figure 35 compares the measured M_R values from this study with the predicted values from the correlations reported in literature. The measured values always lie within the ranges of M_R values predicted from different equations as seen in Figure 35. Considering the fact that each correlation equation was developed using different types of soil under different moisture conditions, this result indicates that the measured M_R values from this study are reasonable.

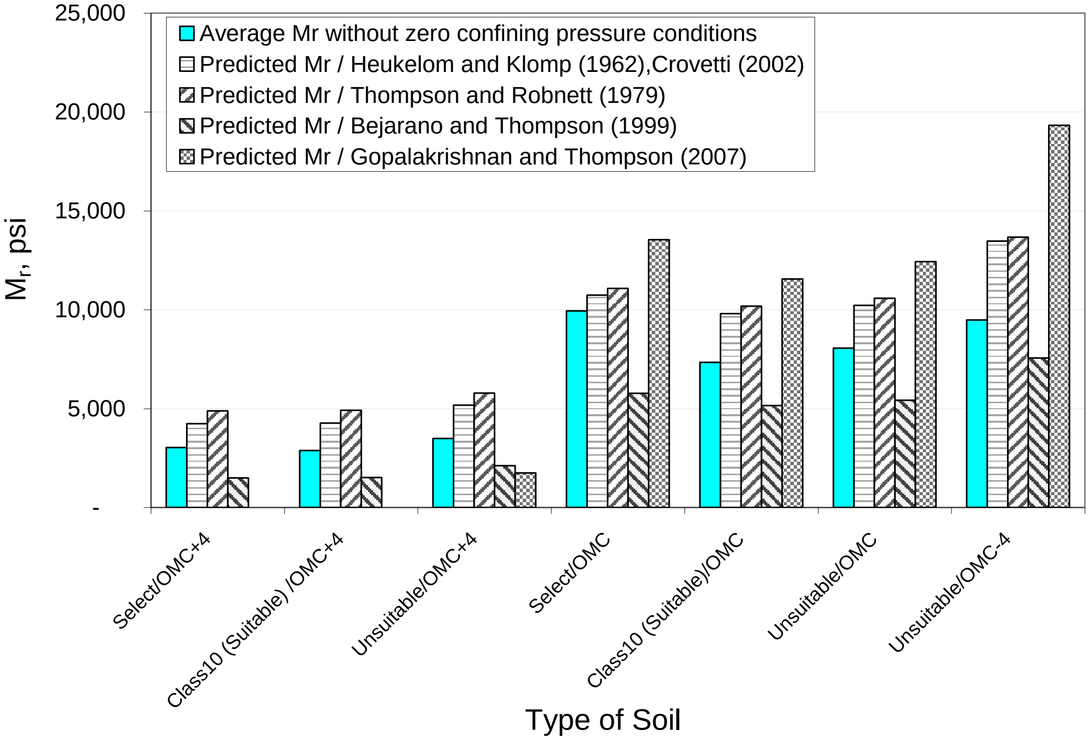

Figure 35. Measured versus predicted M_R values

DETERMINATION OF MEDPG RESILIENT MODULUS INPUTS FOR IOWA UNBOUND MATERIALS

Results obtained from repeated load triaxial test were used to establish the input parameter library at three analysis levels of MEPDG for Iowa condition. As previously stated, MEPDG provides three levels of input depending on the desired level of accuracy of input parameter. The input parameters required at each level were disused previously.

Resilient Modulus Model Coefficients for Level 1 Analysis

The resilient modulus model in MEPDG is a general constitutive equation for all types of unbound materials (See equation 4). The input data required in MEDPG level 1 analysis is not the actual M_R test data but rather the coefficients K_1, K_2, and K_3 of a general constitutive equation. Coefficient K_1, K_2, and K_3 of MEPDG resilient modulus model can be determined using the actual M_R test data through statistical analysis.

