BURNS COOLEY DENNIS, INC.
GEOTECHNICAL AND MATERIALS ENGINEERING CONSULTANTS

Summary of Lessons Learned from the MDOT MEPDG Materials Library Study

Prepared for
Mississippi Department of Transportation

State Study No. 224
Project No. 105803 147000

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From 2004 to 2009, Burns Cooley Dennis, Inc. (BCD) participated in two important research studies designed to populate the materials library for implementation of the new Mechanistic-Empirical pavement design method (MEPDG) in Mississippi. The purpose of this report was to capture the experiences BCD obtained with the resilient modulus test during the conduct of these important studies. Observations made during the course of testing the various materials for developing the materials library for typical Mississippi materials were documented during Task 1. Observations about sample preparation, test methods and potential test method improvements were deemed important. The second task was designed to provide discussion on the materials that were selected within the two studies. In order to populate the materials library, it was deemed important to encompass the extremes of material properties found in Mississippi. However, whenever a finite amount of time and funding are available for a project, all possible materials could not be fully characterized. Also included within this task was a critical review of test results. Task 3 was designed to discuss any differences in Mississippi resilient modulus test results and typical national results for similar materials. If differences were found, discussion on why the differences occurred was also to be provided. In order to assist MDOT and other pavement designers in Mississippi transition to the MEPDG, tables for typical resilient modulus values for AASHTO, USCS and MDOT classifications were developed within the final task.</td></tr>
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NOTICE

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1.0 INTRODUCTION AND OBJECTIVE

From 2004 to 2009, Burns Cooley Dennis, Inc. (BCD) participated in two important research projects funded by the Mississippi Department of Transportation (MDOT). The first study, MDOT State Study (SS)-170, "Implementation of MEPDG for MDOT," was initiated in 2004. For this study, BCD was a subcontractor to Applied Research Associates, Inc. (ARA). The purpose of BCD's portion of SS-170 was to provide the laboratory data required to assist in developing a materials library of typical roadway subgrade soils, granular materials and chemically stabilized materials used in Mississippi roadway construction.

Materials tested during SS-170 were selected in collaboration with MDOT and ARA personnel. Classification testing was performed on each of the selected materials by either MDOT or BCD. Additionally, moisture-density testing (Standard Proctor tests) were also conducted (by BCD) for each material to determine target density and moisture content for test specimens. At the time SS-170 began, MDOT required subgrade soils be compacted in the field to 95 percent of the maximum dry density and at optimum moisture content as determined by a standard compactive effort. Subgrade soils within the top 3 ft of the pavement structure, defined as design soils, must be compacted to 98 percent of a standard compactive effort and at optimum moisture content. Density requirements for chemically stabilized materials vary. Lime stabilized subgrade must average 95 percent of standard maximum dry density while cement and lime/fly ash stabilized materials must average 98 percent.

A total of 34 subgrade materials were tested as part of SS-170. As required per the new Mechanistic-Empirical Pavement Design Guide (MEPDG), the resilient modulus test was utilized to characterize the subgrade materials. Based upon mutual agreement between MDOT, ARA and BCD prior to initiating the project, it was decided that all subgrade materials would be tested at 95 percent of maximum dry density and at optimum moisture content in accordance with the resilient modulus procedure outlined in National Cooperative Highway Research Program (NCHRP) Research Results Digest 285 (or sometimes called the 1-28A method) (NCHRP, 2004).

For unbound granular base/subbase category, a total of 13 typical materials were selected for inclusion in the study. Test specimens were compacted to between 95 and 99 percent of standard Proctor maximum dry density at optimum moisture content. Again, the 1-28A method was utilized for determining the resilient modulus.

Three chemical stabilization techniques were included within the study: lime, cement and lime/fly ash. These chemical stabilization techniques are typical for roadway construction in Mississippi. At the onset of the study, there was discussion on how to conduct the experimental design associated with the testing of the chemically stabilized materials. One option was to conduct specific mix designs for each material in accordance with the appropriate MDOT design procedure. The second option was to select a typical application rate for the given chemical stabilization technique. One advantage of this second option was that more materials could be included within the experimental plan. Because of this advantage and the finite amount of funds, the second option was selected. Lime treated materials were tested to determine the resilient modulus in accordance with the 1-28A method. For the cement and lime/fly ash stabilized materials, an unconfined compression test was utilized to characterize the materials.

The second important research study funded by MDOT was SS-205 which began in 2008 and was completed in 2009 and was entitled, "Chemically Stabilized Soils." This study arose through conversations with MDOT about the influence of density and moisture content on the strength of chemically stabilized materials. Therefore, the objective of this study was to conduct laboratory evaluations to quantify the effects of compaction (density level) and moisture conditions on the strength of chemically stabilized subgrade and subbase/base materials.

SS-205 included two phases of research. Within the first phase, 14 combinations of various Mississippi subgrade materials and stabilization techniques were tested according to ASTM D1883, "Standard Test Method for CBR (California Bearing Ratio) of Laboratory Compacted Soils," and Mississippi Test (MT)-26, "Compressive Strength of Soil Cement Cylinders and Cores" as shown in Table 1. The selected materials were tested at various compaction levels (designated as low, standard, and high) at optimum moisture content and at 3 percent above optimum. The compaction levels selected were based upon consistent compactive efforts. Compactive efforts of 10, 25 and 40 or 56 blows per lift with a standard hammer were used to produce the low, standard and high compaction levels (ranged from about 90% to 105% of standard Proctor density). The virgin materials were also tested to determine the CBR at similar density and moisture content levels.

Table 1: Soil and Stabilized Soil Combinations Investigated in this Research

Material No.	Soil Type		Virgin	Chemical Treatment		
	ASTM	AASHTO		Lime	Lime-Fly Ash	Cement
1	CL	A-7-6	X	X	X	--
2	CL	A-6	X	X	X	X
3	ML	A-4	X	--	X	X
4	CL	A-4	X	X	X	X
5	SM	A-2-4	X	--	--	X
6	SM	A-2-4	X	--	--	X
7	SC	A-2-4	X	--	X	X

The second phase of SS-205 involved testing the same materials (14 stabilized and 7 virgin materials) in accordance with the protocols within the MEPDG for the respective material (Table 2). These tests were also conducted at the low, standard and high compaction levels at optimum and optimum plus 3 percent moisture contents. The MEPDG recommends the resilient modulus for lime stabilized materials and unconfined compression testing for cement and lime/fly ash stabilized materials. Elastic modulus, the required input within the MEPDG, is calculated from the unconfined compressive test results for cement and lime/fly ash stabilized materials.

Table 2: MEPDG Protocol for Strength Testing of Soils and Stabilized Soils

Virgin Material No.	Classifications		Stabilization Method	MEDPG Protocol
	AASHTO	USCS		
1	A-7-6 (23)	CL	--	Resilient Modulus
2	A-6 (17)	CL	--	Resilient Modulus
3	A-4 (1)	ML	--	Resilient Modulus
4	A-4 (5)	CL	--	Resilient Modulus
5	A-2-4 (0)	SM	--	Resilient Modulus
6	A-2-4 (0)	SM	--	Resilient Modulus
7	A-2-4 (0)	SC	--	Resilient Modulus
1	A-7-6 (23)	CL	Lime	Resilient Modulus
2	A-6 (17)	CL	Lime	Resilient Modulus
4	A-4 (5)	CL	Lime	Resilient Modulus
1	A-7-6 (23)	CL	LFA	Unconfined Compression
2	A-6 (17)	CL	LFA	Unconfined Compression
3	A-4 (1)	ML	LFA	Unconfined Compression
4	A-4 (5)	CL	LFA	Unconfined Compression
7	A-2-4 (0)	SC	LFA	Unconfined Compression
2	A-6 (17)	CL	Cement	Unconfined Compression
3	A-4 (1)	ML	Cement	Unconfined Compression
4	A-4 (5)	CL	Cement	Unconfined Compression
5	A-2-4 (0)	SM	Cement	Unconfined Compression
6	A-2-4 (0)	SM	Cement	Unconfined Compression
7	A-2-4 (0)	SC	Cement	Unconfined Compression

*LFA - Lime-Fly Ash

During the conduct of these two research projects, valuable practical experience regarding the testing of subgrade and granular materials using the resilient modulus test was obtained. The purpose of this report is to capture these experiences and document observations about the test results and test method.

2.0 SCOPE

During conversations with MDOT for the development of this project, four primary issues were identified as far as being able to capture the experiences of the two research projects. Each of these issues was identified as a specific task within this research. Following describes the four issues.

2.1 Task 1 – Observations Made During Resilient Modulus Testing

Observations made during the course of testing the various materials for developing the materials library for typical Mississippi materials were to be documented during Task 1. Observations about sample preparation, test methods and potential test method improvements were deemed important.

2.2 Task 2 – Critical Review of Selected Materials and Results

This task was designed to provide discussion on the materials that were selected within the two studies. In order to populate the materials library, it was deemed important to encompass the extremes of material properties found in Mississippi. However, whenever a finite amount of time and funding are available for a project, all possible materials could not be fully characterized. Also included within this task was a critical review of test results. Although three replicate specimens were tested for each individual test result, some test results did not have expected values. Test results for the individual replicates for all materials tested can be found within the final reports for SS-170 and SS-205.

