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LABORATORY SUBGRADE RESILIENT MODULUS DESIGN  
VALUES FOR THE STATE OF MICHIGAN

presented by

Colin Patrick Sessions

has been accepted towards fulfillment  
of the requirements for the

MS

degree in

Civil and Environmental  
Engineering

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LABORATORY SUBGRADE RESILIENT MODULUS DESIGN VALUES FOR THE  
STATE OF MICHIGAN

By

Colin Patrick Sessions

A THESIS

Submitted to  
Michigan State University  
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## ABSTRACT

### LABORATORY SUBGRADE RESILIENT MODULUS DESIGN VALUES FOR THE STATE OF MICHIGAN

By

Colin Patrick Sessions

The Michigan Department of Transportation (MDOT) currently uses several different procedures for determining the resilient modulus (MR) of the roadbed soil. Therefore, a consistent procedure is needed to unify the state and to meet the requirements of the Mechanistic-Empirical Pavement Design Guide (M-E PDG). To do this, the State of Michigan was divided, by soil type, into 15 clusters and 99 areas. Disturbed soil samples were collected from 75 areas along with 10 undisturbed Shelby tube samples. The samples were then tested in the laboratory to determine the natural moisture content, grain size distribution, and Atterberg limits. Selected samples were chosen to undergo cyclic load triaxial tests to determine the MR value. Empirical correlations were then developed for estimating the MR value for the different soil types by comparing them to the results of the moisture content, grain size distribution, dry unit weight, and Atterberg limits.

TO MY PARENTS

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# **CHAPTER 1**

## **INTRODUCTION AND RESEARCH PLAN**

### **1.1 Background**

The state of Michigan is geographically located within the glaciated section of North America and most of its soil has developed from glacial deposits. The ice sheet advanced over the state in three lobes, one along Lake Michigan, one along Lake Huron and the third along Lake Erie. A branch from Lake Huron lobe advanced southwesterly and connected to the other two lobes. During the advance of ice a large amount of soil and bedrock along the path of each ice lobe were pulverized and incorporated into the ice sheet to be later redeposited. When the Wisconsin ice sheet retreated to the north, these materials (known as glacial drift) were superimposed on sedimentary rock of the Michigan Basin in the Lower Peninsula and the Eastern part of the Upper Peninsula and on igneous and metamorphic rocks in the Western part of the Upper Peninsula. The thickness and composition of the drift varies from one location to another. For example, the thickness of the drift in the Alpena area is only few inches whereas it is more than 1200 ft thick in the Cadillac area. The glacial drift also varies from clay to gravel; the granular texture may be segregated or mixed heterogeneously with boulders and clays. Because of these complex arrangements, about one hundred and sixty-five different soil types were formed and are being used for engineering purposes by the Michigan Department of Transportation (MDOT) (MDOT 1970). The engineering and physical characteristics of these soils vary significantly from those of gravel and sand in the Western side of the Lower Peninsula, to clay in the Eastern side and to varved clay in the Western part of the Upper Peninsula.

For a given type of roadbed soil, its mechanical (engineering) properties (the resilient modulus (MR) and the plastic properties) are a function of the physical parameters (moisture content, grain size, grain angularity, Atterberg limits, etc.) of the soil and have a major impact on the performance of pavement structures. In the past, MDOT funded several research projects to study the engineering properties of certain types of roadbed soils (Goitom 1981, Lentz 1979). The results of those studies will be incorporated into the results of this research.

In this study, the MR of various roadbed soil types will be determined in the laboratory using cyclic load triaxial tests and in the field using the Falling Weight Deflectometer (FWD) deflection data. Statistical correlations between the laboratory and field MR will be obtained. The major objective of this study is to determine whether or not the MR of a given roadbed soil type can be estimated using the results of simple tests.

In the laboratory, the MR of a given soil type is calculated as the ratio of the applied deviatoric stress,  $\sigma_d$ , (the difference between the axial and lateral stresses) to the recoverable axial strain ( $\epsilon_r$ ) of the soil (Goitom 1981, Lentz 1979, Young and Baladi 1977, and Yau and Von Quintus 2002). Mathematically, the MR is expressed as follows:

$$MR = \frac{\sigma_d}{\epsilon_r} \quad \text{Equation 1.1}$$

## **1.2 Problem Statement**

The roadbed soils in the state of Michigan consist of glacial soils with distinct seasonal stiffness changes due to temperature (possible frozen condition) and moisture levels. MDOT's current pavement design process follows the procedure outlined in the 1993 American Association of State Highway and Transportation Officials (AASHTO) Design Guide. One of the inputs of said procedure is the effective value of the resilient

modulus of the roadbed soil, which is a function of seasonal changes. The pending new AASHTO Mechanistic-Empirical Pavement Design Guide (M-E PDG) procedure is even more stringent for defining MR in terms of seasonal effects. Currently, MDOT's various regions provide the "adjusted" MR value used for pavement design. The MR value is derived from either backcalculated deflection data or a correlation with known Soil Support Values (SSV).

### **1.3 Objectives**

The main objectives of this study are to:

- Evaluate the existing processes used by all regions of MDOT for determining the MR value of the roadbed soil for flexible pavement design and the modulus of subgrade reaction (k) for rigid pavement design.
- Determine the needed modifications to make the process compatible with the M-E PDG.

### **1.4 Research Plan**

To accomplish the objectives, a research plan consisting of five tasks was developed and is presented below.

#### **Task 1— Review and Information Gathering**

In this task, the research team will become familiar with MDOT's current and historical processes/procedures for selecting MR and k values for the design of flexible and rigid pavements. The information could be obtained by calling the various regions and talking to the soil engineers. The research team will also obtain information from MDOT that is needed for the other tasks in this study. These include:

1. The locations of FWD tests that were conducted in the past and the availability of the measured deflection data and the pavement cross-section data that existed at the time of testing.
2. The depth of frost penetration especially in the northern part of the Lower Peninsula and in the Upper Peninsula.
3. The repeated load triaxial test data that were obtained as part of research projects that were sponsored by MDOT from 1975 to 1979. The data will be digitized and tabulated along with the roadbed soil type and will be used in later tasks.
4. Traffic data in terms of average daily traffic (ADT) and percent commercial.

The effort of this task should produce:

1. Tabulation of the procedures used by the various Regions for selecting MR and k values and the basis of such selection. Based on the information, differences and similarity in these procedures will also be tabulated.
2. Tabulation of the range and typical MR and k values used by the regional soil engineers for the various soil types.
3. A brief summary of the background and the development of the SSV-resilient modulus chart provided in Figure 2.
4. Assessment of the adequacy and sufficiency of the existing process for estimating MR and k values to be used in the new M-E PDG.
5. For all available deflection data, tabulation of the locations of all FWD tests that were conducted in the past and the pavement cross-section that existed at the time of testing.
6. A map or a chart showing the depth of frost penetration where data are available.

7. Tabulation of the cyclic stress, confining pressure, vertical and horizontal deformations and strains, and the resilient modulus of the various roadbed soils included in the MDOT sponsored research projects during the period of 1975 to 1979.

### **Task 2— Partitioned State Map**

Based on the MDOT Field Manual of Soil Engineering, the information obtained from the various regions in Task 1, the trunkline locations, and the soil maps of the US Soil Conservation Services (USCS), the state will be partitioned into geological zones for the purpose of field testing and soil sampling. The state will be divided into a maximum of 15 coarse clusters where the soil within any given cluster would have similar range of engineering and physical characteristics. Each coarse cluster will then be divided into areas to narrow the range of the soil characteristics. A maximum of 99 areas will be produced. The results will be presented to members of the technical advisory group (TAG) for review and possible modification. The main use of the partitioned soil map is to determine the locations of field testing and soil sampling.

### **Task 3— Field and Laboratory Testing and Soil Sampling**

In this task, the research team will finalize the field sampling and the laboratory testing plans based upon the information obtained in Tasks 1 and 2. The total number of tests to be conducted is based purely on cost and available budget. The field sampling and the laboratory testing plans are presented in three subtasks below.

#### **Subtask 3.1 - Soil Sampling Plan**

From each area on the State Partitioned map, soil samples will be obtained. In areas where the roadbed soil is predominantly sand, only disturbed bag samples will be collected. In clay areas, both disturbed and undisturbed thin Shelby tube sample will be

obtained. In total, 75 disturbed roadbed soil samples and 11 undisturbed (Shelby tube) samples will be collected. All samples will be transported to the laboratory for testing as presented in Subtask 3.2 below.

### **Subtask 3.2 – Laboratory Testing Plan**

The laboratory plan consists of moisture content, sieve analysis, Atterberg limits, and cyclic load triaxial tests. All tests will be conducted according to MDOT, AASHTO or ASTM standard test procedures. Results of the laboratory testing will be analyzed (see Task 4) to determine:

1. Soil classification - For each of the 75 disturbed samples (bag samples), the soil will be subjected to sieve analyses to determine the breakdown fractions between sand and clay/silt particles. Any sample where the fine fraction (passing sieve number 200) is more than seven percent, plastic and liquid limit tests will also be conducted. Results of the sieve analyses and Atterberg limit tests will be used to:
  - Classify the soil according to the AASHTO and the USCS soil classification systems.
  - Develop, if possible, statistical correlations between the resilient modulus of the roadbed soils and the gradation and Atterberg limits of the material.
2. Cyclic load triaxial tests - For each location where Shelby tubes were collected, repeated load triaxial tests will be conducted. The samples will be tested at three moisture contents to simulate the effects of seasonal changes on the resilient modulus of the soils. The water content of the samples will be changed to the desired level by either drying or by using back pressure technique in the triaxial cell. For sand subgrade soils, the test specimens will be compacted at three moisture contents and

subjected to cyclic load triaxial tests. Since, the resilient moduli of sand roadbed soils are heavily dependent upon the deviatoric stress; the laboratory tests will be conducted at three stress states which will be estimated through mechanistic analyses to simulate the probable in-situ field conditions.

### **Subtask 3.3 –Field Test Plan**

This plan consists of Falling Weight Deflectometer (FWD) tests. The FWD tests will be conducted at the network- and project-levels. At the network level, one FWD tests will be conducted at 500 feet interval along the state trunkline. At the project level, 20 FWD tests will be conducted within  $\pm 50$  ft from all locations where Shelby tubes (undisturbed soil samples) will be extracted.

All FWD tests will be conducted in the spring and in the late summer – early fall seasons). For those areas where FWD tests were conducted in the past and the deflection and pavement cross-section data are available at MDOT, the data will be used and the number of FWD tests (to be conducted in those areas in this study) will be reduced depending on the availability of spring and fall deflection data. .

It should be noted that analyses of various damage models including AASHTO indicate that the two point FWD testing (spring and fall seasons) is adequate to assess the relative pavement damage caused by the roadbed soil due to different degrees of saturation.

### **Task 4 – Data Analyses**

The data analysis, in this study, will be accomplished according to the three subtasks presented below. First, it should be noted that for all soil types, the relationship between the MR and k found in the M-E PDG was used. Since the relationship applies to

all MR and k values, the analyses stated in the subtasks below will be conducted on the MR values and the results will be converted to k values.

#### **Subtask 4.1 – Backcalculation of Layer Moduli**

All deflection data, whether collected during this study or other studies, will be used (depending on the availability of the pavement cross-section data) to backcalculate the layer moduli using the MICHBACK computer program. Although the moduli of all pavement layers will be backcalculated, only the resilient modulus of the roadbed soils will be subjected to further analyses. The moduli of the pavement layers will be reported without further analyses. For each test area on the partition map, two sets of moduli will be backcalculated; one set is based on the spring deflection data and the other on the late summer-early fall data. The two sets will be further analyzed to estimate the seasonal damage factor as presented in task five below.

#### **Subtask 4.2 – Laboratory Test Data**

Results of the cyclic load tests conducted on Shelby tube and reconstituted bag samples at three moisture contents were analyzed to determine the laboratory values of the resilient modulus of the roadbed soil. Results of the analyses were used to assess the impact of moisture (season) on pavement damage and to compare the values to those obtained from backcalculation.

In addition, the digitized cyclic stress-strain data of those research studies that were sponsored by MDOT from 1975 to 1979 were analyzed. This pool of information will be used as supplement to verify the relationships or to increase the pool of data to develop more accurate relationships.



The Atterberg limits (liquid limit, plastic limit, and plasticity index) and sieve analysis data will be used to classify the soil and to develop correlations to MR whenever possible. Correlations will also be developed between the laboratory and the backcalculated MR values.

### **Task 5— Damage Assessment Analyses**

The damage assessment analyses (noted in subtask 4.1) was conducted based on the seasonal MR and k values obtained from the backcalculation of the FWD deflection data. The purpose of the analyses was to determine the effective MR and k values to be used in the design and rehabilitation of flexible and rigid pavements. The effective roadbed resilient modulus is an equivalent modulus that would result in the same damage as if the various seasonal resilient modulus values were used (Huang 2004). In the analyses, three methods will be used as follows:

1. The existing AASHTO 1993 damage model shown below.

$$u_f = 1.18 \times 10^8 \times (\text{MR})^{-2.32} \quad \text{Equation 1.2}$$

Where  $u_f$  = relative seasonal damage

2. The existing damage model in the M-E Design Guide, which is based on Miner's hypothesis of cumulative damage represented by the following equation.

$$D_r = \sum \frac{n_{ijklmn}}{N_{ijklmn}} \quad \text{Equation 1.3}$$

Where,  $D_r$  = damage ratio

$n_{ijklmn}$  = actual number of load repetitions

$N_{ijklmn}$  = allowable number of load repetitions, for the  $i^{\text{th}}$  age, the  $j^{\text{th}}$  season, the  $k^{\text{th}}$ , axle combination, the  $l^{\text{th}}$ , load level, the  $m^{\text{th}}$  temperature and the  $n^{\text{th}}$  traffic path.

3. Mechanistic analyses of stresses and strains induced in the roadbed soil due to traffic load. The magnitudes of the induced stresses and strains for various roadbed moduli were compared as to arrive at a damage model or to verify the above models.

## **1.5 Thesis Layout**

This thesis is composed of five chapters and three appendices as follows:

Chapter 1 – Introduction

Chapter 2 – Review

Chapter 3 – Field and Laboratory Investigation

Chapter 4 – Data Analysis

Chapter 5 – Conclusions and Recommendations

Appendix A – Soil Classification Systems

Appendix B – Laboratory Resilient Modulus Results

## CHAPTER 2

### REVIEW

This review chapter consists of two parts; review of the existing MDOT practices regarding the determination of MR and literature review.

#### 2.1 Review of MDOT Practices

As shown in Figure 2.1, MDOT divides the State of Michigan into seven self administered regions; Superior, North, Bay, Grand, University, Southwest and Metro. The practices of each region in determining the MR of roadbed soils differs slightly from one region to another. Table 2.1 summarizes the procedures used by each region. In general, the soil engineers use Figure 2.2 to estimate the MR of roadbed soils. The chart in Figure 2.2 is based on the soil support values (SSV) and the USDA soil classification system. It provides correlations between the SSV, the AASHTO layer coefficient for subbase and base materials and the resilient modulus.

Table 2.1 MDOT procedures for determining resilient modulus

| Region     | Procedure                                                      | Typical MR Values (psi) |
|------------|----------------------------------------------------------------|-------------------------|
| Bay        | Soil boring & visual identification                            | 3600                    |
| Grand      | FWD data (if available) or soil boring & visual identification | 2700 - 8600             |
| Metro      | Soil boring & visual identification                            | 3000 - 4500             |
| North      | FWD data (if available) or soil boring & visual identification | 2500 - 6000             |
| Southwest  | California Bearing Ratio correlations                          |                         |
| Superior   | Soil boring & visual identification                            | 4500 - 7000             |
| University | Soil boring & visual identification                            | 3000 - 4000             |



Figure 2.1 MDOT regions (MDOT)

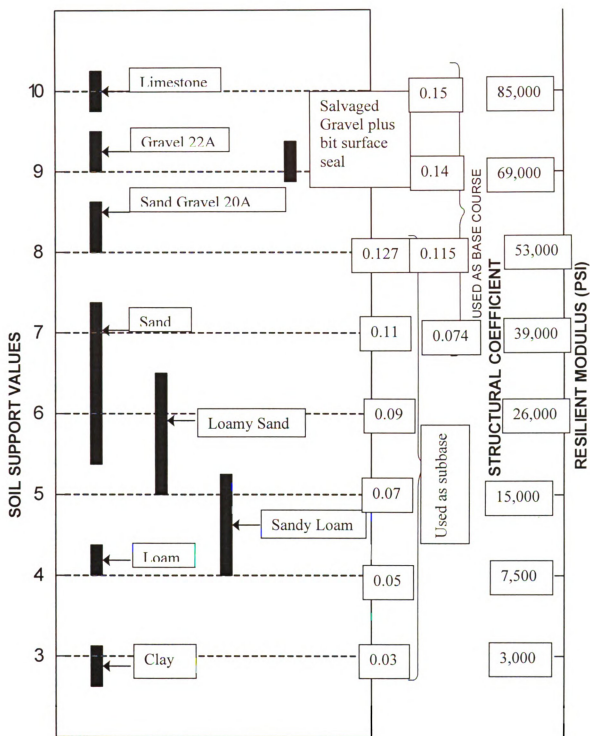


Figure 2.2 Range of soil support values, structural coefficients, and resilient modulus for various materials (MDOT)

## **2.2 Role of Roadbed Resilient Modulus in the M-E PDG**

The required inputs to the 2002 Design Guide can be broadly classified under four main categories - general, traffic, climatic and structural inputs. The Design Guide uses a three level hierarchical approach for selecting traffic and structural inputs. This gives designers the flexibility of using very specific or very general input data for the design process, depending on the agency's resources and the requirements of each specific design project (Coree et. al 2005).

The procedure for level one design can be thought of as "first class" and requires high accuracy inputs. The level one procedure will typically be used for obtaining inputs for the design of pavement sections subjected to heavy traffic or wherever there is safety and/or economic consequences of early failure. The procedure requires laboratory or field testing, such as the dynamic modulus testing of hot-mixed AC or site-specific axle load spectra data collections, or FWD deflection testing. Hence, the inputs for level one design require more resources and time than other two levels.

Level two is an intermediate design level whose required inputs are similar to those used for many years in the earlier editions of the AASHTO design guides. This level is used when resources and/or testing equipment are not available to obtain level one input. The required design data inputs for level two could be selected from an agency database, derived from a limited testing program, or estimated through correlations. Examples would be dynamic modulus estimated from binder, aggregate, and mix properties, or PCC elastic moduli estimated from unconfined compressive strength tests.

The required pavement design inputs for level three have the lowest level of accuracy. This design level might be used for pavement sections where there are

minimal consequences of early failure (low volume roads). The data inputs consist of typical default or average values used by the agency.

Further, the input data requirements can vary from one input parameter to another, which makes the procedure more flexible. For example, on a given project, the pavement designer could use level one for the subgrade resilient modulus input and level three for the traffic distribution data. Regardless of the selected input level, the 2002 design process is the same (Prozzi and Hong 2006).

Finally, regardless of the design level used, the resilient modulus of the roadbed soil is a required input to the pavement structural response model. It has a significant effect on the computed pavement responses and on the dynamic modulus of subgrade reaction, k-value, which is computed internally by the Design Guide software. The resilient modulus of the roadbed soil can be measured directly from the laboratory or obtained through correlations with other material parameters such as California Bearing Ratio (CBR) and Dynamic Cone Penetrometer (DCP). The procedures for obtaining the resilient modulus for the various design levels are described in the following subsections (NCHRP 2004).

### **2.2.1 Procedures for Determining the Resilient Modulus of the Roadbed Soil for Design Level One**

For level one design, the resilient modulus of the roadbed soil is determined using cyclic load triaxial tests in accordance with one of the following standard test methods:

- NCHRP 1-28A, “Harmonized Test Methods for Laboratory Determination of Resilient Modulus for Flexible Pavement Design.”

- AASHTO T307, “Determining the Resilient Modulus of Soil and Aggregate Materials.”

The stress conditions used in laboratory testing must represent the range of stress states likely to be developed beneath the pavements. Stress states used for modulus testing are based upon the depth at which the material will be located within the pavement system (i.e., the stress states for specimens to be used as base or subbase or subgrade may differ considerably).

The M-E PDG recommends Equation 2.1 for calculating MR. The nonlinear elastic coefficients and exponents of the model are determined by using linear or nonlinear regression analyses to fit the model to laboratory generated MR test data (NCHRP 2004):

$$MR = k_1 P_a \left( \frac{\theta}{P_a} \right)^{k_2} \left( \frac{\tau_{oct}}{P_a} + 1 \right)^{k_3} \quad \text{Equation 2.1}$$

Where,  $MR$  = resilient Modulus (psi);

$$\theta = \text{bulk stress} = \sigma_1 + \sigma_2 + \sigma_3;$$

$$\sigma_1 = \text{major principal stress};$$

$$\sigma_2 = \text{intermediate principal stress};$$

$$\sigma_3 = \text{minor principal stress/confining pressure};$$

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



Please note that the above described procedure for level one design applies equally to reconstruction and rehabilitation where destructive material samples can be obtained. Alternatively, for pavement rehabilitation, nondestructive deflection tests can be performed and the MR values can be determined using back calculation routine.

### **2.2.2 Procedures for Determining the Resilient Modulus of the Roadbed Soil for Design Level Two**

The MR values for pavement design level two can be estimated using existing direct or indirect correlation equations between MR and other material parameters. Indirect correlation implies, for a given soil, correlating parameter A to B and then B to the soil MR. Table 2.2 provides a list of correlation equations included in the M-E PDG. Further, the Design Guide software allows the use of the following two options:

- Input a representative value of MR and use Enhanced Integrated Climatic Model (EICM) to adjust the MR value for the effect of seasonal climate (i.e., the effect of freezing, thawing, and so on).
- Input an MR value for each month (season) of the year (total of 12 months).

The primary use of EICM in this design procedure is to estimate the temperature and moisture profiles within the pavement system throughout its design life. The estimated temperature and moisture profiles within the subgrade layers can also be used to modify the representative MR to account for the effects of climate. The procedure for pavement design level two is applicable to new, reconstruction, and rehabilitation design.

Table 2.2 Models relating material index and strength properties to MR (NCHRP 2004)

| Strength/index property  | Model                                        | Comments                                                                       | Test Standard                                      |
|--------------------------|----------------------------------------------|--------------------------------------------------------------------------------|----------------------------------------------------|
| CBR                      | $MR = 2555 (CBR)^{0.64}$                     | CBR = California bearing ratio                                                 | AASHTO T193                                        |
| R-value                  | $MR = 1155 + 555R$                           | R = R-value                                                                    | AASHTO T190                                        |
| AASHTO layer coefficient | $MR = 30,000 \left( \frac{ai}{0.14} \right)$ | ai = AASHTO layer coefficient                                                  | AASHTO guide for the design of pavement structures |
| PI and gradation         | $CBR = \frac{75}{1 + 0.728(wPI)}$            | wPI = P200*PI<br>P200 = percent passing sieve No. 200<br>PI = plasticity index | AASHTO T27,<br>AASHTO T90                          |
| DCP                      | $CBR = \frac{292}{DCP^{1.12}}$               | DCP = DCP index, mm/blow                                                       | ASTM D6951                                         |

### 2.2.3 Procedures for Determining the Resilient Modulus of the Roadbed soil for Design Level Three

For level-three design, the MR value is determined based on the classification of the soil. Table 2.4 provides a list of MR values that are recommended in the M-E PDG. For this design level one typical representative MR value at the optimum moisture content is required. Users have the option to use the EICM to modify the MR value for the effect of climate.

This design level can be used for new, reconstruction, and rehabilitation projects. The material type can be obtained from historical boring record, material reports or county soil maps. The bedrock depth is important and it should be investigated.

The MR values presented in Table 2.4 are approximate and should be cautiously used. The reason is that these values are based on the assumption of a semi-infinite media. For a finite roadbed soil thickness (less than 5ft), the MR of the lower and weaker material should be used to obtain a composite MR value.

## **2.3 Literature Review**

Early in this study, an extensive literature review was conducted to study and summarize the results reported by previous investigators regarding:

- The advantages and shortcomings of the laboratory and field test procedures used to determine the MR of roadbed soils.
- The relationships between the laboratory determined and the backcalculated resilient modulus using deflection data.
- The resilient characteristics of various types of roadbed soils.
- The factors affecting the MR of roadbed soils including moisture contents (seasonal effects), particle size, Atterberg limits, and grain size distribution.
- The reported correlations between MR and the modulus of subgrade reaction (k) of roadbed soils.
- The reported correlations, if any, between the results of simple tests such as Atterberg Limits, grain size distribution, pocket penetrometer, and hand held shear vane and the MR of the roadbed soils.

Results of the literature review are summarized below.

### **2.3.1 Resilient Modulus and the Soil Classification Systems**

There are currently several common soil classification systems. The most popular of these are the United States Department of Agriculture (USDA), the Unified Soil

Classification System (USCS), and the AASHTO soil classification system (Holtz and Kovacs 1981). Table 2.3 provides comparison between the three classification systems. Such comparison chart is important because it allows the users of one highway authority to compare their roadbed soils to another agency that uses different classification system.

Nevertheless, several correlations between the soil classification systems and the resilient modulus of the roadbed soils can be found. These include:

- The data in Figure 2.2, which is used mainly by MDOT.
- The data in Table 2.4 of the AASHTO mechanistic-empirical pavement design procedure (M-E PDG), which provide estimate of a typical range of values of the resilient modulus of roadbed soils based on their AASHTO classification system and USCS.
- The data in Figure 2.3, which provide estimates of various roadbed soil parameters based on their AASHTO and USCS classification systems (NHI 1998).

Although the data in Table 2.4 and Figure 2.3 provide, for each soil classification, a range of values, the exact value to be used in the pavement design process is a decision that must be made by the engineer on the job.

## **2.4 Laboratory Testing**

The resilient modulus (MR) of a soil is an index that describes its stress-strain relation under cyclic loads (Maher et. al 2000). Mechanistic-based pavement and overlay design procedures require as input the subgrade MR to determine layer thicknesses and the overall system response to traffic loads. MR can be obtained in the laboratory and from the backcalculation of nondestructive deflection test (NDT) data. The laboratory

Table 2.3 Comparison between three soil classification systems (USDA 1992)

| USDA texture                       | Classification                  |                                  | Percent Passing Sieve Number |        |        |        | Liquid Limit | Plastic Limit |
|------------------------------------|---------------------------------|----------------------------------|------------------------------|--------|--------|--------|--------------|---------------|
|                                    | USCS                            | AASHTO                           | 4                            | 10     | 40     | 200    |              |               |
| Muck                               | PT                              | A-8                              | 100                          | 100    | 90-100 | 40-100 | 0-14         | NP            |
| Sand                               | SP-SM, SM, SP, GP, GP-GM, GM    | A-2-4, A-3, A-1-b, A-2, A-3, A-2 | 40-100                       | 25-100 | 15-90  | 0-35   | <25          | NP            |
| Loamy Sand                         | SM, SC-SM, ML, CL-ML, SP-SM, SP | A-2, A-4, A-1-b, A-1, A-2-4, A-3 | 85-100                       | 60-100 | 30-90  | 3-55   | <30          | NP            |
| Silty Loam                         | ML, CL, CL-ML, SC, SM, CH       | A-4, A-6, A-7, A-2               | 95-100                       | 85-100 | 60-100 | 30-95  | <45          | NP/P          |
| Sandy Loam                         | SM, SC-SM, ML, CL-ML, SC, CL    | A-2-4, A-4, A-2, A-1, A-1-b, A-6 | 70-100                       | 60-100 | 35-90  | 15-75  | <35          | NP            |
| Clay Loam                          | CL, CL-ML, SC, SC-SM            | A-6, A-4, A-7, A-2               | 95-100                       | 75-100 | 70-100 | 35-90  | 25-45        | NP/P          |
| Loam                               | CL, CL-ML, ML                   | A-4, A-6, A-7                    | 90-100                       | 75-100 | 70-100 | 50-90  | 15-45        | NP/P          |
| Mucky Sand                         | SM, SP, SP-SM                   | A-1-b, A-2-4, A-3                | 95-100                       | 75-100 | 30-70  | 0-15   | 0-14         | NP            |
| Clay                               | CH, CL                          | A-6, A-7-6                       | 90-100                       | 85-100 | 65-95  | 45-95  | 30-65        | P             |
| Silty Clay                         | CL, SC, CL-ML                   | A-4, A-6, A-7                    | 85-100                       | 60-100 | 50-100 | 30-90  | 25-50        | NP/P          |
| NP = non-plastic, plastic limit<10 |                                 |                                  |                              |        |        |        |              |               |
| P = plastic soil, plastic limit>10 |                                 |                                  |                              |        |        |        |              |               |

determination of MR of roadbed soils is reviewed below, along with factors that affect the MR values.

#### 2.4.1 Resilient Modulus Test Procedure

In general, laboratory test procedures for the determination of MR value are essentially based on the existing cyclic triaxial test methods used for the determination of

soil properties under repeated loads. A schematic of the test apparatus for conducting MR tests is shown in Figure 2.4. Figure 2.5 shows a typical hysteresis loop output (stress-strain of one load unload cycle) used in the calculation of MR (Hall et al. 2001).

Figure 2.5 also shows the recoverable ( $\epsilon_R$ ) and plastic ( $\epsilon_P$ ) portions of the axial strain of the sample and the equation for calculating the MR of the soil.

Guidelines for conducting laboratory MR testing are given in the 2001 AASHTO T 307 standard test procedure. The procedure calls for placing a compacted soil sample in a triaxial test apparatus, applying confining pressure and a sustained load to the sample, and then applying a repeated axial load and measuring the resulting vertical deformations (AASHTO 2001).

The history of the development of the AASHTO T 307 standard test procedure traces back to the Strategic Highway Research Program (SHRP) protocol P 46-94 “Resilient Modulus of Unbound Base/Subbase Materials and Subgrade Soil.” The protocol is based on determining MR in a repeatable, practical, and productive way. After eight years of implementation, the protocol was adopted in 1992 by AASHTO as test method T 294 replacing its predecessor T 274-82. The procedure has further evolved to incorporate additional technical requirements and currently is labeled AASHTO T 307 standard test procedure (Groeger et al. 2003). According to Maher et al, 2000, some of the most recognized changes from the AASHTO T 274-82 and T 294-92 procedures to the most recent AASHTO T 307 are:

Table 2.4 Typical resilient modulus values for unbound granular and subgrade materials  
(NCHRP 2004)

| Classification System | Material Classification | pounds/square inch |            |
|-----------------------|-------------------------|--------------------|------------|
|                       |                         | MR Range           | Typical MR |
| AASHTO                | 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      |
| USCS                  | 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     |

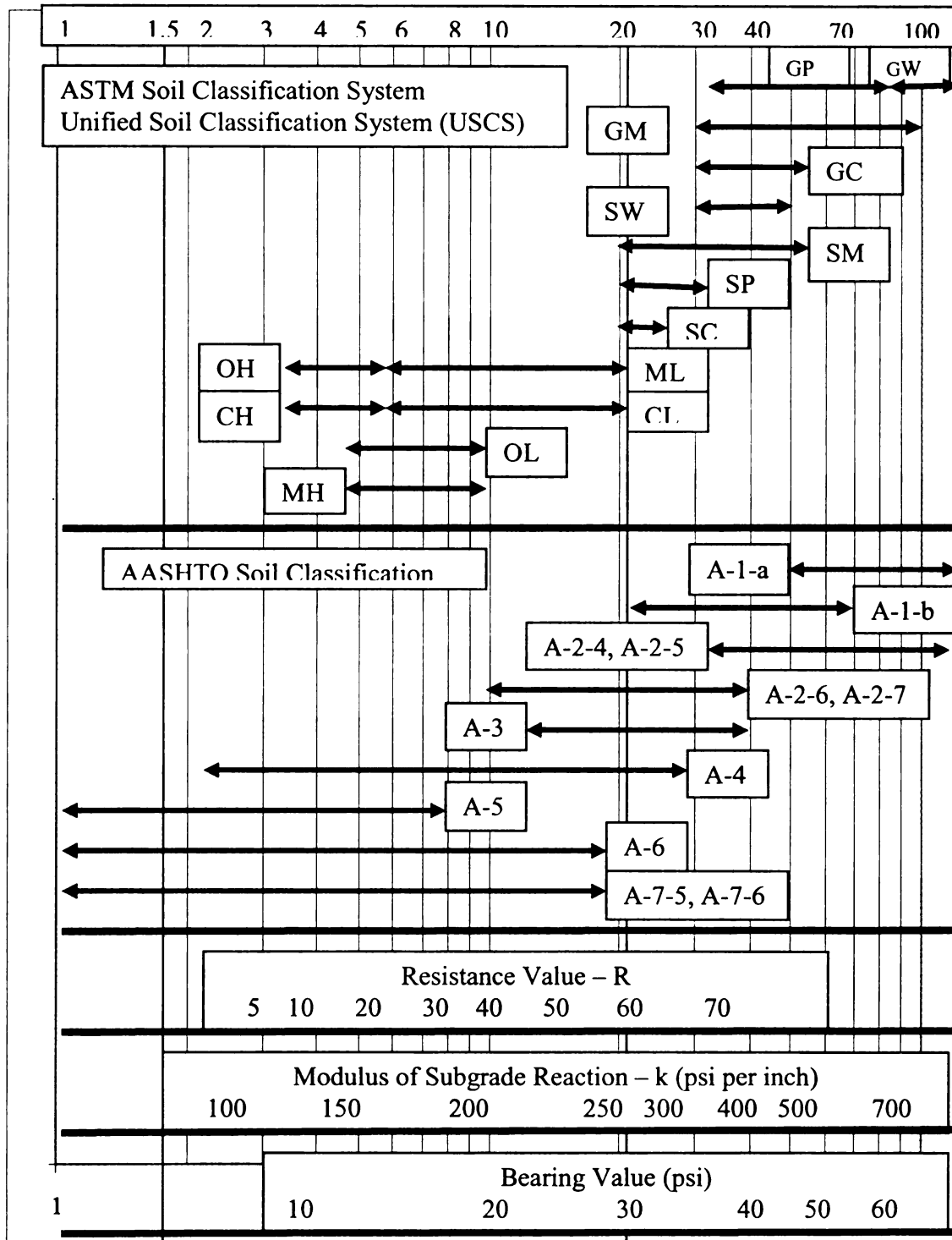


Figure 2.3 Soil classification related to strength parameters (NHI 1998)



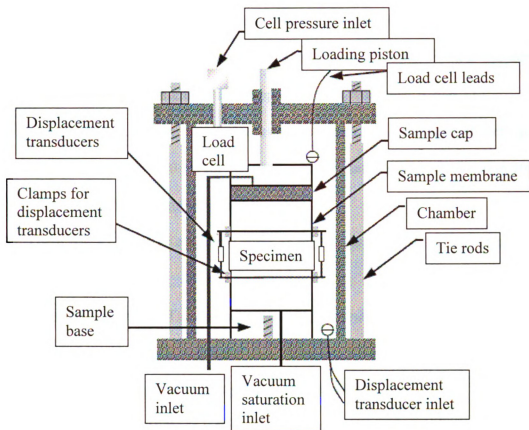


Figure 2.4 Resilient modulus testing apparatus for soils (NHI 1998)

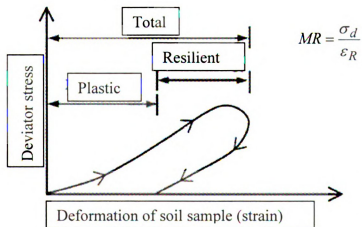


Figure 2.5 Resilient modulus concept (NHI 1998)

1. The number of loading sequences has been decreased from 27 to 15 and the number of loading cycle per loading sequence has been decreased from 200 to 100 cycles. The decrease in testing sequences and load cycles led to a reduction in the sample deformation and testing time from approximately five hours to two.
2. The maximum axial stress range was changed from 1.0 to 20.0 pounds per square inch (psi) to 3.0 to 40.0 psi for base and subbase materials, and from 1.0 to 10.0 psi to 2.0 to 10.0 psi for subgrade materials.
3. There was a change of confining stress in the subbase testing sequence from 0 to 2.0 psi.
4. The implementation of a constant sustained stress of 10% of the applied deviatoric stress (the difference between the axial stress and the confining pressure) to ensure full contact between the loading piston and the sample.
5. Granular soils (Type I) are tested using a sample size of 6.0 inches in diameter and, 12.0 inches high. Cohesive soils (Type II) are tested using a sample size of 2.8 inches in diameter and 5.6 inches high.

#### **2.4.2 Issues with Current Test Standards**

The AASHTO requirement to apply and remove the deviator load in 0.1 seconds is difficult and costly. It requires high performance servo-valves and fast electronics. It is believed that dynamic effects may become significant for 12 inch high specimens with stiffness less than 20,000 psi and for 6 inch high specimens with stiffness less than 10,000 psi (Marr et al. 2003). While the rapid loading rate is used to model moving vehicles on a pavement system, it is not clear that this fast loading rate is necessary. The

test would be a lot simpler to run and the equipment less expensive if the loading period is increased to 0.5 seconds.