Statistical analysis was carried out for each soil type with three different moisture content levels and one aggregate type with two different moisture content levels to determine the MEPDG model coefficients (K_1, K_2, and K_3). Two data sets for each analysis of Type 2 soil materials were used as follows: one from the M_R results of the standard 15 stress combinations without zero-confining stress conditions (standard 15 load sequences according to AASHTO T 307) and the other from M_R results of the 20 stress combination with zero-confining stress conditions (standard 15 load sequences followed by 5 load sequences under zero-confining stress conditions). However, one data set, M_R results for the standard 15 stress combinations without zero confining stress conditions, was used for analysis of type 1 aggregate materials.

The statistical analysis was also carried out for the same databases to determine the coefficients (K_1, K_2, and K_3) of Uzan's model which is one of the well-known models to characterize the nonlinear stress-dependent behavior of unbound materials. The model coefficient values determined in this study are summarized in Tables 10 to 12. The magnitude of K_1 in both models was always greater than zero since the resilient modulus should always be greater than zero. The values of K_2 in both models were also greater than zero since the resilient modulus increases with the increase in the bulk stress (confinement). Since the resilient modulus of soil decreases with the increase in the deviator stress, the values of K_3 in soil materials were smaller than zero. In general, the magnitudes of K_1 in MEPDG model for soil materials are greater than those of Uzan's model.

Table 10. Summary of model coefficients values for soil materials M_R results without zero confining stress conditions

	MEPDG model					Uzan model				
	$M_R(psi) = K_1 P_a \left(\theta/P_a\right)^{K_2} \left(\tau_{oct}/P_a + 1\right)^{K_3}$					$M_R(psi) = K_1 \mathrm{P_a} \left(\theta/P_a\right)^{K_2} \left(\sigma_d/P_a\right)^{K_3}$				
Sample I.D	K_1	K_2	K_3	R-sqr	SEE	K_1	K_2	K_3	R-sqr	SEE
Select/OMC+4	284.582	0.322	-2.217	0.777	0.089	134.309	0.337	-0.319	0.896	0.026
Select/OMC	921.706	0.305	-2.105	0.983	0.021	464.692	0.301	-0.281	0.978	0.010
Select/OMC-4	1,002.829	0.277	-1.523	0.990	0.012	612.569	0.273	-0.201	0.970	0.009
Class10/OMC+4	293.805	0.252	-2.658	0.940	0.050	123.125	0.251	-0.359	0.957	0.018
Class10/OMC	618.125	0.247	-1.476	0.969	0.020	384.965	0.241	-0.192	0.924	0.014
Class10/OMC-4	927.177	0.236	-1.335	0.993	0.009	603.274	0.231	-0.175	0.953	0.010
Unsuitable/OMC+4	363.946	0.335	-2.855	0.968	0.038	146.050	0.319	-0.369	0.901	0.029
Unsuitable/OMC	671.567	0.234	-1.401	0.983	0.014	428.226	0.228	-0.182	0.937	0.012
Unsuitable/OMC-4	792.418	0.164	-1.352	0.983	0.013	515.084	0.156	-0.173	0.904	0.014

Table 11. Summary of model coefficients values for soil materials M_R results with zero confining stress conditions

	MEPDG model					Uzan model				
	$M_R(psi) = K_1 P_a \left(\theta/P_a\right)^{K_2} \left(\tau_{oct}/P_a + 1\right)^{K_3}$					$M_R(psi) = K_1 \mathrm{P_a} \left(\theta/P_a\right)^{K_2} \left(\sigma_d/P_a\right)^{K_3}$				
Sample I.D	K_1	K_2	K_3	R-sqr	SEE	K_1	K_2	K_3	R-sqr	SEE
Select/OMC+4	275.416	0.174	-1.853	0.693	0.102	146.338	0.185	-0.274	0.814	0.034
Select/OMC	929.167	0.284	-2.145	0.977	0.032	459.750	0.288	-0.291	0.986	0.011
Select/OMC-4	1,051.485	0.368	-1.951	0.956	0.052	557.276	0.365	-0.261	0.956	0.023
Class10/OMC+4	286.969	0.158	-2.401	0.913	0.057	130.329	0.159	-0.327	0.939	0.021
Class10/OMC	604.558	0.267	-1.346	0.967	0.033	392.171	0.266	-0.175	0.948	0.018
Class10/OMC-4	934.862	0.230	-1.389	0.987	0.018	594.504	0.232	-0.185	0.980	0.010
Unsuitable/OMC+4	363.946	0.335	-2.855	0.968	0.038	N/A	N/A	N/A	N/A	N/A
Unsuitable/OMC	667.032	0.230	-1.352	0.992	0.014	430.343	0.231	-0.178	0.976	0.011
Unsuitable/OMC-4	773.535	0.141	-1.166	0.946	0.026	530.710	0.141	-0.153	0.914	0.014