2.3 Task 3 – Differences Between Mississippi and National Typical Values

This task was designed to discuss any differences in Mississippi resilient modulus test results and typical national results for similar materials. If differences were found, discussion on why the differences occurred was also to be provided.

2.4 Task 4 – Estimates of Resilient Modulus for Typical Materials

Following a research study conducted for MDOT in 1983, Teng and Crawley (1983) provided tables of estimated CBR values for typical Mississippi materials. This table has been used for pavement structural designs by MDOT and consultants for over 20 years. In order to assist MDOT and other pavement designers in Mississippi transition to the MEPDG, MDOT desired a similar table for resilient modulus values.

3.0 OBSERVATIONS MADE DURING RESILIENT MODULUS TESTING

This section of the report provides observations about the resilient modulus test method utilized within SS-170 and SS-205. In portions of this section opinions and/or concerns with the test method are also highlighted. Again, the 1-28A test method was utilized for all resilient modulus testing. An Interlaken Soil and Asphalt Test System was used for all testing (Figure 1). BCD was one of the first users of this system to have the

1-28A pre-programmed software for conducting the resilient modulus test method. The triaxial cell utilized during all testing was 11 in. in diameter (Figure 2) which allowed easy instrumentation of 4 in. and 6 in. diameter test specimens. LVDT's utilized during testing were mounted on the top and bottom platens within the cell. The large diameter of the cell allowed easy access for instrumenting the samples (also shown within Figure 2). The only problem, though only slight, with the large diameter triaxial cell was the weight of the cell. All work had to be conducted on the load platform of the test system. The following sections provide discussion about the test method.

Figure 1: Servo-Hydraulic Test Equipment

Figure 2: Triaxial Cell

3.1 Classification Testing

Each of the materials was classified according to AASHTO and the Unified Soil Classification System (USCS). In order to classify the soils, the Atterburg Limits were performed according to AASHTO T 90 "Determining the Plastic Limit and Plasticity Index of Soils." A sieve analysis was also performed on the materials according to the AASHTO T11 "Materials Finer than 75 μm (No. 200) Sieve in Mineral Aggregates by Washing" and AASHTO T 88 "Particle Size Analysis of Soils." The granular materials in SS-170 were classified and tested the same way except that the subbase/base materials were labeled with the appropriate MDOT Classification. The stabilized materials were classified based upon the virgin material.

Each material was also tested for their moisture-density relationship (Proctor) using Mississippi test methods to establish maximum dry density and optimum moisture content. A standard compactive effort is designated by MDOT. The coarse aggregate was scalped over a ½ inch sieve for Proctor testing as required by the test method. The calculation of the Proctor density curve was corrected to account for this scalped material.   Proctor testing was also performed on each of the stabilized materials. Results of classification and Proctor testing are presented in the respective SS-170 and SS-205 final reports.

3.2 Preparation of Test Specimens

The initial step in performing the resilient modulus test, like any other materials testing, is to collect a representative sample. Depending upon the properties of the material being tested, either a 4 in. or 6 in. diameter specimen was tested. For most subgrades, 4 in. diameter specimens where tested while 6 in. diameter specimens were utilized for the granular materials. Each 4 in. diameter specimen required about 7 to 8 lbs. of material. Three replicates were tested for each material. From a practical standpoint, a **<u>single full</u>** 5-gallon bucket of fine-grained subgrade materials was sufficient to provide enough material for typical classification testing, a standard Proctor test, and four to five resilient modulus test specimens (assuming one or two samples did not meet density or moisture content requirements). For materials that are tested using a 6 in. diameter specimen, **<u>two full</u>** 5-gallon buckets provided sufficient material.

Once the materials were obtained for testing, they were prepared using the recommendations of Annex A-1 of the 1-28A method with some minor modifications. Once received in the laboratory, all samples were air dried, generally under a fan. After air drying, the samples were processed. Next, all classification testing was conducted as was the Proctor test.

When preparing for the fabrication of resilient modulus test specimens, the moisture content of the air dried material was determined utilizing a microwave oven. After determining the moisture content of the material, the proper amount of water was added to the material and mixed into the material by hand. The loose material was then placed in a sealable plastic bag and stored overnight to mellow. The importance of allowing the materials to mellow overnight must be stated here; especially clayey fine-grained subgrade type materials and some granular materials. Clayey fine-grained materials are low permeability materials that require some time for the moisture content to equalize within the hand-mixed sample. If these materials are not allowed to mellow, in a closed plastic bag, some portions of the samples will have higher moisture contents than others. Though the literature may address this issue (a cursory review of literature did not), the influence of plasticity index (PI) and mellow time on the variability of resilient modulus test results would be an interesting research project. Simply from the conduct of SS-170 and SS-205, fine-grained materials with plasticity indexes (PIs) greater than, say, 15 to 20 percent should probably mellow for 48 hours.

At the beginning, BCD did try to test granular materials without the overnight storage in the sealed plastic bags because of the relatively low moisture contents required; however, this caused some variability issues. Many of the granular materials tested within the projects had some absorptive characteristics. By omitting the overnight storage, all of the water did not have time to be absorbed. Therefore, the samples actually had too much free water. If a replicate sample was allowed to sit longer than others prior to compaction, then this sample would have less free water than those aggregates that had more time to absorb water. This led to variability in the densities of compacted specimens. Once this observation came to light, BCD began to store the granular materials overnight. Because of this observation, some consideration should be given to how absorptive granular materials are treated during Proctor testing as granular materials in the field will generally not lose their internal moisture like laboratory dried samples. Cooley et al (2007) noted differences when testing crushed concrete which is generally a relatively absorptive material.

Lime stabilized specimens were allowed to mellow for four days after the samples were compacted. Some samples were tested after a single day of mellowing and the differences in stiffness were significant. Lime stabilized samples allowed to mellow for four days had significantly higher stiffnesses than those that only mellowed for one day. The four day mellow time was selected because of MDOT's design procedure for lime-stabilized soils. The four days corresponds to the four day soak period used for California Bearing Ratio (CBR) testing. A question that must be raised is whether the four day mellowing period for compacted lime-stabilized subgrade materials is correct for developing the materials library within the MEPDG for Mississippi.

After storage of the samples in the sealed bags overnight and prior to fabricating the test specimens, the moisture content of each replicate was verified using a microwave oven. Subgrade samples that were to be compacted in the 4 in. by 8 in. molds were "bulk-batched." In other words, enough material for the three replicates were combined and handled as one sample. This methodology seemed to minimize variability. The granular materials that were to be compacted in 6 in. by 12 in. molds were handled individually because of the large volume of material required, i.e., each replicate was considered a single sample. While handling all samples, a wet burlap cloth was placed over the sample container to prevent moisture loss.

Figure A-1 within the 1-28A method is a flowchart describing the resilient modulus test method. A portion of this flow chart describes the method by which samples must be compacted to create test specimens. The flowchart contains two criteria which determines the required method of specimen compaction. First, samples with a maximum particle size of 3/8 in. or greater are to be compacted utilizing an impact or vibratory compaction effort. Compaction by impact entails the use of a typical Proctor hammer. Vibratory compaction entails a rotary or demolition type hammer. For most of the granular materials tested in the two projects, vibratory compaction was utilized; however, for some problematic materials an impact hammer had to be used. The vibratory compaction effort was selected in an effort to minimize aggregate breakdown. Figure 3 shows the vibratory compactor used to compact most of the granular samples.

Figure 3: Vibratory Hammer Utilized for Compaction of Test Specimens

A second criteria used for materials having a maximum particle size less than 3/8 in. is the percentage of material passing the No. 200 sieve. Materials with less than 10 percent passing the No. 200 sieve are to be compacted using a vibratory compactor. Materials with more than 10 percent passing the No. 200 sieve can be compacted using either an impact or kneading compactive effort. For all materials meeting this latter category, an impact hammer was used to compact the specimens.

No particular problems were encountered during the compaction of the various materials. There were some instances, as noted above, in which it was difficult to achieve the target density for some granular materials utilizing the vibratory compaction effort. In these instances, an impact hammer was used. Generally, the sandy materials were the easiest to compact to the target density and the coarser granular materials were the most difficult. No particular problems were encountered when preparing the lime stabilized subgrades.

The MEPDG allows the use of the 1-28A procedure or AASHTO T 307 “Determining the Resilient Modulus of Soil and Aggregate Materials” test standard. These two methods are generally the same. One exception is the tolerances of moisture and density between replicate samples. AASHTO T 307 allows a tolerance of 3 percent on density and 1 percent for moisture. The 1 percent density requirement and 0.5 percent moisture requirement contained within the 1-28A method were very difficult to achieve at times. The moisture tolerances on four subgrade samples (sandy materials with low minus No. 200 contents) and one granular material were increased to the 1 percent tolerance level due to the difficulty of achieving the 0.5percent tolerance. In these instances, the low minus No. 200 fractions resulted in some of the water added to reach the appropriate moisture content draining to the bottom of the sample.