Accurate measurements of the axial deformations are essential in obtaining reliable MR results. The AASHTO requirements for such measurements have been changed from two linear variable differential transducers (LVDT) mounted internally at 180° along the specimen's axis, to two LVDTs clamped to the loading rod inside the triaxial chamber to one LVDTs externally mounted to the loading piston and resting on a rigid surface. These changes have made the test procedure manageable. It should be noted that using the average of two LVDTs mounted at 180° would decrease measurements error if the sample is subjected to a slight rocking motion.

## **2.5 Field Testing**

Field testing for determining or estimating MR is divided into two categories; destructive and nondestructive.

### **2.5.1 Destructive Testing**

The following five destructive tests are often used to estimate MR or k values.

#### **2.5.1.1 California Bearing Ratio**

The California Bearing Ratio (*CBR*) is the ratio between the soil's resistance to 0.1 inch penetration of a standard piston to the resistance of a well graded and crushed stone to the same penetration level. The test can be conducted in the field and the laboratory as described in the AASHTO T193 standard test procedure (AASHTO 2001).

The 1993 AASHTO Pavement Design Guide uses Equation 2.2 to estimate the MR from the CBR (AASHTO 1993). It should be noted that the 1500 constant in Equation 2.2 can vary from 750 to 3000 (NHI 1998).

$$MR = 1500CBR \quad \text{Equation 2.2}$$

Whereas the new M-E PDG recommends the use of Equation 2.3 for estimating the MR value (NCHRP 2004).

$$MR = 2555(CBR)^{0.64} \quad \text{Equation 2.3}$$

### 2.5.1.2 Dynamic Cone Penetrometer

The Dynamic Cone Penetrometer (*DCP*) shown in Figure 2.6 is a graduated rod with a metal cone on one end and a mass which is repeatedly lifted and dropped to drive the cone into the soil. The *DCP* is an efficient and inexpensive way to estimate the in-place *CBR*. The cone's penetration rate (*PR*) is measured after every drop and is labeled the *DCP* index. The *DCP* index (*DCP* = mm/blow) correlates well to *CBR* for fine grained soils up to *CBR* value of about 15 percent. Equation 2.4 from the M-E PDG provides a correlation between the *CBR* and the *DCP* index (NCHRP 2004).

$$CBR = \frac{292}{DCP^{1.12}} \quad \text{Equation 2.4}$$

Equations 2.3 and 2.4 are combined in Equation 2.5.

$$MR = 96658 \left( \frac{1}{DCP} \right)^{0.72} \quad \text{Equation 2.5}$$

Equation 2.6 provides another correlation between the *CBR* and the penetration rate (*PR*) of a 60° cone (NHI, 1998).

$$CBR = \frac{405.3}{PR^{1.259}} \quad \text{Equation 2.6}$$

Where,  $PR$  = penetration rate, mm/blow

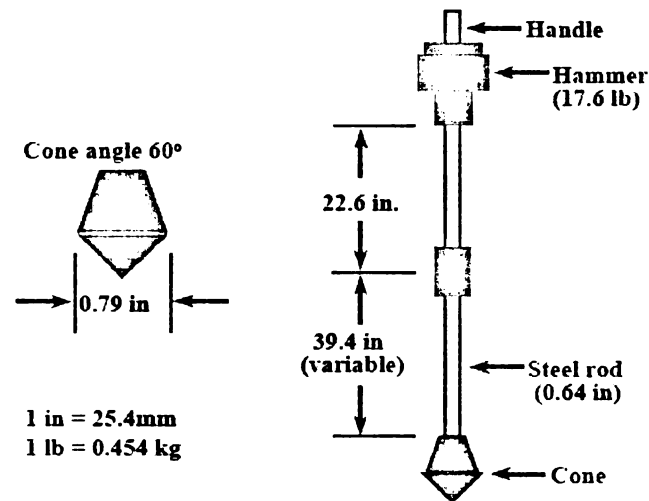


Figure 2.6 Schematic of a dynamic cone penetrometer (NHI 1998)

### 2.5.1.3 Plate Load Test

Plate load testing of subgrade soils is not commonly used because it is laborious and slow destructive test that requires the removal of segments from the pavement surface and base layers (Yoder 1959). It is, nonetheless, a direct method for determining the modulus of subgrade reaction which is a required input in the current AASHTO concrete pavement design procedure. Figure 2.7 depicts a photo of the plate load testing apparatus. Guidelines for repetitive static plate load testing are given in ASTM D1195 “Standard Test Method for Repetitive Static Plate Load Tests of Soils and Flexible Pavement Components” for use in evaluation and design of airport and highway pavements, and in AASHTO T 221 standard test procedure (AASHTO 2001). The static elastic  $k$  value is calculated as the ratio of the applied pressure to the elastic deformation, which is the recoverable portion of the total measured deformation (Yoder 1959).

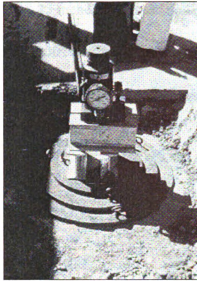


Figure 2.7 Photo of plate load testing apparatus (NHI 1998)

#### 2.5.1.4 Pocket Penetrometer

The pocket penetrometer is a small hand held device with a spring loaded probe at one end. The probe is pushed to penetrate the soil 0.25 inches; the spring measures the resistance of the soil to penetration. The pocket penetrometer is used to estimate the unconfined compressive strength of the soil. Since the MR is a nonlinear elastic soil property it is logical to assume that there is a relationship between soil strength and MR (Han et al. 2006). Thompson and Robnett (1979) proposed estimating the MR value from the unconfined compressive strength using Equation 2.7.

$$MR = 0.86 + .307q_u \quad \text{Equation 2.7}$$

Where,  $MR$  = resilient modulus, ksi

$q_u$  = unconfined compressive strength, psi

#### 2.5.1.5 Pocket Vane Shear Tester

The pocket shear tester is used to estimate the undrained shear strength of the

soil. The shear tester is inserted 0.25 inches into a flat soil surface and rotated until failure. The maximum pressure required to cause failure is the  $S_u$  value. Sukerman et al (2002) suggested a relationship between the undrained shear strength and MR.

$$MR = 100 - 500s_u \quad \text{PI} > 30 \quad \text{Equation 2.8}$$

$$MR = 500 - 1500s_u \quad \text{PI} < 30 \quad \text{Equation 2.9}$$

Where,  $MR$  = resilient modulus, psi

$S_u$  = undrained shear strength, psi

PI = plasticity index

### 2.5.2 Nondestructive Testing

The nondestructive deflection test (NDT) is the most popular test in this category. In recent years, the use of NDT has become an integral part of the structural evaluation and rehabilitation of pavement structures. Various types of equipment are available including the Road Rater, Kuab, Dynaflect and the falling weight deflectometer (FWD). NDT devices are used by state highway agencies to apply patterns of loading and record deflection data along the pavement surface. The deflection data measured along the pavement surface at different distances from the center of the load are typically used to backcalculate the modulus values of the various pavement layers and the roadbed soil. Numerous backcalculation software packages are available either in the public domain or can be purchased. Most of these use more or less the common procedures presented in the next sections.

### 2.5.2.1 Backcalculation of Resilient Modulus from Deflection Data

The subgrade modulus can be determined by using the pavement surface deflection measured at distances of 48-inches or more from the center of the load. Because of arching effects, at these distances, the pavement surface deflection is influenced mainly by the roadbed soils. Hence, the subgrade MR can be backcalculated from a single deflection measurement. The most widely used routine to backcalculate the subgrade MR from a single deflection measurement is the Boussinesq equation (George 2003).

$$d_r = \frac{CP(1-\nu^2)}{\pi r MR} \text{ or } MR = \frac{CP(1-\nu^2)}{\pi r d_r} \quad \text{Equation 2.10}$$

Where,  $d_r$  = the surface deflection in inch at a distance  $r$  in inch from the the load

$P$  = applied load in pounds

$C$  = correlation/adjustment factor accounts for the difference between the backcalculated and the laboratory obtained MR value.

$MR$  = resilient modulus in psi

By assuming a Poisson's ratio of 0.5, equation 2.10 can be reduced to the following equation (AASHTO 1993).

$$MR = \frac{0.24CP}{d_r r} \quad \text{Equation 2.11}$$

AASHTO recommends the use of  $C$  value not greater than 0.33

The minimum distance ( $r$ ) in Equations 2.10 and 2.11 is given by the following relationship.



$$r = 0.7 \sqrt{a_2 + \left\{ D \sqrt[3]{\frac{E_p}{M_R}} \right\}^2} \quad \text{Equation 2.12}$$

Where,  $a_2$  = radius of load plate

$D$  = total thickness of pavement layers above the subgrade

$E_p$  = effective modulus of all layers above the subgrade

$E_p$  in equation 2.12 can be calculated by using the following equation:

$$\frac{M_R d_o}{qa} = 1.5 \left\{ \frac{1}{\sqrt{1 + \left[ \frac{D}{a} \sqrt[3]{\frac{E_p}{M_R}} \right]^2}} + \frac{1 - \frac{1}{\sqrt{1 + \left( \frac{D}{a} \right)^2}}}{\left( \frac{E_p}{M_R} \right)} \right\} \quad \text{Equation 2.13}$$

Where,  $d_o$  = deflection measured at the center of the load plate after adjustment to a temperature of 68 °F

$q$  = pressure on load plate

The Washington State Department of Transportation (WSDOT) developed, for asphalt pavements, Equations 2.14 through 2.16 and, for concrete pavements, Equation 2.17 to estimate the subgrade modulus from deflection sensors located at various distances from the center of the load (Pierce 1999).

$$M_R(psi) = 9000 \times \frac{0.2892}{24 \left( \frac{d_{24}}{1000} \right)} \quad \text{Equation 2.14}$$

$$M_R(psi) = -466 + 9000 \times \frac{0.00762}{\left( \frac{d_{36}}{1000} \right)} \quad \text{Equation 2.15}$$

$$M_R(psi) = -198 + 9000 \times \frac{0.00567}{\left( \frac{d_{48}}{1000} \right)} \quad \text{Equation 2.16}$$

$$M_R = 9000 \frac{0.00577}{\left( \frac{d_{48}}{1000} \right)} - 111 \quad \text{Equation 2.17}$$

Where,  $d_{24}$ ,  $d_{36}$  and  $d_{48}$  are the pavement surface deflections in inches measured at 24, 36, and 48 inches from the center of the load.

### 2.5.2.2 Backcalculation of K Value Using Pavement Surface Deflections

Deflection testing at the center of a slab can be used to determine the value of the dynamic modulus of subgrade reaction (k) and the effective thickness of the concrete slab, based on an assumed modulus of elasticity of concrete of 5,000,000 psi (Hall and Croveti 2000).

Two different analyses were presented with and without the use of the deflections recorded at the center of the loading plate. Initially, deflections are used to compute the deflection basin AREA using the following equations:

$$AREA4 = \frac{6}{d_0} (d_0 + 2d_{12} + 2d_{24} + d_{36}) \quad \text{Equation 2.18}$$

$$AREA5 = \frac{3}{d_{12}} (1 + 2d_{18} + 3d_{24} + 6d_{36} + 4d_{60}) \quad \text{Equation 2.19}$$

Where,  $AREAi$  = deflection basin AREA, inches

$di$  = surface deflection measured at  $i$  inches from the load center

The calculated AREA values are then used to backcalculate initial estimates of the radius of relative stiffness (dense-liquid foundation model), using the following equations (Hall and Croveti 2000).

$$l_{k4-est} = \left[ \frac{\ln\left(\frac{36 - AREA4}{1812.279}\right)}{-2.559} \right]^{4.387} \quad \text{Equation 2.20}$$

$$l_{k5-est} = \left[ \frac{\ln\left(\frac{48 - AREA5}{158.40}\right)}{-0.476} \right]^{2.22} \quad \text{Equation 2.21}$$

Where,  $l_{ki-est}$  = estimated dense-liquid radius of relative stiffness, inches

Hall and Croveti initially estimated the dynamic foundation  $k$  value, based on infinite slab size assumptions, are backcalculated using the following equations (2000).

$$k4_{est} = \frac{0.1245e^{\left[-0.14707e^{(-0.07565l_{k4-est})}\right]}P}{d_0(l_{k4-est})^2} \quad \text{Equation 2.22}$$

$$k5_{est} = \frac{0.12188e^{\left[-0.79432e^{(-0.07074l_{k5-est})}\right]}P}{d_{12}(l_{k5-est})^2} \quad \text{Equation 2.23}$$

Where,  $ki_{est}$  = estimated dynamic interior foundation k value, psi/in

$P$  = applied load, lb

$d_i$  = utilized maximum deflection at i inches from the load, inches

$l_{ki-est}$  = estimated radius of relative stiffness, inches

Based on slab size, correction factors for the estimated radius of relative stiffness are computed using the following equations.

$$CF_{lk-est} = 1 - 0.89434 \exp \left[ -0.61662 \left( \frac{L_{eff}}{l_{k-est}} \right)^{1.04831} \right] \quad \text{Equation 2.24}$$

$$CF_{Di} = 1 - 1.15085 \exp \left[ -0.71878 \left( \frac{L_{eff}}{l_{k-est}} \right)^{0.80151} \right] \quad \text{Equation 2.25}$$

Where,  $CF_{lk-est}$  = correction factor for  $l_{k-est}$

$CF_{Di}$  = correction factor for utilized maximum interior deflection

$L_{eff}$  = effective slab length, inches

The effective slab length is computed based on the length and width of the test slab, using Equation 2.26 (Hall and Croveti 2000).

$$L_{eff} = \sqrt{L_s \times L_w} \quad \text{Equation 2.26}$$

Where,  $L_s$  = slab length, inches

$L_w$  = slab width, inches

After computation of slab size correction factors, the adjusted radius of relative stiffness and dynamic foundation k value are computed using the following equations.

$$l_{k-adj} = CF_{lk-est} \times l_{k-est} \quad \text{Equation 2.27}$$

$$k_{adj} = \frac{K_{est}}{(CF_{lk-est})^2 \times CF_{Di}} \quad \text{Equation 2.28}$$

Other backcalculation procedures exist for pavement surface deflections including one presented by Frabizzo (1998). From FWD data a backcalculation procedure can be used to calculate the deflection basin area (AREA), radius of relative stiffness ( $l$ ), elastic modulus of the concrete ( $E_c$ ), and the modulus of subgrade reaction for rigid pavements.

AREA is the cross-sectional area of the deflection basin between the center of the FWD load plate and the outer most deflection sensor. It is calculated using deflection data at various distances “r” from the center of the load plate. AREA calculation is normalized with respect to the sensor beneath the load; resulting in units of length (Frabizzio 1998).

$$AREA = \left[ 4 + 6 \left( \frac{\delta_8}{\delta_0} \right) + 5 \left( \frac{\delta_{12}}{\delta_0} \right) + 6 \left( \frac{\delta_{18}}{\delta_0} \right) + 9 \left( \frac{\delta_{24}}{\delta_0} \right) + 18 \left( \frac{\delta_{36}}{\delta_0} \right) + 12 \left( \frac{\delta_{60}}{\delta_0} \right) \right]$$

Equation 2.29

Where,  $AREA$  = deflection basin area, inches

$\delta_r$  = deflection of the  $r^{\text{th}}$  sensor, inches

The radius of relative stiffness, which characterizes the stiffness of the slab-foundation system, can now be calculated. Equation 2.30 is used to calculate  $l$  if the load radius is 5.91 in (Frabizzio 1998).

$$l = \left[ LN \left( \frac{60 - AREA}{289.708} \right) / (-0.698) \right]^{2.566} \quad \text{Equation 2.30}$$

Where,  $l$  = radius of relative stiffness, in

Now the elastic modulus of the concrete can be calculated at each sensor location.

$$E_c = \frac{12(1 - \nu^2)Pl^2\delta_r^*}{\delta_r h^3} \quad \text{Equation 2.31}$$

Where,  $E_c$  = elastic modulus of the concrete, psi

$\nu$  = Poisson's ratio for concrete = .15

$P$  = FWD load, pounds

$l$  = radius of relative stiffness, inches

$\delta_r^*$  = non-dimensional deflection coefficient at distance " $r$ "

$h$  = concrete slab thickness, inches

$\delta_r$  = deflection of the  $r^{\text{th}}$  sensor, inches

$$\delta_r^* = ae^{[-be^{(-cl)}]}$$

Equation 2.32

Where,  $a, b$  and  $c$  = regression coefficients (see Table 2.5)

$l$  = radius of relative stiffness, inches

Table 2.5 Regression coefficients for  $\delta_r^*$

| Radial Distance, r<br>(inches) | a       | b       | c       |
|--------------------------------|---------|---------|---------|
| 0                              | 0.12450 | 0.14707 | 0.07565 |
| 8                              | 0.12323 | 0.46911 | 0.07209 |
| 12                             | 0.12188 | 0.79432 | 0.07074 |
| 18                             | 0.11933 | 1.38363 | 0.06909 |
| 24                             | 0.11634 | 2.06115 | 0.06775 |
| 36                             | 0.10960 | 3.62187 | 0.06568 |
| 60                             | 0.09521 | 7.41241 | 0.06255 |

The seven elastic moduli of the concrete are averaged to obtain a representative

$E_c$ . Now, the modulus of subgrade reaction, which characterizes the stiffness of the

foundation, can be calculated.

$$k = \frac{E_c h^3}{12(1 - \nu^2) l^4}$$

Equation 2.33

Where,  $k$  = modulus of subgrade reaction, pci

$E_c$  = concrete modulus of elasticity, psi

$h$  = concrete slab thickness, inches

$l$  = radius of relative stiffness, inches

## **2.6 Correlations Between Backcalculated Modulus, Laboratory-Based Modulus, DCP, and Soil Physical Properties**

Many correlations exist to convert laboratory modulus to backcalculated modulus. There are also correlations between soil properties and their MR. An introduction to these correlations can be found below.

### **2.6.1 Correlations between Laboratory and Backcalculated Resilient Modulus**

The primary purpose of establishing relationships between backcalculated FWD modulus and laboratory modulus is for the design of pavement overlays. The laboratory MR values are stress dependent. Therefore, in order to compare the different modulus values, the stress state in which the FWD test was performed must be known (George 2003).

Whether the laboratory modulus or field modulus of the subgrade soil is used in the pavement design and analysis depends on the input required for the model being used. For example, the original AASHO road test was calibrated to the laboratory MR of the soil. Therefore, when using the 1993 AASHTO pavement design or overlay procedures the appropriate input for the subgrade soil is the laboratory MR (AASHTO 1993).

MR values obtained from laboratory tests may be considerably lower than the backcalculated MR values due to differences in the magnitudes of the deviatoric stress, confining pressure, and loading rate (George 2003). Similarly, field MR values for fine grained soils, obtained by backcalculation from FWD deflections, have been reported in a number of studies to exceed the laboratory resilient modulus values by factors between 3 and 5 (AASHTO 1993).



Layer theory was employed for the analysis of the stress state under a 9000 pound FWD load. It was found that a reasonable correlation exists between FWD backcalculated moduli and the laboratory moduli based on the in-situ conditions with identical stress states (Ping et al. 2002).

$$MR_{FWD} = 1.6539MR_{lab} \quad \text{Equation 2.34}$$

From Equation 2.34 the FWD backcalculated moduli were about 1.65 times higher than the laboratory MR. The ratio is in agreement with the suggestion by the AASHTO design guide (AASHTO 1993) that the FWD backcalculated moduli are approximately two to three times higher than the laboratory determined moduli, considering that the AASHTO relationships were based primarily on clay soils. In addition, for this comparison the FWD tests were performed under in-situ soil conditions and the laboratory determined MR were obtained from the reconstituted soil samples; simulating the in-situ moisture and density conditions under identical states of stress. The possible causes for the difference between the lab *MR* and backcalculated values as reported in this study (Ping et al. 2002) were:

- The FWD backcalculation program is based on the linear elastic theory of multiple layer pavement structures while the pavement materials are not elastic.
- The FWD backcalculation method is not a unique solution method; therefore, different layer moduli could be obtained from the same FWD data.
- The lab specimens were tested almost immediately after they were compacted, and the confining pressure for the triaxial test was applied by air; the in-situ soil had been there for a long time, and the confining pressure was caused by vertical load and soil weight.

Von Quintus and Killingsworth believed the reasons for the differences in the laboratory and field moduli were related to the inability of the laboratory tests to simulate the actual in-situ confinement and effect of the surrounding materials in both the lateral and vertical direction (1998).

For rigid pavements the dynamic k value obtained from backcalculation is about two times greater than the static elastic k value that would be obtained from plate load testing of the same soil. This is due to the difference in the soil's response to dynamic and static loads. Correlations have been developed to estimate the k value as a function of CBR, density, and soil class. Additional correlations between soil properties (gradation, density, moisture content), soil classification, CBR, DCP penetration rate, and MR are available in the literature.

#### **2.6.2 Relationship between Laboratory and Backcalculated Resilient Modulus and Physical Soil Properties**

Many research studies (George 2003; George 2004; George et al. 2004; Janoo et al. 2003; Janoo et al. 1999; Maher et al. 2000; Rahim and George 2003; Yau and Von Quintus 2002) are available in the literature which investigated correlating the laboratory or backcalculated MR to soil index or physical properties.

Correlations have been developed to estimate soil k value as a function of CBR, density, and soil class. Several of these correlations are summarized in Table 2.6. Additional correlations between soil properties such as gradation, density, moisture content, soil classification, CBR, DCP penetration rate, and MR are given in the Illinois Department of Transportation's Guidelines on Subgrade Inputs and Subgrade Stability Requirements for Local Road Pavement Design (Hall et al. 2001).

Table 2.6 Range of k value for soil type, density, and CBR (Hall et al. 2001)

| AASHTO Class                                   | Soil Description                | USCS Classification | Dry Density (lb/ft <sup>3</sup> ) | CBR (%) | Static k value (psi/inch) |
|------------------------------------------------|---------------------------------|---------------------|-----------------------------------|---------|---------------------------|
| Coarse grained soils                           |                                 |                     |                                   |         |                           |
| A-1-a, well graded                             | Gravel                          | GW, GP              | 125 - 140                         | 60 - 80 | 300 - 450                 |
| A-1-a, poorly graded                           |                                 |                     | 120 - 130                         | 35 - 60 | 300 - 400                 |
| A-1-b                                          | Coarse sand                     | SW                  | 110 - 130                         | 20 - 40 | 200 - 400                 |
| A-3                                            | Fine sand                       | SP                  | 105 - 120                         | 15 - 25 | 150 - 300                 |
| A-2 soils (granular materials with high fines) |                                 |                     |                                   |         |                           |
| A-2-4, gravelly                                | Silty gravel                    | GM                  | 130 - 145                         | 40 - 80 | 300 - 500                 |
| A-2-5, gravelly                                | Silty sandy gravel              |                     |                                   |         |                           |
| A-2-4, sandy                                   | Silty sand                      | SM                  | 120 - 135                         | 20 - 40 | 300 - 400                 |
| A-2-5, sandy                                   | Silty gravelly sand             |                     |                                   |         |                           |
| A-2-6, gravelly                                | Clayey gravel                   | GC                  | 120 - 140                         | 20 - 40 | 200 - 450                 |
| A-2-7, gravelly                                | Clayey sandy gravel             |                     |                                   |         |                           |
| A-2-6, sandy                                   | Clayey sand                     | SC                  | 105 - 130                         | 10 - 20 | 150 - 350                 |
| A-2-7, sandy                                   | Clayey gravelly sand            |                     |                                   |         |                           |
| Fine grained soils                             |                                 |                     |                                   |         |                           |
| A-4                                            | Silt                            | ML, OL              | 90 - 105                          | 4 - 8   | 25 - 165                  |
|                                                | Silt/sand/gravel mix            |                     | 100 - 125                         | 5 - 15  | 40 - 220                  |
| A-5                                            | Poorly graded silt              | MH                  | 80 - 100                          | 4 - 8   | 25 - 190                  |
| A-6                                            | Plastic clay                    | CL                  | 100 - 125                         | 5 - 15  | 25 - 225                  |
| A-7-5                                          | Moderately plastic elastic clay | CL, OL              | 90 - 125                          | 4 - 15  | 25 - 215                  |
| A-7-6                                          | Highly plastic elastic clay     | CH, OH              | 80 - 110                          | 3 - 5   | 40 - 220                  |

It should be noted that the k value of fine grained soil is highly dependent on the degree of saturation. Adjustments to the k value are required for embankments less than 10 feet thick over a softer subgrade, and/or for bedrock at a depth within 10 feet.

## **CHAPTER 3**

### **FIELD AND LABORATORY INVESTIGATIONS**

#### **3.1 Introduction**

At the outset, field and laboratory investigation plans were designed to accomplish the objectives of this study. The plan consisted of the following activities and tests:

- Soil delineation in the State of Michigan
- Soil sampling
- Field tests which consist of:
  - Penetration resistance using pocket size penetrometer
  - Shear strength using pocket vane shear tester
  - Deflection using falling weight deflectometer (FWD)
- Laboratory tests which consist of:
  - Moisture content
  - Sieve analysis
  - Atterberg limits (liquid and plastic limits and plasticity index)
  - Hydrometer analysis
  - Cyclic load triaxial test

#### **3.2 Soil Delineation**

As stated in Chapter 1, the State of Michigan is geographically located within the glaciated section of North America and most of its soil has developed from glacial deposits. The thickness and composition of the drift varies from clay to gravel depending on the location. Because of the complexity of the glacial drift, about one hundred and

sixty-five different soil types were formed and are being used for engineering purposes by MDOT. To characterize the resilient modulus of the glacial drifts in an economical and practical manner, the State of Michigan was divided into 15 clusters where the soil in each cluster has similar engineering and physical characteristics. The boundaries of the 15 clusters were established based on the 1982 Quaternary Geology map of Michigan (DEQ 1982), inputs from members of the research Technical Advisory Group (TAG) of MDOT, and inputs from the soil engineers in the various MDOT Regions. After establishing the cluster boundaries, each cluster was divided into areas based on the percentages of each soil type found in the Natural Resources Conservation Service (NRCS) Web Soil Survey (Web Soil Survey). Once again, the boundaries of each area were slightly modified based on inputs from the TAG members and from the soil engineers in the various MDOT Regions. The final state divisions consisted of 99 areas within the 15 clusters. Figures 3.1 through 3.4 depict the boundaries of the clusters shown by the dashed lines and the boundaries of the 99 areas (lightly shaded) shown by the green lines. Once again it should be noted that the division between the clusters was based on similar (not the same) soil types whereas the boundaries between the areas were based on narrowing the range of the soil parameters within each cluster.

### **3.3 Roadbed Soil Sampling**

After dividing the State of Michigan into 15 clusters and 99 areas, the percent of each soil type (sand, clay, silt, etc) in each area was obtained from the Natural Resources Conservation Service (NRCS) Web Soil Survey (Web Soil Survey). Table 3.1 shows the percentages of each soil type in each of the 99 areas. Because of budget constraints and based on similar soil makeup, some areas within some clusters were grouped together

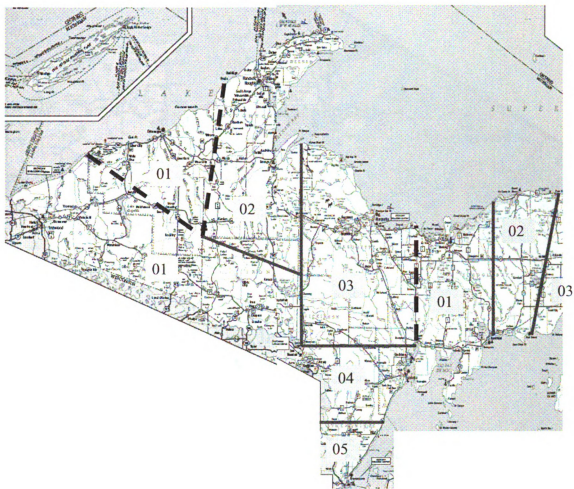


Figure 3.1 Western portion of the Upper Peninsula

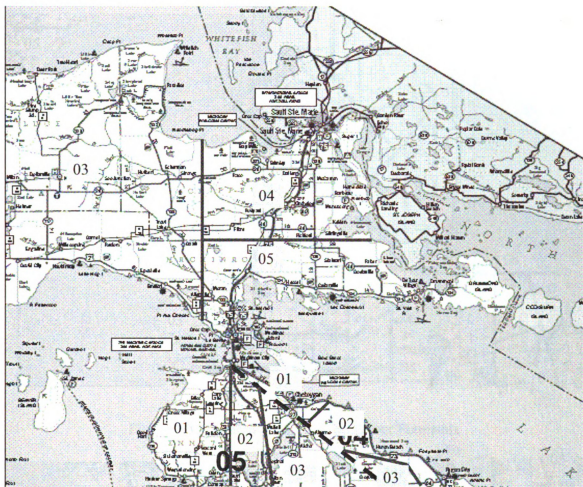


Figure 3.2 Eastern portion of the Upper Peninsula

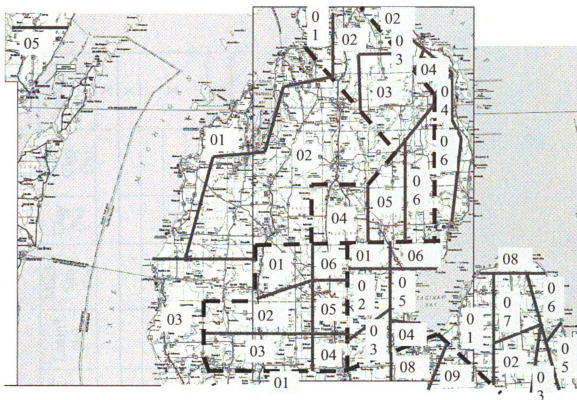


Figure 3.3 Northern portion of the Lower Peninsula

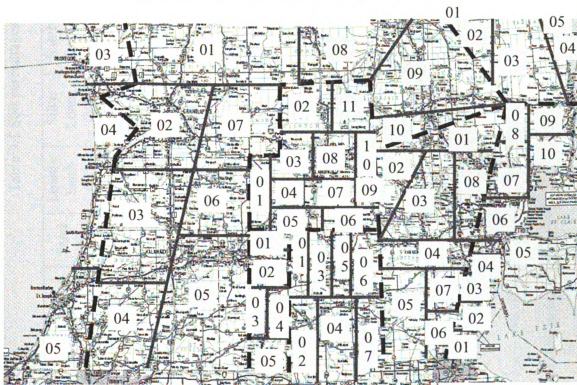


Figure 3.4 Southern portion of the Lower Peninsula



Table 3.1 Soil percentages for each area within the 15 clusters

| Cluster | Area | Muck (%) | Sand (%) | Loamy Sand (%) | Silty Loam (%) | Sandy Loam (%) | Clayey Loam (%) | Loam* (%) | Mucky Sand (%) | Clay (%) | Silty Clay (%) | Proposed Sampling |
|---------|------|----------|----------|----------------|----------------|----------------|-----------------|-----------|----------------|----------|----------------|-------------------|
| 01      | 01   |          |          |                |                | NO DATA        |                 |           |                |          |                | X                 |
|         | 02   | 12.8     | 18.6     | 38             | 18.7           | 9              |                 |           |                |          |                | X                 |
|         | 03   | 24.3     | 30.6     | 12             | 3              | 13.4           | 9.1             |           |                |          |                |                   |
|         | 04   | 24.2     | 12       | 9.4            | 9.3            | 24.9           | 18.3            |           |                |          |                | X                 |
|         | 05   | 25       | 12.8     | 15.3           | 5.6            | 28.1           | 12.5            |           |                |          |                |                   |
| 02      | 01   |          |          |                |                | NO DATA        |                 |           |                |          |                | X                 |
|         | 01   | 21       | 37       | 9.2            | 7.3            | 6.7            | 11.3            |           |                |          |                | X                 |
|         | 02   | 20       | 29.1     | 8.6            | 12.2           | 5.3            | 14.8            |           |                |          |                |                   |
|         | 04   | 9.2      | 8        | 16             | 63             |                |                 |           |                |          |                | X                 |
|         | 05   | 14.8     | 37       | 33.1           | 13             |                |                 |           |                |          |                | X                 |
| 03      | 03   | 29.2     | 29.6     | 9.4            | 11.5           | 16             |                 |           |                |          |                |                   |
|         | 06   | 20       | 13.2     | 9.4            |                | 37.4           |                 |           | 10             |          |                | X                 |
|         | 02   | 25       | 15.2     | 34.4           | 16.2           |                |                 |           |                |          |                |                   |
|         | 01   | 58.4     | 33.3     | 4.1            |                |                |                 |           |                |          |                | X                 |
|         | 05   | 37.4     | 35       | 4.4            | 10             | 6.5            |                 |           |                |          |                | X                 |
| 04      | 03   | 16.1     | 50       |                |                | 28.4           |                 |           |                |          |                | X                 |
|         | 04   | 24.8     |          |                |                | 59.9           |                 | 14.5      |                |          |                | X                 |

Note: empty cells indicate 0 percent of that soil type.

\* Loam contains sand, silt and clay. The breakdown of the loam is unknown at this point.

Table 3.1 (cont'd)

| Cluster | Area | Muck (%) | Sand (%) | Loamy Sand (%) | Silty Loam (%) | Sandy Loam (%) | Clayey Loam (%) | Loam* (%) | Mucky Sand (%) | Clay (%) | Silty Clay (%) | Proposed Sampling |
|---------|------|----------|----------|----------------|----------------|----------------|-----------------|-----------|----------------|----------|----------------|-------------------|
| 05      | 01   | 22       | 5        | 72.4           |                |                |                 |           |                |          |                | X                 |
|         | 02   | 13.1     | 41.5     | 39.3           |                |                |                 |           |                |          |                |                   |
|         | 03   | 14.3     | 74.7     | 7.8            |                | 2              |                 |           |                |          |                | X                 |
|         | 04   | 26.3     | 51.4     | 17.4           |                |                |                 |           |                |          |                |                   |
|         | 05   |          | 97.9     | 1.7            |                |                |                 |           |                |          |                | X                 |
|         | 06   | 4.4      | 14.4     | 25.2           |                | 13             |                 | 39.2      |                |          |                | X                 |
| 06      | 01   | 3.3      | 53.5     | 30.4           |                | 9.3            |                 |           |                |          |                | X                 |
|         | 02   | 8.1      | 71.8     | 7.5            |                | 8.2            |                 |           |                |          |                | X                 |
|         | 03   | 8.1      | 75.6     | 5.9            |                | 4.7            |                 |           |                |          |                | X                 |
|         | 04   |          | 25.7     | 39.5           |                | 8              |                 | 26        |                |          |                | X                 |
|         | 05   |          | 23.6     | 41.6           |                | 12.2           |                 | 17.1      |                |          |                |                   |
| 07      | 04   |          | 14.9     | 6.8            |                | 11.4           |                 | 65.3      |                |          |                | X                 |
|         | 02   |          | 63.2     | 7              |                |                |                 |           | 25.1           |          |                | X                 |
|         | 05   | 2        | 18.4     | 18.6           |                | 7.9            |                 | 48        |                |          |                | X                 |
|         | 03   | 6.2      | 53.9     | 26.3           |                | 12.7           |                 |           |                |          |                | X                 |
|         | 01   | 15.1     | 32.1     | 28.6           |                | 10             |                 | 10.1      |                |          |                |                   |
|         | 06   | 13       | 34.3     | 36.6           |                | 7.5            |                 | 7.1       |                |          |                | X                 |

Note: empty cells indicate 0 percent of that soil type.

\* Loam contains sand, silt and clay. The breakdown of the loam is unknown at this point.

Table 3.1 (cont'd)

| Cluster | Area | Muck (%) | Sand (%) | Loamy Sand (%) | Silty Loam (%) | Sandy Loam (%) | Clayey Loam (%) | Loam* (%) | Mucky Sand (%) | Clay (%) | Silty Clay (%) | Proposed Sampling |
|---------|------|----------|----------|----------------|----------------|----------------|-----------------|-----------|----------------|----------|----------------|-------------------|
| 08      | 03   |          | 2        | 24.9           |                |                |                 | 72.1      |                |          |                | X                 |
|         | 04   |          | 2        | 8.6            |                | 2.6            |                 | 86.8      |                |          |                | X                 |
|         | 01   |          | 12.4     | 15.6           |                | 11.3           |                 | 58.8      |                |          |                | X                 |
|         | 05   |          | 15       | 29.2           |                | 6.1            |                 | 49.7      |                |          |                |                   |
|         | 02   |          | 29.8     | 44.9           |                |                |                 | 21.1      |                |          |                | X                 |
|         | 06   | 19.2     | 39.4     | 22.2           |                | 11             |                 | 8         |                |          |                | X                 |
| 09      | 10   |          |          | 8.2            | 43.3           | 3.2            | 9.6             | 33.4      |                |          |                | X                 |
|         | 01   | 16       | 6.7      | 64.4           |                | 3.3            |                 | 7.3       |                |          |                | X                 |
|         | 08   |          | 12.1     | 19.1           |                | 3.4            |                 | 62.8      |                |          |                | X                 |
|         | 05   | 8.9      |          |                |                | 6.4            |                 | 83        |                |          |                | X                 |
|         | 03   | 33.4     |          | 19.4           |                | 18.1           |                 | 21.4      |                |          |                | X                 |
|         | 02   |          | 22.8     | 40.5           |                | 10.1           | 6.3             | 12.4      |                |          |                | X                 |
|         | 09   | 4.3      | 14.8     | 43.3           |                | 22.4           |                 | 9.6       |                |          |                |                   |
|         | 07   | 4.8      | 3        | 11.2           |                | 23.2           |                 | 52        |                |          |                | X                 |
|         | 04   | 12.2     |          | 22.5           |                | 28.3           |                 | 32.9      |                |          |                |                   |
|         | 06   | 2.2      |          | 8.6            |                | 44.5           |                 | 41.9      |                |          |                |                   |

Note: empty cells indicate 0 percent of that soil type.