Table 12. Summary of model coefficients values for aggregate materials M_R results without zero confining stress conditions

	MEPDG model					Uzan model				
	$M_R(psi) = K_1 P_a \left(\theta/P_a\right)^{K_2} \left(\tau_{oct}/P_a + 1\right)^{K_3}$					$M_R(psi) = K_1 \mathrm{P_a} \left(\theta/P_a\right)^{K_2} \left(\sigma_d/P_a\right)^{K_3}$				
Sample I.D	K_1	K_2	K_3	R-sqr	SEE	K_1	K_2	K_3	R-sqr	SEE
Aggregate/MC=10%	1,080.55	0.585	-0.103	0.997	0.021	1,032.048	0.584	-0.028	0.997	0.010

Table 13 presents the overall statistical summary of the MEPDG resilient modulus model coefficients for soil materials. The analysis showed that the K_1 values for select soil range from 285 to 1,003 with a mean value of 736, from 294 to 927 with a mean value of 613 for class 10 (suitable) soil, and from 364 to 792 with a mean value of 609 for unsuitable soil. The parameter K_2 which, is related to the bulk stress, vary between 0.277 and 0.322 with mean value of 0.301 for select soil, between 0.236 to 0.252 with mean value of 0.245 for class 10 (suitable) soil, and between 0.164 to 0.335 with mean value of 0.244 for unsuitable soil. The parameter K_3 which, is related to the deviator stress, varies between -2.217 and -1.523 with mean value of -1.948 for select soil, between -2.658 to -1.335 with mean value of -1.823 for class 10 (suitable) soil, and between -2.855 to -1.352 with mean value of -1.869 for unsuitable soil.

Table 13. Overall statistical summary of the MEPDG resilient modulus model coefficients

Type of soils	Coefficient	Mean	Minimum	Maximum	Std. Dev.
Select	K_1	736	285	1,003	393
	K_2	0.301	0.277	0.322	0.022
	K_3	-1.948	-2.217	-1.523	0.373
Class 10 (Suitable)	K_1	613	294	927	317
	K_2	0.245	0.236	0.252	0.008
	K_3	-1.823	-2.658	-1.335	0.726
Unsuitable	K_1	609	364	792	221
	K_2	0.244	0.164	0.335	0.086
	K_3	-1.869	-2.855	-1.352	0.854

Unbound Material Properties Values Correlated to Resilient Modulus for Level 2 Analysis

The input data required in MEDPG level 2 analysis are material physical properties including CBR, R-value, AASHTO layer coefficient, and DCP since the materials properties are correlated resilient modulus using typical correlations (See Table 1). The values of unbound material properties were calculated from the measured resilient modulus in this study. Table 14 summaries the unbound material properties values computed from the M_R results without zero confining stress conditions (standard test procedure). Table 15 presents the overall statistical summary for the computed soil material properties.