3.3 Testing

The methods and test sequences of 1-28A were followed during all testing. No particular problems were encountered with the test procedures. The only item worth mentioning relative to the testing is the calibration of the servo-hydraulic test system. BCD did have the manufacturer of the equipment check the calibration of the system several times during the project (it should be noted that the total length of time for the two projects was five years). However, another equipment check that was employed was obtaining a 4 in diameter by 8 in height hard solid rubber sample (Figure 4). This sample was placed in the triaxial cell and set up like a typical resilient modulus test and subjected to test sequences. This allowed a practical routine check of the equipment. When not in use, this hard rubber sample was stored in a cooling cabinet out of the reach of sunlight.

A slight deviation to the test set up was previously mentioned. The 1-28A method states that axial deformation should be measured using an optical extensometer, non-contact sensors or clamps attached to the specimen. For the two projects, spring-loaded LVDTs were mounted platen to platen (Figure 2) to measure axial deformation. No issues were perceived with this set up.

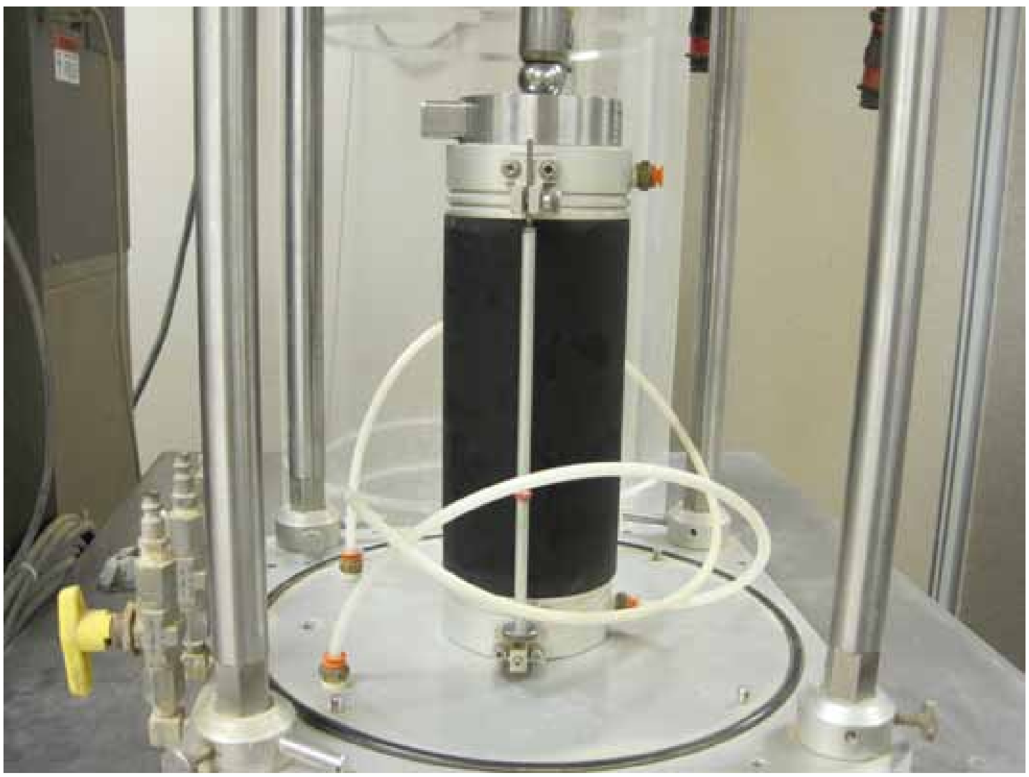

Figure 4: Hard Rubber Specimen Utilized to Check Equipment Calibration

4.0 CRITICAL REVIEW OF SELECTED MATERIALS AND RESULTS

This chapter provides discussion on the selected materials and test results from SS-170 and SS-205. The first part of this chapter discusses test results and the second part provides a critical review of the materials selected during the research.

4.1 Discussion on Test Results

The required inputs developed for MDOT's materials library during SS-170 were the regression coefficients of the constitutive model shown in Equation 1. These k-coefficients were developed for each replicate of each material tested. Individual k-coefficients for each material are provided within the final reports for SS-170 and SS-205.

$$M_R = k_1 * p_a * \left(\frac{\theta}{p_a}\right)^{k_2} * \left(\frac{\tau_{oct}}{p_a} + 1\right)^{k_3}$$ **Equation 1**

Where:

M_R = Resilient Modulus

θ = Bulk Stress:

$$\theta = \sigma_1 + \sigma_2 + \sigma_3$$

τ_{oct} = Octahedral Shear Stress:

$$\tau_{oct} = \frac{1}{3} * \sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2 + (\sigma_2 - \sigma_3)^2}$$

$\sigma_1, \sigma_2, \sigma_3$ = Principal Stresses

p_a =atmospheric pressure (14.7 psi)

k_i = regression constants

In order to determine the k-coefficients, an Excel spreadsheet was developed. Within this spreadsheet, the raw resilient modulus data for each stress state were sorted by test sequence (as defined in 1-28A) number. A nonlinear optimization function called Solver was then utilized within Excel to select the k-coefficients that minimized the standard error of the estimate between the measured resilient modulus and the estimated resilient modulus calculated using Equation 1. Figure 5 presents a plot of the predicted versus measured resilient modulus for each replicate tested within SS-170. As shown in this figure, Equation 1 was successful in developing predicted resilient modulus values from the measured results.

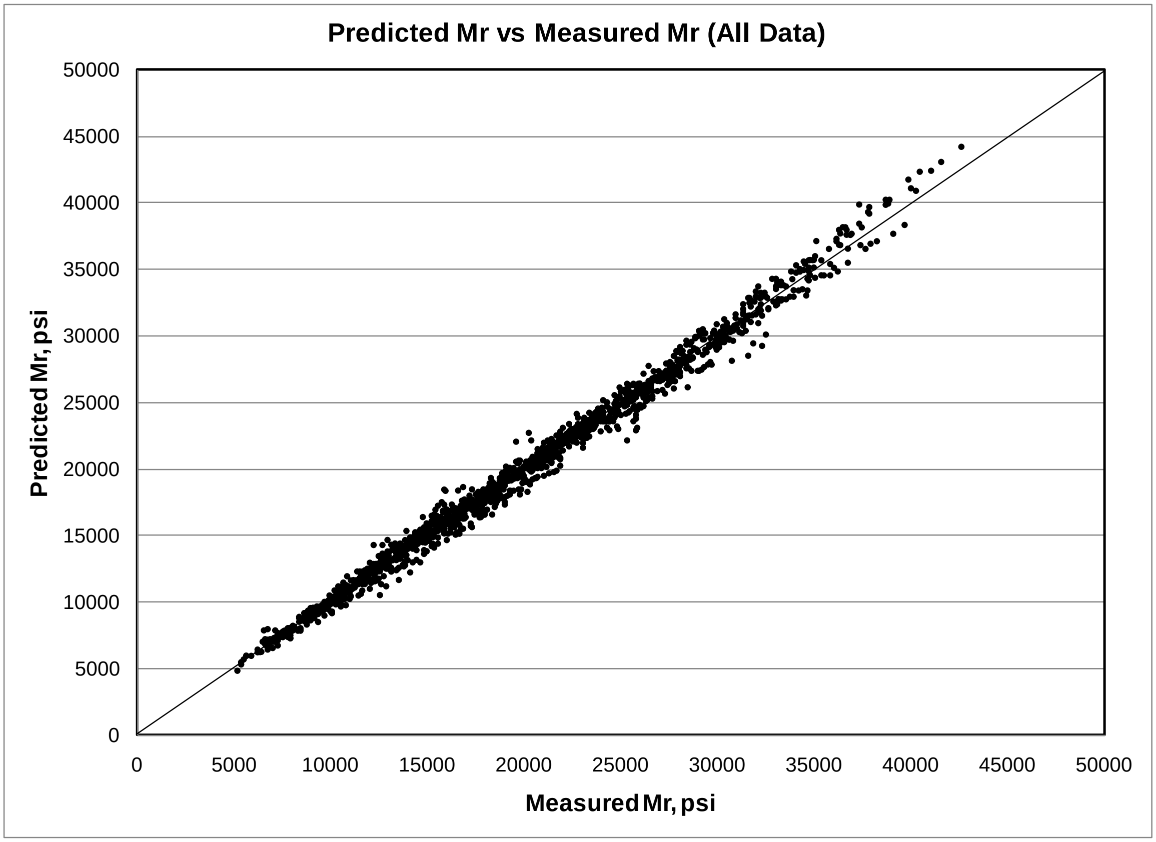

Figure 5: Predicted versus Measured Resilient Modulus for All Data

During the course of the studies, several data checks were utilized to evaluate the regressed k-coefficients and the reasonableness of the test results. The first check was to evaluate the coefficient of determination (R^2) for the predicted resilient modulus versus the measured resilient modulus for each individual replicate. Within Chapter 2 of Part 2, “Materials Characterization,” of the MEPDG software user’s guide (Version 1.100), it states that the R^2 for the fitted constitutive model should be 0.90 or above. Figures 6 and 7 present the average R^2 values for each subgrade soil type grouped by AASHTO and Unified Soil Classification System (USCS) classifications, respectively. As shown in the figures, the average R^2 values were all well above 0.95. The average R^2 value for all individual replicates was above 0.97.