\* Loam contains sand, silt and clay. The breakdown of the loam is unknown at this point.

Table 3.1 (cont'd)

| Cluster | Area | Muck (%) | Sand (%) | Loamy Sand (%) | Silty Loam (%) | Sandy Loam (%) | Clayey Loam (%) | Loam (%) | Mucky Sand (%) | Clay (%) | Silty Clay (%) | Proposed Sampling |
|---------|------|----------|----------|----------------|----------------|----------------|-----------------|----------|----------------|----------|----------------|-------------------|
| 10      | 08   |          |          |                |                | 4.1            |                 | 94.8     |                |          |                | X                 |
|         | 10   |          |          | 8.5            |                | 12.7           |                 | 75.8     |                |          |                |                   |
|         | 11   |          |          |                |                | 13.2           | 11.8            | 73.8     |                |          |                | X                 |
|         | 06   | 10.8     |          | 11.5           |                | 15.3           |                 | 60.9     |                |          |                | X                 |
|         | 05   | 3.7      |          | 11.4           |                | 29.3           |                 | 55       |                |          |                |                   |
|         | 09   | 30.1     |          | 27.6           |                | 29.8           |                 | 11.1     |                |          |                | X                 |
|         | 04   | 16.7     |          |                |                | 31.3           |                 | 48.5     |                |          |                | X                 |
|         | 03   | 10.6     |          | 11.1           |                | 34.4           |                 | 38.1     |                |          |                | X                 |
|         | 01   |          |          | 6.2            |                | 34.4           |                 | 57.5     |                |          |                |                   |
|         | 07   | 3.2      |          | 8              |                | 39.9           |                 | 46.1     |                |          |                | X                 |
| 11      | 02   | 7.1      |          |                |                | 40.6           |                 | 48.4     |                |          |                |                   |
|         | 01   | 17       |          | 34.5           |                | 27.6           |                 | 15.6     |                |          |                | X                 |
|         | 02   | 6.9      |          | 5.8            |                | 54.8           |                 | 25.3     |                |          |                | X                 |
|         | 05   | 11.4     |          | 11.6           |                | 65.4           |                 | 10.3     |                |          |                | X                 |
|         | 03   |          |          |                |                | 67.2           |                 | 30.5     |                |          |                |                   |
|         | 04   | 6        |          |                |                | 72.6           |                 | 18.5     |                |          |                | X                 |

Note: empty cells indicate 0 percent of that soil type.

\* Loam contains sand, silt and clay. The breakdown of the loam is unknown at this point.

Table 3.1 (cont'd)

| Cluster | Area | Muck (%) | Sand (%) | Loamy Sand (%) | Silty Loam (%) | Sandy Loam (%) | Clayey Loam (%) | Loam (%) | Mucky Sand (%) | Clay (%) | Silty Clay (%) | Proposed Sampling |
|---------|------|----------|----------|----------------|----------------|----------------|-----------------|----------|----------------|----------|----------------|-------------------|
| 12      | 01   | 9.2      | 3.9      | 18.2           |                | 36.4           |                 | 24.7     |                |          |                | X                 |
|         | 02   | 7.9      | 9.2      | 5.6            | 11.4           | 53.2           |                 | 9.4      |                |          |                |                   |
|         | 06   | 22.7     | 17.4     |                |                | 34.3           | 17.9            |          |                |          |                | X                 |
|         | 04   | 5.4      |          | 12             |                | 16.5           | 26.5            | 37.6     |                |          |                | X                 |
|         | 07   | 6.2      |          |                |                | 7              |                 | 84       |                |          |                | X                 |
|         | 03   | 18.5     |          |                |                | 56.5           |                 | 17.7     |                |          |                | X                 |
|         | 05   | 9.2      |          | 5.8            |                | 62.5           |                 | 19       |                |          |                |                   |
| 13      | 08   |          | 4.4      | 5.7            |                | 28.1           | 39.8            | 14.8     |                |          |                | X                 |
|         | 07   |          | 5.1      | 28.5           |                | 30.5           | 28.8            | 5.8      |                |          |                | X                 |
|         | 06   |          | 7.2      | 36.2           |                | 34.3           | 17.9            | 4.4      |                |          |                |                   |
|         | 05   |          |          |                |                | 6.6            | 37.8            | 55.5     |                |          |                | X                 |
|         | 04   | 6.2      |          | 4              | 13.6           |                | 14.2            | 60       |                |          |                | X                 |
|         | 02   | 12       |          | 11.6           |                | 37.1           |                 | 34.3     |                |          |                | X                 |
|         | 03   | 13.1     |          | 4.3            | 28.6           | 20             | 24.9            |          |                |          |                | X                 |
|         | 01   | 12.4     |          | 31.4           |                | 44             |                 | 4.8      |                |          |                | X                 |

Note: empty cells indicate 0 percent of that soil type.

\* Loam contains sand, silt and clay. The breakdown of the loam is unknown at this point.

Table 3.1 (cont'd)

| Cluster | Area | Muck (%) | Sand (%) | Loamy Sand (%) | Silty Loam (%) | Sandy Loam (%) | Clayey Loam (%) | Loam (%) | Mucky Sand (%) | Clay (%) | Silty Clay (%) | Proposed Sampling |
|---------|------|----------|----------|----------------|----------------|----------------|-----------------|----------|----------------|----------|----------------|-------------------|
| 14      | 01   | 8.2      |          | 29             |                | 20.3           | 18.7            | 14.8     |                |          |                | X                 |
|         | 02   | 9.5      | 3        | 28.4           |                | 21.4           | 35.5            |          |                |          |                | X                 |
|         | 03   | 5.2      |          | 11             | 25.5           |                |                 | 3.5      |                |          |                | X                 |
|         | 04   |          |          |                | 28.4           |                | 13.2            | 50       |                |          |                | X                 |
|         | 07   |          | 21.4     | 7.2            | 12.3           | 28.9           | 13.5            | 12.9     |                |          |                | X                 |
|         | 08   |          |          | 9              |                | 36.7           |                 | 50.9     |                |          |                | X                 |
|         | 09   |          | 11.2     | 3.5            |                | 16.2           |                 | 64.3     |                |          |                |                   |
|         | 10   |          |          | 5.8            | 4.6            | 9              | 57              |          |                | 7        | 12.5           | X                 |
|         | 05   |          |          |                |                | NO DATA        |                 |          |                |          |                |                   |
|         | 06   |          |          |                |                | NO DATA        |                 |          |                |          |                |                   |
| 15      | 04   |          | 7.4      | 6.1            | 22.5           | 4.9            | 33.7            | 17.7     |                |          |                | X                 |
|         | 06   |          | 5.1      | 13.8           | 3.8            | 7              |                 | 62.8     |                |          |                | X                 |
|         | 02   | 20.9     | 6.4      | 5.5            | 14.9           | 15.3           |                 | 33.1     |                |          |                | X                 |
|         | 07   |          |          | 36             |                | 16.2           |                 | 39.1     |                |          |                | X                 |
|         | 01   |          | 15       | 28             |                | 23.5           |                 | 31       |                |          |                |                   |
|         | 03   |          |          | 4.8            | 60.3           | 23.9           |                 | 8.5      |                |          |                | X                 |
|         | 08   |          |          | 7.8            | 10.4           | 37.5           |                 | 37       |                |          |                |                   |
|         | 05   |          |          | 4.4            |                | 38.6           |                 | 56       |                |          |                | X                 |

Note: empty cells indicate 0 percent of that soil type.

\* Loam contains sand, silt and clay. The breakdown of the loam is unknown at this point.

which reduced the number of areas from 99 to 75. The combined areas are collectively marked by the letter “X” in Table 3.1. For each of the 75 areas, disturbed roadbed soil samples were obtained. Table 3.2 provides a list of the designation number and the location of each of the disturbed roadbed soil samples. The designation number consists of 9 characters A-BCD-E-(FG-HI) where A designates the road type (I=interstate, U=US road, M=Michigan road), BCD represents the route number, E shows the traveling direction (N=North, E=East, S=South, W=West), FG is the cluster number (01, 02, ...15), and HI is the area number (01, 02, ... 10). For example, the sample designation number M-059-W-(13-02) implies that the sample was obtained from Westbound M-59 in cluster 13 and area 02. Table 3.2 also shows the results, when available, of the pocket penetrometer and the pocket vane shear tester. It should be noted that empty cells indicate no tests were performed at those locations.

In addition, 10 undisturbed Shelby tube samples were collected at locations where the disturbed soil samples indicated the presence of clay subgrade soil. The locations of the Shelby tube samples can be found in Table 3.3. Both the disturbed and undisturbed soil samples were properly transported to the Geotechnical Laboratory at Michigan State University where each soil sample was subjected to various laboratory tests. These tests and the test results are presented in section 3.5 below.

Table 3.2 Locations of pocket penetrometer and vane shear tests

| Sample number   | Location                                            | Vane shear test | Pocket penetrometer |
|-----------------|-----------------------------------------------------|-----------------|---------------------|
| M-045-S (01-01) | 405 feet South of Ontonagon River                   |                 |                     |
| U-002-E (02-01) | 385 feet East of M-45                               | 2               | 2.3                 |
| M-028-W (02-02) | ~1000 feet West of M-141                            | 4               | 3.5                 |
| M-028-W (02-03) | ~2000 feet East of M-35                             | 0.25            | 1.4                 |
| U-002-E (02-04) | 765 feet East of Spalding Rd                        | didn't fail     | didn't penetrate    |
| U-002-E (03-01) | 400 feet East of Hwy 13                             | 0.26            | 0.4                 |
| M-028-W (03-02) | 1500 feet North of M-77                             | 0.5             | 0.7                 |
| M-028-W (03-03) | 500 feet West of Basnau Rd                          | 0.25            | 3                   |
| U-002-E (03-03) | 200 feet East of M-117                              | 1               | 1.3                 |
| I-075-N (03-04) | mile marker 380                                     | 0.25            | 0.4                 |
| I-075-N (03-05) | mile marker 368                                     | didn't fail     | didn't penetrate    |
| U-023-S (04-01) | 320 feet North of F 05 Co Rd                        | 0.5             | 0.9                 |
| M-068-W (04-02) | 180 feet West of US-23                              | 0.5             | 2                   |
| M-068-W (04-03) | 150 feet West of Little Ocqueoc River               | 0.5             | 0.9                 |
| M-065-S (04-04) | 160 feet South of Elm Hwy                           | didn't fail     | didn't penetrate    |
| M-032-W (04-05) | 220 feet East of Herron Rd                          | 3               | 5.1                 |
| U-131-N (05-01) | 200 feet South of Michigan Fisheries Visitor Center | 0.25            | 1                   |
| U-127-N (05-04) | 120 feet North of Co Rd 300                         | 0.25            | 0.4                 |
| M-033-S (05-05) | 750 feet South of Peters Rd                         | didn't fail     | didn't penetrate    |
| M-072-W (05-06) | 330 feet West of M-32                               | 6               | 3.7                 |
| M-132-N (06-01) | 1000 feet North of Addis Rd (paved rd)              | 0.75            | 1.4                 |



Table 3.2 (cont'd)

| Sample number   | Location                                                                                    | Vane shear test | Pocket penetrometer |
|-----------------|---------------------------------------------------------------------------------------------|-----------------|---------------------|
| I-075-N (06-02) | 160 feet North of Co Rd 662                                                                 | 0.25            | 1.8                 |
| U-031-N (06-03) | 307 feet North of M-46                                                                      |                 |                     |
| I-196-N (06-05) | 110 feet North of Schmuhl Rd                                                                | 1               | 3.3                 |
| M-020-W (07-02) | ~.5 mile East of 13 Mile Rd                                                                 |                 |                     |
| M-020-E (07-03) | ~500 feet East of Cottonwood Ave                                                            |                 |                     |
| U-127-N (07-04) | 100 feet North of Jefferson Rd                                                              | didn't fail     | didn't penetrate    |
| U-127-N (07-05) | 65 feet North of Vernon Rd                                                                  | 5               | 3.6                 |
| M-061-E (07-06) | 420 feet East of left hand turn on M-61 (off US-127)                                        |                 |                     |
| M-061-E (08-02) | 165 feet West of Hockaday                                                                   | 0.5             | 0.6                 |
| U-010-W (08-03) | 65 feet West of bridge before Stark Rd                                                      | didn't fail     | 2.3                 |
| U-010-W (08-04) | 145 feet West of Mackinaw Rd                                                                | didn't fail     | didn't penetrate    |
| I-075-S (08-05) | 115 feet South of Prevo Rd                                                                  | didn't fail     | didn't penetrate    |
| I-075-N (08-06) | 80 feet North of bridge after exit 195                                                      | 1.7             | 2.1                 |
| U-131-S (09-01) | 160 feet South of Lake Montcalm Rd                                                          |                 |                     |
| I-096-W (09-02) | 141 feet West of Morse Lake Ave                                                             |                 |                     |
| U-131-S (09-03) | 105 feet South of 110th Ave                                                                 | 0.5             | 1.1                 |
| U-131-S (09-05) | 60 feet South of 'Reduce Speed 55 MPH' sign right where it turns from interstate to freeway | 0.5             | 1.1                 |
| M-044-E (09-07) | Station 137+10                                                                              |                 |                     |
| I-075-S (09-08) | 650 feet South of Wadsworth Rd                                                              |                 |                     |
| M-024-S (09-09) | 20 feet North of Burley Rd                                                                  | 1.25            | 1.9                 |

Table 3.2 (cont'd)

| Sample number   | Location                                  | Vane shear test | Pocket penetrometer |
|-----------------|-------------------------------------------|-----------------|---------------------|
| I-069-E (09-10) | 172 feet East of Grand River Rd           | 0.5             | 1                   |
| I-069-N (10-01) | 75 feet North of Base Line Hwy            | 3               | 4                   |
| I-096-W (10-03) | 210 feet West of bridge before exit 97    | 1               | 1.3                 |
| I-069-N (10-04) | 150 feet North of Island Hwy              | 1.75            | 4                   |
| I-069-N (10-05) | 100 feet North of Five Points Hwy         | 2.5             | 3.2                 |
| I-096-W (10-09) | 140 feet West of Dietz Rd                 | 2.7             | 3.1                 |
| I-069-E (10-10) | 120 feet East of Britton Rd               | didn't fail     | didn't penetrate    |
| M-021-E (10-11) | 800 feet East of Shepards Rd              | 3               | 2.6                 |
| I-069-N (11-01) | 160 feet North of mile marker 42          |                 |                     |
| I-094-W (11-02) | 132 feet West of exit 110 on ramp         | 1.5             | 2.5                 |
| M-060-W (11-03) | 135 feet West of Southbound I-69 overpass | 3               | 5.5                 |
| I-069-S (11-05) | 95 feet South of Bridge after exit 10     |                 |                     |
| I-094-W (12-01) | 95 feet West of 29 Mile Rd                | 1               | 2.6                 |
| I-094-W (12-03) | 36 feet West of bridge after exit 135     | 1               | 1.5                 |
| U-012-E (12-04) | 100 feet East of Emarld Rd                | didn't fail     | 6                   |
| I-094-W (12-06) | 53 feet West of Mt Hope Rd                | 3               | 3.5                 |
| U-012-E (12-07) | 120 feet West of Person Hwy               | 0.5             | 0.9                 |
| M-024-S (13-01) | 250 feet North of Best Rd                 | 3.5             | 5                   |
| M-059-W (13-02) | Station 131+29                            |                 |                     |
| M-014-W (13-03) | 255 feet West of Napier Rd                | didn't fail     | 4.5                 |

Table 3.2 (cont'd)

| Sample number   | Location                                                          | Vane shear test | Pocket penetrometer |
|-----------------|-------------------------------------------------------------------|-----------------|---------------------|
| I-094-W (13-04) | Station 75+02                                                     |                 |                     |
| U-012-E (13-05) | Between Maple Rd and Industrial Ave                               | didn't fail     | didn't penetrate    |
| U-023-N (13-07) | 60 feet North of Sherman                                          | 0.75            | 1.6                 |
| M-010-E (13-08) | Station 38+00                                                     | didn't fail     | 3.5                 |
| I-075-S (14-01) | 60 feet South of Gaynier Rd                                       | 3               | 3.5                 |
| I-075-S (14-02) | 40 feet South of Nadeau Rd                                        | 4.5             | 3.5                 |
| U-024-S (14-03) | ~1000 feet South of Ready Rd                                      | 4.5             | 5                   |
| U-024-S (14-04) | 150 feet North of Pardee                                          | 0.25            | 0.5                 |
| I-075-S (14-04) | Station 23+00                                                     |                 |                     |
| I-094-W (14-05) | 300 feet West of Monroe Blvd                                      | 3.5             | 4.3                 |
| M-153-E (14-06) | ~800 feet East of Greenfield Rd                                   | didn't fail     | 4.5                 |
| M-053-S (14-07) | 1500 feet South of Canal Rd                                       |                 |                     |
| I-094-W (14-09) | 350 feet West of Wadhams Rd                                       | 2.5             | 3                   |
| I-094-W (14-10) | 227 feet West of Palms Rd                                         | didn't fail     | 4                   |
| M-053-S (15-02) | 300 feet South of M-46                                            | 2               | 2.3                 |
| M-090-E (15-03) | 210 feet East of Murray Rd                                        | 0.5             | 0.7                 |
| M-090-E (15-04) | 200 feet East of Bobcock St<br>37 feet East of Village Limit sign | didn't fail     | didn't penetrate    |
| M-025-S (15-05) | 200 feet North of Day Rd                                          | 1.5             | 2.8                 |
| M-25-N (15-06)  | 170 feet North of North Huron Dr                                  | 1.3             | 2.2                 |
| M-019-S (15-07) | 650 feet South of Thompson Rd<br>1 mile South of M-142            | 1.5             | 2.7                 |

Table 3.3 Locations of Shelby tube samples

| Region     | Sample number   | Control Section | Number of Shelby tubes |
|------------|-----------------|-----------------|------------------------|
| Metro      | M-153-E (14-06) | 82081           | 1                      |
|            | M-010-E (13-08) | 82111           | 1                      |
|            | I-094-W (14-09) | 77111           | 2                      |
| University | I-075-S (14-01) | 58151           | 2                      |
| Bay        | U-010-W (08-04) | 9101            | 2                      |
|            | U-127-N (07-05) | 37014           | 2                      |

### 3.4 Field Testing

The field testing consists of measuring the soils penetration resistance using pocket penetrometer, the shear strength resistance using pocket size vane shear tester, and pavement surface deflection using FWD. The pocket penetrometer and pocket vane shear tests were conducted at the same time and at the same location where some of the disturbed roadbed soil samples were obtained. The FWD tests, on the other hand, were conducted during the fall and spring seasons to assess the impact of the two seasons on the measured deflection and consequently on the backcalculated roadbed soil modulus. The three tests are presented below.

#### 3.4.1 Penetration Resistance Using Pocket Penetrometer

The pocket penetrometer is a small hand held device that consists of a spring loaded probe that slides into a cylinder. The maximum pressure required to push the probe 0.25 inches into the soil is recorded. Pocket penetrometer is typically used to estimate the bearing capacity of the soil surface (Liu and Evett 2008). However, for this project the penetration resistance will be recorded and correlations between MR and penetration resistance will be developed (if possible). A total of 67 pocket penetrometer

tests were conducted and the locations where pocket penetrometer tests were performed and the results can be found in Table 3.2.

### **3.4.2 Pocket Vane Shear Test**

The field vane test is used to estimate the undrained shear strength of the soil. To perform the test the full depth of the vane is inserted into the soil. The vane is then rotated by applying torque at the top of the rod until the soil fails (Das 2004). The maximum torque required to fail the sample will be used in an attempt to develop correlations to the MR. The locations of the 67 tests are listed in Table 3.2 along with the results of the tests.

### **3.4.3 Falling Weight Deflectometer (FWD)**

FWD tests were/are being performed as a supplement to the laboratory tests as a second technique to calculate the MR. MSU requested and received 502 FWD files from MDOT from FWD tests that were conducted prior to the start of this research project. After the locations of all FWD files were established, MSU obtained thickness data during the time of the test for every FWD file that could be found at MDOT. The total thickness data for 103 files were obtained. Therefore, only 103 of the existing FWD files were backcalculated for this project because the cross section data is required to accurately backcalculate the MR values. To supplement the existing FWD data, test locations were requested for this project. FWD tests were conducted at every Shelby tube location to provide laboratory and backcalculated values at the same location so the values can be compared. The Shelby tube locations were chosen based on the results of the disturbed soil sampling. Additional FWD tests were/are being performed along pavements in intervals of 528 feet (0.1 miles) in order to determine the variability in the

roadbed soil. Initially, 208 locations were requested for FWD testing. Of those, 124 were ranked as high priority for the fall season and 84 for the spring season. However, due to delays in starting the FWD testing the list had to be reduced to 86 high priority fall testing locations and 58 for the spring season. Then, due to difficulties in obtaining traffic control for the FWD tests the list was further reduced to contain locations only on interstates. This created 52 high priority spring and fall test locations. Due to FWD testing delays at MDOT, FWD data is not discussed here. Discussion on the FWD testing can be found in Tyler Dawson's thesis (Dawson 2008).

### **3.5 Laboratory Testing**

Once the disturbed and undisturbed Shelby tube samples were received in the laboratory, they were subjected to a battery of tests that include: the natural moisture content, grain size test that included dry and wet sieving and hydrometer tests, Atterberg limits (liquid and plastic limits and plasticity index), and cyclic load triaxial tests. These tests and the test results are presented in the next subsections.

#### **3.5.1 Moisture Content**

All 81 soil samples collected underwent natural moisture content tests according to ASTM C 29 standard test procedure. The results of the moisture content tests can be found in Table 3.4. It should be noted that samples with an "X" under the Shelby tube column were taken from undisturbed Shelby tubes and those with nothing in the cell are from disturbed samples. A detailed review of the affect of moisture content on the MR values was conducted and it is included in Chapter 2. The effects of moisture content on the MR values in this study are discussed in Chapter 4.

### 3.5.2 Grain Size Distribution

The grain size distribution for soils with more than 10 percent passing sieve number 200 was determined using sieve and hydrometer analyses. For soils with less than 10 percent passing sieve number 200 the grain size distribution was determined by sieve analysis only.

#### 3.5.2.1 Sieve Analysis

All bag samples were subjected to either wet (see Figure 3.5) or dry sieve (see Figure 3.6) analysis according to ASTM C 117 and ASTM C136 standard test procedures, respectively. First all soils were subjected to dry sieving. When the test results showed more than 10 percent passing sieve number 200, the soil was subjected to wet sieve and hydrometer analyses. The objective of the test is to determine the particle size distribution and the classification of the roadbed soil. In all analyses, the sieve sizes and the sieve arrangement were chosen based on the MDOT Uniform Field Soil Classification (see Appendix A). A total of 81 dry sieves and 56 wet sieve tests were run. Results of the dry and wet sieve analyses can be found in Table 3.4.

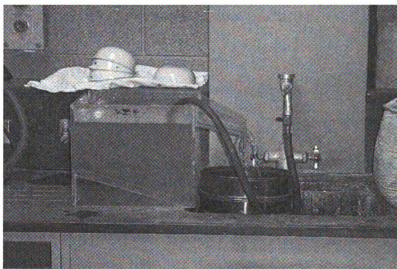


Figure 3.5 Wet sieve test



Figure 3.6 Dry sieve test

#### **3.5.2.2 Hydrometer Analysis**

Soil samples which have more than 10 percent passing sieve number 200 were subjected to hydrometer analysis according to the AASHTO T 88 standard test procedure. A total of 56 hydrometer analyses were conducted.

#### **3.5.3 Atterberg Limits**

Soil samples with more than eight percent passing the #200 sieve were subjected to Atterberg limit tests. The Atterberg limits consist of liquid limit, plastic limit, and plasticity index. The liquid limit is the water content at which soils change behavior from plastic to liquid. Whereas the plastic limit is the water content at which soils possess plastic behavior (Liu and Evett 2008). Both the liquid and the plastic limit tests were conducted according to the AASHTO T 89 standard test procedure. Figure 3.7 shows the



Table 3.4 Laboratory test results

| Sample number   | Shelby tube | Natural water content (%) | Sample weight (g) | Percent passing sieve # |       |       |       |       |       |       |    | Atterberg limits |    |        | D <sub>10</sub> | D <sub>30</sub> | D <sub>60</sub> | C <sub>u</sub> = D <sub>60</sub> /D <sub>10</sub> | C <sub>c</sub> = D <sub>30</sub> <sup>2</sup> /(D <sub>60</sub> (D <sub>10</sub> )) | Classification |  |
|-----------------|-------------|---------------------------|-------------------|-------------------------|-------|-------|-------|-------|-------|-------|----|------------------|----|--------|-----------------|-----------------|-----------------|---------------------------------------------------|-------------------------------------------------------------------------------------|----------------|--|
|                 |             |                           |                   | 3/8 inch                | 4     | 10    | 20    | 40    | 100   | 200   | LL | PL               | PI | AASHTO |                 |                 |                 |                                                   |                                                                                     | USCS           |  |
|                 |             |                           |                   | 9.500                   | 4.750 | 2.000 | 0.850 | 0.425 | 0.150 | 0.075 |    |                  |    |        |                 |                 |                 |                                                   |                                                                                     |                |  |
| M-045-S (01-01) |             | 11.5                      | 298.8             | 99.5                    | 99.3  | 98.9  | 96.8  | 96.7  | 77.2  | 66.7  | 26 | 16               | 10 | 0.0030 | 0.006           | 0.040           | 13.33           | 0.30                                              | A-6                                                                                 | CL             |  |
| U-002-E (02-01) |             | 16.8                      | 303.3             | 99.1                    | 97.8  | 96.6  | 92.3  | 68.1  | 46.4  | 39.2  | 18 | -                | NP | 0.008  | 0.040           | 0.300           | 37.50           | 0.67                                              | A-4                                                                                 | SM             |  |
| M-028-W (02-02) |             | 21.0                      | 200.0             | 100.0                   | 99.4  | 98.0  | 93.4  | 83.2  | 64.5  | 56.1  | 23 | -                | NP | 0.0080 | 0.024           | 0.110           | 13.75           | 0.65                                              | A-4                                                                                 | ML             |  |
| M-028-W (02-03) |             | 6.6                       | 535.8             | 100.0                   | 99.3  | 97.2  | 92.1  | 81.8  | 23.4  | 6.1   | 16 | -                | NP | 0.091  | 0.175           | 0.285           | 3.13            | 1.18                                              | A-1-b                                                                               | SP-SM          |  |
| U-002-E (02-04) |             | 10.8                      | 200.0             | 100.0                   | 99.4  | 98.0  | 93.4  | 83.2  | 64.5  | 54.1  | 19 | -                | NP | 0.0100 | 0.050           | 0.110           | 11.00           | 2.27                                              | A-4                                                                                 | ML             |  |
| U-002-E (03-01) |             | 5.0                       | 525.3             | 100.0                   | 99.8  | 99.6  | 98.5  | 92.6  | 15.8  | 6.5   | 13 | -                | NP | 0.130  | 0.190           | 0.275           | 2.12            | 1.01                                              | A-3                                                                                 | SP-SM          |  |
| M-028-W (03-02) |             | 3.1                       | 519.1             | 99.9                    | 99.6  | 99.3  | 97.9  | 89.7  | 14.0  | 3.0   | NA | NA               | NP | 0.150  | 0.190           | 0.280           | 1.87            | 0.86                                              | A-3                                                                                 | SP             |  |
| U-002-E (03-03) |             | 13.1                      | 222.9             | 100.0                   | 96.8  | 93.7  | 88.7  | 77.8  | 31.7  | 25.1  | 15 | -                | NP | 0.002  | 0.120           | 0.300           | 150.00          | 24.00                                             | A-2-4                                                                               | SM             |  |
| M-028-W (03-03) |             | 4.8                       | 520.2             | 94.1                    | 87.5  | 82.6  | 71.2  | 45.5  | 11.1  | 6.4   | 21 | -                | NP | 0.140  | 0.285           | 0.600           | 4.29            | 0.97                                              | A-3                                                                                 | SP-SM          |  |
| I-075-N (03-04) |             | 9.4                       | 549.2             | 99.9                    | 99.8  | 99.5  | 98.4  | 91.3  | 10.0  | 1.5   | NA | NA               | NP | 0.160  | 0.200           | 0.280           | 1.75            | 0.89                                              | A-3                                                                                 | SP             |  |
| I-075-N (03-05) |             | 21.2                      | 197.8             | 100.0                   | 99.9  | 94.1  | 92.4  | 80.9  | 60.3  | 48.2  | 55 | 22               | 33 | 0.001  | 0.002           | 0.150           | 150.00          | 0.03                                              | A-7-6                                                                               | SC             |  |
| U-023-S (04-01) |             | 22.0                      | 547.2             | 98.8                    | 98.8  | 98.5  | 96.4  | 90.3  | 10.3  | 4.3   | NA | NA               | NP | 0.170  | 0.200           | 0.280           | 1.65            | 0.84                                              | A-3                                                                                 | SP             |  |
| M-068-W (04-02) |             | 4.0                       | 205.0             | 99.9                    | 98.6  | 91.0  | 51.3  | 25.2  | 16.0  | 14.1  | 18 | 12               | 6  | 0.040  | 0.500           | 1.000           | 25.00           | 6.25                                              | A-2-4                                                                               | SC-SM          |  |
| M-068-W (04-03) |             | 33.3                      | 515.6             | 100.0                   | 100.0 | 99.7  | 98.7  | 89.8  | 14.3  | 3.7   | NA | NA               | NP | 0.160  | 0.190           | 0.280           | 1.75            | 0.81                                              | A-3                                                                                 | SP             |  |
| M-065-S (04-04) |             | 8.1                       | 201.5             | 99.3                    | 95.4  | 91.3  | 87.5  | 72.7  | 30.4  | 21.5  | 30 | -                | NP | 0.001  | 0.150           | 0.300           | 300.00          | 75.00                                             | A-2-4                                                                               | SM             |  |
| M-032-W (04-05) |             | 9.6                       | 203.4             | 100.0                   | 99.8  | 99.6  | 99.0  | 95.0  | 64.6  | 48.7  | 19 | 12               | 7  | 0.001  | 0.006           | 0.130           | 130.00          | 0.28                                              | A-4                                                                                 | SC-SM          |  |
| U-131-N (05-01) |             | 13.1                      | 199.4             | 99.8                    | 99.2  | 96.4  | 95.0  | 78.7  | 43.5  | 29.2  | 14 | -                | NP | 0.016  | 0.140           | 0.280           | 17.50           | 4.38                                              | A-2-4                                                                               | SM             |  |
| U-127-N (05-04) |             | 8.9                       | 527.6             | 91.8                    | 84.4  | 79.1  | 73.3  | 53.6  | 6.4   | 3.7   | NA | NA               | NP | 0.180  | 0.260           | 0.500           | 2.78            | 0.75                                              | A-3                                                                                 | SP             |  |
| M-033-S (05-05) |             | 3.5                       | 525.7             | 63.1                    | 57.5  | 45.4  | 35.7  | 26.7  | 7.8   | 4.6   | NA | NA               | NP | 0.185  | 0.510           | 6.000           | 32.43           | 0.23                                              | A-1-a                                                                               | SG             |  |
| M-072-W (05-06) |             | 14.3                      | 201.0             | 100.0                   | 99.6  | 98.8  | 97.3  | 91.4  | 56.1  | 39.9  | 22 | 11               | 11 | 0.0070 | 0.035           | 0.160           | 22.86           | 1.09                                              | A-6                                                                                 | SC             |  |
| M-132-N (06-01) |             | 15.0                      | 521.7             | 99.5                    | 99.0  | 98.5  | 96.8  | 78.7  | 8.8   | 4.2   | NA | NA               | NP | 0.160  | 0.220           | 0.320           | 2.00            | 0.95                                              | A-3                                                                                 | SP             |  |
| I-075-N (06-02) |             | 3.4                       | 518.0             | 95.1                    | 93.7  | 92.8  | 90.4  | 63.4  | 5.8   | 4.1   | NA | NA               | NP | 0.170  | 0.260           | 0.400           | 2.35            | 0.99                                              | A-3                                                                                 | SP             |  |
| U-031-N (06-03) |             | 5.8                       | 1060.3            | 99.5                    | 99.1  | 98.4  | 97.4  | 87.2  | 7.9   | 0.5   | NA | NA               | NP | 0.170  | 0.210           | 0.300           | 1.76            | 0.86                                              | A-3                                                                                 | SP             |  |
| I-196-N (06-05) |             | 10.5                      | 1085.6            | 99.6                    | 98.4  | 96.2  | 91.2  | 84.4  | 26.5  | 5.9   | 15 | -                | NP | 0.089  | 0.160           | 0.275           | 3.09            | 1.05                                              | A-2-4                                                                               | SP-SM          |  |
| M-020-W (07-02) |             | 4.2                       | 1003.7            | 99.6                    | 99.3  | 98.7  | 97.9  | 88.0  | 2.1   | 0.8   | NA | NA               | NP | 0.180  | 0.220           | 0.300           | 1.67            | 0.90                                              | A-3                                                                                 | SP             |  |
| M-020-E (07-03) |             | 4.5                       | 513.3             | 99.2                    | 97.9  | 96.8  | 94.5  | 89.6  | 21.2  | 3.3   | NA | NA               | NP | 0.110  | 0.190           | 0.280           | 2.55            | 1.17                                              | A-3                                                                                 | SP             |  |
| U-127-N (07-04) |             | 10.9                      | 200.8             | 100.0                   | 98.8  | 96.6  | 95.4  | 90.3  | 38.3  | 26.9  | 22 | 12               | 10 | 0.001  | 0.100           | 0.230           | 230.00          | 43.48                                             | A-2-6                                                                               | SC             |  |
| U-127-N (07-05) | X           | 11.2                      | 203.9             | 100.0                   | 98.3  | 92.6  | 87.3  | 79.9  | 53.7  | 40.5  | 23 | 14               | 9  | 0.0011 | 0.006           | 0.190           | 172.73          | 0.17                                              | A-6                                                                                 | SC             |  |
| U-127-N (07-05) |             | 14.4                      | 213.7             | 99.8                    | 98.2  | 85.2  | 81.0  | 74.8  | 52.1  | 43.7  | 24 | 14               | 10 | 0.0010 | 0.008           | 0.210           | 210.00          | 0.30                                              | A-6                                                                                 | SC             |  |