Table 14. Unbound material properties from M_R results without zero confining stress conditions

Sample I.D	CBR, %	R-value	AASHTO layer coefficient	DCP, in/blow
Select/OMC+4	1.3	3	0.01	125.1
Select/OMC	8.4	16	0.05	23.9
Select/OMC-4	11.0	19	0.06	18.7
Class10(Suitable)/OMC+4	1.2	3	0.01	134.6
Class10(Suitable)/OMC	5.2	11	0.03	36.5
Class10(Suitable)/OMC-4	10.1	18	0.05	20.1
Unsuitable/OMC+4	1.6	4	0.02	102.7
Unsuitable/OMC	6.0	12	0.04	32.0
Unsuitable/OMC-4	7.8	15	0.04	25.5
Aggregate/MC=10%	44.3	50	0.13	5.4

Table 15. Overall statistical summary for the soil material properties

Type of Materials	Material Physical Property	Mean	Minimum	Maximum	Std. Dev.
Select	CBR, %	7	1	11	5
	R-value	13	3	19	8
	AASHTO layer coefficient	0.04	0.01	0.06	0.02
	DCP, in/blow	56	19	125	60
Class10(Suitable)	CBR, %	6	1	10	4
	R-value	11	3	18	8
	AASHTO layer coefficient	0.03	0.01	0.05	0.02
	DCP, in/blow	64	20	135	62
Unsuitable	CBR, %	5	2	8	3
	R-value	11	4	15	6
	AASHTO layer coefficient	0.03	0.02	0.04	0.01
	DCP, in/blow	53	26	103	43

Typical Resilient Modulus Values for Level 3 Analysis

MEPDG level 3 requires only a typical representative M_R value at OMC condition. Table 16 presents the overall statistical summary of M_R results without zero confining stress conditions (standard test procedure) for three types of soil with OMC conditions and one type of aggregate with 10% moisture condition. However, these values can vary under different stress conditions.

Table 16. Typical representative M_R values identified in this study

		M_R, psi			
Type of Materials	Moisture Content	Mean	Minimum	Maximum	Std. Dev.
Select	OMC = 15.7%	9,946	7,956	13,068	1,505
Class 10(Suitable)	OMC = 17.7%	7,340	6,361	9,058	809
Unsuitable	OMC = 20.4%	8,057	6,990	9,831	832
Aggregate	10%	35,063	15,261	55,734	13,113

CASE STUDY: SELECT SOILS FROM LEE COUNTY PROJECT

Soil samples collected from Lee County construction project were tested in addition to the designed experimental testing program. Even though the Lee County project soils can be categorized as select soil based on Iowa DOT specifications, they can be categorized as belonging to both A-6 (select 1) and A-7-6 (select 2) in the accordance with the standard AASHTO soil classification. Maximum dry unit weight of both types is around 120 pcf. Two compacted soil samples for each type were prepared at around 12% moisture contents (12.7% for A-6 (select 1) and 12.9 % for A-7-6 (select 2)) which are at or slightly below OMC. The differences between target and actual moisture contents were less than 1%. The standard 15 loading test sequences according to AASHTO T 307 were applied on these compacted specimens to measure resilient modulus values under different loading conditions.

The effects of stress condition on resilient modulus values are illustrated in Figures 36 to 38. Similar to resilient modulus of the investigated soils under the experimental testing program (See Figures 21 to 29), resilient modulus of Lee county select soils increased with increasing overall stress (bulk stress) and confining stress, and decrease with the increase in deviator stress (stress-softening behavior).