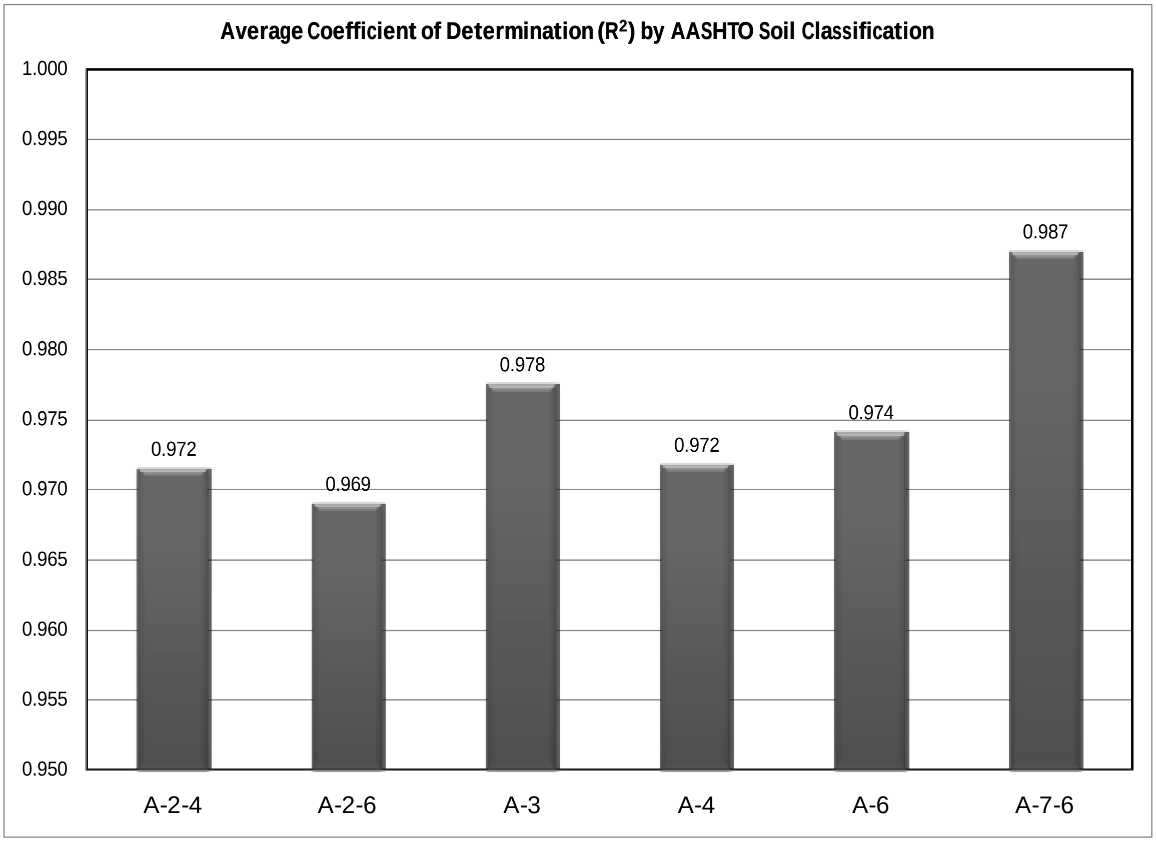

Figure 6: Average Coefficient of Determination by AASHTO Soil Classification

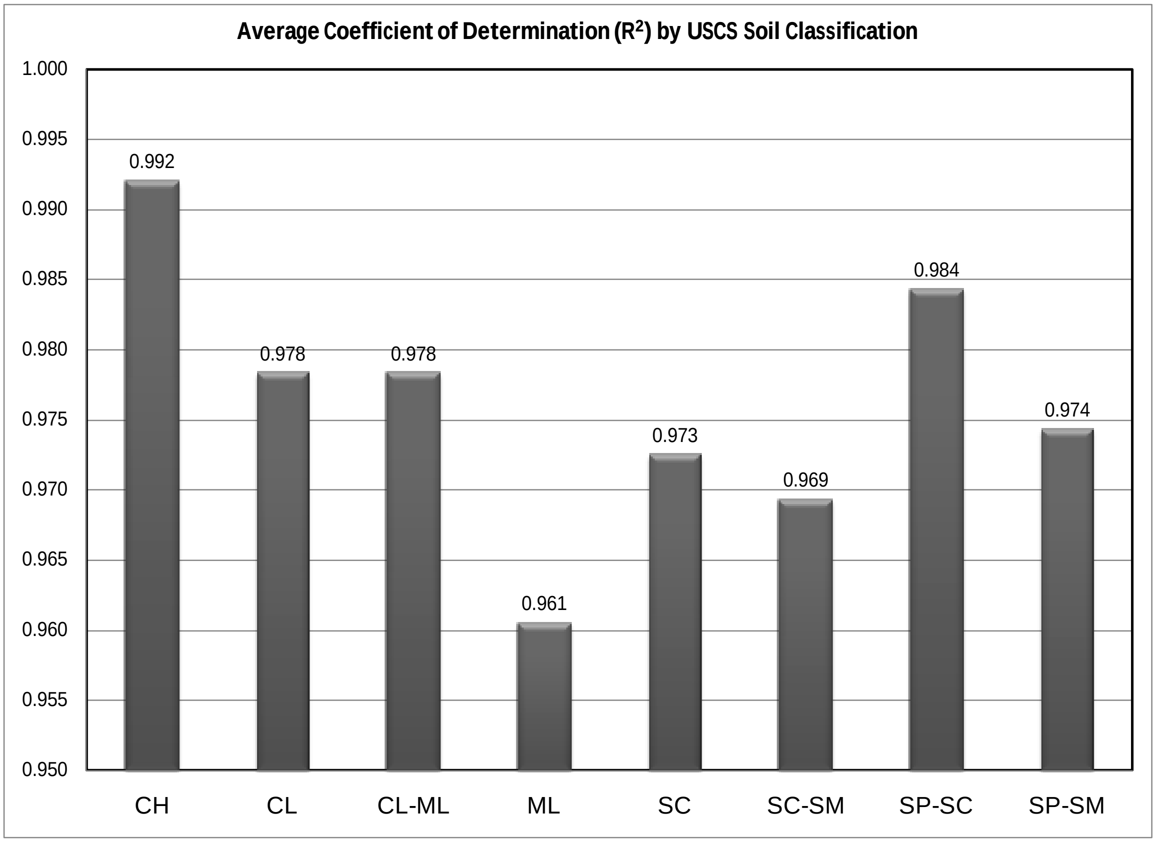

Figure 7: Average Coefficient of Determination by USCS Soil Classification

Another data check utilized to evaluate reasonableness of individual test results was to calculate the standard deviation and coefficient of variation for the three replicates of a given material. For each replicate of a given material, a resilient modulus value was calculated based upon the regressed k-coefficients. The stress states used in the calculations were: 1) a confining stress of 2 psi and cyclic stress of 6 psi for subgrades and 2) a confining stress of 5 psi and cyclic stress of 15 psi for aggregate bases/subbases. These stress states are cited in the 1-28A document for reporting resilient modulus results. Using the calculated resilient modulus for each replicate at the appropriate stress state, the average, standard deviation and coefficient of variation were calculated. Figures 8 and 9 present the calculated coefficients of variation for subgrade samples classified by the AASHTO and USCS methods, respectively.

In most cases, Figures 8 and 9 show that the coefficient of variation within replicates were below 10 percent. There are instances where the values are above 10 percent. These instances occurred when the average calculated resilient modulus was relatively low. As an example, the highest coefficient of variation that was allowed was 17.6 percent for an A-2-6 (SP-SC) material in which the three calculated resilient modulus values were 6340, 8910, and 8579 psi. This was the only SP-SC material tested.