Table 3.4 (cont'd)

| Sample number   | Shelby tube | Natural water content (%) | Sample weight (g) | Percent passing sieve # |       |       |       |       |       |       | Atterberg limits |    |    | D <sub>10</sub> | D <sub>30</sub> | D <sub>60</sub> | C <sub>u</sub> = D <sub>60</sub> /D <sub>10</sub> | C <sub>c</sub> = D <sub>30</sub> <sup>2</sup> /D <sub>10</sub> | Classification |       |
|-----------------|-------------|---------------------------|-------------------|-------------------------|-------|-------|-------|-------|-------|-------|------------------|----|----|-----------------|-----------------|-----------------|---------------------------------------------------|----------------------------------------------------------------|----------------|-------|
|                 |             |                           |                   | 3/8 inch                | 4     | 10    | 20    | 40    | 100   | 200   | LL               | PL | PI |                 |                 |                 |                                                   |                                                                | AASHTO         | USCS  |
|                 |             |                           |                   | 9.500                   | 4.750 | 2.000 | 0.850 | 0.425 | 0.150 | 0.075 |                  |    |    |                 |                 |                 |                                                   |                                                                |                |       |
| M-061-E (07-06) |             | 22.1                      | 198.5             | 100.0                   | 98.8  | 93.3  | 84.7  | 59.3  | 23.7  | 17.9  | 19               | -  | NP | 0.040           | 0.190           | 0.430           | 10.75                                             | 2.10                                                           | A-2-4          | SM    |
| M-061-E (08-02) |             | 20.3                      | 223.1             | 100.0                   | 99.7  | 93.9  | 77.8  | 51.9  | 26.1  | 23.2  | 11               | -  | NP | 0.050           | 1.000           | 0.520           | 10.40                                             | 38.46                                                          | A-2-4          | SM    |
| U-010-W (08-03) |             | 21.4                      | 200.2             | 100.0                   | 100.0 | 99.8  | 99.7  | 97.6  | 61.0  | 55.2  | 32               | 14 | 18 | 0.001           | 0.002           | 0.140           | 140.00                                            | 0.02                                                           | A-6            | CL    |
| U-010-W (08-04) |             | 8.2                       | 200.1             | 99.9                    | 99.9  | 98.8  | 96.6  | 84.5  | 48.8  | 36.7  | 29               | 13 | 16 | 0.001           | 0.011           | 0.200           | 200.00                                            | 0.61                                                           | A-6            | SC    |
| U-010-W (08-04) | X           | 15.0                      | 205.1             | 98.0                    | 98.9  | 96.5  | 95.8  | 80.3  | 42.5  | 33.3  | 27               | 13 | 14 | 0.0009          | 0.018           | 0.200           | 222.22                                            | 1.80                                                           | A-6            | SC    |
| I-075-S (08-05) |             | 8.9                       | 201.0             | 100.0                   | 99.9  | 97.7  | 94.5  | 69.4  | 40.3  | 33.5  | 25               | 12 | 13 | 0.001           | 0.011           | 0.300           | 300.00                                            | 0.40                                                           | A-2-6          | SC    |
| I-075-N (08-06) |             | 11.8                      | 201.5             | 100.0                   | 99.2  | 96.8  | 93.7  | 85.4  | 36.6  | 26.2  | 17               | 10 | 7  | 0.001           | 0.011           | 0.270           | 270.00                                            | 0.45                                                           | A-2-4          | SC-SM |
| U-131-S (09-01) |             | 4.6                       | 1056.3            | 99.0                    | 98.0  | 97.4  | 97.0  | 83.7  | 2.5   | 0.5   | NA               | NA | NP | 0.180           | 0.220           | 0.300           | 1.67                                              | 0.90                                                           | A-3            | SP    |
| I-096-W (09-02) |             | 9.9                       | 206.2             | 100.0                   | 99.0  | 97.3  | 93.8  | 82.7  | 40.9  | 30.5  | 17               | 13 | 4  | 0.001           | 0.075           | 0.240           | 240.00                                            | 23.44                                                          | A-2-4          | SC-SM |
| U-131-S (09-03) |             | 1.9                       | 530.4             | 100.0                   | 100.0 | 99.9  | 99.8  | 97.2  | 6.0   | 0.4   | NA               | NA | NP | 0.180           | 0.200           | 0.290           | 1.61                                              | 0.77                                                           | A-3            | SP    |
| U-131-S (09-05) |             | 3.6                       | 1025.6            | 97.5                    | 90.2  | 80.8  | 69.5  | 45.8  | 3.1   | 1.3   | NA               | NA | NP | 0.185           | 0.295           | 0.605           | 3.27                                              | 0.78                                                           | A-3            | SP    |
| M-044-E (09-07) |             | 8.7                       | 206.5             | 100.0                   | 99.5  | 97.7  | 94.1  | 85.5  | 37.7  | 26.7  | 14               | -  | NP | 0.020           | 0.110           | 0.250           | 12.50                                             | 2.42                                                           | A-2-4          | SM    |
| I-075-S (09-08) |             | 20.2                      | 216.1             | 99.1                    | 96.1  | 91.8  | 89.7  | 85.5  | 62.3  | 45.8  | 31               | 14 | 17 | 0.001           | 0.004           | 0.140           | 140.00                                            | 0.11                                                           | A-4            | SC    |
| M-024-S (09-09) |             | 13.3                      | 198.6             | 100.0                   | 99.6  | 97.6  | 95.4  | 93.2  | 45.0  | 24.1  | 20               | -  | NP | 0.012           | 0.090           | 0.200           | 16.67                                             | 3.38                                                           | A-2-4          | SM    |
| I-069-E (09-10) |             | 7.1                       | 527.8             | 98.3                    | 93.4  | 83.0  | 66.3  | 36.8  | 5.2   | 3.1   | NA               | NA | NP | 0.190           | 0.340           | 0.700           | 3.68                                              | 0.87                                                           | A-3            | SP    |
| I-069-N (10-01) |             | 10.1                      | 534.1             | 94.9                    | 88.7  | 81.1  | 67.6  | 49.2  | 16.7  | 8.0   | 16               | 11 | 5  | 0.093           | 0.230           | 0.600           | 6.45                                              | 0.95                                                           | A-3            | SP-SM |
| I-096-W (10-03) |             | 14.7                      | 199.7             | 100.0                   | 98.4  | 93.9  | 90.1  | 82.0  | 29.5  | 17.5  | 29               | 14 | 15 | 0.0600          | 0.150           | 0.280           | 4.67                                              | 1.34                                                           | A-2-6          | SC    |
| I-069-N (10-04) |             | 11.1                      | 198.5             | 100.0                   | 99.3  | 94.1  | 86.4  | 74.9  | 30.1  | 17.6  | 16               | -  | NP | 0.010           | 0.150           | 0.200           | 20.00                                             | 11.25                                                          | A-2-4          | SM    |
| I-069-N (10-05) |             | 24.0                      | 204.0             | 100.0                   | 100.0 | 97.8  | 87.6  | 54.9  | 43.2  | 37.3  | 19               | -  | NP | 0.010           | 0.070           | 0.500           | 50.00                                             | 0.98                                                           | A-2-4          | SM    |
| I-096-W (10-09) |             | 15.1                      | 200.9             | 100.0                   | 99.6  | 93.7  | 91.0  | 61.1  | 38.0  | 30.4  | 19               | -  | NP | 0.006           | 0.075           | 0.410           | 68.33                                             | 2.29                                                           | A-2-4          | SM    |
| I-069-E (10-10) |             | 12.8                      | 204.9             | 98.0                    | 96.1  | 92.4  | 90.5  | 84.7  | 57.2  | 37.7  | 26               | 15 | 11 | 0.001           | 0.009           | 0.170           | 170.00                                            | 0.48                                                           | A-6            | SC    |
| M-021-E (10-11) |             | 15.0                      | 230.2             | 99.4                    | 92.1  | 85.9  | 79.5  | 72.2  | 46.3  | 33.8  | 23               | 14 | 9  | 0.001           | 0.030           | 0.270           | 270.00                                            | 3.33                                                           | A-2-4          | SC    |
| I-069-N (11-01) |             | 9.1                       | 1032.9            | 90.3                    | 87.1  | 83.0  | 77.8  | 63.9  | 15.9  | 6.9   | 14               | -  | NP | 0.120           | 0.210           | 0.390           | 3.25                                              | 0.94                                                           | A-3            | SP-SM |
| I-094-W (11-02) |             | 7.1                       | 1022.7            | 95.0                    | 91.7  | 87.1  | 77.5  | 51.2  | 6.2   | 2.7   | NA               | NA | NP | 0.170           | 0.270           | 0.510           | 3.00                                              | 0.84                                                           | A-3            | SP    |
| M-060-W (11-03) |             | 10.5                      | 199.3             | 99.7                    | 99.0  | 97.4  | 90.6  | 67.0  | 37.6  | 31.1  | 22               | 15 | 7  | 0.004           | 0.025           | 0.330           | 82.50                                             | 0.47                                                           | A-2-4          | SC-SM |
| I-069-S (11-05) |             | 6.6                       | 201.1             | 100.0                   | 99.1  | 93.9  | 86.9  | 77.3  | 49.3  | 38.6  | 15               | 11 | 4  | 0.002           | 0.034           | 0.210           | 105.00                                            | 2.75                                                           | A-4            | SC-SM |
| I-094-W (12-01) |             | 8.6                       | 199.8             | 100.0                   | 95.2  | 81.8  | 73.9  | 51.8  | 26.5  | 20.0  | 16               | 12 | 4  | 0.038           | 0.180           | 0.560           | 14.74                                             | 1.52                                                           | A-2-4          | SC-SM |
| I-094-W (12-03) |             | 13.2                      | 527.4             | 97.4                    | 95.4  | 91.6  | 83.0  | 68.3  | 18.7  | 7.4   | 16               | -  | NP | 0.095           | 0.195           | 0.345           | 3.63                                              | 1.16                                                           | A-3            | SP-SM |
| U-012-E (12-04) |             | 4.9                       | 200.4             | 99.9                    | 98.9  | 94.2  | 89.4  | 73.7  | 36.6  | 23.0  | 16               | -  | NP | 0.003           | 0.110           | 0.300           | 100.00                                            | 13.44                                                          | A-2-4          | SM    |



Table 3.4 (cont'd)

| Sample number   | Shelby tube | Natural water content (%) | Sample weight (g) | Percent passing sieve # |       |       |       |       |       |       | Atterberg limits |    |    | D <sub>10</sub> | D <sub>30</sub> | D <sub>60</sub> | C <sub>u</sub> = D <sub>60</sub> /D <sub>10</sub> | C <sub>c</sub> = D <sub>30</sub> <sup>2</sup> /(D <sub>60</sub> (D <sub>10</sub> )) | Classification |       |
|-----------------|-------------|---------------------------|-------------------|-------------------------|-------|-------|-------|-------|-------|-------|------------------|----|----|-----------------|-----------------|-----------------|---------------------------------------------------|-------------------------------------------------------------------------------------|----------------|-------|
|                 |             |                           |                   | 3/8 inch                | 4     | 10    | 20    | 40    | 100   | 200   | LL               | PL | PI |                 |                 |                 |                                                   |                                                                                     | AASHTO         | USCS  |
|                 |             |                           |                   | 9.500                   | 4.750 | 2.000 | 0.850 | 0.425 | 0.150 | 0.075 |                  |    |    |                 |                 |                 |                                                   |                                                                                     |                |       |
| I-094-W (12-06) |             | 12.1                      | 213.7             | 100.0                   | 99.8  | 92.2  | 90.5  | 86.0  | 35.2  | 23.8  | 15               | -  | NP | 0.005           | 0.130           | 0.250           | 50.00                                             | 13.52                                                                               | A-2-4          | SM    |
| U-012-E (12-07) |             | 7.0                       | 513.8             | 67.5                    | 57.0  | 42.2  | 25.8  | 16.0  | 10.0  | 8.1   | 18               | -  | NP | 0.160           | 1.000           | 6.000           | 37.50                                             | 1.04                                                                                | A-1-a          | SG    |
| M-024-S (13-01) |             | 10.6                      | 196.0             | 100.2                   | 98.4  | 93.4  | 90.2  | 85.2  | 59.4  | 45.1  | 18               | 15 | 3  | 0.001           | 0.013           | 0.150           | 150.00                                            | 1.13                                                                                | A-4            | SM    |
| M-059-W (13-02) |             | 11.6                      | 1033.3            | 99.4                    | 97.9  | 95.1  | 91.2  | 65.7  | 8.9   | 1.7   | NA               | NA | NP | 0.160           | 0.220           | 0.380           | 2.38                                              | 0.80                                                                                | A-3            | SP    |
| M-014-W (13-03) |             | 9.3                       | 198.1             | 100.0                   | 99.1  | 94.0  | 90.0  | 85.7  | 62.7  | 49.2  | 22               | 13 | 9  | 0.001           | 0.006           | 0.130           | 130.00                                            | 0.28                                                                                | A-4            | SC    |
| I-094-W (13-04) |             | 8.0                       | 1005.6            | 98.1                    | 95.8  | 90.5  | 82.8  | 65.9  | 13.1  | 3.5   | NA               | NA | NP | 0.140           | 0.210           | 0.390           | 2.79                                              | 0.81                                                                                | A-3            | SP    |
| U-012-E (13-05) |             | 14.9                      | 205.0             | 100.0                   | 99.9  | 99.0  | 97.8  | 95.5  | 65.6  | 56.7  | 33               | 17 | 16 | 0.001           | 0.002           | 0.100           | 111.11                                            | 0.04                                                                                | A-6            | CL    |
| U-023-N (13-07) |             | 9.8                       | 529.5             | 94.1                    | 83.4  | 66.2  | 53.5  | 43.3  | 12.0  | 5.7   | 13               | -  | NP | 0.130           | 0.280           | 1.350           | 10.38                                             | 0.45                                                                                | A-3            | SP-SM |
| M-010-E (13-08) |             | 14.0                      | 201.0             | 100.0                   | 99.7  | 98.1  | 95.0  | 90.8  | 74.3  | 59.9  | 24               | 14 | 10 | 0.0010          | 0.003           | 0.075           | 75.00                                             | 0.12                                                                                | A-6            | CL    |
| M-010-E (13-08) | X           | 12.3                      | 207.0             | 100.0                   | 98.0  | 95.6  | 93.5  | 88.3  | 72.6  | 54.8  | 23               | 14 | 9  | 0.0009          | 0.015           | 0.090           | 100.00                                            | 2.78                                                                                | A-6            | CL    |
| I-075-S (14-01) | X           | 18.4                      | 204.5             | 100.0                   | 99.9  | 89.4  | 87.9  | 67.6  | 54.2  | 48.2  | 42               | 21 | 21 | 0.0090          | 0.015           | 0.250           | 27.78                                             | 0.10                                                                                | A-7-6          | SC    |
| I-075-S (14-01) |             | 25.4                      | 200.6             | 100.0                   | 96.9  | 78.9  | 76.2  | 68.4  | 47.8  | 41.2  | 45               | 19 | 26 | 0.0007          | 0.003           | 0.270           | 385.71                                            | 0.05                                                                                | A-7-6          | SC    |
| I-075-S (14-02) |             | 18.7                      | 201.0             | 100.0                   | 98.3  | 97.6  | 92.6  | 85.5  | 64.1  | 46.1  | 41               | 19 | 22 | 0.001           | 0.003           | 0.190           | 211.11                                            | 0.06                                                                                | A-7-6          | SC    |
| U-024-S (14-03) |             | 19.2                      | 202.3             | 100.0                   | 99.4  | 98.8  | 91.8  | 79.7  | 55.3  | 41.4  | 40               | 13 | 27 | 0.001           | 0.003           | 0.190           | 271.43                                            | 0.07                                                                                | A-6            | SC    |
| I-075-S (14-04) |             | 15.8                      | 200.8             | 100.0                   | 99.9  | 99.8  | 99.7  | 96.4  | 59.4  | 46.9  | 34               | 17 | 17 | 0.001           | 0.003           | 0.260           | 288.89                                            | 0.04                                                                                | A-6            | SC    |
| U-024-S (14-04) |             | 22.2                      | 543.7             | 100.0                   | 100.0 | 99.8  | 99.6  | 96.3  | 23.3  | 2.5   | NA               | NA | NP | 0.100           | 0.170           | 0.255           | 2.55                                              | 1.13                                                                                | A-3            | SP    |
| I-094-W (14-05) |             | 21.6                      | 199.0             | 99.7                    | 97.6  | 97.5  | 89.7  | 78.0  | 56.7  | 46.7  | 34               | 21 | 13 | 0.001           | 0.013           | 0.160           | 160.00                                            | 1.06                                                                                | A-6            | SC    |
| M-153-E (14-06) | X           | 26.0                      | 209.4             | 100.0                   | 99.8  | 99.0  | 98.3  | 92.7  | 70.1  | 51.1  | 51               | 19 | 32 | 0.0090          | 0.018           | 0.100           | 11.11                                             | 0.36                                                                                | A-7-6          | SC    |
| M-153-E (14-06) |             | 21.6                      | 202.9             | 100.0                   | 100.0 | 98.4  | 98.1  | 94.1  | 64.4  | 49.9  | 52               | 20 | 32 | 0.0007          | 0.001           | 0.140           | 200.00                                            | 0.02                                                                                | A-7-6          | SC    |
| M-053-S (14-07) |             | 5.9                       | 529.1             | 93.1                    | 87.5  | 81.5  | 70.3  | 55.0  | 9.3   | 4.7   | NA               | NA | NP | 0.170           | 0.240           | 0.500           | 2.94                                              | 0.68                                                                                | A-3            | SP    |
| I-094-W (14-09) | X           | 26.3                      | 205.1             | 100.0                   | 100.0 | 98.5  | 97.9  | 85.2  | 59.8  | 55.8  | 42               | 23 | 19 | 0.0010          | 0.010           | 0.150           | 150.00                                            | 0.67                                                                                | A-7-6          | CL    |
| I-094-W (14-09) |             | 21.9                      | 197.3             | 99.7                    | 99.2  | 97.7  | 96.6  | 90.8  | 66.8  | 60.9  | 44               | 21 | 23 | 0.0010          | 0.002           | 0.075           | 75.00                                             | 0.05                                                                                | A-7-6          | CL    |
| I-094-W (14-10) |             | 21.5                      | 198.9             | 100.0                   | 99.5  | 93.3  | 91.6  | 80.3  | 65.2  | 56.3  | 42               | 19 | 23 | 0.001           | 0.002           | 0.100           | 166.67                                            | 0.07                                                                                | A-7-6          | CL    |
| M-053-S (15-02) |             | 17.2                      | 200.4             | 100.0                   | 99.5  | 96.8  | 94.4  | 87.5  | 42.8  | 26.2  | 14               | -  | NP | 0.008           | 0.100           | 0.210           | 26.25                                             | 5.95                                                                                | A-2-4          | SM    |
| M-090-E (15-03) |             | 38.0                      | 204.1             | 100.0                   | 99.9  | 98.8  | 96.1  | 90.7  | 73.1  | 55.8  | 35               | 20 | 15 | 0.001           | 0.005           | 0.088           | 88.00                                             | 0.28                                                                                | A-6            | CL    |
| M-090-E (15-04) |             | 12.4                      | 199.6             | 100.0                   | 99.7  | 97.4  | 95.0  | 90.6  | 67.4  | 52.8  | 24               | 15 | 9  | 0.0010          | 0.006           | 0.100           | 100.00                                            | 0.36                                                                                | A-4            | CL    |
| M-025-S (15-05) |             | 4.4                       | 532.8             | 99.3                    | 98.7  | 98.2  | 97.3  | 84.4  | 1.9   | 1.1   | NA               | NA | NP | 0.180           | 0.210           | 0.300           | 1.67                                              | 0.82                                                                                | A-3            | SP    |
| M-25-N (15-06)  |             | 16.4                      | 206.4             | 100.0                   | 98.9  | 94.0  | 90.8  | 85.1  | 54.2  | 42.3  | 24               | 13 | 11 | 0.001           | 0.007           | 0.190           | 190.00                                            | 0.26                                                                                | A-4            | SC    |
| M-019-S (15-07) |             | 11.4                      | 199.4             | 99.9                    | 95.1  | 83.9  | 76.4  | 61.5  | 29.0  | 17.2  | 14               | -  | NP | 0.065           | 0.160           | 0.400           | 6.15                                              | 0.98                                                                                | A-2-4          | SM    |

devices for both tests. After obtaining the liquid and plastic limits, the plasticity index was calculated as the difference between the two limits. A total of 60 Atterberg limit tests were performed. Results of the Atterberg limit tests are listed in Table 3.4.

#### **3.5.4 Cyclic Load Triaxial Test**

Cyclic load triaxial tests were conducted to determine the resilient modulus of laboratory compacted sand and clay samples and Shelby tube samples. The sample preparation procedures are presented below.

**Preparation of Sand Samples** - All sand samples were compacted in 2.125 inches diameter and 4.8 inches high split mold using a 10 pounds static load and a vibrating table. The split mold has two outlets connected on the outside of the mold by small diameter drainage tubes and protected on the inside by two small porous stones tightly fitted to the holes. First, the split mold was assembled and a rubber membrane was stretched along the interior walls of the mold. The membrane was then flipped over the edges of the split mold and a vacuum was applied between the rubber membrane and the interior walls of the mold. The vacuum forced the membrane to stick to the wall and hence eliminates wrinkling. The split mold and the rubber membrane were then placed around the bottom pedestal on the base of the triaxial cell and a paper filter was then placed on top of the pedestal. The entire assembly was then placed on the vibrating table. The total weight of the sand was then measured and recorded and the sand was then compacted in five lifts. Each lift was subjected to a 10 pound static load while being vibrated at the maximum amplitude for a period of three minutes. Figure 3.8 shows the vibrating table, static load, vacuum pump, split mold, and triaxial cell base. When the last sand lift was compacted, a paper filter and the top pedestal were respectively placed

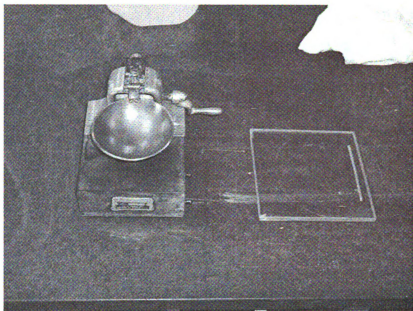


Figure 3.7 Liquid and plastic limit apparatus

in orderly fashion on top of the sand. The rubber membrane was then secured around the top and bottom pedestals using rubber bands. The vacuum lines were removed from the split mold and connected to the drainage lines at the bottom of the triaxial cell to apply vacuum to the sand. The split mold was then removed. After assembling the triaxial cell, a confining pressure of 7.5 psi was then applied while the vacuum was decreased to zero by disconnecting the vacuum line. The weight of the left over sand was measured and recorded. The difference between the initial and final weights represents the weight of the sand sample. After determining the water content in the sample, its dry unit weight was calculated.

**Preparation of Clay Samples** - Disturbed clay samples were compacted according to the AASHTO standard proctor test procedure T99. After compaction, the samples were then trimmed to the desired length of 4.5 inches and diameter of 2.25 inches. The samples were then placed in a rubber membrane (which was stretched tightly around the interior

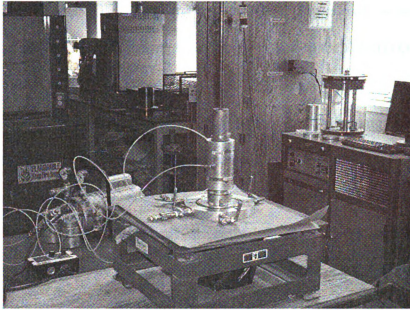


Figure 3.8 Vibrating table setup

of a split mold). The sample was then sealed from the atmosphere by securing the rubber membrane to the bottom and top pedestals. The entire mold assembly was then transferred to the triaxial cell where the cell was assembled and a confining pressure of 7.5 psi was applied to the sample.

**Preparation of the Undisturbed Shelby Tube Samples** – First, the Shelby tubes were cut to several segments 6 inches long. The clay soil was then extracted from the tube segment and was trimmed to a height of 5.6 inches. The diameter of the soil was kept the same as the interior diameter of the Shelby tube (2.8 inches). A rubber membrane was placed around the soil (see clay samples above) and the sample was placed in the triaxial cell and was subjected to 7.5 psi confining pressure.

After placing the sample in the triaxial cell and subjecting it to 7.5 psi confining pressure, the cyclic load test commenced. The detailed steps are presented below.

**Cyclic Load Test Procedure** – All cyclic load triaxial tests were mainly conducted according to the AASHTO T307 standard test procedure. Because of the type of tests and equipment available, the following three modifications to the AASHTO standard test procedure were made:

- The load cell of the available MTS system is located below the sample instead of above it as stated in the standard test procedure.
- The loading and unloading time of 0.1 seconds and the relaxation time of 0.9 second were changed to 0.5 and 0.9 seconds, respectively to more accurately simulate the load pulse experienced by a roadbed soil located about 30 inches below the pavement surface (see Figure 3.9). The figure shows the distances from the load that the stress is felt in the pavement based on the shown thicknesses.
- The sample was conditioned by applying 498 load cycles instead of the conditioning sequences outlines in the standard test procedure.

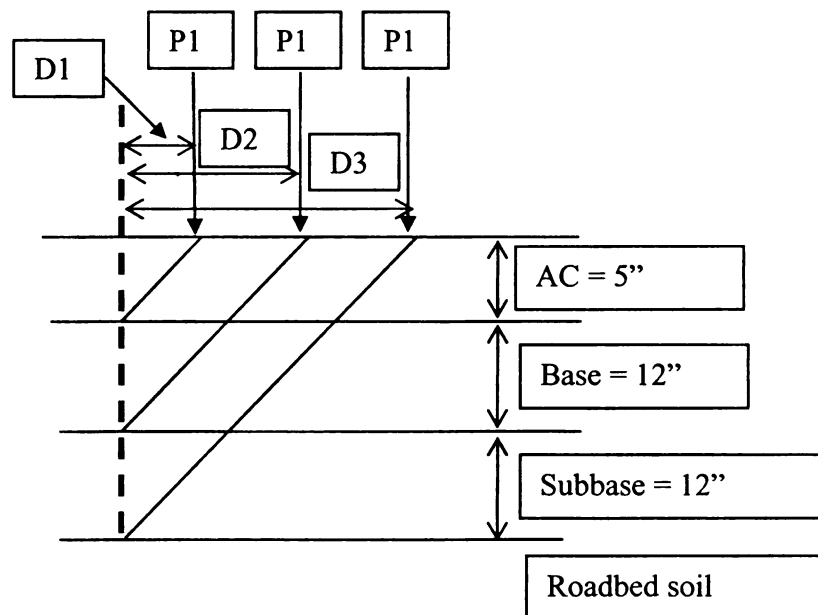


Figure 3.9 Stress influence with depth

Cyclic load triaxial tests are difficult to conduct and require extreme care and patience. The resulting MR values obtained from the test are typically affected by several test and sample variables including: confining pressure, deviatoric stress, loading frequency, soil type, moisture content, and specimen conditioning. In this study, all cyclic load triaxial tests were performed using:

- A sustained load of 10 pounds was applied to maintain contact between the MTS actuator and the piston of the triaxial cell.
- A confining pressure of 7.5 psi.
- A frequency of 0.71 hertz.
- Cyclic axial stress of 10 psi followed immediately by cyclic axial stress of 15 psi.
- For each axial stress level, the samples were conditioned to 498 load cycles.
- The axial sample deformations were measured using two linear variable differential transducers (LVDTs) located at 180 degrees from the longitudinal axis of the sample.
- The resilient moduli of the samples were calculated as the average resilient modulus obtained at cycles 499, 500, 501, 799, 800, 801, 999, 1000 and 1001. The resilient modulus at each cycle was calculated using the average deformation of the two LVDTs.

The test setup used for the cyclic load tests is shown in Figure 3.10. Figure 3.11 shows two Hysteresis loops from load cycles 800 and 1000. The figure shows that as the load increases the sample deformation increases and vice versa. The shift in the two loops represents the cumulative plastic deformation that took place in the sample between cycles 800 and 1000.



Results of the cyclic load tests for both the 10 and the 15 psi cyclic stresses are listed in Table 3.5. The highlighted rows in the table indicate tests which were run to verify the developed models. The verification is discussed in Chapter 4. The table also includes the moisture content and degree of saturation, the dry unit weight of the test sample, the USCS and the AASHTO soil classifications, and the sample type (disturbed or undisturbed). It should be noted that the data in the table are sorted based on the USCS. As can be seen from the table, 81 samples were subjected to cyclic load tests. These include 25 SP tests, 16 SM tests, 9 CL tests, 14 SC tests, 2 ML tests, 7 SC-SM tests, and 8 SP-SM tests.

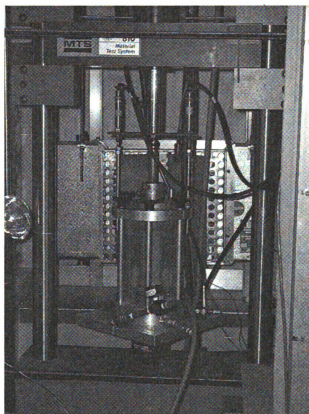


Figure 3.10 Cyclic load test setup

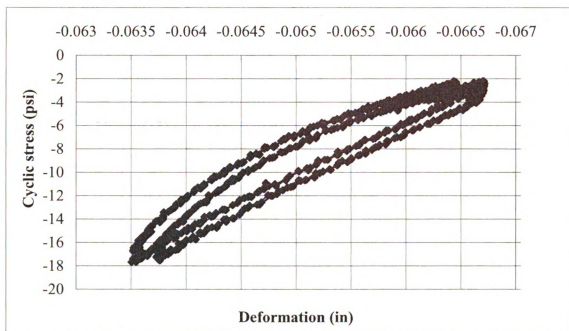


Figure 3.11 Typical cyclic load test results

Table 3.5 Laboratory MR test results

| Sample number   | Sample type |           | Classification |       | Dry unit weight (lb/ft <sup>3</sup> ) | Water content for cyclic test | Saturation | MR at cyclic stress (psi) |        |
|-----------------|-------------|-----------|----------------|-------|---------------------------------------|-------------------------------|------------|---------------------------|--------|
|                 | Shelby tube | Disturbed | AASHTO         | USCS  |                                       |                               |            | 10.0                      | 15.0   |
| M-028-W (02-03) |             | X         | A-1-b          | SP-SM | 113.4                                 | 8.5                           | 47.3       | 19,195                    | 17,845 |
| U-002-E (03-01) |             | X         | A-3            | SP-SM | 108.7                                 | 4.5                           | 22.1       | 22,787                    | 19,592 |
| M-028-W (03-03) |             | X         | A-3            | SP-SM | 105.5                                 | 2.0                           | 9.0        | 16,895                    | 15,941 |
| I-196-N (06-05) |             | X         | A-2-4          | SP-SM | 111.5                                 | 3.7                           | 19.5       | 23,009                    | 21,964 |
| I-069-N (10-01) |             | X         | A-3            | SP-SM | 116.1                                 | 9.9                           | 59.2       | 15,858                    | 15,682 |
| I-069-N (11-01) |             | X         | A-3            | SP-SM | 118.0                                 | 7.0                           | 44.2       | 30,701                    | 28,120 |
| I-094-W (12-03) |             | X         | A-3            | SP-SM | 121.6                                 | 11.4                          | 79.8       | 18,122                    | 15,961 |
| U-023-N (13-07) |             | X         | A-3            | SP-SM | 115.4                                 | 6.5                           | 38.2       | 22,608                    | 20,574 |
| M-068-W (04-03) |             | X         | A-3            | SP    | 100.9                                 | 20.0                          | 80.6       | 9,969                     | 10,004 |
| M-020-W (07-02) |             | X         | A-3            | SP    | 110.5                                 | 11.5                          | 59.2       | 29,418                    | 28,566 |
| M-059-W (13-02) |             | X         | A-3            | SP    | 107.7                                 | 9.0                           | 43.1       | 24,840                    | 23,788 |
| U-127-N (05-04) |             | X         | A-3            | SP    | 112.6                                 | 6.9                           | 37.5       | 37,123                    | 29,921 |
| I-075-N (03-04) |             | X         | A-3            | SP    | 111.7                                 | 6.9                           | 36.6       | 26,115                    | 24,378 |
| I-094-W (11-02) |             | X         | A-3            | SP    | 116.7                                 | 6.2                           | 37.7       | 44,479                    | 27,346 |
| I-094-W (13-04) |             | X         | A-3            | SP    | 114.3                                 | 6.0                           | 34.2       | 21,449                    | 18,842 |
| U-024-S (14-04) |             | X         | A-3            | SP    | 108.2                                 | 10.0                          | 48.5       | 22,768                    | 21,924 |
| M-020-W (07-02) |             | X         | A-3            | SP    | 109.2                                 | 5.3                           | 26.4       | 30,244                    | 24,872 |
| I-069-E (09-10) |             | X         | A-3            | SP    | 116.9                                 | 5.1                           | 31.2       | 28,636                    | 26,070 |
| M-132-N (06-01) |             | X         | A-3            | SP    | 112.9                                 | 4.7                           | 25.8       | 31,711                    | 28,970 |
| M-053-S (14-07) |             | X         | A-3            | SP    | 113.9                                 | 3.9                           | 22.0       | 25,714                    | 22,275 |

Table 3.5 (cont'd)

| Sample number   | Sample type |           | Classification |      | Dry unit weight (lb/ft <sup>3</sup> ) | Water content for cyclic test | Saturation | MR at cyclic stress (psi) |        |
|-----------------|-------------|-----------|----------------|------|---------------------------------------|-------------------------------|------------|---------------------------|--------|
|                 | Shelby tube | Disturbed | AASHTO         | USCS |                                       |                               |            | 10.0                      | 15.0   |
| U-023-S (04-01) |             | X         | A-3            | SP   | 117.8                                 | 3.3                           | 20.7       | 23,039                    | 21,715 |
| U-031-N (06-03) |             | X         | A-3            | SP   | 111.5                                 | 3.3                           | 17.4       | 31,870                    | 29,609 |
| M-020-E (07-03) |             | X         | A-3            | SP   | 113.0                                 | 3.2                           | 17.6       | 32,666                    | 28,156 |
| M-025-S (15-05) |             | X         | A-3            | SP   | 110.3                                 | 3.0                           | 15.4       | 40,115                    | 35,447 |
| U-131-S (09-01) |             | X         | A-3            | SP   | 110.6                                 | 2.7                           | 13.9       | 28,766                    | 27,706 |
| I-075-N (06-02) |             | X         | A-3            | SP   | 110.2                                 | 2.0                           | 10.2       | 32,457                    | 31,187 |
| U-131-S (09-05) |             | X         | A-3            | SP   | 117.3                                 | 1.0                           | 23.3       | 38,423                    | 35,319 |
| M-028-W (03-02) |             | X         | A-3            | SP   | 104.0                                 | 1.3                           | 5.7        | 22,959                    | 22,494 |
| U-131-S (09-03) |             | X         | A-3            | SP   | 108.6                                 | 0.5                           | 2.4        | 30,340                    | 27,995 |
| M-020-W (07-02) |             | X         | A-3            | SP   | 109.1                                 | 0.2                           | 1.0        | 31,460                    | 28,705 |
| M-020-W (07-02) |             | X         | A-3            | SP   | 104.1                                 | 0.2                           | 0.9        | 19,692                    | 20,267 |
| M-020-W (07-02) |             | X         | A-3            | SP   | 107.6                                 | 0.2                           | 1.0        | 24,319                    | 24,552 |
| U-002-E (02-01) |             | X         | A-4            | SM   | 109.3                                 | 9.5                           | 47.4       | 15,352                    | 13,818 |
| U-002-E (03-03) |             | X         | A-2-4          | SM   | 111.5                                 | 7.7                           | 40.7       | 15,969                    | 15,818 |
| M-065-S (04-04) |             | X         | A-2-4          | SM   | 94.6                                  | 7.6                           | 26.3       | 11,932                    | 11,898 |
| U-131-N (05-01) |             | X         | A-2-4          | SM   | 112.9                                 | 5.4                           | 29.6       | 24,627                    | 23,092 |
| M-061-E (07-06) |             | X         | A-2-4          | SM   | 96.0                                  | 17.0                          | 60.8       | 11,480                    | 12,958 |
| M-061-E (08-02) |             | X         | A-2-4          | SM   | 118.6                                 | 5.5                           | 35.3       | 32,200                    | 31,733 |
| M-044-E (09-07) |             | X         | A-2-4          | SM   | 128.8                                 | 7.6                           | 66.6       | 18,416                    | 19,636 |

Table 3.5 (cont'd)

| Sample number   | Sample type |           | Classification |       | Dry unit weight (lb/ft <sup>3</sup> ) | Water content for cyclic test | Saturation | MR at cyclic stress (psi) |        |
|-----------------|-------------|-----------|----------------|-------|---------------------------------------|-------------------------------|------------|---------------------------|--------|
|                 | Shelby tube | Disturbed | AASHTO         | USCS  |                                       |                               |            | 10.0                      | 15.0   |
| M-024-S (09-09) |             | X         | A-2-4          | SM    | 102.9                                 | 9.8                           | 41.5       | 15,142                    | 15,839 |
| I-069-N (10-04) |             | X         | A-2-4          | SM    | 124.2                                 | 8.4                           | 63.6       | 19,172                    | 18,945 |
| I-069-N (10-05) |             | X         | A-2-4          | SM    | 100.2                                 | 23.7                          | 93.9       | 5,290                     | 5,641  |
| I-096-W (10-09) |             | X         | A-2-4          | SM    | 117.9                                 | 14.1                          | 88.7       | 9,509                     | 11,383 |
| U-012-E (12-04) |             | X         | A-2-4          | SM    | 108.0                                 | 3.9                           | 18.8       | 19,152                    | 18,377 |
| I-094-W (12-06) |             | X         | A-2-4          | SM    | 123.2                                 | 10.3                          | 75.7       | 19,406                    | 19,305 |
| M-024-S (13-01) |             | X         | A-4            | SM    | 110.3                                 | 9.5                           | 48.6       | 17,933                    | 16,160 |
| M-053-S (15-02) |             | X         | A-2-4          | SM    | 114.0                                 | 8.5                           | 48.0       | 18,325                    | 18,043 |
| M-019-S (15-07) |             | X         | A-2-4          | SM    | 113.7                                 | 9.2                           | 51.6       | 22,213                    | 19,482 |
| M-068-W (04-02) |             | X         | A-2-4          | SC-SM | 117.5                                 | 2.2                           | 13.7       | 30,928                    | 24,740 |
| M-032-W (04-05) |             | X         | A-4            | SC-SM | 106.3                                 | 8.1                           | 37.4       | 19,255                    | 18,161 |
| I-075-N (08-06) |             | X         | A-2-4          | SC-SM | 131.3                                 | 9.2                           | 87.7       | 15,783                    | 16,562 |
| I-096-W (09-02) |             | X         | A-2-4          | SC-SM | 108.0                                 | 1.2                           | 5.8        | 22,142                    | 19,579 |
| M-060-W (11-03) |             | X         | A-2-4          | SC-SM | 107.0                                 | 8.4                           | 39.5       | 19,812                    | 16,639 |
| I-069-S (11-05) |             | X         | A-4            | SC-SM | 132.6                                 | 6.4                           | 63.9       | 27,276                    | 25,621 |
| I-094-W (12-01) |             | X         | A-2-4          | SC-SM | 128.8                                 | 8.5                           | 74.5       | 27,610                    | 23,849 |