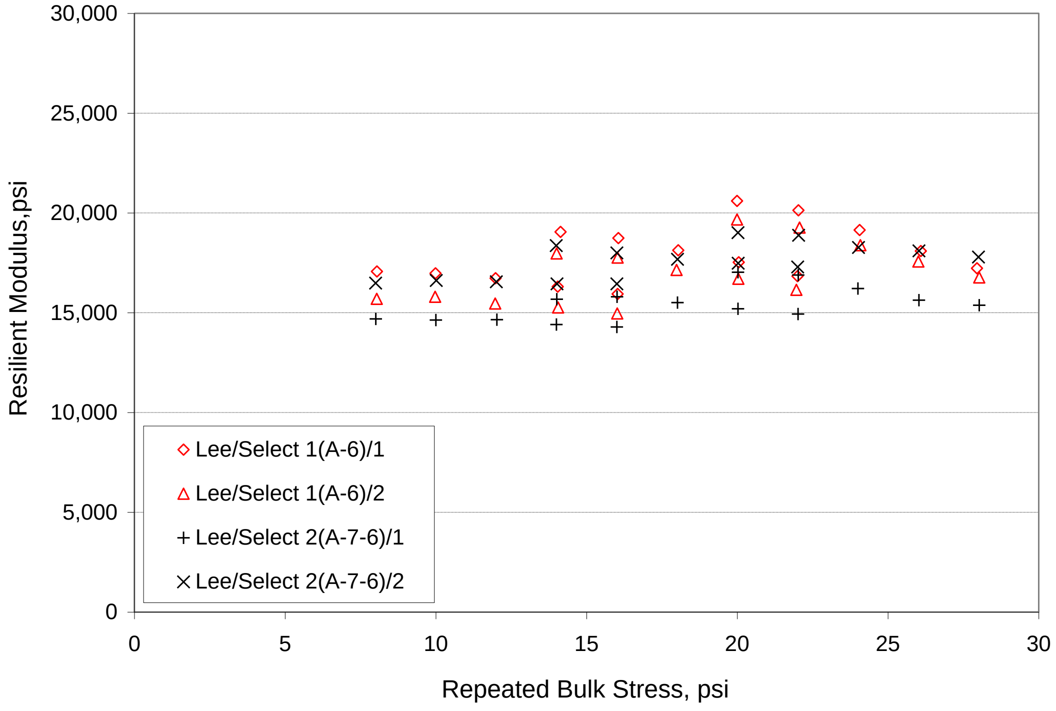

Figure 36. Resilient modulus versus bulk stress for Lee County select soils

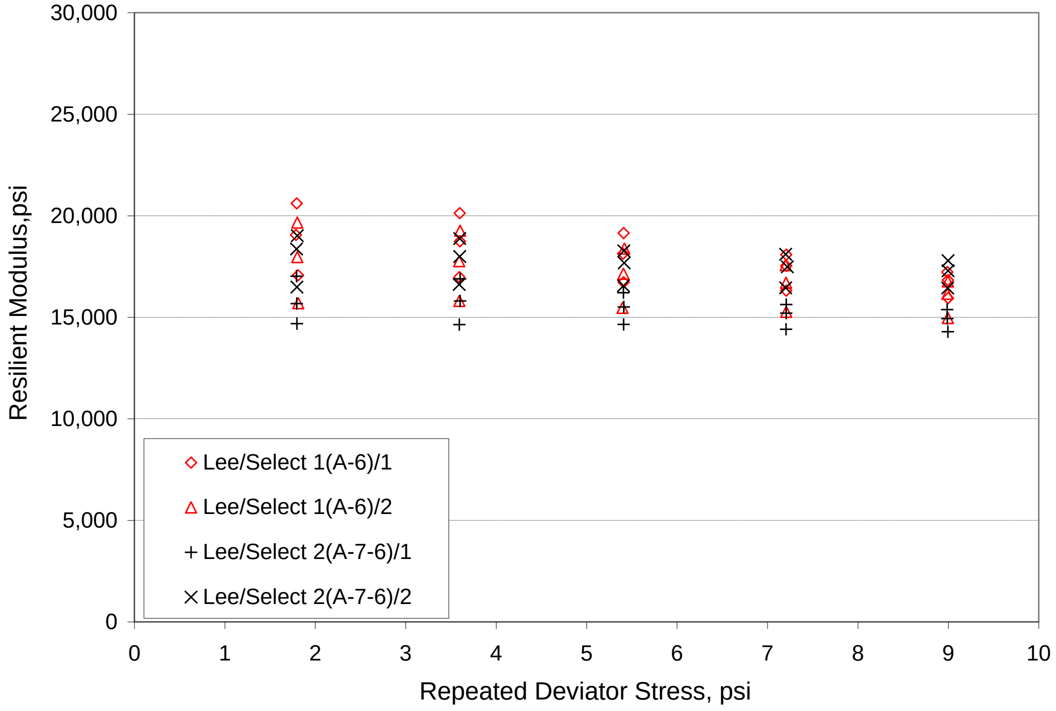

Figure 37. Resilient modulus versus deviator stress for Lee County select soils

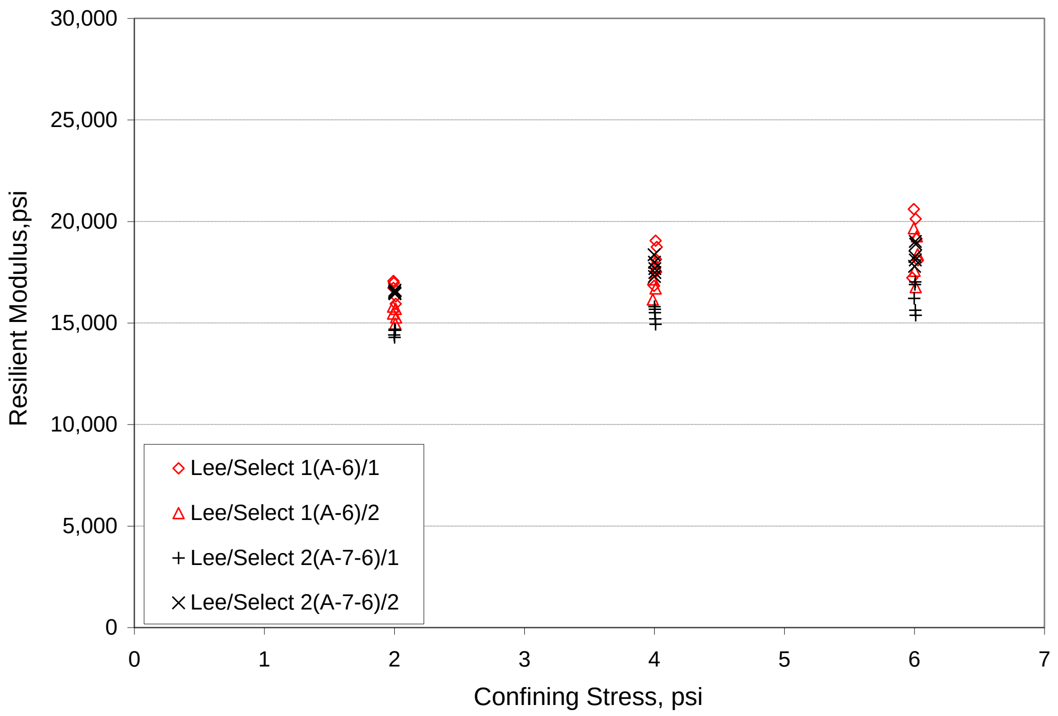

Figure 38. Resilient modulus versus confining stress for Lee County select soils

Figures 39 and 40 present the average resilient moduli and quick shear test results, respectively, for Lee County select soil specimens. As seen in Figure 39, the average M_R values for Lee County select 1 (A-6) soil are not significantly different from the average M_R values of select soils investigated under the experimental program.

The coefficients K_1, K_2, and K_3 of MEPDG resilient modulus model were determined for Lee County project soil materials and summarized in Table 17. Compared to the investigated select soils under the experimental program with OMC and OMC-4 listed in Table 10, the values of K_1 and K_3 of Lee County select soils are higher and the values of K_2 are lower. The OMC and maximum density of investigated select soils are 15.7 % and 110.6 pcf, respectively, while those of Lee County select soil are about 12% and 120 pcf, respectively. These lower OMC values and higher maximum density properties of Lee County select soil may be a contributing factor to the better resilient modulus properties. These results seem to indicate that the Iowa soils classified as select type but sampled at different geographical locations may exhibit different resilient properties.