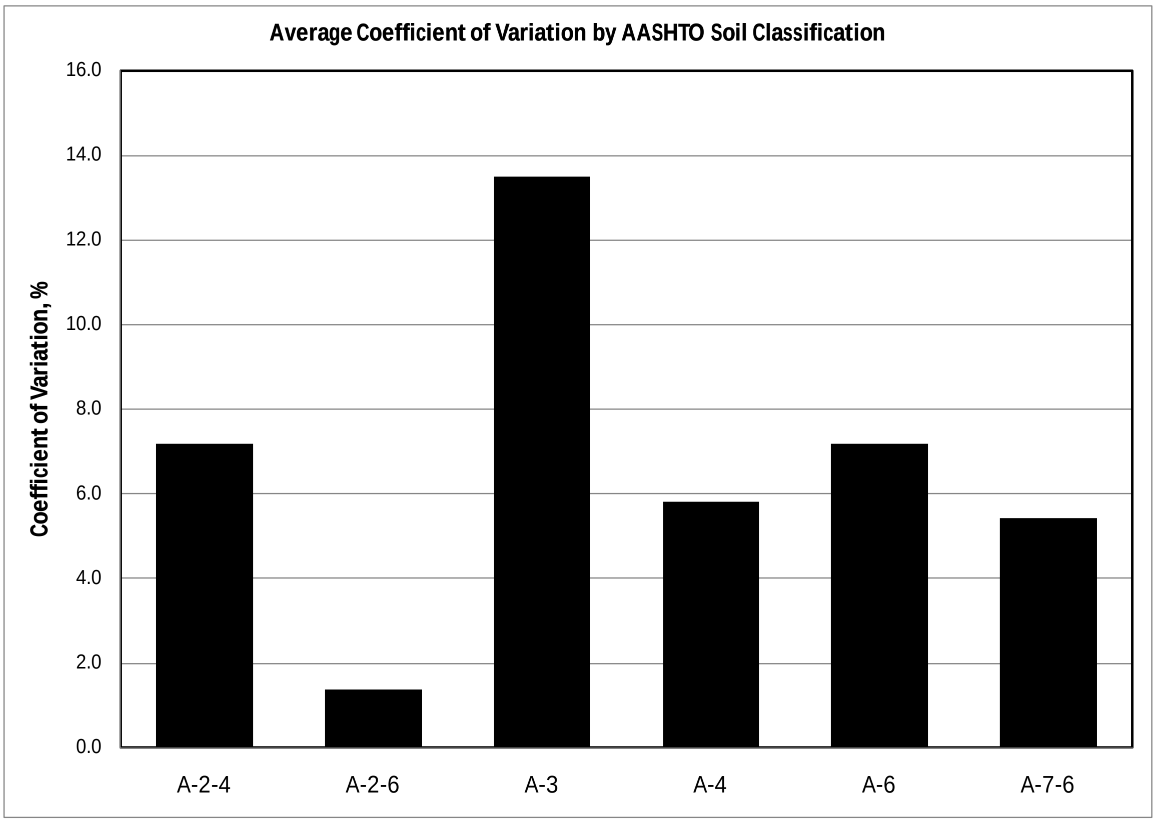

Figure 8: Average Coefficients of Variation of Replicates by AASHTO Classification

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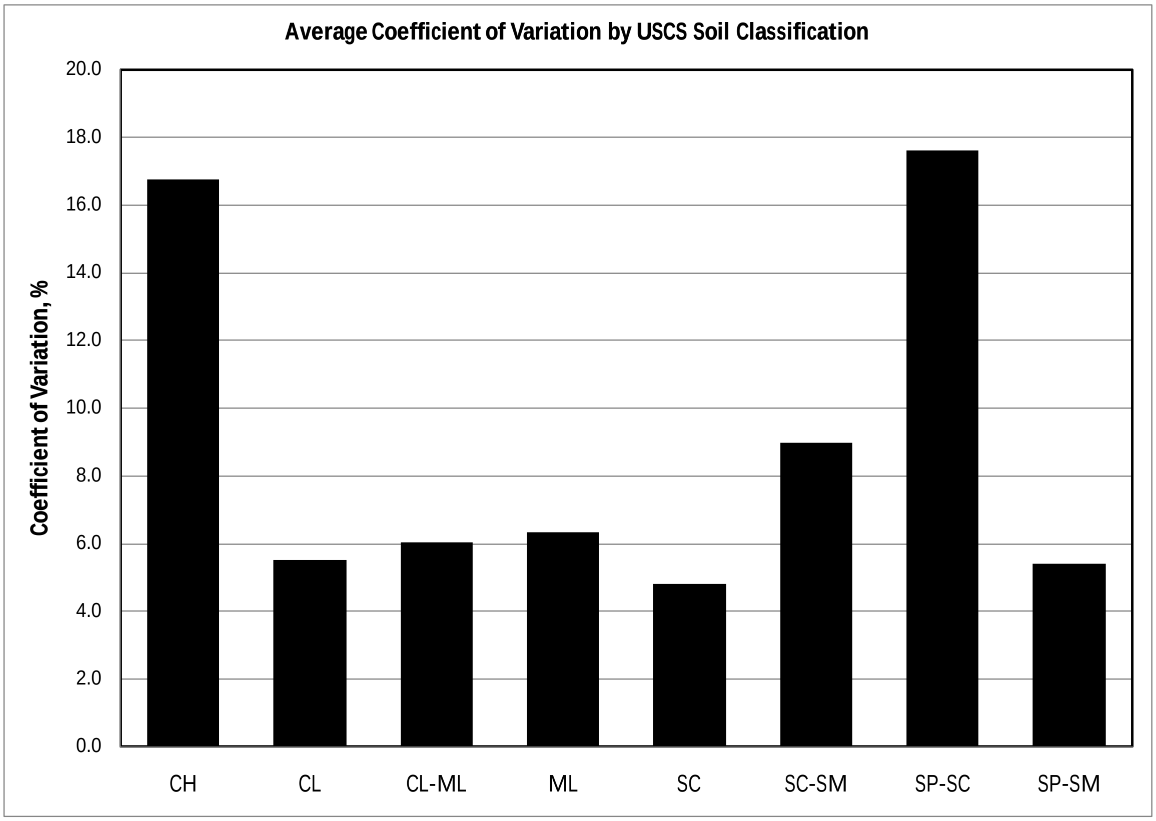

Figure 9: Average Coefficients of Variation of Replicates by USCS Classification

4.2 Critical Review of Test Results

MDOT has long used the California Bearing Ratio (CBR) test to characterize the strength of subgrade and granular materials to be used in pavement structures. As such, the experiences of the authors used to conduct the critical review of the test results are based upon the CBR testing of many native materials.

In order to quickly conduct a critical review of the resilient modulus test results, two plots were prepared. These plots contain the average resilient modulus results for the subgrade materials by material type versus bulk stress. Referring back to Equation 1, the bulk stress is the sum of principal stresses. Because resilient modulus values are dependent upon the stress state tested, these plots allowed evaluation of the test results at various stress states. Figures 10 and 11 present the resilient modulus test results versus bulk stress by AASHTO classification and by USCS classification, respectively.

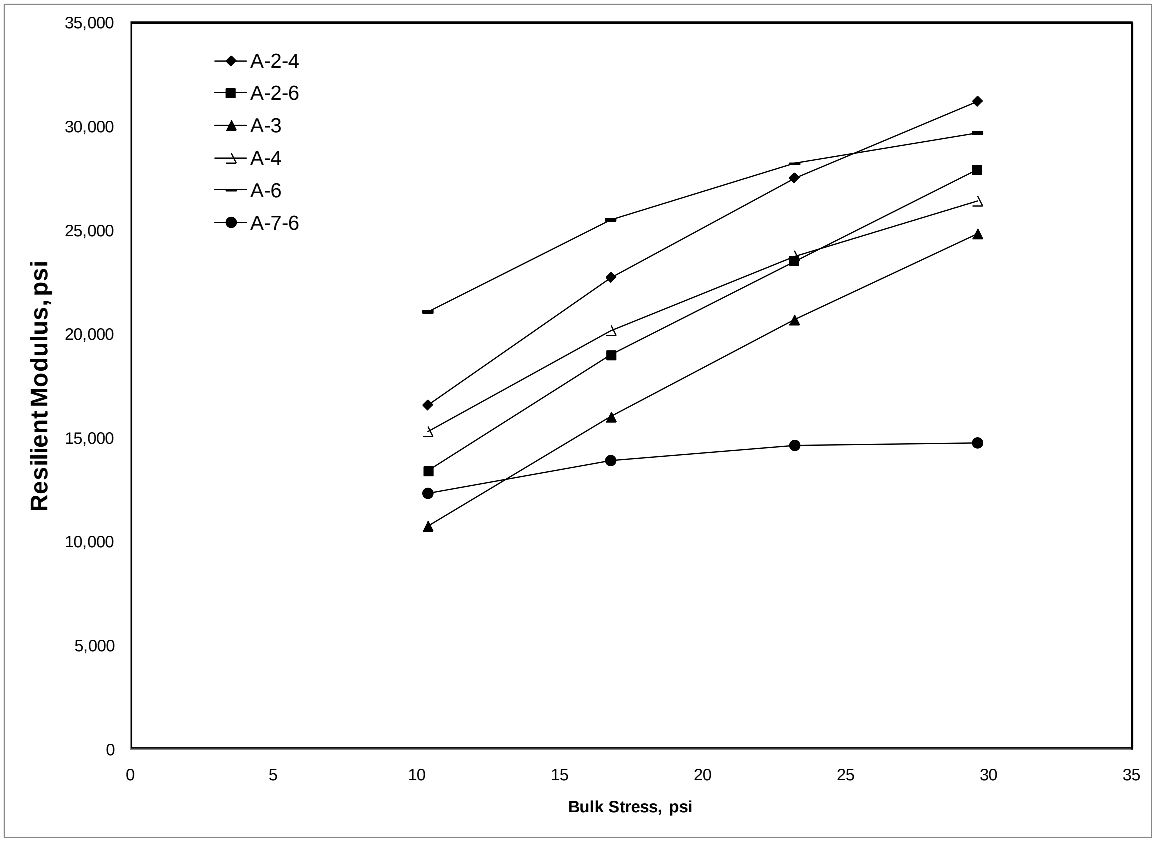

Figure 10: Relationship Between Resilient Modulus and Bulk Stress - AASHTO Classifications