Table 3.5 (cont'd)

| Sample number   | Sample type |           | Classification |      | Dry unit weight (lb/ft <sup>3</sup> ) | Water content for cyclic test | Saturation | MR at cyclic stress (psi) |        |
|-----------------|-------------|-----------|----------------|------|---------------------------------------|-------------------------------|------------|---------------------------|--------|
|                 | Shelby tube | Disturbed | AASHTO         | USCS |                                       |                               |            | 10.0                      | 15.0   |
| M-045-S (01-01) |             | X         | A-6            | CL   | 120.8                                 | 10.2                          | 69.8       | 36,543                    | 31,503 |
| M-010-E (13-08) | X           |           | A-6            | CL   | 118.8                                 | 15.0                          | 96.8       | 9,714                     | 8,235  |
| M-010-E (13-08) |             | X         | A-6            | CL   | 122.1                                 | 10.4                          | 73.9       | 17,150                    | 16,572 |
| M-010-E (13-08) | X           |           | A-6            | CL   | 128.5                                 | 5.7                           | 49.5       | 44,634                    | 41,942 |
| M-010-E (13-08) | X           |           | A-6            | CL   | 122.3                                 | 12.3                          | 88.0       | 15,561                    | 9,553  |
| I-094-W (14-09) | X           |           | A-7-6          | CL   | 101.7                                 | 10.5                          | 43.2       | 73,444                    | 70,095 |
| I-094-W (14-09) |             | X         | A-7-6          | CL   | 101.6                                 | 11.3                          | 46.3       | 60,247                    | 60,327 |
| I-094-W (14-09) | X           |           | A-7-6          | CL   | 96.4                                  | 26.3                          | 95.0       | 9,955                     | 8,080  |
| M-090-E (15-04) |             | X         | A-4            | CL   | 109.5                                 | 10.6                          | 53.1       | 67,778                    | 62,006 |
| M-072-W (05-06) |             | X         | A-6            | SC   | 116.2                                 | 10.7                          | 64.2       | 26,492                    | 27,193 |
| U-127-N (07-05) | X           |           | A-6            | SC   | 120.5                                 | 11.2                          | 75.9       | 7,323                     | 6,925  |
| U-127-N (07-05) | X           |           | A-6            | SC   | 117.5                                 | 14.2                          | 88.4       | 4,713                     | 5,338  |

Table 3.5 (cont'd)

| Sample number   | Sample type |           | Classification |      | Dry unit weight (lb/ft <sup>3</sup> ) | Water content for cyclic test | Saturation | MR at cyclic stress (psi) |        |
|-----------------|-------------|-----------|----------------|------|---------------------------------------|-------------------------------|------------|---------------------------|--------|
|                 | Shelby tube | Disturbed | AASHTO         | USCS |                                       |                               |            | 10.0                      | 15.0   |
| U-127-N (07-05) | X           |           | A-6            | SC   | 126.7                                 | 6.7                           | 54.9       | 54,737                    | 53,030 |
| U-127-N (07-05) | X           |           | A-6            | SC   | 115.3                                 | 16.6                          | 97.2       | 3,984                     | 5,382  |
| U-127-N (07-05) |             | X         | A-6            | SC   | 117.7                                 | 10.3                          | 64.5       | 36,047                    | 27,746 |
| U-010-W (08-04) | X           |           | A-6            | SC   | 111.5                                 | 15.0                          | 79.3       | 5,879                     | 5,105  |
| U-010-W (08-04) | X           |           | A-6            | SC   | 113.8                                 | 16.7                          | 93.8       | 4,134                     | 5,268  |
| I-096-W (10-03) |             | X         | A-2-6          | SC   | 108.3                                 | 11.6                          | 56.4       | 43,783                    | 37,688 |
| I-075-S (14-01) | X           |           | A-7-6          | SC   | 115.7                                 | 8.8                           | 52.1       | 32,569                    | 29,839 |
| I-075-S (14-01) | X           |           | A-7-6          | SC   | 108.7                                 | 18.4                          | 90.3       | 7,187                     | 8,386  |
| I-075-S (14-01) | X           |           | A-7-6          | SC   | 106.2                                 | 20.9                          | 96.2       | 6,069                     | 4,007  |
| I-075-S (14-01) |             | X         | A-7-6          | SC   | 99.8                                  | 18.8                          | 73.8       | 18,147                    | 17,831 |
| M-153-E (14-06) | X           |           | A-7-6          | SC   | 96.6                                  | 26.0                          | 99.1       | 3,731                     | 3,015  |
| M-153-E (14-06) | X           |           | A-7-6          | SC   | 92.5                                  | 30.4                          | 99.9       | 4,430                     | 3,921  |
| M-153-E (14-06) |             | X         | A-7-6          | SC   | 101.8                                 | 10.7                          | 44.1       | 40,864                    | 44,442 |
| M-028-W (02-02) |             | X         | A-4            | ML   | 106.2                                 | 11.0                          | 50.6       | 53,824                    | 41,516 |
| U-002-E (02-04) |             | X         | A-4            | ML   | 113.0                                 | 10.7                          | 58.8       | 37,012                    | 33,191 |

## CHAPTER 4

### DATA ANALYSIS AND DISCUSSION

#### 4.1 Introduction

Recall that (see Chapter 1) the objectives of this study are:

- Evaluate the existing processes used by all regions of MDOT for determining the MR value of the roadbed soil for flexible pavement design and the modulus of subgrade reaction (k) for rigid pavement design.
- Determine the needed modifications to make the process compatible with the M-E PDG.

To accomplish these objectives, a research plan was carefully designed and executed. The plan consists of the following approaches:

1. **Information Gathering** - Various conversations were held with the Soil Engineers from each MDOT Region. During the conversation, the method used by the region to estimate the resilient modulus of the roadbed soil was documented. The results are listed in Table 2.1 of Chapter 2.
2. **Soil Delineation** – The State of Michigan was divided into 15 clusters and 99 areas where the roadbed soils are similar. The 99 areas were later reduced to 75 areas for soil sampling.
3. **Soil Sampling** – From each of the 75 areas, disturbed bag roadbed soils samples were obtained. In addition, 10 Shelby tube samples were collected where the disturbed soil samples showed that there was a substantial amount of clay.
4. **Field Tests** – The field tests consist of:
  - Penetration resistance using pocket size penetrometer



- Shear strength using pocket vane shear tester
- Deflection using falling weight deflectometer (FWD)

The field test results are presented in Chapter 3.

5. **Laboratory Tests** – The laboratory tests consist of:

- Moisture content
- Dry and wet sieve, hydrometer, and Atterberg limits (liquid and plastic limits and plasticity index) to analyze the grain size distribution and to classify the soils according to the USCS and AASHTO soil classification systems
- Cyclic load triaxial test

The laboratory test results are presented in Chapter 3 and in Appendix B.

6. **Data Analysis** – The data analysis and discussion are presented in this chapter in the following order:

- a) Existing MDOT practices regarding the estimation of the resilient modulus of roadbed soils.
- b) Field data analyses and discussion (including a sample backcalculated roadbed resilient modulus).
- c) Laboratory data analyses to classify the soil according to USCS and AASHTO soil classification systems.
- d) Laboratory data analyses and discussion regarding the effects of test and sample variables on the MR values.
- e) The analyses used to develop correlation equations between the resilient modulus of the roadbed soils and simple test results that would satisfy the M-E PDG requirements for design levels 2 and 3.

- f) The seasonal effects on the resilient modulus of the roadbed soils and the determination of the effective design resilient modulus using the damage model found in the 1993 AASHTO Design Guide.

It should be noted that the full analysis and discussion of the FWD deflection data and the correlations between the backcalculated and the laboratory obtained resilient modulus values are presented elsewhere (Dawson 2008).

#### 4.2 MDOT Practice

Existing MDOT practices regarding the estimation of the design resilient modulus of roadbed soils were discussed during interviews, telephone conversations, and e-mail communications with Soil Engineers from the seven MDOT Regions. The findings are listed in Table 2.1, which is repeated herein for convenience.

Table 2.1 MDOT procedures for determining resilient modulus

| Region     | Procedure                                                      | Typical MR Values (psi) |
|------------|----------------------------------------------------------------|-------------------------|
| Bay        | Soil boring & visual identification                            | 3600                    |
| Grand      | FWD data (if available) or soil boring & visual identification | 2700 - 8600             |
| Metro      | Soil boring & visual identification                            | 3000 - 4500             |
| North      | FWD data (if available) or soil boring & visual identification | 2500 - 6000             |
| Southwest  | California Bearing Ratio correlations                          |                         |
| Superior   | Soil boring & visual identification                            | 4500 - 7000             |
| University | Soil boring & visual identification                            | 3000 - 4000             |

Examination of the information provided in Table 2.1 indicates that the existing practice for estimating the resilient modulus of the roadbed soil is mainly based on soil boring, visual identification of the soil type and estimating the resilient modulus of the roadbed soils using Figure 2.2. One region uses correlations between the California Bearing Ratio (CBR) and the resilient modulus of the roadbed soils. On the other hand, two regions use the FWD deflection data, when available, to estimate the resilient modulus of the roadbed soils. However, the exact procedure used by either region to estimate the resilient modulus of the roadbed soils from the deflection data is not clear. The above scenario implies that, the practice in most regions may satisfy the requirement of design level 3 of the M-E PDG. The practice of the Southwest Region may satisfy level 2. Finally, the use of FWD data (when available) in Grand and North Regions may satisfy the pavement rehabilitation requirements in design level 1 of M-E PDG.

#### **4.3 Field Data Analyses and Discussion**

Recall that the following field tests were performed during this study:

- Falling weight deflectometer (FWD)
- Pocket penetrometer
- Pocket vane shear tester

The data analyses and discussion for each one of these tests are presented below.

**Falling Weight Deflectometer** – Unfortunately, due to unforeseen constraints during this study, FWD testing was delayed by MDOT for a period of about one year. During the first year of the study, only 19 FWD tests were conducted. The deflection data from these tests was analyzed and the resilient moduli of the roadbed soils were backcalculated. Due to a limited number of tests, only a sample of the backcalculation is

presented in this section. Analyses and discussion of the entire FWD tests and the correlations between the backcalculated and the laboratory obtained resilient modulus values are included in (Dawson 2008).

In the backcalculation, the area method presented in Chapter 2 was used to backcalculate the modulus of subgrade reaction (k) of the roadbed soils under rigid pavements. Whereas the resilient moduli of the roadbed soils under flexible pavements were backcalculated using the MICHBACK computer program (Harichandran 1994). Nevertheless; sample results of the backcalculated k and MR values for one rigid and one flexible pavement sections are included in Table 4.1. As can be seen, both the k and the MR values presented in the table are reasonable. Unfortunately, no further analyses can be conducted at this time because of the delays in the FWD testing.

Table 4.1 Sample backcalculated k and MR values

| Pavement type           | Load (lbs) | Deflection (mils) at distances behind the load (in) |         |                   |                       |          |      |      |
|-------------------------|------------|-----------------------------------------------------|---------|-------------------|-----------------------|----------|------|------|
|                         |            | 0                                                   | 8       | 12                | 18                    | 24       | 36   | 60   |
| Rigid                   | 8957       | 9.06                                                | 7.7     | 6.63              | 6.07                  | 5.01     | 3.71 | 1.93 |
| Flexible                | 9729       | 12.38                                               | 9.66    | 7.70              | 5.49                  | 4.07     | 2.48 | 1.30 |
| Cross section data (in) |            |                                                     |         |                   | Backcalculated Values |          |      |      |
|                         | Surface    | Base                                                | Subbase | Stiff layer depth | k value (pci)         | MR (psi) |      |      |
| Rigid                   | 9          | 4                                                   | 8       | NA                | 246                   | NA       |      |      |
| Flexible                | 3          | 8                                                   | 18      | 700               | NA                    | 27,898   |      |      |

**Pocket Penetrometer and Pocket Vane Shear Tester** - The locations where pocket vane shear and pocket penetrometer tests were conducted are listed in Table 3.2 of Chapter 3. The pocket penetrometer and vane shear tester results were initially compared to each other. It was found that the pocket penetrometer and vane shear tester correlate with each other. Figure 4.1 shows the pocket penetrometer plotted against the vane shear resistances, the trendline, and the correlation equation relating the two sets of data. As

can be seen, the pocket penetrometer resistance (PPR) is related to the vane shear resistance (VSR) by Equation 4.1 with  $R^2 = 0.59$ .

$$PPR = 0.9888 \ln(VSR)^{0.4685} \quad \text{Equation 4.1}$$

This correlation was expected because both tests measure indirectly (PPR) or directly (VSR) the shear strength of the soils at the same locations.

Although the results of the two tests correlate to each other, as it was expected, neither sets of data were found to correlate to the MR of the soils. This is because the MR values are obtained under low strains (primarily elastic). Whereas, the pocket penetrometer and vane shear tests were conducted at the critical state of stresses and strains (elastic, viscoelastic, and plastic).

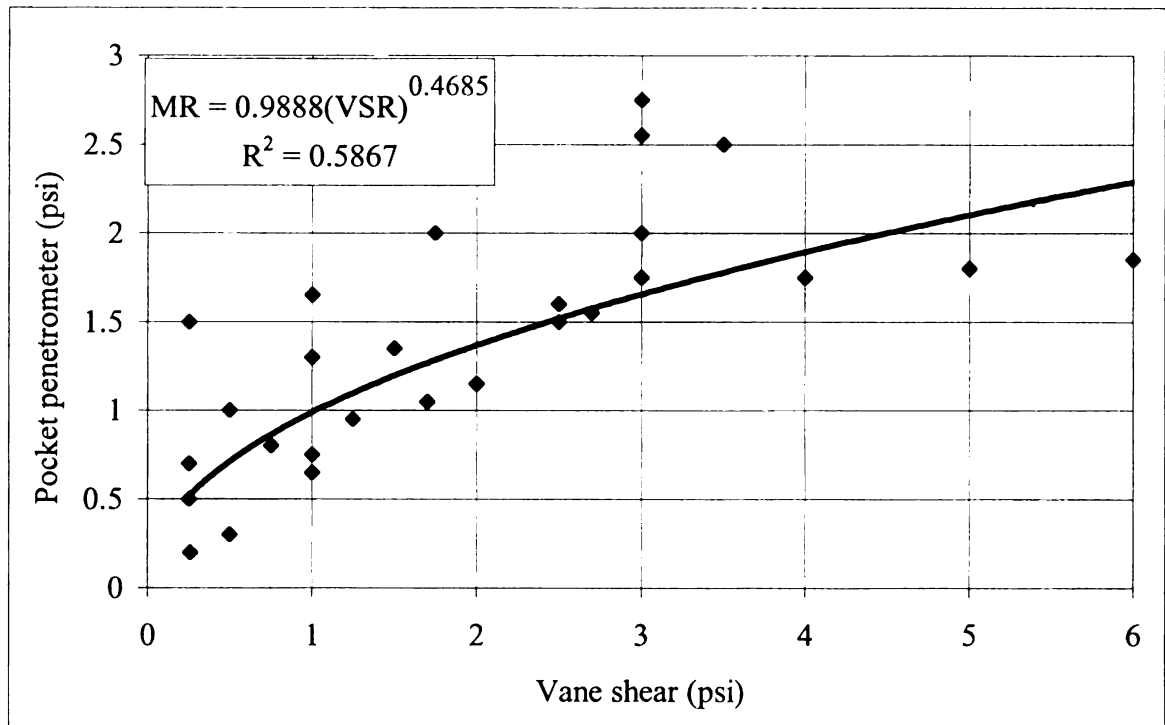


Figure 4.1 Pocket penetrometer versus vane shear tester

#### 4.4 Soil Classification

For each disturbed soil sample the dry and wet sieve test data, the hydrometer test data, and the Atterberg Limits data were analyzed to determine:

- The grain size distribution curve and the coefficients of uniformity and curvature.
- The AASHTO and the USCS soil classifications.

The results of the analyses are listed in Table 3.4. Table 4.2, provides a list of the number of disturbed soil samples for each soil classification type according to the USCS and the AASHTO soil classification systems. As can be seen, the majority of the roadbed soils in the State of Michigan can be divided, in general, into 8 soil classification types for both the USCS and the AASHTO soil classification systems. It is very important to note that the soil in each classification has a wide range of grain size distribution parameters. To illustrate, consider the grain size distribution curves for SC, SM, ML, CL, and SP-SM soils shown in Figure 4.2. It can be seen that the six soils have different grain size distributions and different coefficients of curvature ( $C_c$ ) and uniformity ( $C_u$ ). The  $C_c$  values for the six soils ranged from 0.02 to 1.18 and the  $C_u$  values ranged from 1.67 to 200. Whereas the  $C_c$  range for all the collect soil samples is 0.02 to 75 and the  $C_u$  range is from 1.65 to 385.71. Similar ranges in soil gradation were found for each soil type. The vast ranges in the gradation within a given soil type is the direct result of the glaciations and the glacial deposits in the State of Michigan.

Finally, the details of the USCS, the AASHTO and the MDOT soil classification systems are included in Appendix A.

#### 4.5 Cyclic Load Triaxial Test Results

Recall that, at most sample locations the soil was subjected to pocket vane shear tester and pocket penetrometer (see section 4.3). After the two tests, bag samples were collected and then transported to Michigan State University Geotechnical Laboratory. In the laboratory, most soil samples were tested to determine their natural moisture contents,

Table 4.2 Number of samples per soil type

| USCS                |                   | AASHTO Classification |                   |
|---------------------|-------------------|-----------------------|-------------------|
| Soil classification | Number of samples | Soil classification   | Number of samples |
| SP                  | 20                | A-1-a                 | 2                 |
| SM                  | 16                | A-1-b                 | 2                 |
| CL                  | 8                 | A-2-4                 | 21                |
| ML                  | 2                 | A-2-6                 | 3                 |
| SC                  | 18                | A-3                   | 25                |
| SC-SM               | 7                 | A-4                   | 10                |
| SP-SM               | 8                 | A-6                   | 12                |
| SG                  | 2                 | A-7-6                 | 6                 |

grain size distributions, Atterberg limits, and resilient modulus using cyclic load triaxial tests.

As stated in Chapter 3, all cyclic load tests were conducted using one confining pressure of 7.5 psi. In each test, after applying the confining pressure, the soil samples were subjected to a 10 psi cyclic axial stress and their deformations were recorded at 5 intervals (cycle number 100, 200, 500, 800, and 1000). Each interval consisted of three consecutive load cycles, for example, cycle number 100 consists of the sample deformations at cycles numbered 99, 100, and 101. For each load cycle within a given interval, the resilient modulus was calculated. Afterward, the average resilient modulus from the three consecutive cycles was determined. After terminating the 10 psi axial

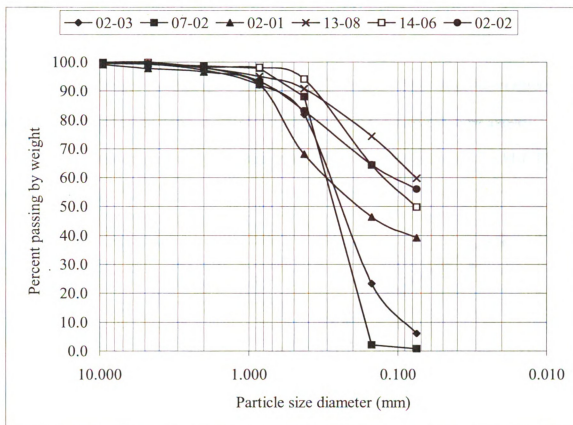


Figure 4.2 Typical particle size distribution curves

stress test at load cycle number 1001, the number of load cycle was reset and the test was started again at the new axial stress level of 15 psi. The new test, and the calculation of the resilient modulus, was conducted in the same manner as that of the 10 psi axial stress test. For each axial stress level, Table 3.5 provides a list of the sample designation number, the sample parameters (moisture content, saturation, and dry unit weight), and the average resilient modulus values, which were calculated as the average of the average resilient modulus values at the three intervals 500, 800, and 1000 load cycles.

**Effects of Axial Stress Level on MR Values** - Figure 4.3 depicts the resilient modulus values obtained at 10 and 15 psi cyclic axial stress levels. The line of equality between the two set of MR values is also shown in the figure. The data in the figure indicates that



the MR values, in general, decrease insignificantly with increasing cyclic axial stress levels, indicating slight non-linearity. This observation was expected because as the axial cyclic stress increases the strain in the sample also increases. This observation agrees with that reported by Young and Baladi (1977). It should be noted that the above observation does not necessarily disagree with bulk stress model stated in the M-E PDG

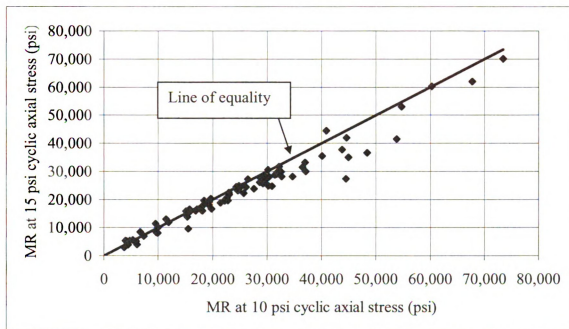


Figure 4.3 Resilient moduli at 10 and 15 psi cyclic axial stresses

(see Equation 2.1 in Chapter 2). In this model, as the axial stress increases, the bulk stress (the sum of the axial stress and twice the confining pressure) and the octahedral shear stresses increase. The effect of the latter is typically greater than that of the former. Since  $k_3$  in Equation 2.1 is negative, it implies increasing the octahedral stress causes decreases in the MR values.

**Effects of the Sample Variables on MR Values** - Given the standard pavement cross-section used in the State of Michigan (the roadbed soil is located between 18 to 36 inches below the pavement surface), the roadbed soil is typically subjected to 4 to 7 psi vertical

stresses due to an 18,000 pounds single axle load. Therefore, the effects of the sample variables on MR values are discussed for the axial stress level of 10 psi only. In addition, the effects of the sample variables on the subgrade MR values were studied in a two step procedure. In the first step, the soils were divided into six groups according to their USCS classification listed below.

1. Poorly graded sand (SP)
2. Silty sand (SM)
3. Clayey sand (SC), low plasticity clay (CL), and low plasticity silt (ML)
4. Poorly graded sand – silty sand (SP-SM)
5. Clayey sand – silty sand (SC-SM)
6. Gravelly sand (SG)

In the second step, univariate and multivariate analyses were conducted to determine the relationships (if any) between the resilient modulus values and the sample parameters. Results of these analyses for each of the six soil types are discussed below.

#### **4.5.1 Poorly Graded Sand (SP)**

Table 4.3 lists the locations, the USCS and the AASHTO soil classifications, and the sample designation number of twenty disturbed soil samples that were collected from various clusters and areas throughout the State of Michigan. Results of the soil classification conducted in step 1 of the analyses indicated that nineteen samples can be designated as A-3 and one sample as A-1-b according to the AASHTO soil classification system. On the other hand, all twenty samples were classified as SP according to the USCS. Please note that, in Table 4.3, twelve subgrade samples are labeled SP1 and eight samples are labeled SP2. The reason for that is stated in section 4.5.1.1; the effects of

grain size on the resilient modulus of SP soils. Nevertheless, in step 2 of the analyses, results of the cyclic load triaxial tests were used to calculate the resilient modulus of all SP samples. Univariate and multivariate analyses were then conducted to determine the relationships between the sample variables and the resilient modulus of the subgrade soils. Results of these analyses are presented in the next two subsections. Results of the cyclic load triaxial tests of three samples (the shaded samples in Table 4.3) were used to verify the statistical models and are presented in section 4.5.1.3.

#### **4.5.1.1 Univariate Analyses**

In the univariate analyses, the effects of each of several sample variables on the MR values of SP soils were studied. These sample variables include: the moisture contents of the samples, the dry unit weight after laboratory compaction, and the grain sizes. The discussion of the effects of each variable is presented below.

**Effect of Sample Grain Size** – To study the effects of sample gradation on the MR values of SP soils, sieve analyses were conducted and grain size distribution curves were plotted to determine the coefficients of curvatures and uniformity. Observation of the grain size distribution curves indicate that the twenty subgrade samples can be divided into two categories according to the slope of the gradation curve between the percent passing sieves number 40 and number 200 as shown in Figure 4.4. Soils having the steep curves are labeled SP1 whereas the others SP2 (see Table 4.3). In general, SP1 soils have lower coarse sand contents and higher fine sand contents than the SP2 soils.

The effects of the sample variables of both SP1 and SP2 soils on their MR values were studied by plotting the MR values versus each of the following grain size parameters:

- Percent passing sieves 200, 100, 40, 20, 10, 4, and 3/8 inch
- The Coefficients of curvature and uniformity
- The average particle size at ten, thirty, and sixty percent passing ( $D_{10}$ ,  $D_{30}$ , and  $D_{60}$ , respectively)
- The coarse sand content (percent passing sieve number 4 – percent passing sieve number 40) and the fine sand contents (percent passing sieve number 40 – percent passing sieve number 200)

The data in most figures were scattered all over the board indicating insignificant or no relationship between the grain size data and the MR values. An example plot between the percent passing sieve number 10 and MR values is shown in Figure 4.5. The scenario however, was drastically different when the data were separated into two groups SP1 and SP2 as shown in Figure 4.6. The data showed moderate degree of correlation ( $R^2$  for SP1 soils of 0.61 and for SP2 soils of 0.15). Given this observation, the particle size parameters will be included in the multivariate analyses for the SP1 and SP2 models. Similar, but stronger scenario was found when the MR values of the SP soils were plotted against the dry density of the samples. This correlation is presented next.

**Effect of Sample Dry Unit Weight** - The effect of the dry unit weight on the MR for SP soils was studied by testing one soil sample compacted at three dry unit weights and the same water content using different compaction effort (vibrating times of 1, 2, and 3 minutes). The three dry unit weights were 104.1, 106.6, and 109.8 pounds per cubic feet. After compaction, the three samples were subjected to cyclic load tests as stated in section 4.5. Results of the cyclic load tests were used to calculate the resilient modulus

Table 4.3 Location of SP subgrade soils

| Sample designation number | Location                                                                                    | AASHTO | USCS |
|---------------------------|---------------------------------------------------------------------------------------------|--------|------|
| I-094-W (11-02)           | 132 feet West of exit 110 on ramp                                                           | A-3    | SP1  |
| U-031-N (06-03)           | 307 feet North of M-46                                                                      | A-3    | SP1  |
| M-028-W (03-02)           | 1500 feet North of M-77                                                                     | A-3    | SP1  |
| I-075-N (03-04)           | mile marker 380                                                                             | A-3    | SP1  |
| M-025-S (15-05)           | 200 feet North of Day Rd                                                                    | A-3    | SP1  |
| M-132-N (06-01)           | 1000 feet North of Addis Rd (paved rd)                                                      | A-3    | SP1  |
| I-075-N (06-02)           | 160 feet North of Co Rd 662                                                                 | A-3    | SP1  |
| M-020-W (07-02)           | ~.5 mile East of 13 Mile Rd                                                                 | A-3    | SP1  |
| M-020-E (07-03)           | ~500 feet East of Cottonwood Ave                                                            | A-3    | SP1  |
| U-131-S (09-01)           | 160 feet South of Lake Montcalm Rd                                                          | A-3    | SP1  |
| U-131-S (09-03)           | 105 feet South of 110th Ave                                                                 | A-3    | SP1  |
| U-131-S (09-05)           | 60 feet South of "Reduce Speed 55 MPH" sign right where it turns from interstate to freeway | A-1-b  | SP1  |
| I-069-E (09-10)           | 172 feet East of Grand River Rd                                                             | A-3    | SP2  |
| U-023-S (04-01)           | 320 feet North of F 05 Co Rd                                                                | A-3    | SP2  |
| M-059-W (13-02)           | Station 131+29                                                                              | A-3    | SP2  |
| U-127-N (05-04)           | 120 feet North of Co Rd 300                                                                 | A-3    | SP2  |
| I-094-W (13-04)           | Station 75+02                                                                               | A-3    | SP2  |
| U-024-S (14-04)           | 150 feet North of Pardee                                                                    | A-3    | SP2  |
| M-053-S (14-07)           | 1500 feet South of Canal Rd                                                                 | A-3    | SP2  |
| M-068-W (04-03)           | 150 feet West of Little Ocqueoc River                                                       | A-3    | SP2  |

of the samples. Figure 4.7 shows the MR plotted as a function of the dry unit weight. As it can be seen from the figure, higher dry unit weights cause higher MR. The observations were expected and have been reported by other researchers (Maher et al. 2000).

**Effect of the Sample Moisture Contents** – To study the effects of moisture contents on the MR values of SP soils, the soil sample with the lowest natural water content (0.2 percent) was selected for testing. This selection allowed the addition of water to increase the water content of the sample from 0.2 percent to 5.3 and to 11.5 percent. The three water contents were selected such that the highest degree of saturation of the samples will be less than eighty percent. The eighty percent saturation level may cause liquefaction and a total loss of shearing resistance (Richart et al 1970). The three selected water contents correspond to degrees of saturation of 1, 26.4, and 59.3 percent, respectively. For each of the three water contents a soil sample was compacted using the same static load and vibrating table described in section 3.5.4 of Chapter 3. It should be noted that all three samples were compacted using the same compaction effort.

After compaction, the sample was subjected to a cyclic load test as stated in section 4.5. Results of the cyclic load tests were used to calculate the resilient modulus of the sample. Figure 4.10 depicts the resilient modulus of the three soil samples plotted as a function of their water contents. The figure shows that for the given range of moisture contents, their effect on MR is insignificant. This was expected because, in general, the strength and stiffness of sand soils are only slightly affected by the water content of the soils. At low water contents, the capillary between the sand particles slightly increases the normal stress and hence, the friction between particles. As the moisture content increases, the lubrication between the sand particles increases, which

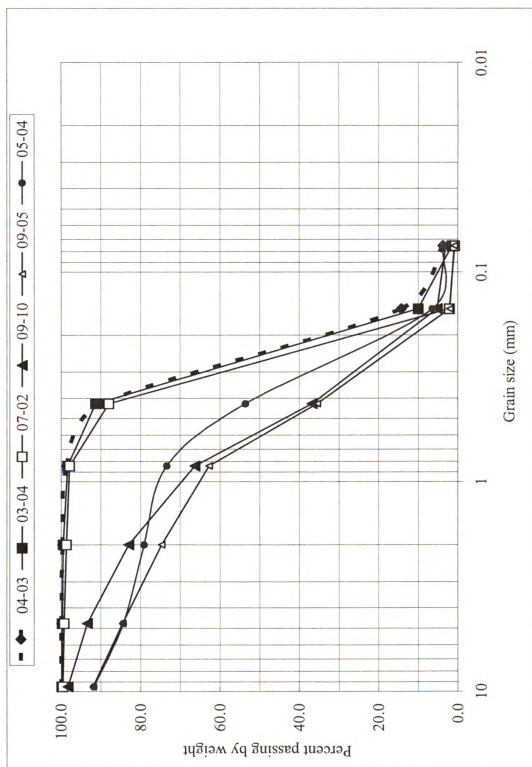


Figure 4.4 Grain size distribution curves for SP soils

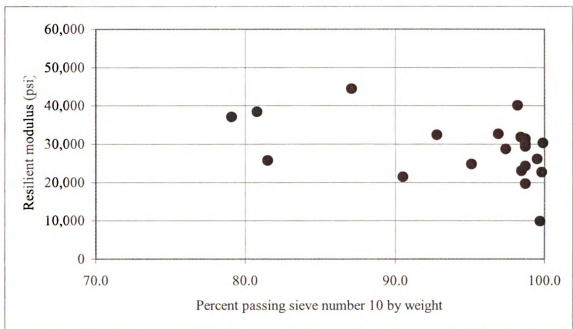


Figure 4.5 Resilient modulus versus the percent passing sieve number 10 for SP soils

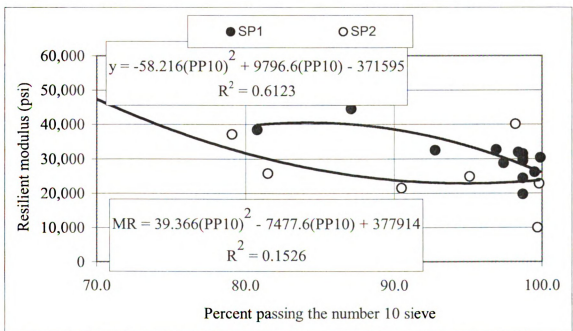


Figure 4.6 Resilient modulus versus the percent passing sieve number 10 for SP1 & SP2



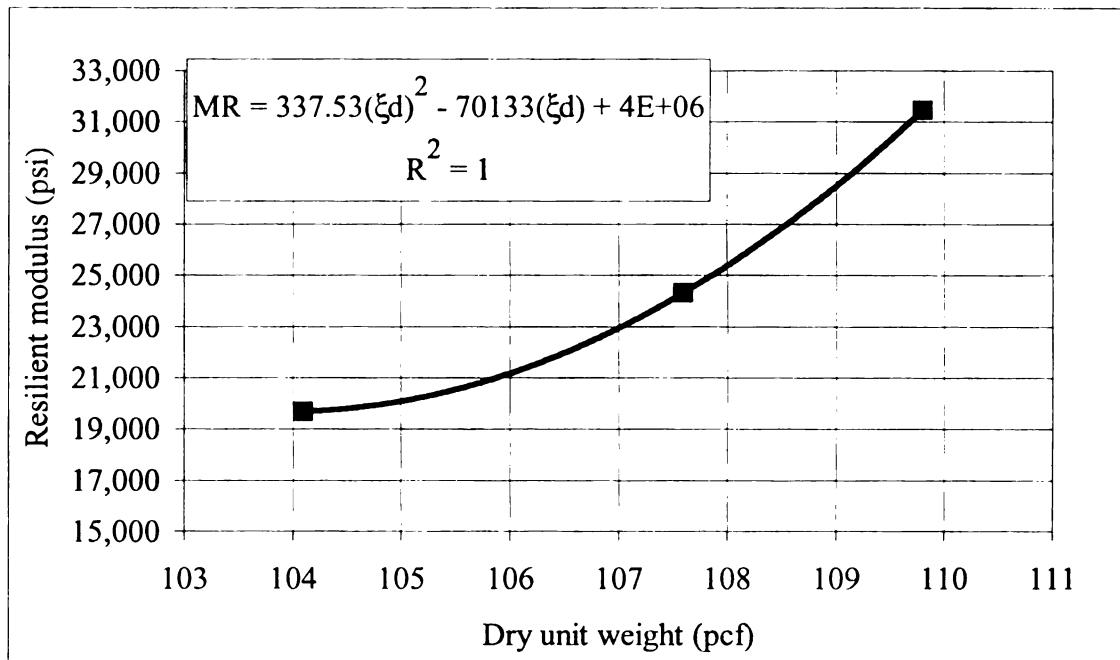


Figure 4.7 Resilient modulus versus the dry unit weights for one SP soil sample

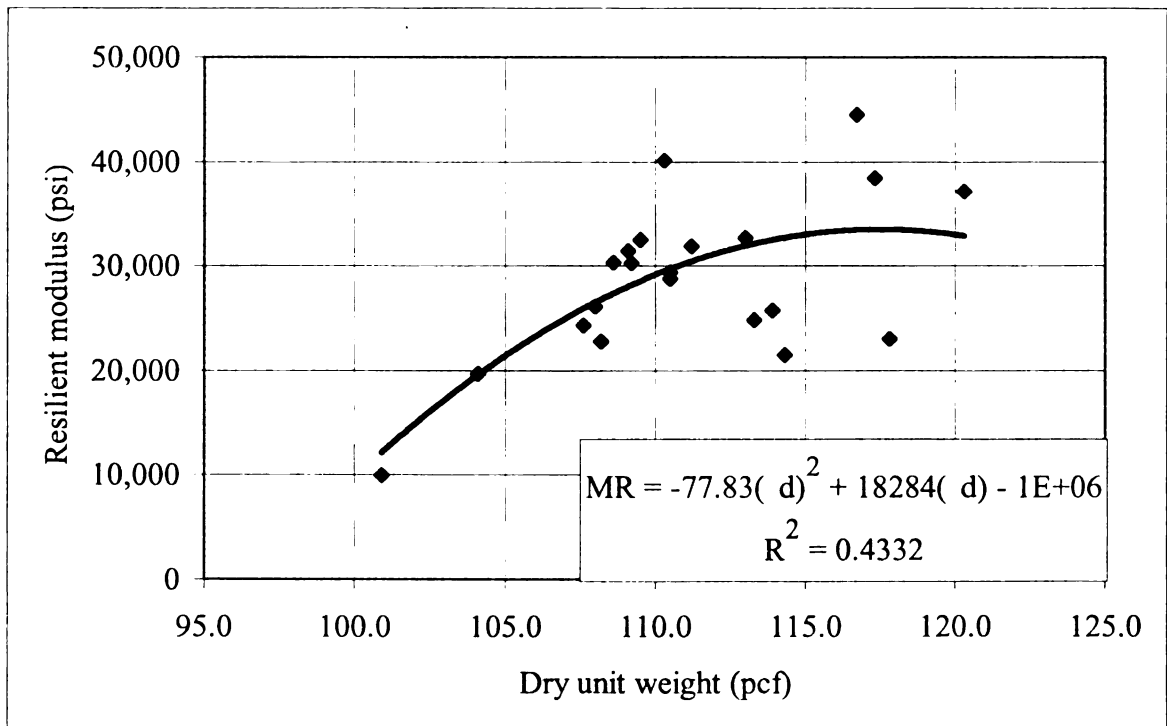


Figure 4.8 Resilient modulus versus the dry unit weight for 20 SP soil samples

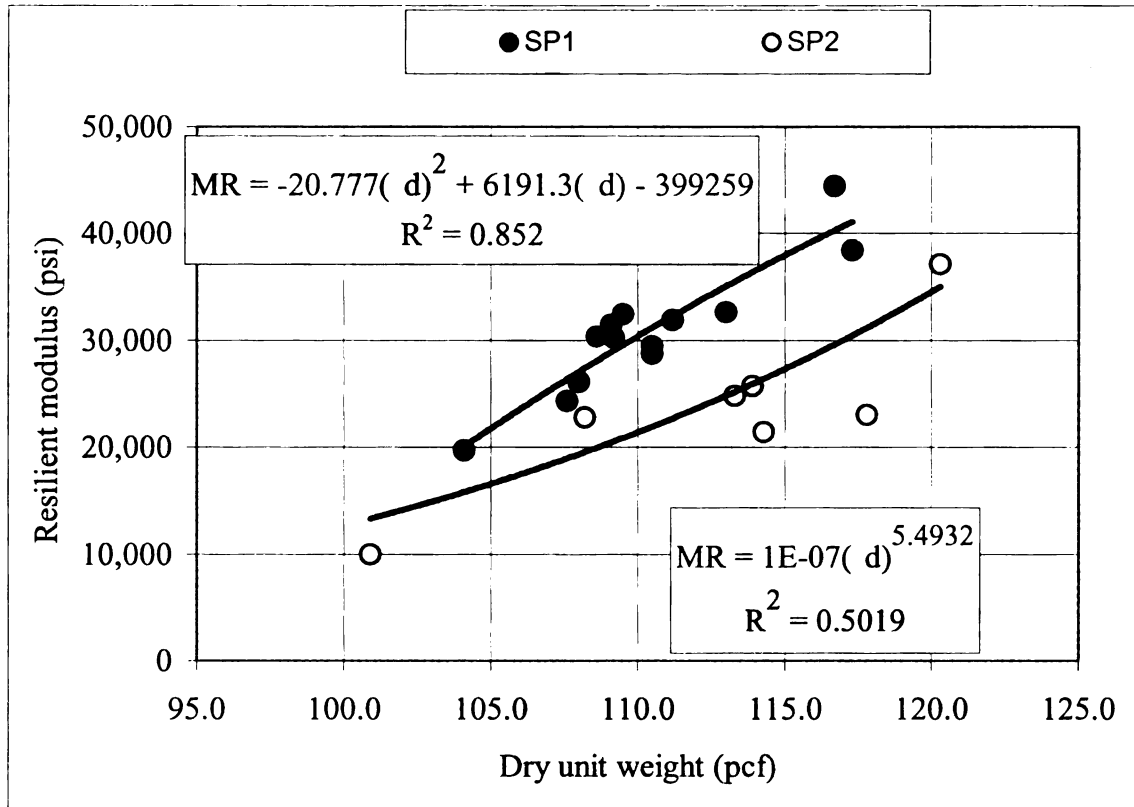


Figure 4.9 Resilient modulus versus the dry unit weight for SP1 and SP2 soil samples

overcomes the capillary effect and the strength begins to decrease. When the sample is at 80 percent saturation level or higher, the pore water pressure increases during shearing and the effective stress decreases causing decreases in the angle of internal friction. At or near saturation, the strength drops to zero and the sand liquefies. Similar results were reported by (Young and Baladi 1977, Holtz and Kovacs 1981, and Richart et al 1970).