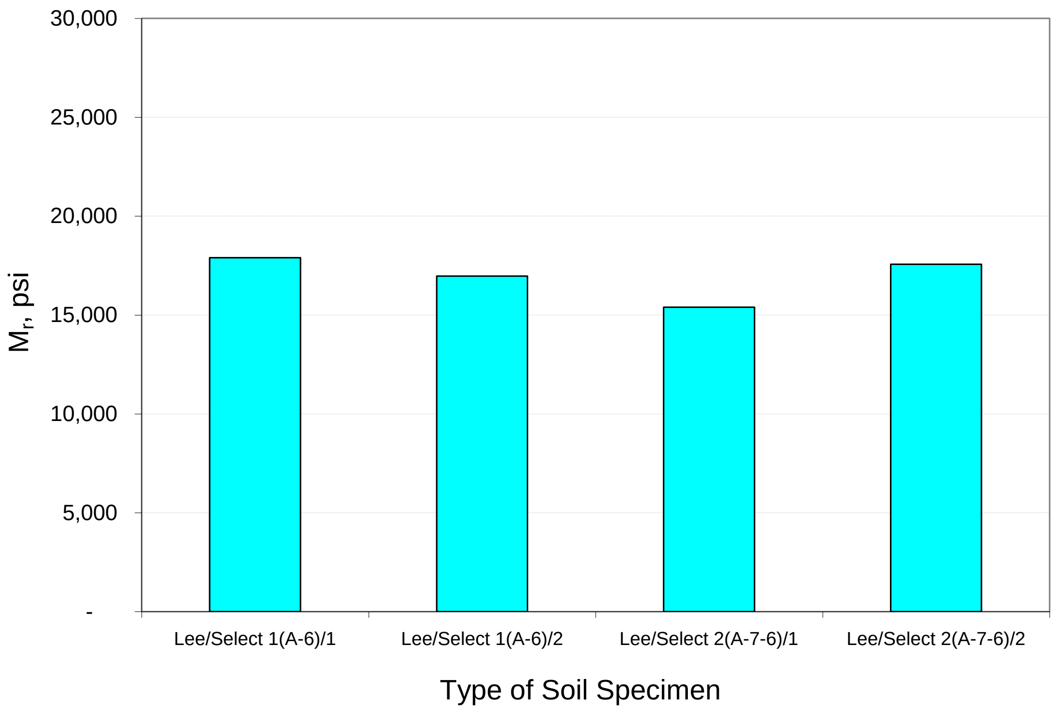

Figure 39. Average resilient modulus of Lee County select soils

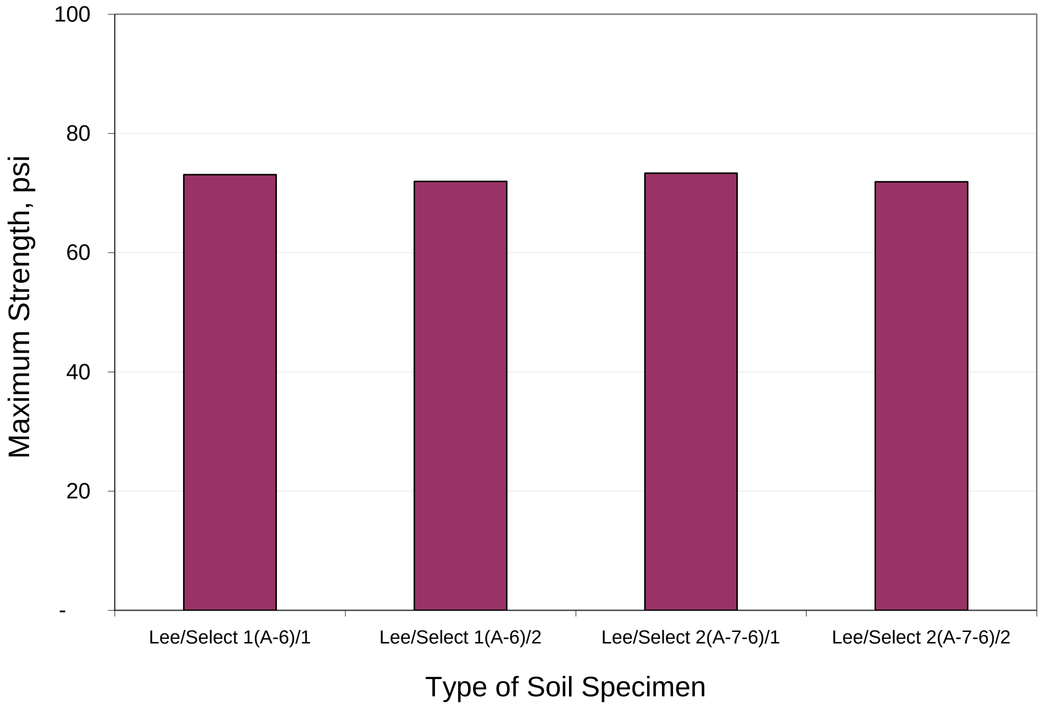

Figure 40. Maximum strength of Lee County select soils in quick shear test

Table 17. Summary of MEPDG M_R model coefficients values for Lee County select soils

	MEPDG model $M_R(psi) = K_1 P_a \left(\theta / P_a\right)^{K_2} \left(\tau_{oct}/P_a + 1\right)^{K_3}$				
Sample I.D	K_1	K_2	K_3	R-sqr	SEE
Lee/Select 1(A-6)/1	1,411.413	0.193	-1.032	0.982	0.011
Lee/Select 1(A-6)/2	1,331.978	0.241	-1.051	0.991	0.009
Lee/Select 2(A-7-6)/1	1,144.396	0.154	-0.652	0.968	0.010
Lee/Select 2(A-7-6)/2	1,285.556	0.155	-0.562	0.985	0.007

CONCLUSIONS AND RECOMMENDATIONS

This research report presented the results of a comprehensive study on the characterization of unbound materials in support of the Mechanistic-Empirical Pavement Design Guide (MEPDG) implementation in Iowa. The primary objective of this research project was to develop a laboratory study for evaluating the unbound materials commonly used in Iowa using the Iowa DOT servo-hydraulic machine system and establishing a database of MEPDG input values for three analysis levels. This was achieved by carrying out a detailed laboratory test program on common Iowa unbound materials. The program included tests to evaluate basic materials physical properties, design of the repeated load triaxial test protocols using Iowa DOT equipment, and repeated load triaxial tests to determine the resilient modulus (M_R) values. M_R results obtained from repeated load triaxial test were used to establish the MEPDG input parameter values for Iowa condition including the resilient modulus model coefficients for level 1 analysis, the unbound material properties values correlated to resilient modulus for level 2 analysis, and the typical resilient modulus values for level 3 analysis.

Based on the results of this research, the following conclusions are drawn:

- The Iowa DOT servo-hydraulic equipment can be applied to a laboratory M_R test protocol (AASHTO T307) to determine the resilient modulus of unbound materials.