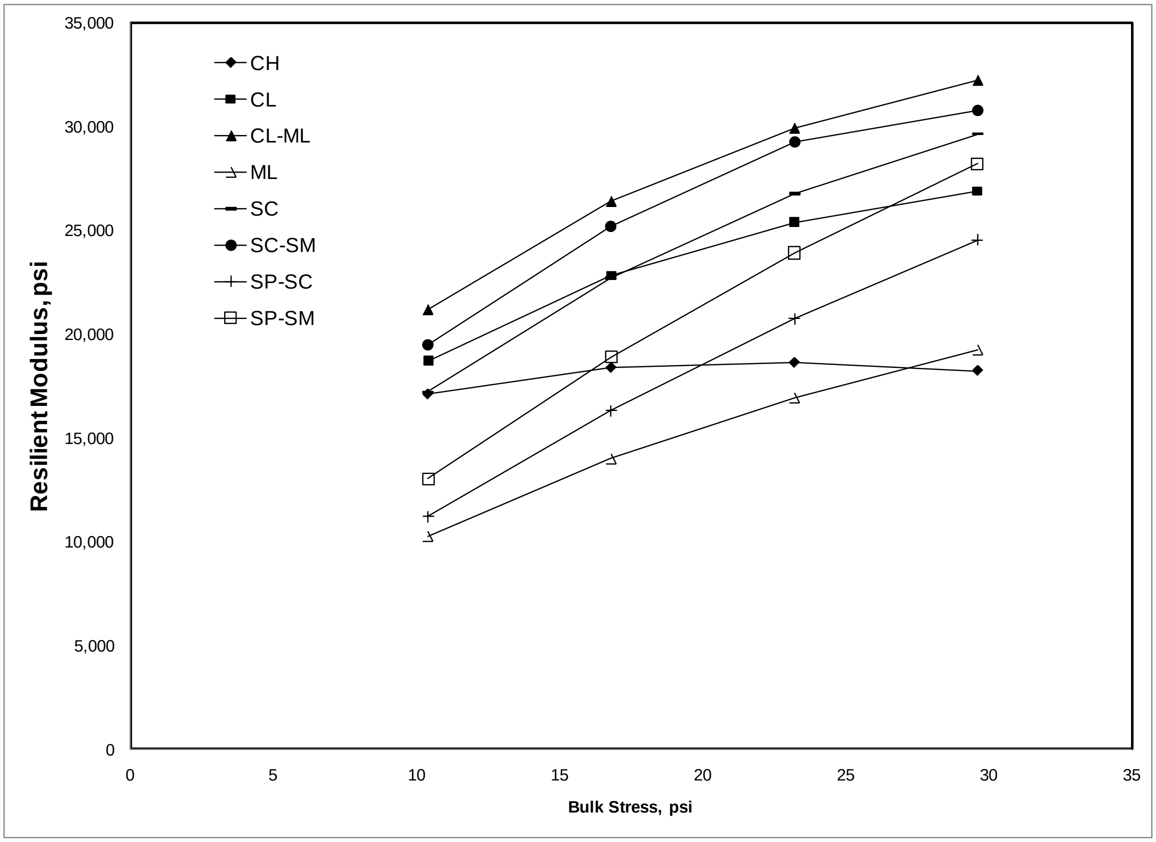

Figure 11: Relationship Between Resilient Modulus and Bulk Stress - USCS Classification

The first observation about the test results is that at lower stress states, the fat clays (A-7-6 or CH) did not have a resilient modulus slightly less than the materials containing sands (A-2-4, A-2-6, A-3, SP-SC, or SP-SM). When testing these materials using the CBR protocols, the clays generally have a much lower CBR ratio than the sandier materials. Therefore, these results were somewhat surprising. However, observation of the two figures shows that the relationship between the resilient modulus and bulk stress for the clay materials is relatively flat. At higher bulk stresses, the sandier materials have a much higher resilient modulus than the clays. It should be stated, however, that there are algorithms within the MEPDG to characterize the strength loss of clays (as well as all subgrade materials) due to seasonal effects.

Another observation that was unexpected concerned the resilient modulus results for the granular base/subbase materials. Figure 12 shows the relationship between resilient modulus and bulk stress for two samples tested during the subgrade portion of the study (labeled A-2-4 and A-2-6) and three materials tested during the granular base/subbase portion of the study (labeled LMS ¾" Down, LMS 610 and LMS 825-B). All three of the base/subbase materials were classified as A-1-a within the AASHTO classification system. It was anticipated that the three granular materials would have a much higher resilient modulus than the other materials based upon history with CBR testing; however, this was not the case. At higher stress states, the LMS 825-B material did have a much higher resilient modulus though.

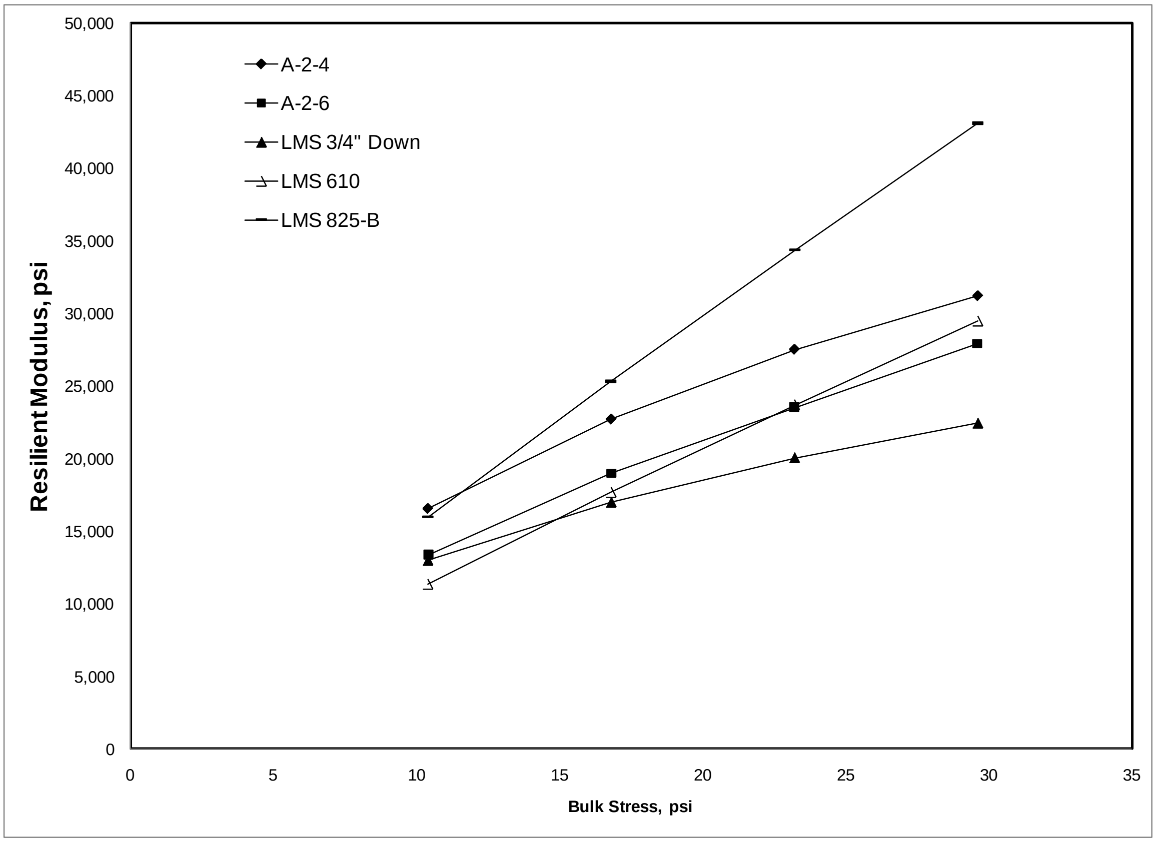

Figure 12: Resilient Modulus versus Bulk Stress for Granular Materials

Another issue considered here within the critical review of the test results is the relative number of samples tested for each material classification. As stated at the beginning of this report, only 34 subgrade type samples were tested. These 34 subgrade materials were sampled from throughout the state in order to try and characterize the wide range of materials encountered within Mississippi. A total of 21 of the 34 materials were classified as either an A-4 or A-6 material. This large proportion of materials does reflect that these two material types are likely the most commonly encountered subgrade materials within the state. Only two of the selected materials were classified as an A-3. Five of the tested materials were classified as an A-2-4 while three were classified as an A-2-6. The remaining three samples were classified as an A-7-6. Additional A-3, A-2-6, A-2-4 and A-7-6 materials should be tested over time to provide a better indication of the stiffness characteristics of these classification types.