#### 4.5.1.2 Multivariate Analyses

Multivariate analyses were conducted to study the combined effects of several independent sample variables of the SP (SVSP) soils on the dependent variable MR of those soils. The term SVSP was divided into two terms; SVSP1 and SVSP2 to express the two SP soil groups; SP1 and SP2. During the multivariate analyses:

- Various models were used in an attempt to maximize the value of the coefficient of determination ( $R^2$ ).

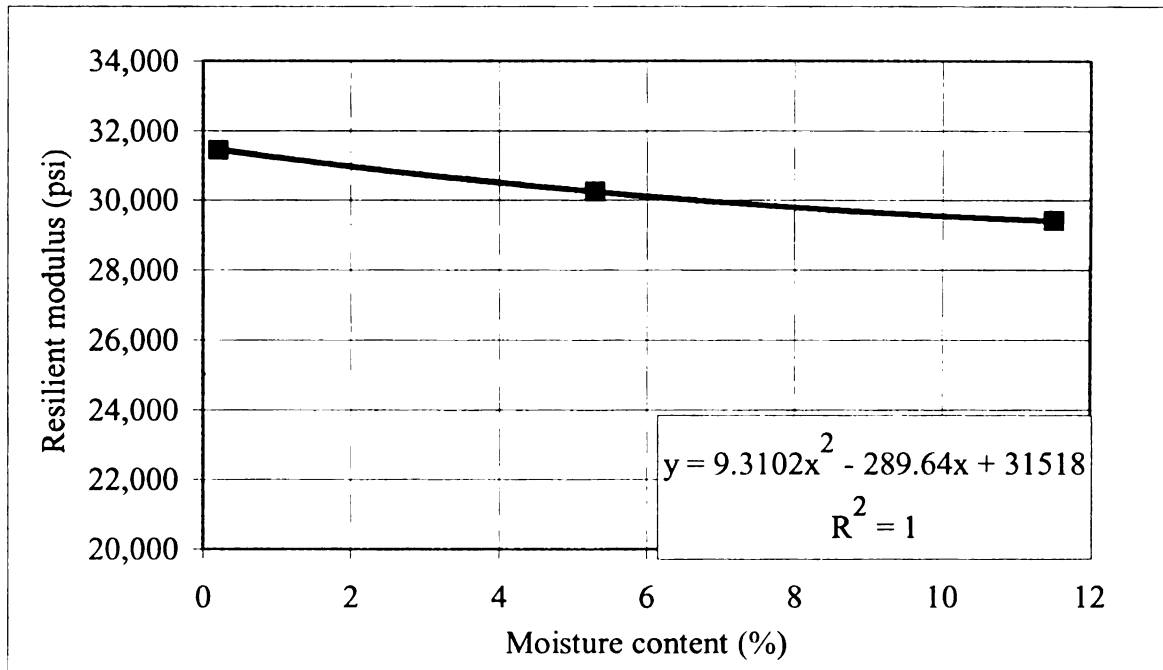


Figure 4.10 Resilient modulus versus the moisture content of one SP soil sample

- Special care was taken to:
  - Ensure that the resulting equation satisfies the known trends between each of the independent variable and the dependent variable MR.
  - Avoid any significant co-linearity between the independent variables.
  - Decrease the number of independent variables in the equation.

The multivariate analyses yielded Equations 4.2 and 4.3 for sets 1 and 2 SP soils, respectively.

$$MR = 89.825(SVSP1^{2.9437}), \quad R^2 \approx 0.78 \quad \text{Equation 4.2}$$

$$MR = 0.8295(SVSP2^{3.6006}); \quad R^2 \approx 0.81 \quad \text{Equation 4.3}$$

Where,

$$SVSP1 = \frac{\gamma_d^{1.15}}{(P_4^{1.5} - P_{40}^{0.25})^{0.5}}$$

$$SVSP2 = \frac{\gamma_d^{1.35} * P_{200}^{-0.1}}{(P_4^{1.5} - P_{40}^{0.25})^{0.5}}$$

$\gamma_d$  = dry unit weight (pcf)

$P_4$ ,  $P_{40}$ , and  $P_{200}$  = percent passing sieves numbers 4, 40, and 200, respectively

Examination of Equations 4.2 and 4.3 indicates that the resilient modulus values of the SP1 and SP2 soil groups are a function of the dry unit weight of the soil and the parameter  $(P_4^\alpha - P_{40}^\beta)^\omega$ , which represents the coarse sand content in the soil. Further, the resilient modulus values of SP2 soil group are also a function of the percent passing sieve number 200. Hence, the data and results of the multivariate analyses reflect the shape of the gradation curves of SP1 and SP2 soils shown in Figure 4.4. The shapes of the gradation curves imply that the mechanistic behavior of SP1 and SP2 soils are not the same. The SP1 soils are deficient in the coarse sand content; hence, coarse sand particles are floating in the fine sand matrix. For SP2 soils, the opposite is true. The SP2 soils contain relatively large amounts of coarse sands; hence, the coarse sand particles are likely in contact with each others while the fine sand particles are filling the voids between the coarse particles.

Figure 4.11 shows the MR values of SP1 and SP2 soils plotted against the sample variables; SVSP1 and SVSP2, respectively. The equations of the best fit lines and the

coefficients of determination are also shown in the figure. Examination of the figure indicates that for SP1 and SP2 soils, higher values of SVSP1 and SVSP2 produce higher MR values. This was expected because higher dry unit weights imply denser particle packing, higher relative density, higher friction, higher stiffness, and hence, higher MR values.

It should be noted that numerous trials were made to unify the two models. Various univariate analyses that included a range of other sample variables were tried without any success. When the locations of SP1 and SP2 soils were studied, it was clear that all SP2 soils are located in the eastern half of the State of Michigan while SP1 soils in the western half. The possible differences between the two soils include:

- The two soils have different origin, the SP2 soils were deposited as the glacial lobe, which was advanced along Lake Huron, retreated. The SP1 soils, on the other hand, were deposited when the glacial lobe, which was advanced along Lake Michigan trough, was retreated.
- The SP1 soils were deposited by gently flowing melted water (it contains higher percent of fine sand) while the SP2 soils were deposited by relatively faster moving melted water.
- The differences in the soil origin and deposition may have created different angularity of the coarse materials. Unfortunately, the soil angularity was not measured due to lack of proper equipment nor was it a part of this study.
- The fine materials (passing sieve number 200) of the SP1 and SP2 soils are different. The fine materials of the SP1 soils is mainly silt while the fine materials of the SP2 soils are a mix of clay and silt.

Equations 4.2 and 4.3 apply to samples with dry unit weight values ranging from 100.9 to 120.3 pcf and percent passing sieve number 4 values between 84.5 and 100.0 percent while the percent passing sieve number 40 is between 36.8 and 97.2 percent. The range in percent passing sieve number 200 is 0.5 to 4.7 percent. This range is the entire allowable range of fine contents of SP soils. The use of the two equations outside the stated ranges may yield high and unrealistic MR values.

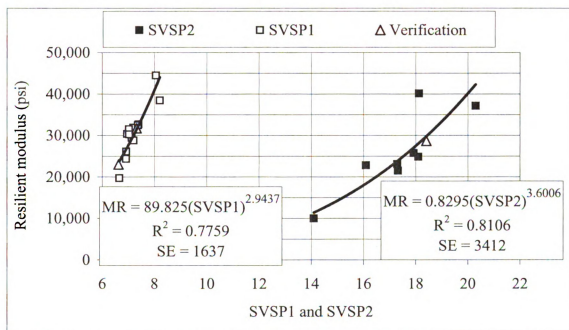


Figure 4.11 Resilient modulus versus SVSP1 and SVSP2

#### 4.5.1.3 Validation

In order to check the validity of Equations 4.2 and 4.3, the two SP1 and the one SP2 samples highlighted in Table 4.3, which were not included in the development of the equations, were subjected to grain size analysis, and cyclic load triaxial tests. The test results were used to calculate the resilient modulus values of the three samples and the sample variables (SVSP1 and SVSP2). The data are shown in Figure 4.11 as open triangles. It can be seen that the data for the three samples are very close to the best fit

curve. Further, the two SVSP1 values for SP1 samples and the SVSP2 value for SP2 sample were used in Equations 4.2 and 4.3, respectively, and the resilient modulus of the three samples were predicted. Figure 4.12 shows the measured and the predicted MR

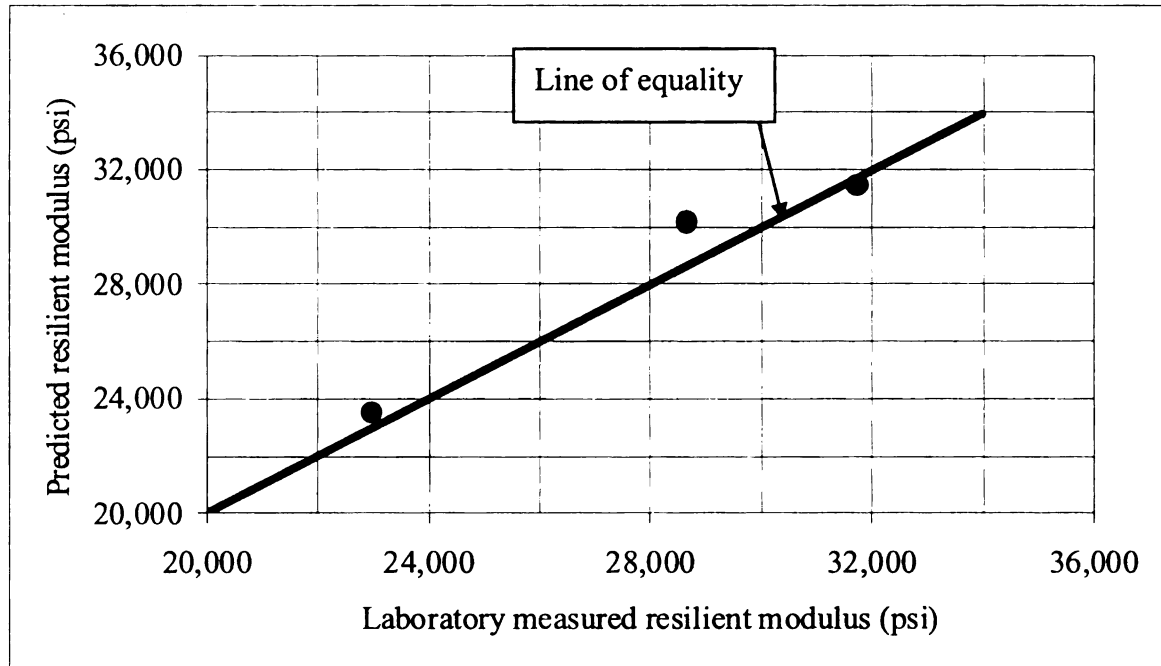


Figure 4.12 Predicted resilient modulus values for the validation points

values of the three samples. The straight line in the figure is the line of equality between the predicted and the measured MR values. As can be seen from the figure, the predicted MR values are almost equal to the laboratory measured values. Hence, one can conclude that the developed models (Equations 4.2 and 4.3) are relatively accurate and can be used to estimate the resilient modulus of the soils based on knowledge of the dry unit weight of the soils and their grain size distribution.

#### 4.5.2 Silty Sand (SM)

Table 4.4 lists the locations, the USCS and the AASHTO soil classifications, and the sample designation number of sixteen disturbed soil samples that were collected from various clusters and areas throughout the State of Michigan. The commonality between

the sixteen samples is that all of them were classified in step 1 of the analyses as silty sand (SM) soils according to the USCS. Recall that the USCS specifies that SM soils may contain anywhere between 12 and 49.9 percent passing sieve number 200 (Holtz and Kovacs 1981). Hence, the fine materials play a major role in the mechanistic behavior and the resilient modulus (MR) values of the soil. In step 2 of the analyses, univariate and multivariate analyses were conducted to develop correlations between the test sample variables and their resilient modulus values. The results are presented and discussed below. It should be noted that the three samples highlighted in Table 4.4 were not included in the development of the correlation equations between the sample variables and their resilient modulus values. They were tested and the test data were used to verify the developed models.

#### **4.5.2.1 Univariate Analysis**

In the univariate analyses, the effects of each of several sample variables on the MR values of SM soils were studied. These sample variables include: the moisture contents of the samples, the degrees of saturation, the liquid limits, the dry unit weight after compaction, and the grain sizes. The effects of each variable on the resilient modulus values are presented and discussion below.

**Effect of the Sample Moisture Contents** – For SM soils, it was hypothesized that because of the high range of fine contents, the water contents should play a major role in determining the elastic response of the soil to the applied loads. Figure 4.13 shows the MR values of thirteen SM soil samples (the three shaded samples in Table 4.4 are not included) plotted against the samples moisture contents. As it was expected, the figure shows increases in the sample moisture contents cause significant decreases in the MR



Table 4.4 Locations of SM subgrade soils

| Sample number   | Location                                             | AASHTO | USCS |
|-----------------|------------------------------------------------------|--------|------|
| U-002-E (02-01) | 385 feet East of M-45                                | A-4    | SM   |
| U-002-E (03-03) | 200 feet East of M-117                               | A-2-4  | SM   |
| M-065-S (04-04) | 160 feet South of Elm Hwy                            | A-2-4  | SM   |
| U-131-N (05-01) | 200 feet South of Michigan Fisheries Visitor Center  | A-2-4  | SM   |
| M-061-E (07-06) | 420 feet East of left hand turn on M-61 (off US-127) | A-2-4  | SM   |
| M-061-E (08-02) | 165 feet West of Hockaday                            | A-2-4  | SM   |
| M-044-E (09-07) | Station 137+10                                       | A-2-4  | SM   |
| M-024-S (09-09) | 20 feet North of Burley Rd                           | A-2-4  | SM   |
| I-069-N (10-04) | 150 feet North of Island Hwy                         | A-2-4  | SM   |
| I-069-N (10-05) | 100 feet North of Five Points Hwy                    | A-2-4  | SM   |
| I-096-W (10-09) | 140 feet West of Dietz Rd                            | A-2-4  | SM   |
| U-012-E (12-04) | 100 feet East of Emarld Rd                           | A-2-4  | SM   |
| I-094-W (12-06) | 53 feet West of Mt Hope Rd                           | A-2-4  | SM   |
| M-024-S (13-01) | 250 feet North of Best Rd                            | A-4    | SM   |
| M-053-S (15-02) | 300 feet South of M-46                               | A-2-4  | SM   |
| M-019-S (15-07) | 650 feet South of Thompson Rd 1 mile South of M-142  | A-2-4  | SM   |

values. This observation tends to validate the hypothesis stated above. Similar results were also reported by many researchers including (Maher et. al 2000, George 2000, and 2003). One observation is important to note herein is that the effect of moisture content on the resilient modulus values of SM soils is much higher than that for the SP soils reported in the previous section. This is mainly due to the much higher fine contents in the SM soils compared to the fine contents of the SP soils (less than 5 percent). Since the water content is strongly correlated to the MR values of SP soils, it will be included in the multivariate analyses.

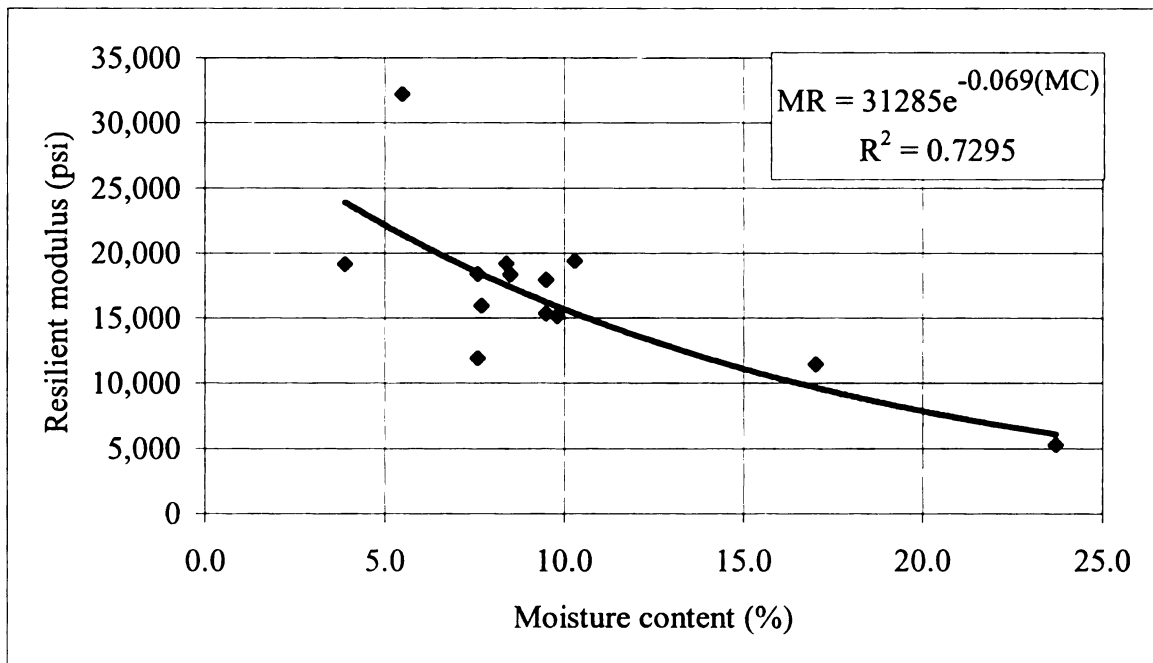


Figure 4.13 Resilient modulus versus water contents of the SM soil samples

**Effect of Sample Dry Unit Weight** - The effect of the test sample dry unit weight on the MR values of SM soils were studied by plotting the MR values as a function of the sample dry unit weight as shown in Figure 4.14. As it was expected, the figure shows a weak correlation between the dry unit weight and the MR values of the test samples. The main reason for the weak correlation is that the water contents of the test samples vary from about 3 to about 23 percent. Such variation in the water content, (when examined in perspective of the compaction curve) covers both the wet and the dry side of the curve. This implies that two soil samples having the same dry unit weight value may have two significantly different water contents. One is located on the wet side of the optimum moisture content and the other on the dry side. Test samples compacted on the dry side of optimum would have higher strength and stiffness and display a more brittle behavior than those compacted wet of optimum. The latter would have lower strength, higher plastic deformation and softer behavior under loads. The differences in the behavior are

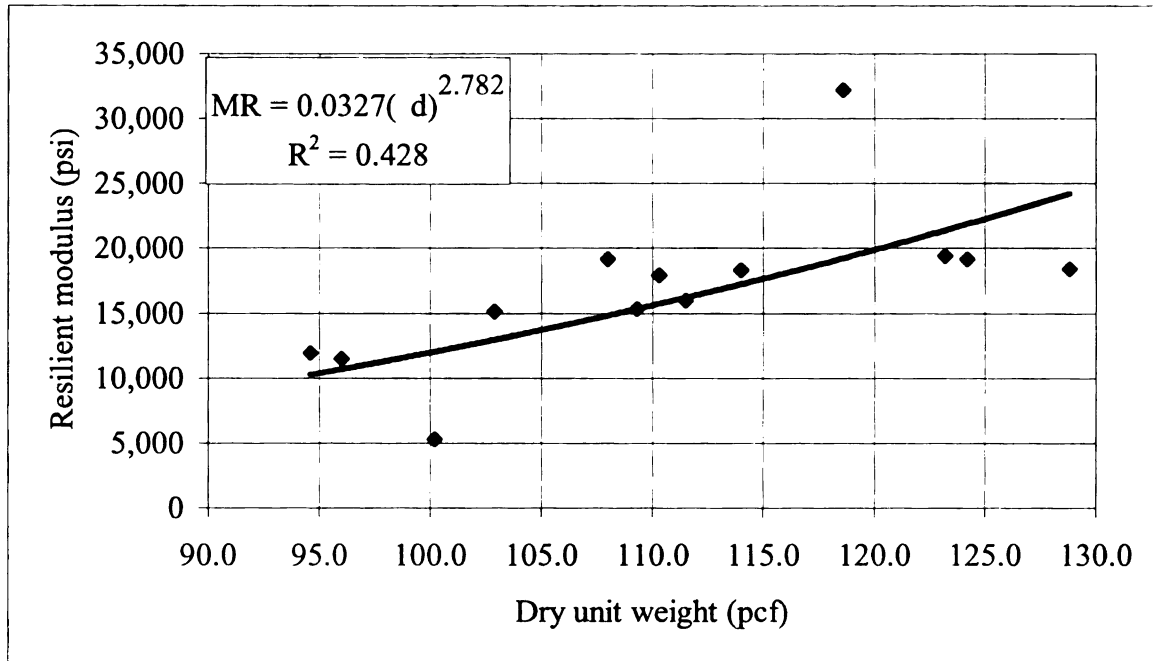


Figure 4.14 Resilient modulus versus dry unit weight of 13 SM soil samples directly related to differences in the degrees of lubrication caused by the water and the particle arrangement on the soil. The soil particles of a soil sample compacted on the dry side of optimum, tend to stay in a flocculated arrangement whereas on the wet side of optimum, they are dispersed (they line up), (Holtz and Kovacs 1981).

The above discussion implies that the true effect of the dry unit weight on MR values cannot be separated from the effect of the water content unless the latter is held constant and the former is changed using different compaction effort. In the multivariate analyses presented in the next subsection, the effect of dry unit weight on the MR values were analyzed in conjunction with the effect of water content of the test samples.

**Effect of the Sample Degree of Saturation** – For each test sample, after the conclusion of the cyclic load test, the sample moisture content and dry unit weights were determined and the degree of saturation (S) was calculated using Equation 4.4. Please note that for

all SM soil samples, a typical value of the specific gravity of the solid ( $G_s$ ) of 2.7 was assumed and used in Equation 4.4.

$$S = \left[ \frac{G_s * (MC/100) * \gamma_d}{G_s * \gamma_w - \gamma_d} \right] * 100 \quad \text{Equation 4.4}$$

Where,

$S$  = degree of saturation (%)

$MC$  = moisture content (%)

$G_s$  = specific gravity of the soil solid = 2.7

$\gamma_d$  = dry unit weight of the sample (pcf)

$\gamma_w$  = unit weight of water = 62.4 pcf

Figure 4.15 shows the MR values plotted against the degree of saturation of the test samples. As it was expected and reported by Maher et al. (2000), the MR values decrease significantly with increasing degrees of saturation. One may argue that the data in Figure 4.15 is repetitive and are the same as the data in Figure 4.13, hence, Figure 4.15 can be eliminated. In reality, the water content of a soil sample is an independent variable whereas the degree of saturation is a function of the dry unit weight and the water content of the soil. Hence, the data in Figure 4.15 show the combined effects of the dry unit weight and the water content of the test samples on their MR values. The degree of saturation will be included with other sample variables in the multivariate analyses to determine their combined effect on MR.

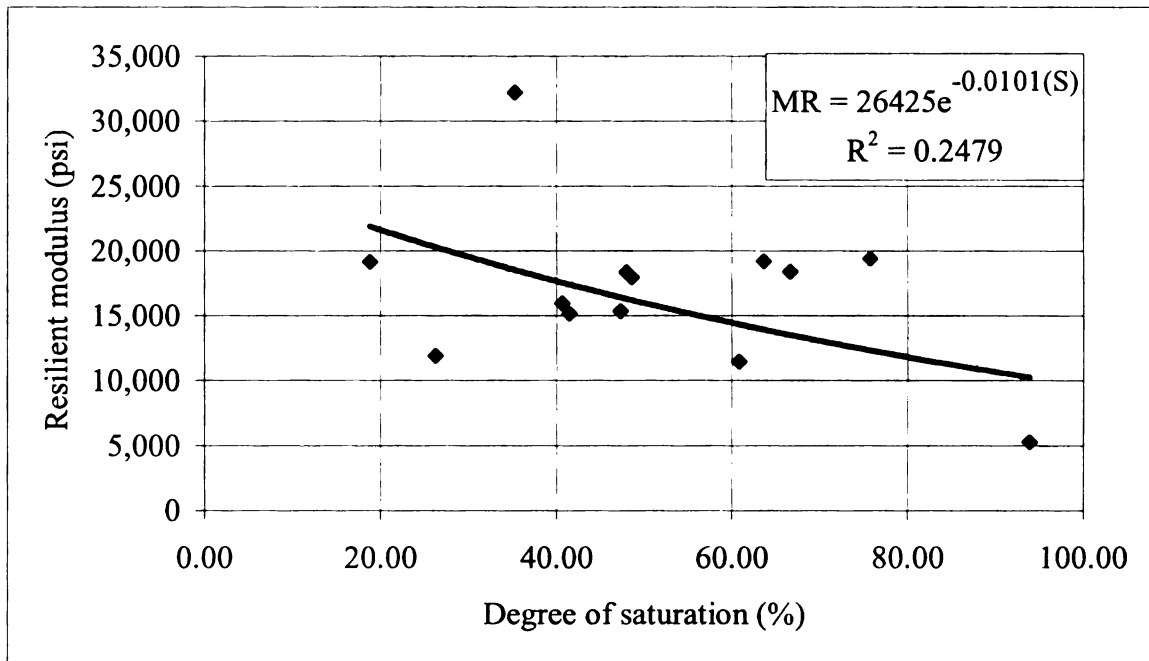


Figure 4.15 Resilient modulus versus the degree of saturation of SM soil samples

**Effect of the Sample Liquid Limit** - For each SM soil sample, the Atterberg limits for all materials passing sieve number 40 were determined in order to classify the type of fine materials (silt or clay). The plastic limit tests showed 15 soil samples can be classified as non-plastic (the plastic limit test failed repeatedly). The plastic limit test was successful for only one soil sample and the plastic limit of the soil was very low. Hence, the effects of the plastic limits and plasticity index on the MR values were not analyzed. However, the effects of the liquid on the MR values of the soils were analyzed. Figure 4.16 depicts the influence of the liquid limits on the MR values of SM soils. The data in the figure indicate that the MR values of SM soils having higher liquid limits are lower than those having lower liquid limits. Such observation was expected and has been reported by many researchers for various soil types including silty and clayey sands, silt, and clay (Gudishala 2004). Given the strong correlation between the liquid limit of the

material passing sieve number 40 and the soils MR values, the liquid limit data were included in the multivariate analyses presented in the next subsection.

**Effect of Sample Grain Size** – Because of high fine contents, all SM soils were subjected to wet sieving and hydrometer analyses to determine their grain size distribution. The effects of sample gradation on MR values were assessed through the following gradation parameters:

- Percent passing sieves 200, 100, 40, 20, 10, 4 and 3/8 inch
- The coefficients of curvature and uniformity
- Average particle size at ten, thirty and sixty percent passing ( $D_{10}$ ,  $D_{30}$ , and  $D_{60}$ , respectively)

The effects of each gradation parameter on the MR values were analyzed by plotting the MR values of the soil samples as a function of that parameter. Only three gradation parameters, the average particle size at 10, 30, and 60 percent passing showed minor correlation to MR values, the others showed no correlation. Figure 4.17 shows the correlation between the average particle size at thirty percent passing and the MR values. Based on these observations, the average particle size at 10, 30, and 60 percent passing were included in the multivariate analyses, which are presented in the next subsection.

#### **4.5.2.2 Multivariate Analysis**

Multivariate analyses were conducted to study the combined effects of several sample variables on the dependent variable MR of SM soils. During the analyses:

- Various models were used in an attempt to maximize the value of the coefficient of determination ( $R^2$ ).

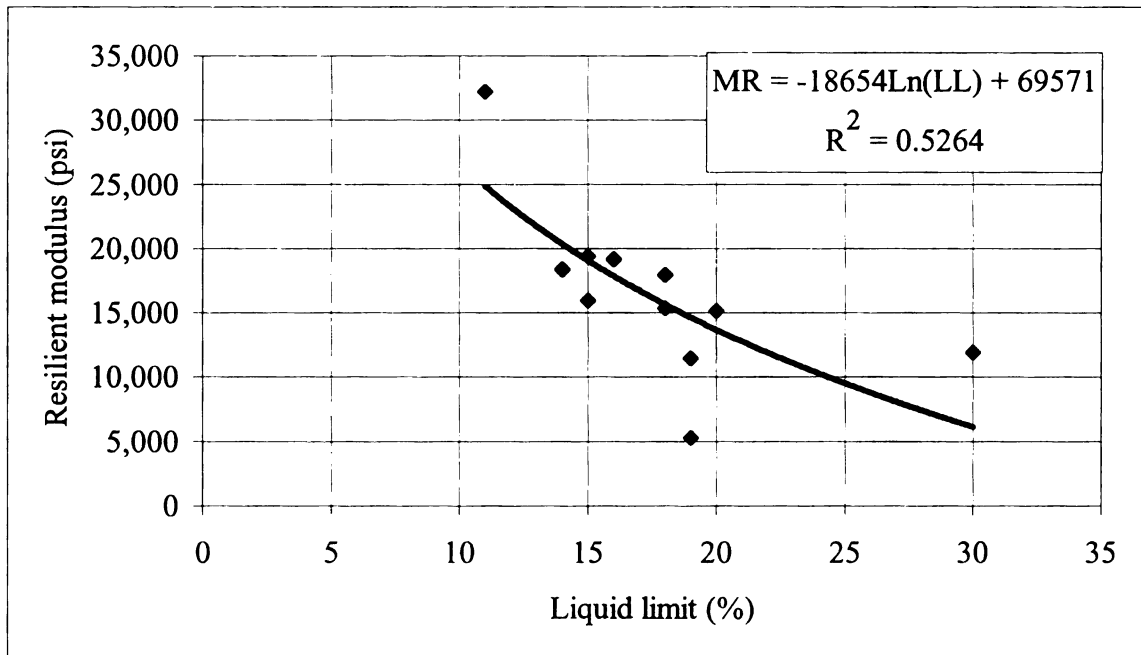


Figure 4.16 Resilient modulus versus the liquid limits of SM soils

- Special care was taken to:
  - Ensure that the resulting equation satisfies the known trends between each of the independent variable and the dependent variable MR.
  - Avoid any significant co-linearity between the independent variables.
  - Minimize the number of independent variables in the equation.

Results of the analyses yielded two models having relatively high  $R^2$  values. The first model is based on two sample variables of the SM (SVSM) soils (the dry unit weight and the degree of saturation) as stated in Equation 4.5.

$$MR = 0.0303(SVSM)^{4.1325} \quad \text{Equation 4.5}$$

Where,

$$SVSM = \frac{\gamma_d^{0.8}}{S^{0.15}}$$

$\gamma_d$  = dry unit weight (pcf)

S = degree of saturation (%)

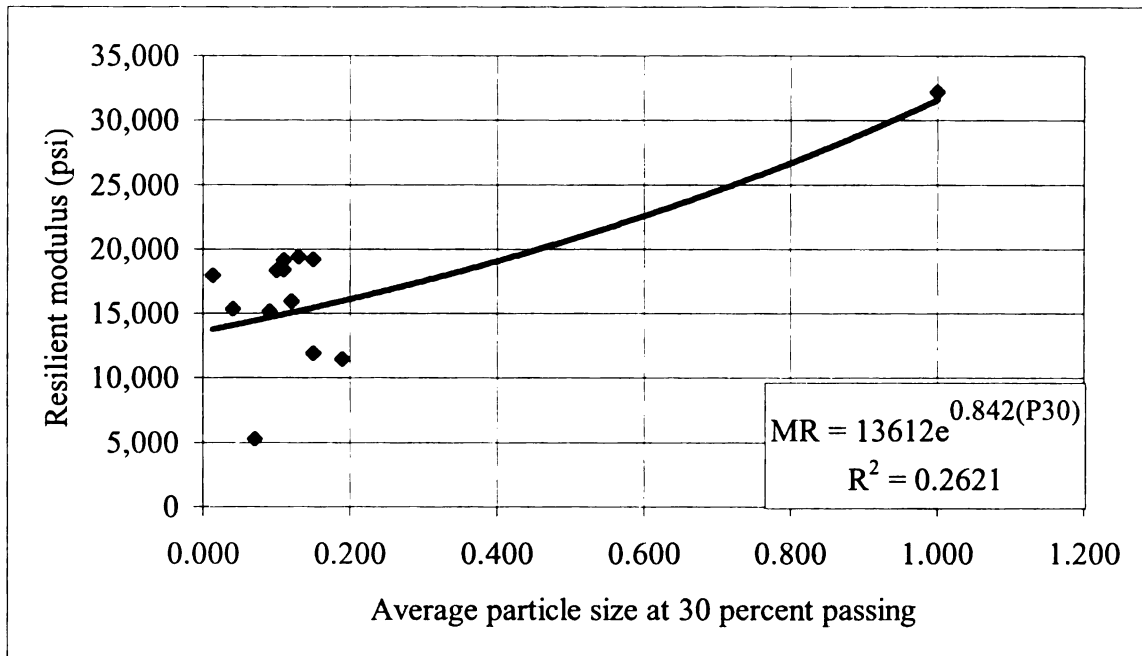


Figure 4.17 Resilient modulus versus the average particle size at thirty percent passing

Although the two variables are somehow co-linear (both are a function of the water content of the soil), the interpretation of the model agrees with most literature. To illustrate, consider the data in Figure 4.18, in which the resilient modulus is graphed as a function of the SVSM. It can be seen from the figure and from Equation 4.5 that increases in the dry unit weight cause increases in the SVSM values and hence, increases in the MR values. Further, increases in the degree of saturation causes decreases in the SVSM and the MR values. That is the MR value can be increased by either increasing the dry unit weight (i.e., higher compaction effort) or by decreasing the degree of saturation or by combination thereof. The reason is that as the dry unit weight of the sample increases, the relative density increases and the particle to particle contact in the sample increases causing higher internal friction and hence, higher stiffness (Perloff and Baron 1976). On the other hand, decreasing degree of saturation implies decreasing moisture contents and



decreasing the degree of lubrication between the soil particles. This causes increases in the soil internal friction, soil stiffness, and MR values. Similar results were also reported by Maher et al. (2000).