- The results of the repeated load triaxial test on the investigated Iowa unbound materials provide resilient modulus database that can be utilized to estimate MEPDG input parameters values for level 3 analysis.
- Typical representative M_R values for level 3 analysis are about 10,000 psi (ranging from 7,000 to 13,000 psi) for select, 7,500 psi (ranging from 6,000 to 9,000 psi) for class 10 (suitable) and 8,000 psi (ranging from 6,500 to 10,000 psi) for unsuitable soils. Typical representative M_R value for the investigated aggregate with 10% moisture content is about 35,000 psi (ranging from 15,000 to 55,000 psi). However, it should be noted that these values can significantly vary under different stress and moisture conditions.
- Iowa soils classified under select type but sampled at different geographical locations may exhibit different resilient properties.

Based on the results of this research, the following recommendations are made:

- The MEPDG input parameter database developed in this study can be used when designing low volume roads in the absence of any basic soil testing.
- Level 2 analysis is recommended with the use of M_R values in MEPDG because the repeated load triaxial test for level 1 is complicated, time consuming, expensive, and requires sophisticated equipment and skilled operators.
- Further research is needed to expand the M_R database to accommodate a variety of Iowa unbound materials.
- Further research is needed to explore the differences between field measured and laboratory measured resilient modulus of Iowa unbound materials.
- Further research is needed to develop correlations between the physical properties of Iowa soils and the corresponding M_R values. Such correlations would greatly help design engineers to quickly determine the M_R value of an Iowa soil based on the physical properties of the soil. Development of such correlations would also lead to great economic savings for the Iowa DOT.

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