Figure 13 presents a plot of average subgrade resilient modulus value by AASHTO classification. The stress state used to calculate resilient modulus values was a confining stress of 2 psi and a cyclic stress of 6 psi. Also included with each average are error bars reflecting one standard deviation in resilient modulus results. As can be seen by the error bars, one standard deviation encompasses a wide range of resilient modulus values. For instance, the average resilient modulus for the subgrades classified as an A-6 is 11,610 psi. The range of results within one standard deviation suggests a wide range of test results for this classification. Figure 13 suggests that additional testing may be required, at least for some of the classifications in which limited samples were tested.

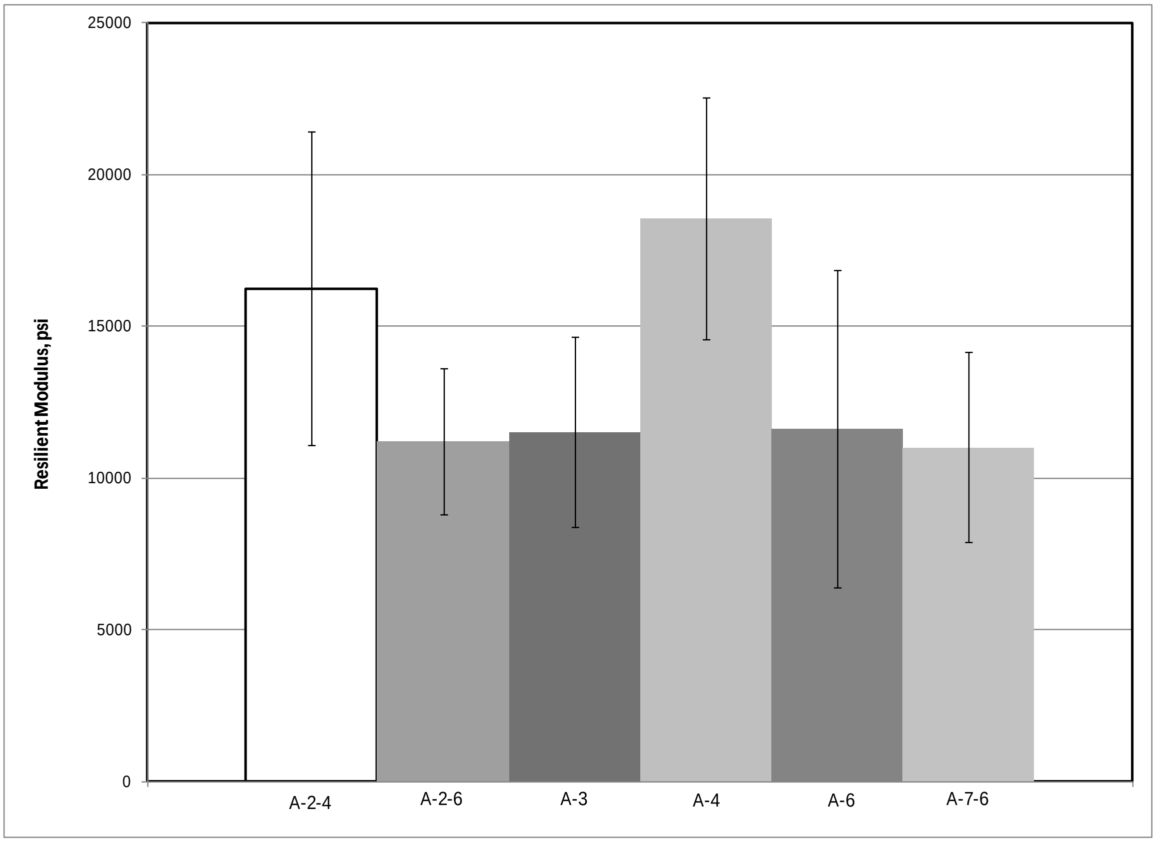

Figure 13: Average Resilient Modulus Values With One Standard Deviation Error Bars

Table 3 presents the MDOT, AASHTO, and USCS classifications of the granular base/subbase materials tested during SS-170. As shown in this table, only one to two materials were tested per Class of MDOT classification. In some cases, different groups within a Class were tested. Because the materials library should encompass the typical materials within the State, additional testing may be warranted. The additional testing would indicate whether a single resilient modulus value is representative of a given Class and Group material, or whether more data is needed to better characterize these materials.

Table 3: Classification of Granular Base/Subbase Materials

Granular Sample No.	Classifications		
	MDOT	AASHTO	USCS
1	Class 1 Group A	A-1-a	SP-SM
2	Class 3 Group A	A-1-b	SP-SM
3	Class 4 Group B	A-1-b	SP-SM
4	Class 5 Group C	A-1-a	SP-SM
5	Class 5 Group A	A-2-4	SP-SM
6	Class 9 Group A	A-4	SP-SM
7	Class 9 Group C	A-2-4	SC
8	Class 10 Group B	A-4	SC
9	Class 10 Group E	A-2-4	CL
10	LMS ¾ down	A-4	GW
11	LMS 610	A-1-a	GW
12	LMS 825-B	A-1-a	GW
13	Crushed Concrete 825-B	A-1-a	GW

A more glaring need is additional testing of the granular crushed stone base materials, LMS ¾ in. down, LMS No. 610 and LMS 825-B. Only single tests were conducted for each of these MDOT classifications. Additional testing likely is needed to verify results or better populate the materials library for these classifications.

5.0 DIFFERENCES BETWEEN MISSISSIPPI AND NATIONAL TYPICAL VALUES

There are a number of established models that have been used to estimate resilient modulus values. Because MDOT has historically utilized the CBR test to characterize subgrade and granular pavement layers, the discussion will be limited to these comparisons. Within the current version of the MEPDG, the relationship between CBR and resilient modulus is as shown in Equation 2. Another model commonly cited in the literature is as shown in Figure 3.

$$Mr = 2555(CBR)^{0.64}$$ **Equation 2**

$$Mr = 1500(CBR)$$ **Equation 3**

where:

Mr = resilient modulus, psi

CBR = California Bearing Ratio, %

Use of Equations 2 and 3 to compare resilient modulus values to CBR pose two problems. First, the stress state at which the resilient modulus was determined for development of the model is not known. Because resilient modulus is stress dependent, the stress state must be known. Secondly, the density and moisture conditions of the test materials must be known. It is well accepted that the strength and/or stiffness properties of subgrade and granular materials are significantly affected by density and moisture content. This was shown within SS-205.

The original research conducted to develop the model shown in Equation 3 was reported by Heukelon and Klomp (1962). The relationship between resilient modulus and CBR was based upon nondestructive testing of pavement structures and field CBR values. Therefore, neither the actual stress state nor density/moisture content data were available.

Equation 2 is cited within Part 2, Chapter 2 of the MEPDG (version 1.100) software. This model can also be found in the 1993 AASHTO Guide for Design of Pavement Structures. Unfortunately, the original research to develop this model could not be found.

Table 4 presents a summary of the measured resilient modulus test results versus calculated resilient modulus results utilizing Equations 2 and 3. CBR values utilized to calculate resilient modulus are based upon work by Teng and Crawley (1983). These CBR estimates have been utilized by MDOT for over 20 years during pavement design. This table shows that for the fine-grained soils the range of measured resilient modulus values are reasonably close to the estimates. However, for the sandier materials, the measured resilient modulus values are lower than the estimates.

Table 4: Comparison of CBR and Resilient Modulus

AASHTO Classification	Range in CBR Values [1]	Resilient Modulus Equation 2, psi	Resilient Modulus Equation 3, psi	Range of Resilient Modulus psi[2]
A-7	1-5	2,500-7,200	1,500-7,500	7,700-13,900
A-6	5-15	7,200-14,500	7,500-22,500	5,700-20,900
A-4	7-20	8,900-17,400	10,500-30,000	13,600-25,500
A-3	11-20	11,800-17,400	16,500-30,000	9,300-13,700
A-2	24-60	19,500-35,100	36,000-90,000	8,800-23,000

[1] From Teng and Crawley (1983)
[2] 2 psi confining pressure, 6 psi cyclic stress: 95 percent of maximum dry density target (Standard Proctor) at optimum moisture content.

Also included within the User's Guide of the MEPDG is a table of typical resilient modulus values. Similar to the above discussion on the models relating resilient modulus and CBR, no specifics are provided for the table concerning stress state, density or moisture content. Table 5 presents a summary of the typical resilient modulus values from the MEPDG User's Guide and the results for subgrades tested in SS-170.