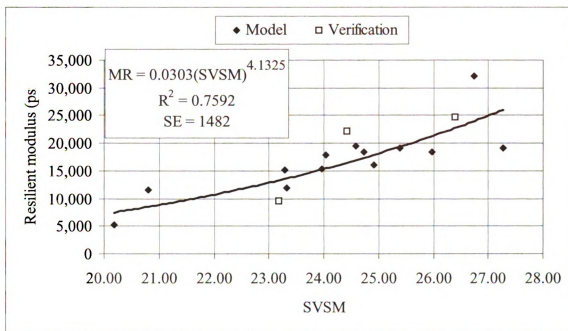


Figure 4.18 Resilient modulus versus the sample variable for SM (SVSM) subgrade

The two important points that should be noted herein are:

1. The data for the three open symbols in Figure 4.18 are those of the three samples used to verify Equation 4.5. They are discussed in the next subsection.
2. The test data used in support of Equation 4.5 have the following ranges: degrees of saturation from 18.8 percent to 93.9 percent and dry unit weight from 94.6 to 128.8 pounds per cubic foot. The use of the equation outside these two ranges is not recommended.

Nevertheless, the multivariate analyses of the SM soils yielded a second model based on two independent variables; the moisture contents (MC) of the test samples and the liquid limits (LL) of the soils passing sieve number 40. In this study, the two

independent variables were combined into one parameter, which was named the moisture index (MI) as stated in Equation 4.6.

$$MR = 45722\exp(-0.0258 * MI) \quad \text{Equation 4.6}$$

Where,

$$MI = \text{Moisture Index} = LL^{1.1} + MC^{1.25}$$

Figure 4.19 depicts the resilient modulus values of the thirteen SM soils plotted against the moisture index. Inspection of the figure indicates that, in general, higher MI values produce lower MR values. That is, increasing either the moisture content or the liquid limit of the soils causes increases in the MI values and hence, decreases in the MR values of the soils. These observations were expected because higher MI values due to higher moisture contents cause softening of the SM soils and hence lower resilient modulus. Likewise, soils having higher liquid limits tend to be more plastic and higher softening potential due to changes in their water contents.

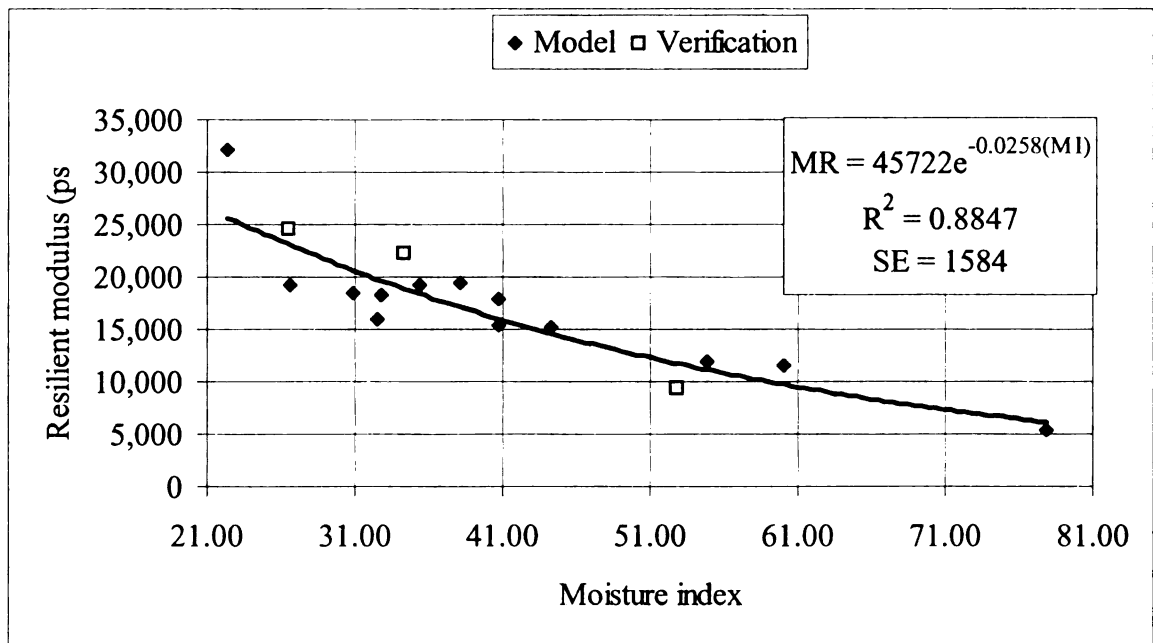


Figure 4.19 Resilient modulus versus the moisture index of the test sample

Equation 4.6 allows the user to estimate the MR values of SM subgrade soils using the results of two simple tests: the natural water content of the entire soil and the liquid limit of the particles passing sieve number 40. It should be noted that, in the field, the natural moisture content of a soil varies from one season to another whereas its liquid limit is constant. Hence, if the LL of a given subgrade soil is known, one needs only to determine the moisture content of the soil only before using Equation 4.6. It is important to note that the data used to generate Equation 4.6 include a range in moisture contents from 3.9 to 23.7 percent and a range in liquid limits from 11 to 30 percent. The use of Equation 4.6 outside the two ranges is not recommended.

#### **4.5.2.3 Verification**

The three shaded SM soil samples in Table 4.4 were not included in the development of the two SM soil models (Equations 4.5 and 4.6). The three samples were subjected to wet size analysis, Atterberg limit tests, and cyclic load triaxial tests to determine the physical parameters and the MR values of the three soils. After the laboratory tests were completed, the data for the three SM soils were plotted in Figures 4.18 and 4.19 as open symbols. It can be seen that the open symbols in both figures are located in the vicinity of the best fit curves.

Finally, Equations 4.5 and 4.6 were used to calculate the resilient modulus values of the three SM soils based on their parameters (dry unit weight and degree of saturation and moisture contents and the liquid limits of the soils). The calculated and the laboratory measured resilient modulus values are plotted in Figures 4.20 and 4.21. As can be seen from the figures, the data for both equations are located close to the line of equality. Based on this observation, one may conclude that the two models presented in

Equation 4.5 and 4.6 are accurate and can be used to estimate the resilient modulus values of SM soils based on the soil parameters. Such parameters can be obtained from simple tests such as water content, liquid limit and dry unit weight tests.

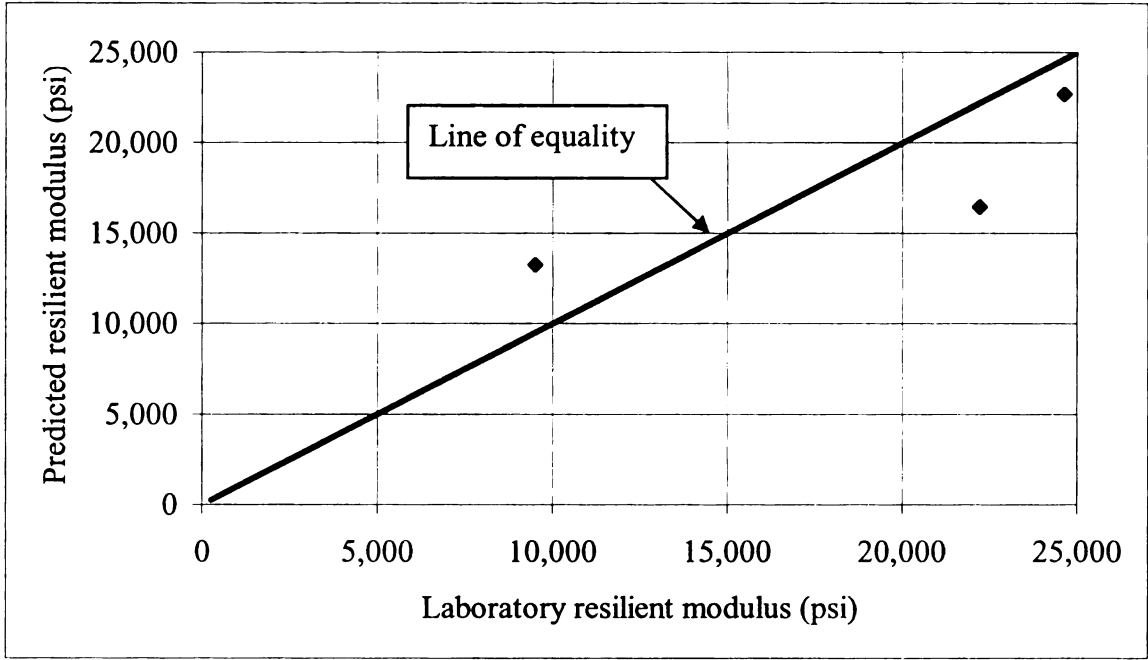


Figure 4.20 Measured and calculated resilient modulus values, Equation 4.5

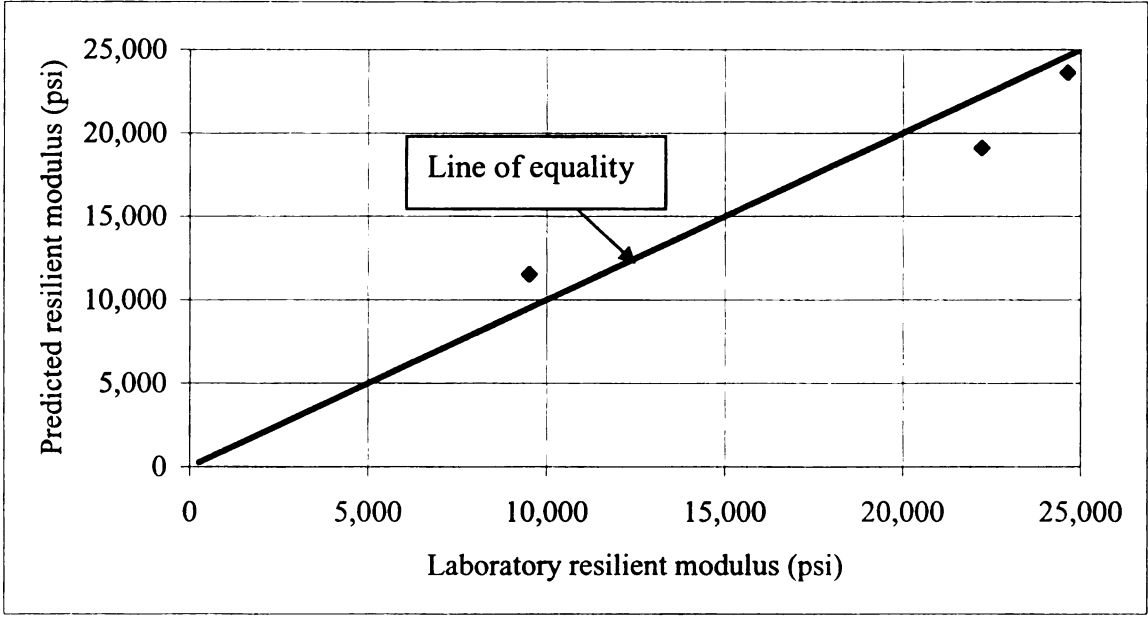


Figure 4.21 Measured and calculated resilient modulus values, Equation 4.6

#### **4.5.3 Clayey Sand (SC), Low Plasticity Clay (CL), and Low Plasticity Silt (ML)**

Table 4.5 lists the locations, the USCS and the AASHTO soil classifications, Atterberg limits, and the sample designation number of twenty two disturbed and six Shelby tube (marked with S in the table) soil samples that were collected from various clusters and areas throughout the State of Michigan. According to the USCS, eighteen samples consists of clayey sand (SC), eight clay (CL), and two low plasticity silt (ML) samples. According to the USCS SC soils may contain anywhere between 12 and 49.9 percent by weight fine materials and the plasticity index and liquid limit of the material passing sieve number 40 plot above the A-line on the plasticity chart. Clay (CL) soils contain more than 50 percent by weight passing sieve number 200 and the plasticity index and liquid limit of the soil plot above the A-line on the plasticity chart. Finally, the ML soils contain more than 50 percent by weight passing sieve number 200 and the plasticity index and liquid limit data plot below the A-line on the plasticity chart (Holtz and Kovacs 1981). All soil samples listed in Table 4.5 were subjected to wet sieve and hydrometer analyses, Atterberg limit tests, and cyclic load tests.

The reason that the three types of soils are housed in Table 4.5 is that, after the completion of the cyclic load tests, the resilient modulus values of the samples were plotted against the sample moisture contents. The three soil types showed the same relationship between the MR values and the sample moisture contents.

A total of 16 cyclic load tests were conducted on SC soils, 11 tests on undisturbed soil samples and 5 tests on disturbed soil samples. Nine cyclic load tests were conducted on CL soils, five tests on undisturbed soil samples and four on disturbed samples. Finally, both ML soil samples were subjected to cyclic load triaxial tests.

Table 4.5 Location of SC, CL, and ML subgrade soils

| Sample designation number | Shelby tube samples | Location                               | Atterberg limits |               | AASHTO | USCS |
|---------------------------|---------------------|----------------------------------------|------------------|---------------|--------|------|
|                           |                     |                                        | Liquid limit     | Plastic limit |        |      |
| I-075-N (03-05)           |                     | mile marker 368                        | 55               | 22            | A-2-7  | SC   |
| M-072-W (05-06)           |                     | 330 feet West of M-32                  | 22               | 11            | A-6    | SC   |
| U-127-N (07-04)           |                     | 100 feet North of Jefferson Rd         | 22               | 12            | A-2-6  | SC   |
| U-127-N (07-05)           | S                   | 65 feet North of Vernon Rd             | 24               | 14            | A-6    | SC   |
| U-010-W (08-04)           |                     | 145 feet West of Mackinaw Rd           | 29               | 13            | A-6    | SC   |
| I-075-S (08-05)           | S                   | 115 feet South of Prevo Rd             | 25               | 12            | A-2-6  | SC   |
| I-075-S (09-08)           |                     | 650 feet South of Wadsworth Rd         | 31               | 14            | A-4    | SC   |
| I-096-W (10-03)           |                     | 210 feet West of bridge before exit 97 | 29               | 14            | A-2-6  | SC   |
| I-069-E (10-10)           |                     | 120 feet East of Britton Rd            | 26               | 15            | A-6    | SC   |
| M-021-E (10-11)           |                     | 800 feet East of Shepards Rd           | 23               | 14            | A-2-4  | SC   |
| M-014-W (13-03)           |                     | 255 feet West of Napier Rd             | 22               | 13            | A-4    | SC   |
| I-075-S (14-01)           | S                   | 60 feet South of Gaynier Rd            | 45               | 19            | A-7-6  | SC   |
| I-075-S (14-02)           |                     | 40 feet South of Nadeau Rd             | 41               | 19            | A-7-6  | SC   |
| U-024-S (14-03)           |                     | ~1000 feet South of Ready Rd           | 40               | 13            | A-6    | SC   |
| I-075-S (14-04)           |                     | Station 23+00                          | 34               | 17            | A-6    | SC   |
| I-094-W (14-05)           |                     | 300 feet West of Monroe Blvd           | 34               | 21            | A-6    | SC   |
| M-153-E (14-06)           | S                   | ~800 feet East of Greenfield Rd        | 52               | 20            | A-7-6  | SC   |
| M-25-N (15-06)            |                     | 170 feet North of North Huron Dr       | 24               | 13            | A-4    | SC   |

Table 4.5 Cont'd

| Sample number   | Shelby tube samples | Location                                                          | Atterberg limits |               | AASHTO | USCS |
|-----------------|---------------------|-------------------------------------------------------------------|------------------|---------------|--------|------|
|                 |                     |                                                                   | Liquid limit     | Plastic limit |        |      |
| M-045-S (01-01) |                     | 405 feet South of Ontonagon River                                 | 26               | 16            | A-6    | CL   |
| U-010-W (08-03) |                     | 65 feet West of bridge before Stark Rd                            | 32               | 14            | A-6    | CL   |
| U-012-E (13-05) |                     | Between Maple Rd and Industrial Ave                               | 33               | 17            | A-6    | CL   |
| M-010-E (13-08) | S                   | Station 38+00                                                     | 24               | 14            | A-6    | CL   |
| I-094-W (14-09) | S                   | 350 feet West of Wadhams Rd                                       | 44               | 21            | A-7-6  | CL   |
| I-094-W (14-10) |                     | 227 feet West of Palms Rd                                         | 42               | 19            | A-7-6  | CL   |
| M-090-E (15-03) |                     | 210 feet East of Murray Rd                                        | 35               | 20            | A-6    | CL   |
| M-090-E (15-04) |                     | 200 feet East of Bobcock St<br>37 feet East of Village Limit sign | 24               | 15            | A-4    | CL   |
|                 |                     |                                                                   |                  |               |        |      |
| M-028-W (02-02) |                     | 1053 feet West of M-141                                           | 23               | NA            | A-4    | ML   |
| U-002-E (02-04) |                     | 765 feet East of Spalding Rd                                      | 19               | NA            | A-4    | ML   |

In step 2 of the analyses, univariate and multivariate analyses were conducted simultaneously on the three soil types to study the effects of the sample variables on their MR values. Results of the analyses are presented and discussed below.

#### **4.5.3.1 Univariate Analyses**

In the univariate analyses, the effects of each of several sample variables on the MR values of SC, CL, and ML soils were studied. These sample variables include: the moisture contents of the samples, the degrees of saturation, the dry unit weight after compaction, and the grain sizes. Results of the analyses are presented and discussed below.

**Effect of Sample Moisture Contents** – As is the case for the SM soils, because of the high fine contents of SC, CL, and ML soils, it was hypothesized that the water contents of the samples would play a major role in determining the elastic response of the soil to the applied loads. Figure 4.22 shows the MR values plotted against the samples moisture contents. As it was hypothesized and expected, the figure shows increases in the sample moisture content cause significant decreases in the MR values. Similar results were also reported by many researchers including (Maher et. al 2000, George 2000, and 2003). Further, the data in Figure 4.22 also show that the three soil types have similar, if not the same, relationship between the sample moisture contents and the MR values. Hence, the moisture content or the degree of saturation will be considered in the multivariate analyses.

**Effect of the Degree of Saturation** – At the conclusion of the cyclic load test, the sample moisture content and dry unit weight were determined and the degree of



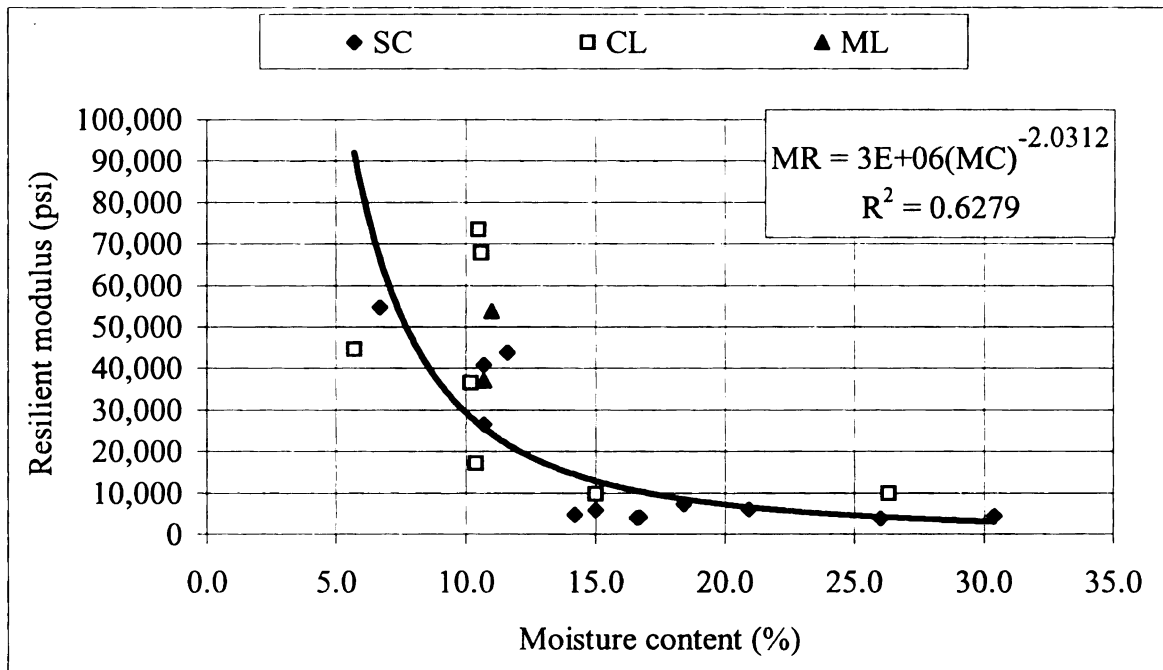


Figure 4.22 Resilient modulus versus the moisture contents of the samples saturation (S) was calculated using Equation 4.4. It should be noted that for all test samples, a typical value of the specific gravity of the solid ( $G_s$ ) of 2.7 was assumed and used in Equation 4.4.

$$S = \left[ \frac{G_s * (MC/100) * \gamma_d}{G_s * \gamma_w - \gamma_d} \right] * 100 \quad \text{Equation 4.4}$$

Where,

S = degree of saturation (%)

MC = moisture content (%)

$G_s$  = specific gravity of the soil solid

$\gamma_d$  = dry unit weight of the sample (pcf)

$\gamma_w$  = unit weight of water = 62.4 pcf

Figure 4.23 shows the MR values plotted against the degree of saturation of the test samples. As it was expected and reported by Maher et al. (2000), the MR values

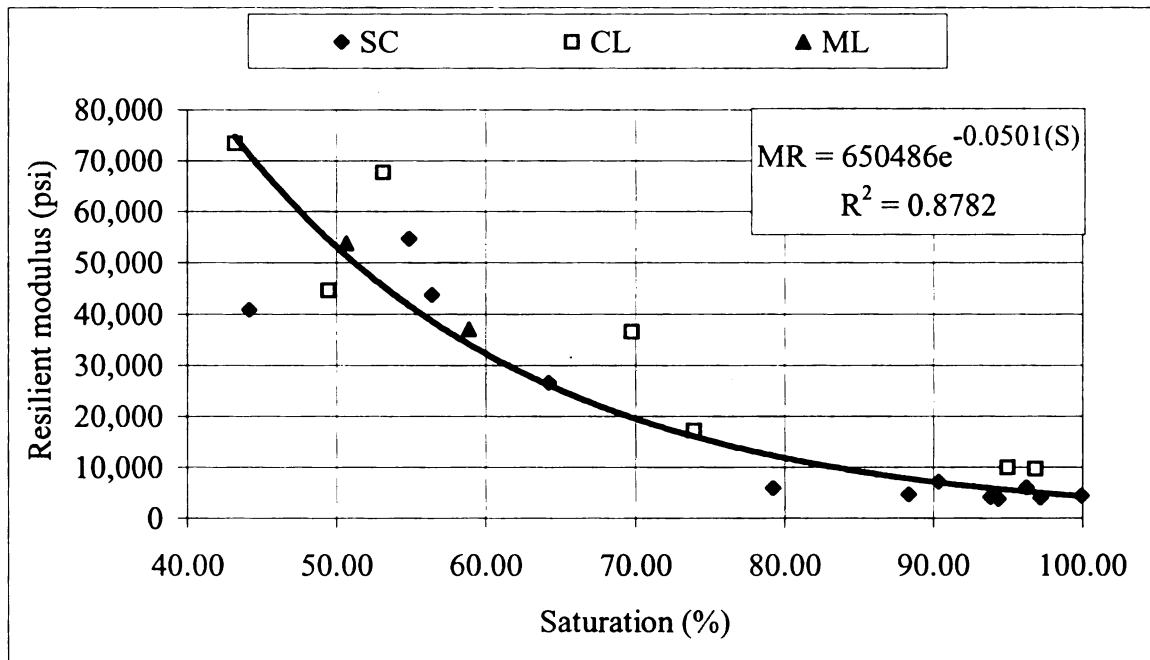


Figure 4.23 Resilient modulus versus degree of saturation for SC, CL, and ML soils decrease with increasing degree of saturation. The difference between this observation and the previous one regarding the sample water content is that the degree of saturation is a function of both the water content of the sample and its dry unit weight. Said functionality caused the coefficient of determination to increase from about 0.63 in Figure 4.22 to about 0.88 in Figure 4.23. Therefore, the degree of saturation will be included in the multivariate analyses.

**Effect of Sample Dry Unit Weight** - The effect of the test sample dry unit weight on the MR values of SC, CL, and ML soils was studied by plotting the MR values as a function of the sample dry unit weight as shown in Figure 4.24. As it was expected, the figure shows a very weak correlation between the dry unit weight and the MR values of the test sample. The main reason for the weak correlation is that the water contents of the test

samples vary from about 6.7 to 30.4 percent. Relative to the compaction curve, this variation causes some test samples to be on the wet side while others on the dry side of optimum. This implies that two compacted samples having the same dry unit weight may

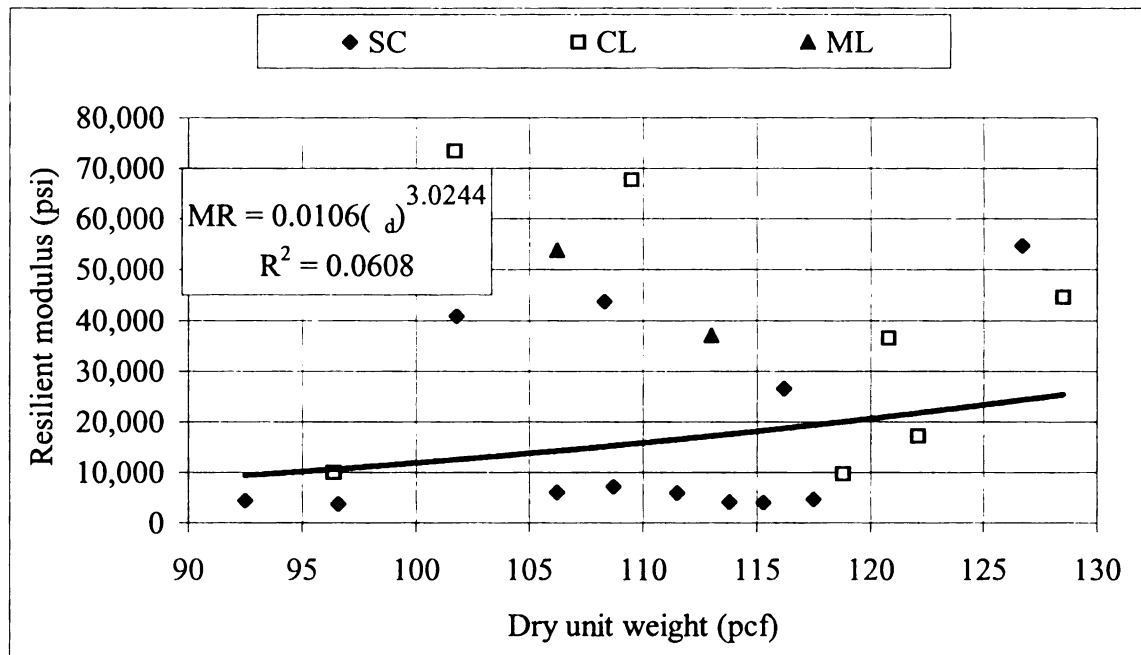


Figure 4.24 Resilient modulus versus dry unit weight for SC, CL, and ML soils or may not have the same water content. Soil samples compacted dry of optimum would have brittle behavior, higher strength, higher stiffness and higher MR values than samples compacted wet of optimum. The latter would have lower strength, higher plastic deformation and softer behavior under loads. In addition, when soil samples are compacted on the dry side of optimum, the soil particles tend to stay in a flocculated arrangement. Samples compacted wet of optimum; the particles tend to disperse (line up) due to the extra water lubrication (Holtz and Kovacs 1981). Nevertheless, the dry unit weight will be included in the multivariate analyses to determine if the dry unit weight interacts with other variables to significantly affect the MR values.

**Effect of Sample Grain Size** – Because of high fine contents, all SC, CL, and ML soils were subjected to wet sieving and hydrometer analyses to determine their grain size distributions. The effects of sample gradation on MR values were assessed through the following gradation parameters:

- Percent passing sieves 200, 100, 40, 20, 10, 4, and 3/8 inch
- The coefficients of curvature and uniformity
- Average particle size at ten, thirty, and sixty percent passing ( $D_{10}$ ,  $D_{30}$ , and  $D_{60}$ , respectively)

The effects of each gradation parameter on the MR values were analyzed by plotting the MR values of the soil samples as a function of that parameter. However, as it was expected, none of the variables showed a good correlation to the MR values.

#### **4.5.3.2 Multivariate Analysis**

Multivariate analyses were conducted to study the combined effects of several independent sample variables on the dependent variable MR of SC, CL, and ML soils.

During the analyses:

- Various models were used in an attempt to maximize the value of the coefficient of determination ( $R^2$ ).
- Special care was taken to:
  - Ensure that the resulting equation satisfies the known trends between each of the independent variable and the dependent variable MR.
  - Avoid any significant co-linearity between the independent variables.
  - Minimize the number of independent variables in the equation.

Results of the analyses yielded models having relatively high  $R^2$  values. However, none of the models produced a better correlation than the degree of saturation (S) alone.

Therefore, it is recommended that the MR values of SC, CL, and ML soils be predicted using the degree of saturation (S) alone through Equation 4.7.

$$MR = 650486 \exp(-0.0501(S)) \quad \text{Equation 4.7}$$

The data used to develop Equation 4.7 have saturation values ranging from 43.2 to 99.9 percent with a corresponding range of dry unit weight from 92.5 to 128.5 pcf and moisture content range from 5.7 to 30.4 percent. The use of Equation 4.7 outside those ranges of values is not recommended.

Figure 4.25 shows the MR values plotted against the degree of saturation. The figure consists of two sets of data. The first set (solid symbols) is the data that was used to develop the model (Equation 4.7) with  $R^2$  value of about 0.88. The second set (open symbols) is the data that was used to validate the developed model. The latter data were obtained from testing three disturbed and three undisturbed soil samples. The sequential procedure used to test the samples is presented in the next subsection.

One important point should be noted herein is that the data used to generate Equation 4.7 were obtained from both disturbed and undisturbed samples. Hence, the equation applies equally to both types of samples. The implication of this is that, the elastic behavior of laboratory compacted samples is equivalent to that of undisturbed samples provided both samples have the same degree of saturation.

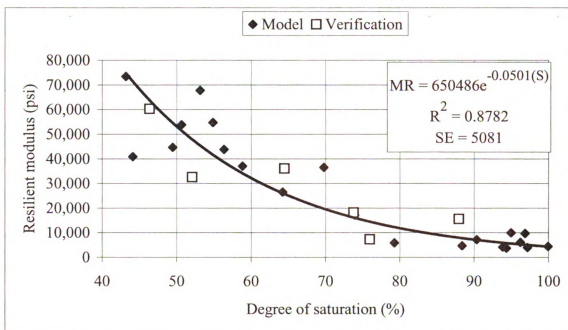


Figure 4.25 Resilient modulus versus degree of saturation

#### 4.5.3.3 Validation

As stated above, six additional soil samples (three disturbed samples and three undisturbed soil samples) were tested to verify the model presented in Equation 4.7. The three disturbed soil samples were allowed to dry from their natural contents of 14.4, 25.4, and 21.9 percent to 10.3, 11.3 and 18.8 percent, respectively. After drying, the soils were compacted using standard proctor and standard compaction mold. The compacted soil was then extracted from the compaction mold, trimmed to the size of the test sample and then subjected to cyclic load triaxial tests. When the test was terminated, the water content and the dry unit weight of each sample were then measured and its degree of saturation was calculated.

The natural water contents of the three undisturbed Shelby tube samples that were tested for verification purposes were 12.3, 18.4 and 11.2 percent. One test sample was extracted from each of the three Shelby tubes. Two test samples were subjected to cyclic

load triaxial tests at their natural water contents of 12.3 and 11.2 percent. The third sample was dried at room temperature for two days then it was sealed in a plastic bag for one week to even up the moisture in the sample and then it was tested. After the cyclic load triaxial test was terminated the moisture content of each sample and its dry unit weight were determined.

For the six validation samples, results of the cyclic load triaxial test data were used to calculate the resilient modulus of the soil. The data are shown in Figure 4.25 by the open symbols. After measuring the test sample water content and dry unit weight, the data were used in Equation 4.7 to estimate the resilient modulus values of the soils.

Figure 4.26 shows the laboratory measured resilient modulus values plotted against the MR values calculated using Equation 4.7 and the degree of saturation of the test samples. It can be seen from Figure 4.26 that all six data points are located near the line of equality. Hence, the six data points validate the accuracy of Equation 4.7.

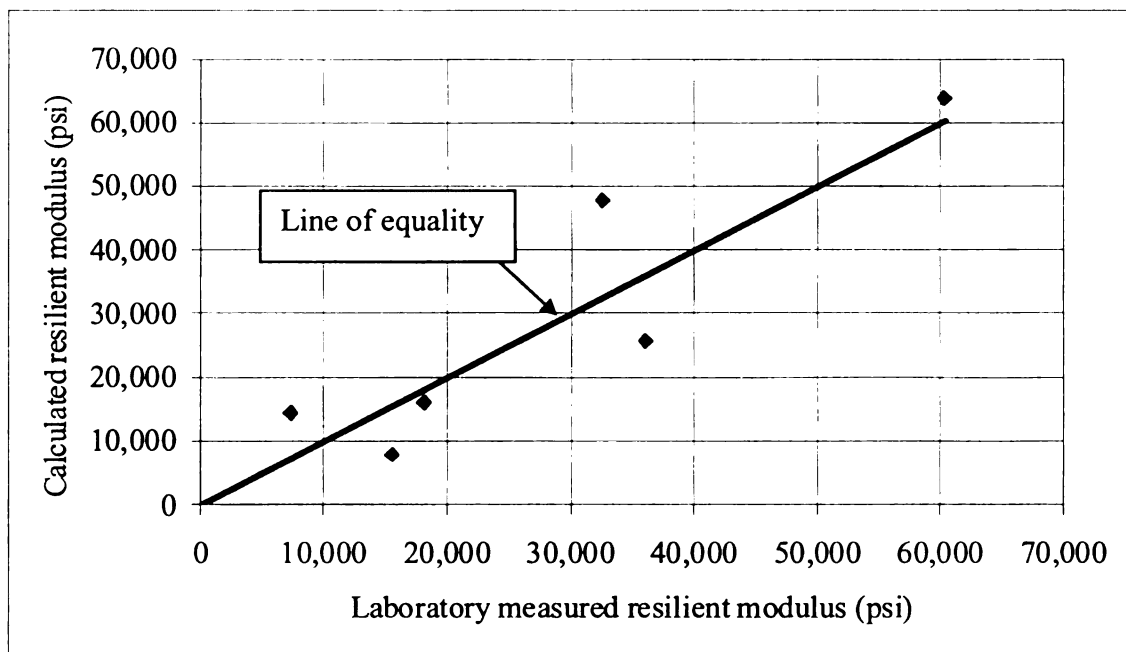


Figure 4.26 Laboratory measured and calculated MR values for SC, CL, and ML soils

#### 4.5.4 Poorly graded sand – silty sand (SP-SM)

Table 4.6 lists the locations, the USCS and the AASHTO soil classifications, and the sample designation number of eight disturbed soil samples that were collected from various clusters and areas throughout the State of Michigan. The commonality between the eight samples is that all of them were classified in step 1 of the analyses as SP-SM according to the USCS. SP-SM soils may contain anywhere between 5 and 12 percent passing sieve number 200 materials and a plasticity index less than 4 (Holtz and Kovacs 1981). In step 2 of the analyses, univariate and multivariate analyses were conducted and are discussed below.

##### 4.5.4.1 Univariate Analysis

In the univariate analyses, the effects of each of several sample variables on the MR values of SP-SM soils were studied. These sample variables include: the moisture contents of the samples, the dry unit weight after compaction, and the grain sizes.

Discussion of the effects of each variable is presented below.