Table 5: Comparison of Typical Resilient Modulus Values to Test Results - Subgrades

AASHTO Classification	Typical Resilient Modulus, psi [1]	Range of Test Results, psi [2]
A-2-4	28,000-37,500	10,500-23,000
A-2-6	21,500-31,000	8,800-13,600
A-3	24,500-35,500	9,300-13,700
A-4	21,500-29,000	13,600-25,500
A-6	13,500-24,000	5,700-20,900
A-7-6	5,000-13,500	7,700-13,900

[1] From MEPDG User's Guide
[2] 2 psi confining pressure, 6 psi cyclic stress: 95 percent maximum dry density (Standard Proctor) at optimum moisture content.

Based upon Table 5, the resilient modulus values for the A-4, A-6 and A-7-6 seem to correspond well to typical resilient modulus values. However, the A-2-4, A-2-6 and A-3 classifications tend to have lower resilient modulus values than typical. This could be a by-product of the sandier materials generally being reported at higher stress states or the materials were compacted using a modified effort instead of standard effort.

Table 6 presents a summary of the typical resilient modulus values and the results for granular base/subbase materials tested in SS-170. This table shows that the resilient modulus values obtained in SS-170 are generally lower than the reported values. It is unclear why the values are lower; however, the most likely reason for the lower values is density. During SS-170, density values for the tested materials ranged from 95 to 99 percent of Standard Proctor. Stress states could also be an issue.

Table 6: Comparison of Typical Resilient Modulus Values to Test Results - Base/Subbase

AASHTO Classification	Typical Resilient Modulus, psi [1]	Range of Test Results, psi [2]
A-1-a	38,500-42,000	16,700-28,000
A-1-b	35,500-40,000	24,000-28,200
A-2-4	28,000-37,500	16,000-17,000
A-4	21,500-31,000	18,000-20,000

[1] From MEPDG User's Guide
[2] 5 psi confining stress, 15 psi cyclic stress: 95 to 99 percent maximum dry density (Standard Proctor) at optimum moisture content.

6.0 ESTIMATES OF RESILIENT MODULUS FOR TYPICAL MATERIALS

As stated previously, Teng and Crawley (1983) developed tables of estimated CBR values for typical Mississippi materials. These tables have been used by MDOT and consultants in the design of pavements in Mississippi for over 20 years. The purpose of this task was to recommend typical resilient modulus values to assist MDOT and consultant pavement designers transition to the MEPDG.

There are several ways that typical resilient modulus values could be presented. First, tables similar to those developed by Teng and Crawley (1983) could be developed that provide estimated resilient modulus values by AASHTO Classification. Another method would be to develop models using results of classification testing to predict the k-coefficients shown in Equation1. Equation 1 could then be used to calculate the resilient modulus for a given stress state.

Both of these alternatives have drawbacks. Because resilient modulus is stress dependent, a single table of typical resilient modulus values may or may not be applicable for a given pavement structure. In reality, the resilient modulus value for a specific subgrade material would be different for thin pavement sections versus thick pavement section. Thick pavement structures will result in more overburden than thin pavement sections. More vertical stress resulting from the increased overburden means higher resilient modulus values (Figures 10 through 12).

Development of models alleviates this problem to some extent, especially considering the iterative nature of the MEPDG. A pavement designer could assume a pavement structure and calculate the stresses on the given material using simple linear elastic principles. Next, using classification results for materials generally used in pavement construction near the project, calculate a resilient modulus value for input into the MEPDG software.

Another potential problem that exists with either of the aforementioned methods is that of density. The resilient modulus data developed during this study were based upon MDOT requirements when the project was initiated. Any changes to density requirements will affect the resilient modulus values. Practically, any potential density requirements changes will likely lead to more conservative pavement designs. It’s highly unlikely that density requirements will lessen. Therefore, estimated typical values of resilient modulus presented herein will likely be lower than actual if density requirements are increased.

As stated above, there are advantages and disadvantages for both methods of selecting typical estimated resilient modulus values for Mississippi. The method selected for providing the typical estimated resilient modulus is tabular form. The reason this method was ultimately selected is simple, practicality. In order to assist MDOT and consultant pavement designers transition to the MEPDG, the tables will be easier and more straight forward to implement, similar to the CBR tables developed by Teng and Crawley (1983).

MDOT generally has two pavement structures that are utilized. Pavements for high traffic loads generally have 12 in. of HMA while pavements for lower traffic are generally 6.5 in. of HMA. These two pavement structures and a typical 32,000 lb tandem axle were used as the stress states to calculate typical estimated resilient modulus values. Tables 7 and 8 present the recommended resilient modulus values for typical Mississippi subgrade materials underlying thin and thick pavement structures, respectively.

Table 7: Estimated Subgrade Resilient Modulus Values - Thin Pavement Sections

AASHTO Soil Class	Unified Soil Class	P_{200}[1]	Plasticity Index	Estimated $M_{R,\ psi}$
A-7	CH CL	---	---	9,000
A-6	"C" Soils	50 min.	---	12,000
	"S" Soils	50 max.	---	18,000
A-4	"C" and "M" Soils	50 to 90	---	20,000
		90 min.	---	13,000
	"S" Soils	50 max.	---	25,000
A-3	"S" Soils	---	---	12,000
A-2	"S" Soils	---	10 max.	20,000
		---	10 min.	15,000

[1] – Percent passing No. 200 sieve
"S" – Sandy materials in Unified Classification System
"C" – Clayey materials in Unified Classification System
"M" – Silty materials in Unified Classification System

Table 8: Estimated Subgrade Resilient Modulus Values - Thick Pavement Sections

AASHTO Soil Class	Unified Soil Class	P_{200}[1]	Plasticity Index	Estimated $M_{R,\ psi}$
A-7	CH CL	---	---	10,000
A-6	"C" Soils	50 min.	---	18,000
	"S" Soils	50 max.	---	25,000
A-4	"C" and "M" Soils	50 to 90	---	25,000
		90 min.	---	18,000
	"S" Soils	50 max.	---	30,000
A-3	"S" Soils	---	---	18,000
A-2	"S" Soils	---	10 max.	25,000
		---	10 min.	20,000

[1] – Percent passing No. 200 sieve
"S" – Sandy materials in Unified Classification System
"C" – Clayey materials in Unified Classification System
"M" – Silty materials in Unified Classification System

Table 9 presents the estimated typical resilient modulus values for granular materials. Only a single table is provided for the granular materials because of the relative location of these layers within the pavement structure. The estimated typical values are based upon the MDOT Class (those tested) of material for subbases and for stone bases. However, recall from Section 4.2 of this report, only single crushed stone materials were tested for each classification. For this reason, the estimated resilient modulus values are somewhat conservative.

Table 9: Estimates of Resilient Modulus Values for Granular Base/Subbase Materials

MDOT Classification	Estimated M_R, psi
Class 1	28,000
Class 3	28,000
Class 4	24,000
Class 5	24,000
Class 9	20,000
Class 10	20,000
LMS ¾ down	24,000
LMS 610	17,000
LMS 825-B	34,000

7.0 PROJECT SUMMARY

From 2004 to 2009, BCD participated in two important research studies designed to populate the materials library for implementation of the new Mechanistic-Empirical pavement design method. The purpose of this report was to capture the experiences BCD obtained with the resilient modulus test during the conduct of these important studies. Since no specific research was conducted within this project, no conclusions or recommendations are provided; rather, a summary of the project is provided.

At the onset of this project, there were four specific issues that MDOT identified for capturing BCD's experience. First, observations made during the course of testing the various materials were deemed important. Section 3 of this report documents these various observations. Section 4 of this report provides a critical review of the materials tested and test results. The third issue identified by MDOT was the differences in resilient modulus values between BCD's test results and typical national values. These differences are discussed in Section 5 of this report. The final task identified by MDOT was to develop estimates of resilient modulus values for materials typical of Mississippi. These estimates are provided in Section 6 of this report.

8.0 POTENTIAL FUTURE RESEARCH

In development of this report, a number of issues were identified that could be further researched in the future. Following is a listing of potential research projects that may be warranted.

1. Figure 13 of this report indicated the range in resilient modulus test results within a given classification. In some instances, the standard deviation within a classification was large. The large variability within a subgrade classification suggests that more resilient modulus testing may be warranted in order to provide proper default resilient modulus values.
2. Within Section 6 of this report, two methods were discussed in developing typical default values for the MEPDG. One method entailed developing models to predict the K-coefficients and the second method entailed developing tables similar to those developed by Teng and Crawley (1983). If MDOT so desired, models could be developed to predict the K-coefficients. The strength of these models will likely improve if the additional testing mentioned in Item 1 above is completed.
3. Because the resilient modulus of subgrade and base materials are stress dependent, results of testing conducted to date, and any additional testing conducted in the future, could ultimatley be utilized to develop design charts that relate pavement thickness to resilient modulus. Similar to Tables 7 and 8, a

number of design curves would be required because of the range of resilient modulus values within a given classification (Figure 13).

4. As discussed several times within this report, resilient modulus is highly related to the density of the material. The effect of density on resilient modulus was shown within SS-205. At the conclusion of SS-205, it was recommended that subgrade soils and chemically treated layers be compacted to at least 98 percent of standard Proctor density. If this recommendation is adopted, then additional testing should likely be conducted to provide more accurate estimations of default resilient modulus values.

9.0 REFERENCES

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