Table 4.6 Locations of SP-SM subgrade soils

| Sample number   | Location                              | AASHTO | USCS  |
|-----------------|---------------------------------------|--------|-------|
| M-028-W (02-03) | ~2000 feet East of M-35               | A-3    | SP-SM |
| U-002-E (03-01) | 400 feet East of Hwy 13               | A-3    | SP-SM |
| M-028-W (03-03) | 500 feet West of Basnau Rd            | A-2-4  | SP-SM |
| I-196-N (06-05) | 110 feet North of Schmuhl Rd          | A-3    | SP-SM |
| I-069-N (10-01) | 75 feet North of Base Line Hwy        | A-1-b  | SP-SM |
| I-069-N (11-01) | 160 feet North of mile marker 42      | A-3    | SP-SM |
| I-094-W (12-03) | 36 feet West of bridge after exit 135 | A-3    | SP-SM |
| U-023-N (13-07) | 60 feet North of Sherman              | A-3    | SP-SM |

**Effect of the Sample Moisture Contents** – Because of the narrow range in fine contents, it is expected that the water contents would have minimal effects on the elastic response



of the soil to the applied loads. Figure 4.27 shows the MR values of all SP-SM soil samples plotted against the samples moisture contents. The figure shows that the sample moisture content has no effect on the MR values. This result was not expected and it contradicts findings by many researchers including (Maher et. al 2000, George 2000, and 2003) who stated that the MR value decreases with increasing moisture contents. One possible explanation of the above result is that the effects of moisture contents on the MR values interact with other variables that are not included in the equation. This issue is addressed in the multivariate analyses subsection.

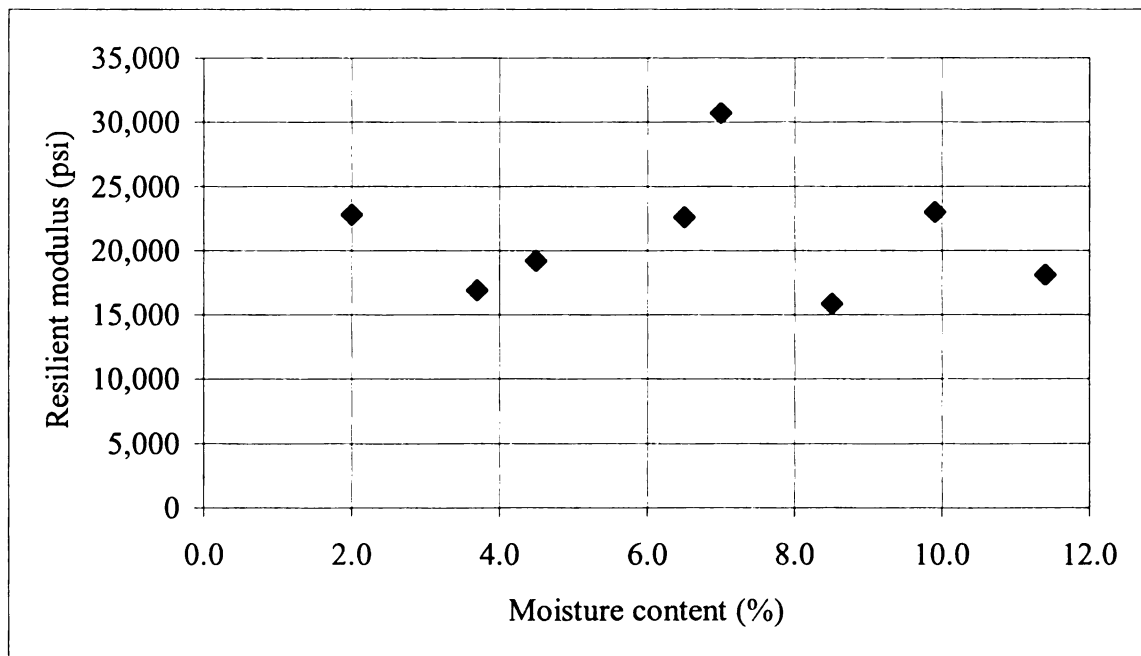


Figure 4.27 Resilient modulus versus moisture content for SP-SM soils

**Effect of Sample Dry Unit Weight** - The effect of the test sample dry unit weights on the MR values of SP-SM soils was studied by plotting the MR values as a function of the sample dry unit weights as shown in Figure 4.28. As it was expected, the figure shows a weak correlation between the dry unit weights and the MR values of the test samples.

The main reason for the weak correlation is that it is possible for two test samples to have the same dry unit weight but significantly different elastic behavior under load. This scenario is certain if one sample was compacted dry of optimum and the second wet of optimum. A sample compacted dry of optimum has higher strength and stiffness and displays more brittle behavior than the one compacted wet of optimum. The latter would have lower strength, higher plastic deformation and softer behavior under loads (Holtz and Kovacs 1981). For the SP-SM soils, the water contents of the test samples varied from about 2 to about 11 percent. Such range in the water content extends from the dry side to the wet side of the optimum moisture content on the compaction curve. To overcome the problem, the dry unit weight was included in the multivariate analyses to determine whether or not it interacts with other variables to significantly affect the MR values.

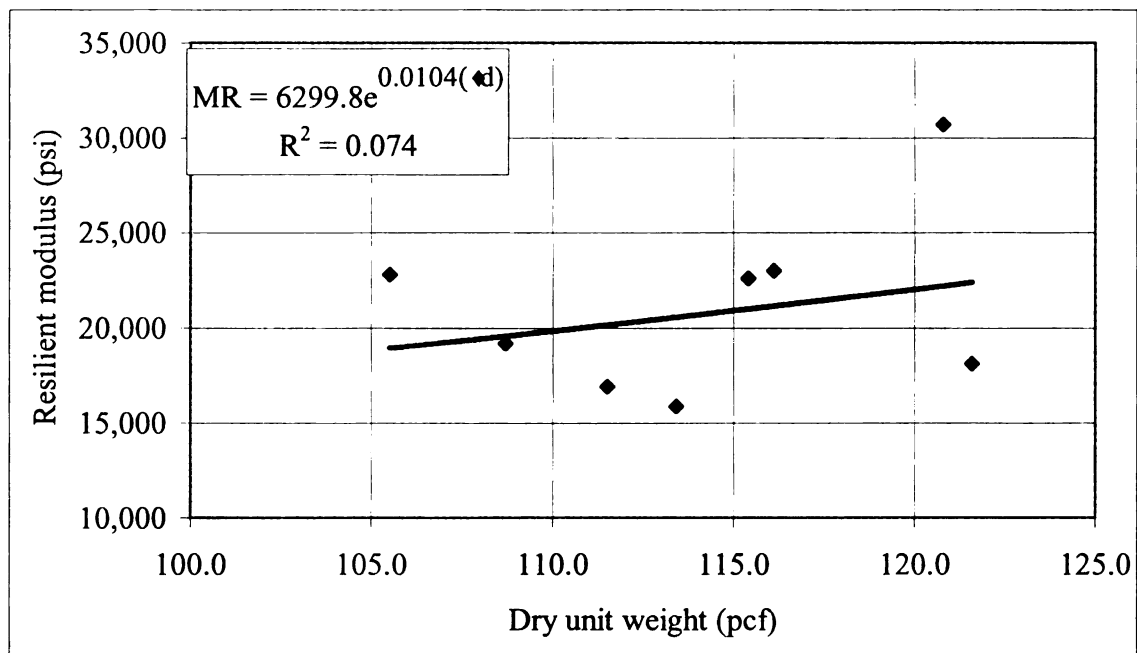


Figure 4.28 Resilient modulus versus the dry unit weight of the test samples

**Effect of Sample Grain Size** – Because of low fine contents of SP-SM soils, all soil samples were subjected to dry sieving to determine the grain size distribution shown in Figure 4.29. Examination of the figure indicates that the SP-SM subgrade soil samples contain variable amount of fine and coarse sands. Since the fine and coarse sand contents are co-linear or dependent, both variables should not be included in the analyses. Hence, the effect of either the fine or coarse sand contents on the MR values should be included in the analyses. The effects of sample gradation on MR values were also assessed through the following gradation parameters:

- Percent passing sieves 200, 100, 40, 20, 10, 4 and 3/8 inch
- The coefficients of curvature and uniformity
- Average particle size at ten, thirty and sixty percent passing ( $D_{10}$ ,  $D_{30}$ , and  $D_{60}$ , respectively)

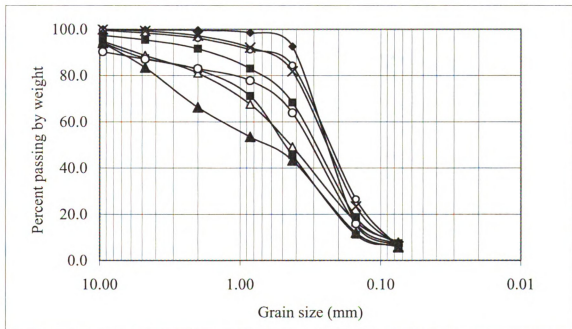


Figure 4.29 Eight gradation curves of the SP-SM subgrade samples

The effects of each gradation parameter on the MR values were analyzed by graphing the MR values of the soil samples as a function of that parameter. Few gradation parameters; the percent passing sieve number 200, the percent fine sand content, and the coefficients of uniformity and curvature showed minor correlation to MR values. For example, the effect of the percent passing sieve number 200 and the MR values is shown in Figure 4.30. Although the data in the figure shows that the percent passing sieve number 200 has insignificant effects on the MR values, it also show that increasing the percent fine materials (passing sieve number 200) causes decreases in the MR values.

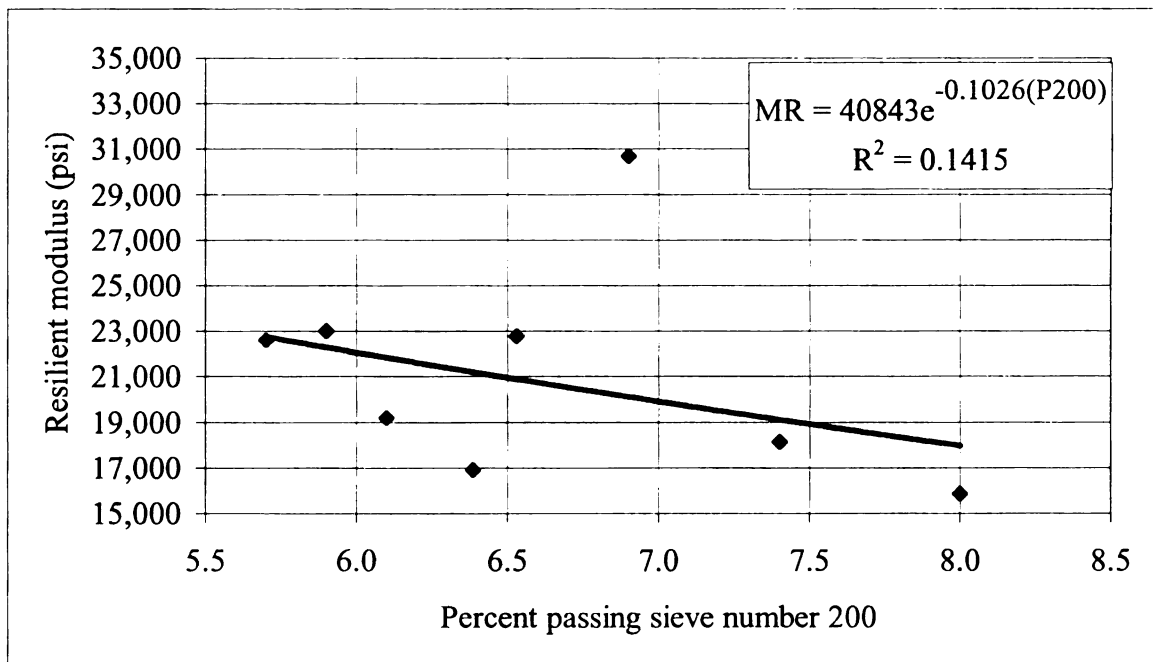


Figure 4.30 Resilient modulus versus percent passing sieve number 200 for SP-SM soils

#### 4.5.4.2 Multivariate Analysis

Multivariate analyses were conducted to study the combined effects of several independent sample variables on the dependent variable MR of SP-SM soils. During the analyses:

- Various models were used in an attempt to maximize the value of the coefficient of determination ( $R^2$ ).
- Special care was taken to:
  - Ensure that the resulting equation satisfies the known trends between each of the independent variable and the dependent variable MR.
  - Avoid any significant co-linearity between the independent variables.
  - Minimize the number of independent variables in the equation.

Results of the analyses yielded several different models with coefficient of determination values from 0.62 to about 0.93. For example, the model shown in Figure 4.31 and Equation 4.8 has a coefficient of determination of slightly higher than 0.93.

$$MR = 1357.5(SVSP - SM)^2 - 6145.3(SVSP - SM) + 23613$$

Equation 4.8

Where,

$$SVSP - SM = \frac{\gamma^{3.95}}{10^7 (D_{30}^{2.66} (D_{10}^{2.25} (D_{60}^{0.41} (S^{0.03})))$$

SVSP-SM = Sample variable for the SP-SM soils

$\gamma_d$  = dry unit weight of the test sample (pcf)

$D_{30}$ ,  $D_{10}$ ,  $D_{60}$  = the particle diameter at 30, 10 and 60 percent passing (mm)

S = degree of saturation

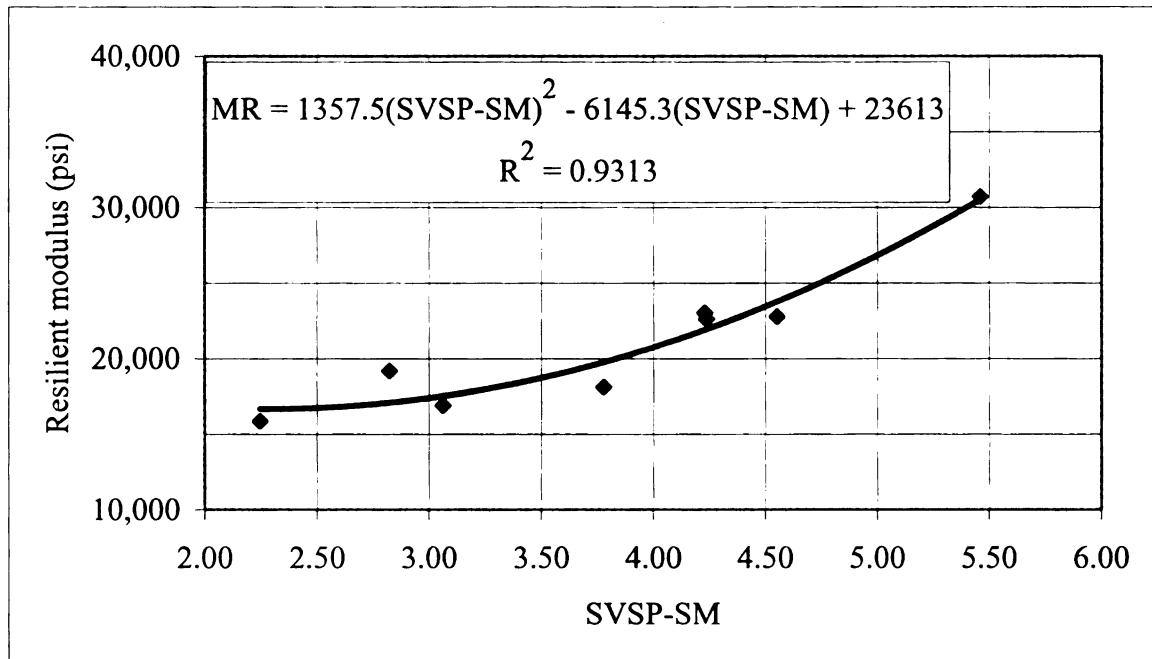


Figure 4.31 Resilient modulus versus the sample variable model, SP-SM soils

The model was not accepted although the value of the coefficient of determination is relatively high. Three reasons can be cited for rejection; first the model has too many variable for a sample size of 8, second, the model interpretation (higher particle size yield lower modulus) cannot be physically supported, and third, the three particle sizes in the denominator are not truly independent variable, which makes the model very sensitive to small changes in the values of the variables.

Several other models were also rejected for similar reasons. Finally the model presented in Figure 4.32 and expressed in Equation 4.9 was accepted although the value of the coefficient of determination is moderate (0.74).

$$MR = 1749.6 \exp(0.0054(SVSP - SM)) \quad \text{Equation 4.9}$$

Where,

$$SVSP - SM = \frac{\gamma_d^{1.75}}{MC^{0.5} + LL^{0.6} + (P_{40} - P_{200})^{0.01}}$$

$\gamma_d$  = dry unit weight (pcf)

LL = liquid limit

MC = moisture content (%)

$P_{40}$ ,  $P_{200}$  = percent passing sieves number 40 and 200, respectively

The term  $(P_{40} - P_{200})$  expresses the percent fine sand content in the soils.

Examination of the data in Figure 4.32 and Equation 4.9 indicates that increases in the values of the dry unit weight cause increases in the MR values whereas increases in the values of either the moisture content, liquid limit, or the percent fine sand content cause decreases in the resilient modulus values. .

It is important to note that the data used in support of Equation 4.9 includes soil samples having dry unit weights range from 105.5 to 121.6 pcf, percent passing sieve number 40 from 43.2 to 92.6, percent passing sieve number 200 from 5.7 to 8, liquid limit from 13 to 21 and moisture content from 2.0 to 11.4 percent.

#### **4.5.5 Clayey sand – silty sand (SC-SM)**

Table 4.7 lists the locations, the USCS and the AASHTO soil classifications, and the sample designation number of seven disturbed soil samples that were collected from various clusters and areas throughout the State of Michigan. The commonality between the seven samples is that all of them were classified in step 1 of the analyses as SC-SM

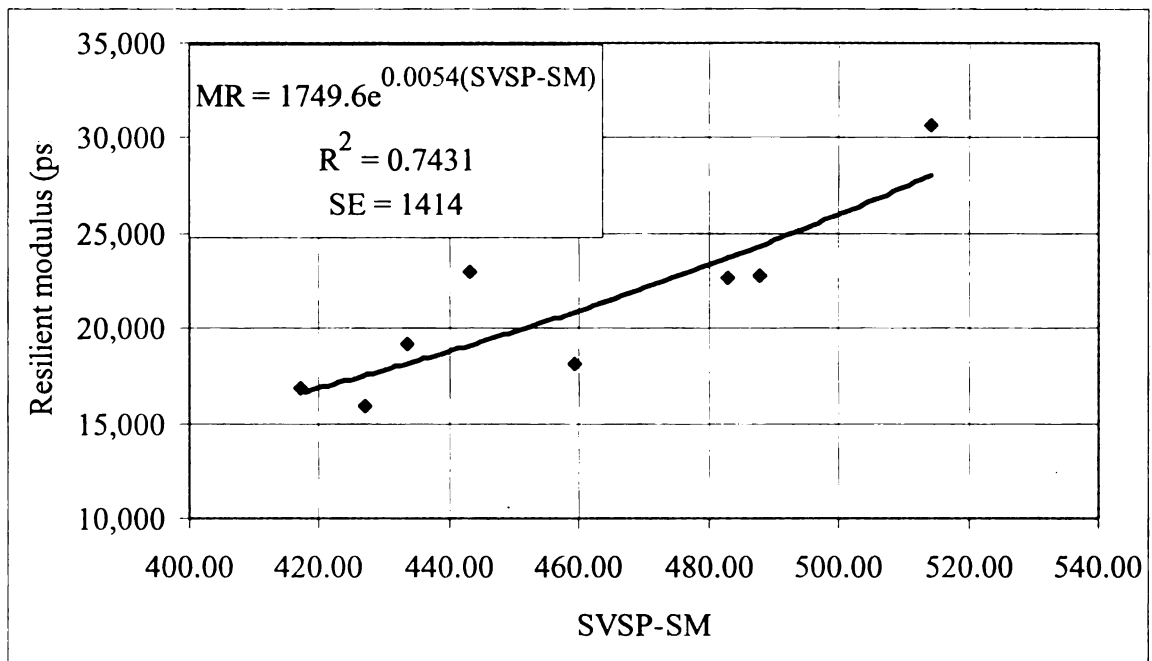


Figure 4.32 Resilient modulus versus SVSP-SM soils

according to the USCS. SC-SM soils may contain anywhere between 12 and 49.9 percent passing sieve number 200 and a plasticity index between 4 and 7 (Holtz and Kovacs 1981). Hence, the fine materials may play a major role in the mechanistic behavior of the soil. In step 2 of the analyses, univariate and multivariate analyses were conducted and are discussed below.

Table 4.7 Locations of SC-SM subgrade soils

| Sample number   | Location                                  | AASHTO | USCS  |
|-----------------|-------------------------------------------|--------|-------|
| M-068-W (04-02) | 180 feet West of US-23                    | A-2-4  | SC-SM |
| M-032-W (04-05) | 220 feet East of Herron Rd                | A-4    | SC-SM |
| I-075-N (08-06) | 80 feet North of bridge after exit 195    | A-2-4  | SC-SM |
| I-096-W (09-02) | 141 feet West of Morse Lake Ave           | A-2-4  | SC-SM |
| M-060-W (11-03) | 135 feet West of Southbound I-69 overpass | A-2-4  | SC-SM |
| I-069-S (11-05) | 95 feet South of Bridge after exit 10     | A-4    | SC-SM |
| I-094-W (12-01) | 95 feet West of 29 Mile Rd                | A-2-4  | SC-SM |



#### 4.5.5.1 Univariate Analysis

In the univariate analyses, the effects of each of several sample variables on the MR values of SC-SM soils were studied. These sample variables include: the moisture contents of the samples, the degrees of saturation, the liquid limits, and the grain sizes. The effects of each variable are presented and discussed below.

**Effect of the Sample Moisture Contents** – Because of the high range in fine contents, water content may play a significant role in determining the elastic response of the soil to the applied loads. Figure 4.33 shows the MR values of all seven SC-SM soil samples plotted against the samples moisture contents. As it was expected, the figure shows increases in the sample moisture contents cause decreases in the MR values. Similar results were also reported by many researchers including (Maher et. al 2000, George 2000, and 2003). The low value of the coefficient of determination of about 0.25 implies that MR values cannot be explained accurately by the moisture content alone. Therefore, it will be included with other sample variables in the multivariate analyses to determine their combined effect.

**Effect of the Degree of Saturation** – At the conclusion of the cyclic load test, the sample moisture content and dry unit weight were determined and the degree of saturation (S) was calculated using Equation 4.4 assuming a specific gravity of the solids of 2.7.

$$S = \left[ \frac{G_s * (MC/100) * \gamma_d}{G_s * \gamma_w - \gamma_d} \right] * 100 \quad \text{Equation 4.4}$$

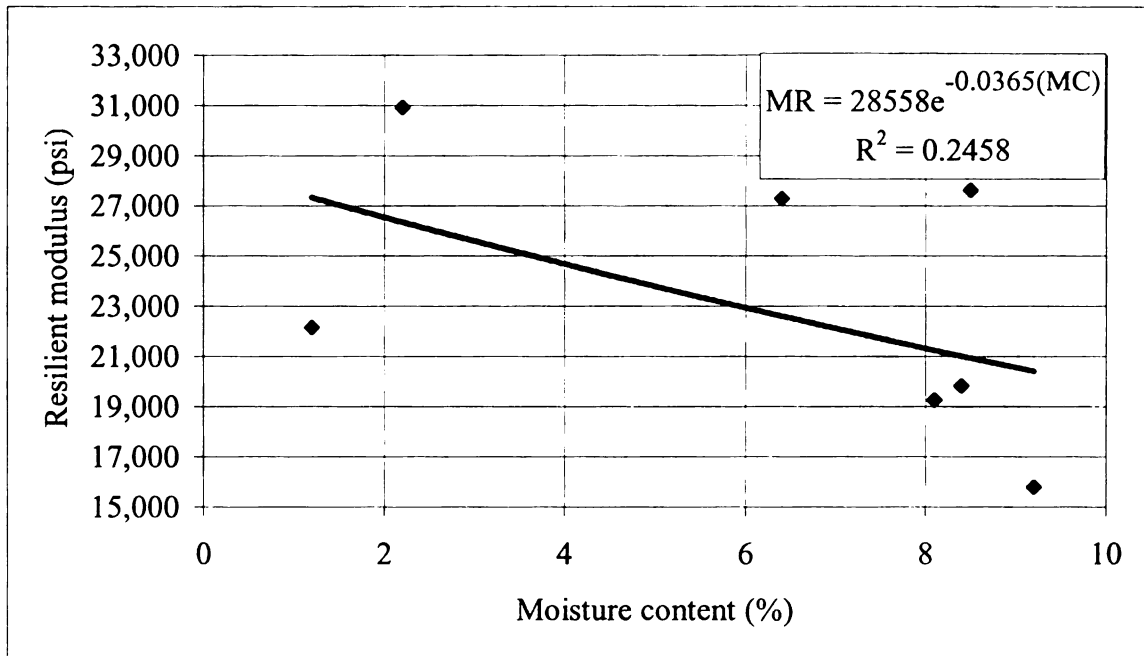


Figure 4.33 Resilient modulus versus moisture content for SC-SM soils

Where,

$S$  = degree of saturation (%)

$MC$  = moisture content (%)

$G_s$  = specific gravity of the soil solid

$\gamma_d$  = dry unit weight of the sample (pcf)

$\gamma_w$  = unit weight of water = 62.4 pcf

Figure 4.34 shows the MR values plotted against the degree of saturation of the test samples. The data in the figure indicates an insignificant correlation between the MR values and the degree of saturation although increasing degree of saturation causes decreases in the MR values as it was reported by Maher et al. (2000). When the data and the values of the coefficients of determination of Figure 4.33 are compared to those in Figure 4.34, it becomes clear that the effects of moisture contents on the MR values can

be better expressed using the water content. The reason is that the water content is an independent variable whereas the degree of saturation is a function of both the water contents and the dry unit weights. Figure 4.35 depicts the MR values plotted against the dry unit weights of the test samples. It can be seen that correlation between them is insignificant although, as it was expected, increasing the values of the dry unit weight cause increases in the MR values. The reason for the insignificant correlation is that the dry unit weight of the test sample is a function of its water content. Further, it is possible for two test samples having the same dry unit weight to have drastically different mechanistic behavior. The scenario is possible provided that the two samples were compacted at two different water contents on the opposite sides of the optimum moisture content (Holtz and Kovacs 1981).

**Effect of the Sample Liquid Limit** - For each SC-SM soil sample, the Atterberg limits for all materials passing sieve number 40 were determined in order to classify the type of fine materials (silt or clay). The test results indicate that for all samples the liquid limit varied from 15 to 22, the plastic limit from 10 to 15 and the plasticity index from 4 to 7. The effects of the liquid limit on the MR values of the soils were analyzed. Figure 4.36 depicts the influence of the liquid limits on the MR values of SC-SM soils. The data in the figure indicate that the MR values of SC-SM soils decrease as the liquid limit of the material passing sieve number 40 increases. This observation was expected and has been reported by many researchers for various soil types including silty and clayey sands, silt, and clay (Gudishala 2004). Therefore, the liquid limit will be included in the multivariate analyses.

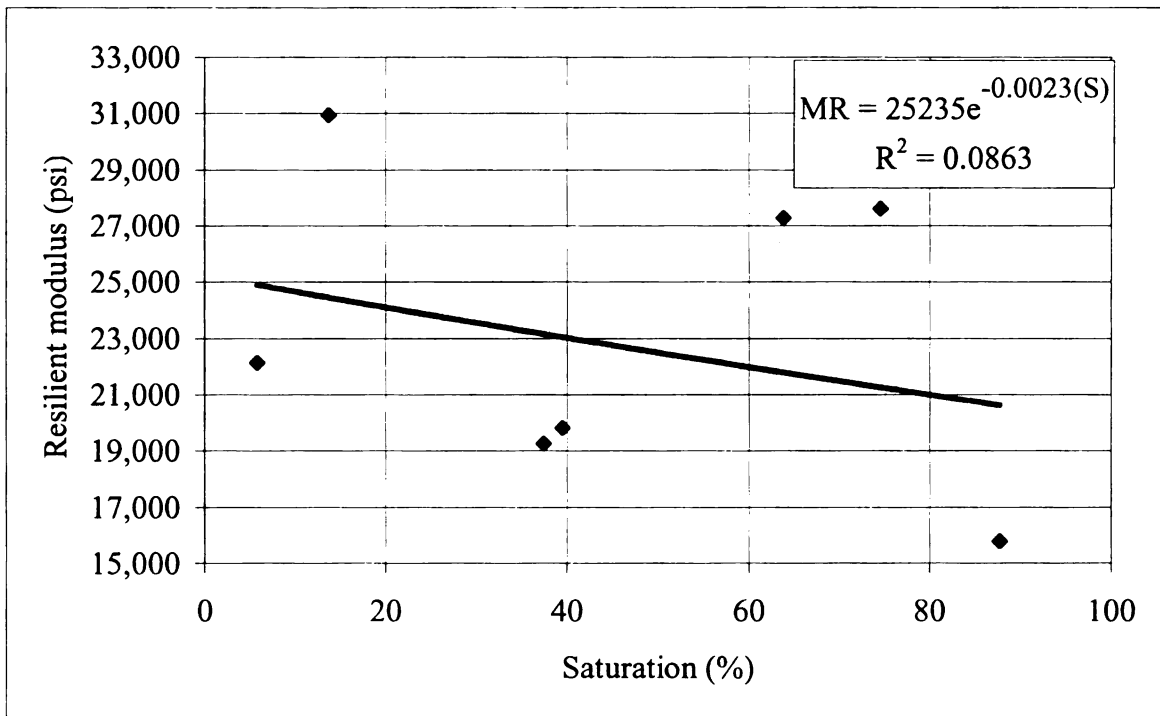


Figure 4.34 Resilient modulus versus saturation for SC-SM soils

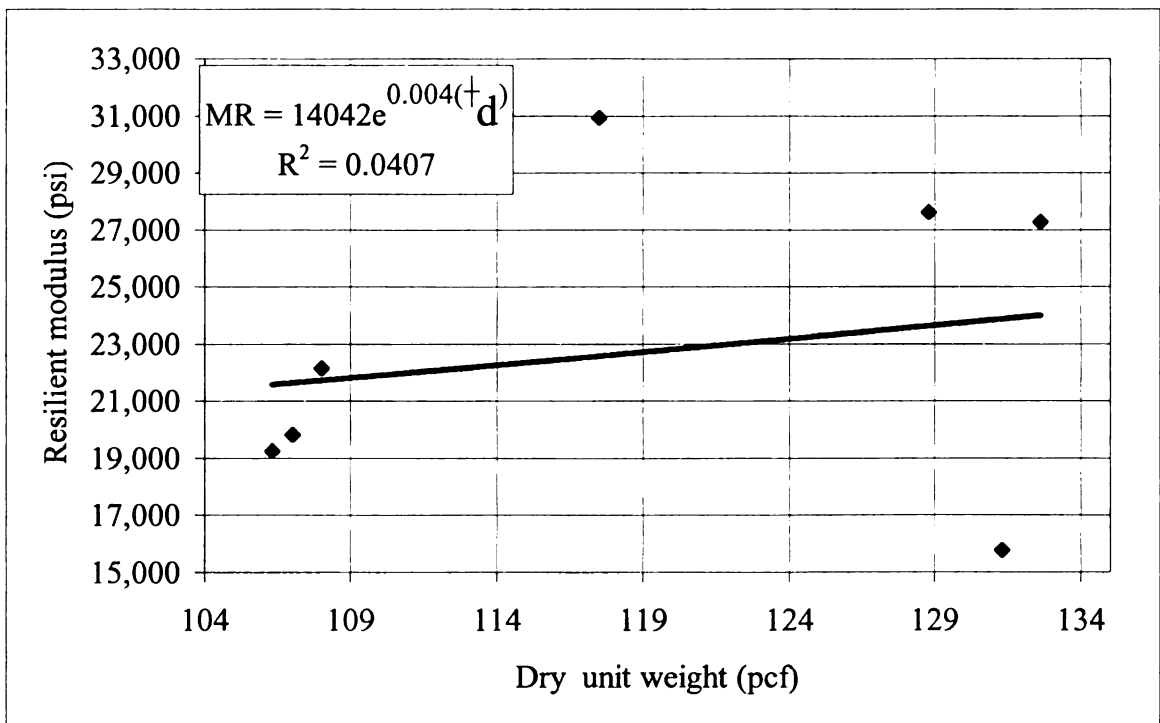


Figure 4.35 Resilient modulus versus the dry unit weight for SC-SM soils

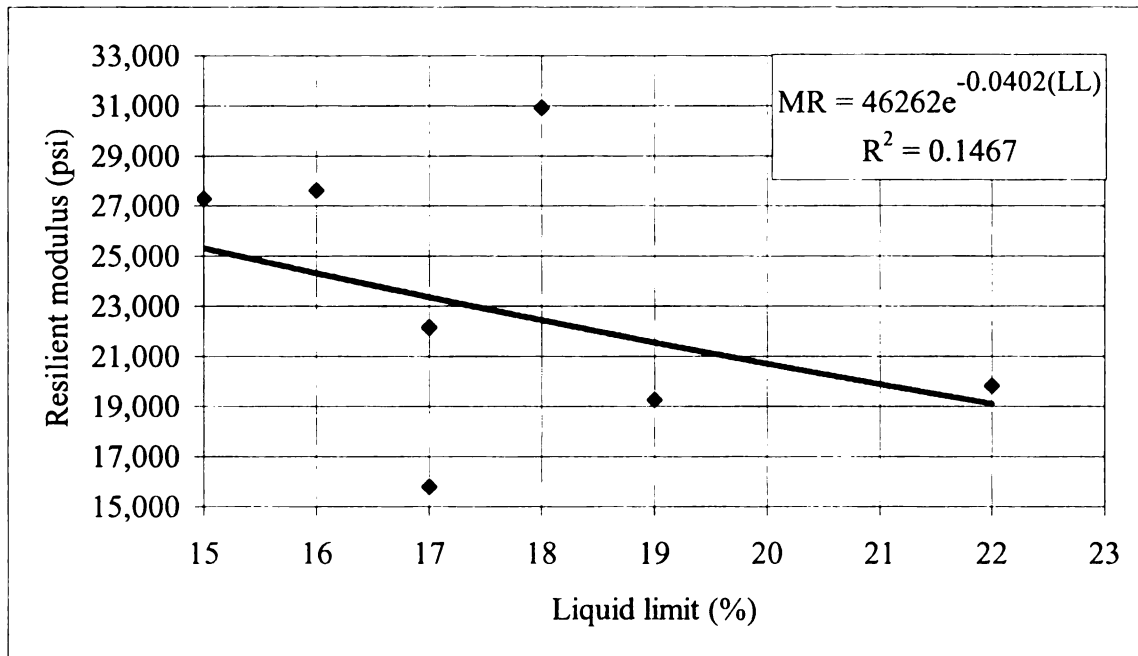


Figure 4.36 Resilient modulus versus liquid limit for SC-SM soils

**Effect of Sample Grain Size** – Because of the relatively high fine contents, all SC-SM soils were subjected to wet sieving and hydrometer analyses to determine their grain size distribution. The effects of sample gradation on the MR values were assessed through the following gradation parameters:

- Percent passing sieves 200, 100, 40, 20, 10, 4, and 3/8 inch
- The coefficients of curvature and uniformity
- The average particle size at ten, thirty, and sixty percent passing ( $D_{10}$ ,  $D_{30}$ , and  $D_{60}$ , respectively)

The effects of each gradation parameter on the MR values were analyzed by plotting the MR values of the soil samples as a function of that parameter. All gradation parameters showed minor correlations to the MR values. Despite this, several attempts were made to include gradation variables in the multivariate analyses as presented in the next subsection.

#### 4.5.5.2 Multivariate Analyses

Multivariate analyses were conducted to study the combined effects of several independent sample variables on the dependent variable MR of SC-SM soils. During the analyses:

- Various models were used in an attempt to maximize the value of the coefficient of determination ( $R^2$ ).
- Special care was taken to:
  - Ensure that the resulting equation satisfies the known trends between each of the independent variable and the dependent variable MR.
  - Avoid any significant co-linearity between the independent variables.
  - Minimize the number of independent variables in the equation.

Results of the analyses yielded a model having a relatively high  $R^2$  value. The model is based on three sample variables of the SC-SM (SVSC-SM) soils (the water content, liquid limit, and the coefficient of uniformity) as stated in Equation 4.10. Figure 4.37 depicts the resilient modulus values plotted as a function of the SVSC-SM. It can be seen from the figure that higher SVSC-SM values yield lower MR values.

$$MR = 39638 \exp - 0.0037(SVSC - SM) \quad \text{Equation 4.10}$$

Where,

$$SVSC - SM = C_u^{0.2} * (LL^{1.15} + MC^{1.3})$$

LL = liquid limit (%)

MC = degree of saturation (%)

$C_u$  = coefficient of uniformity

The liquid limit and coefficient of uniformity are constant for a given soil.

Therefore, lower SVSC-SM can be obtained by decreasing the moisture content of the test sample. As the moisture content of the sample increases, the lubrication between the sand particles increases, thus reducing the MR values (Perloff and Baron 1976). The term  $(LL^{1.15} + MC^{1.3})$  can be thought of as the moisture index of the SC-SM subgrade soils.

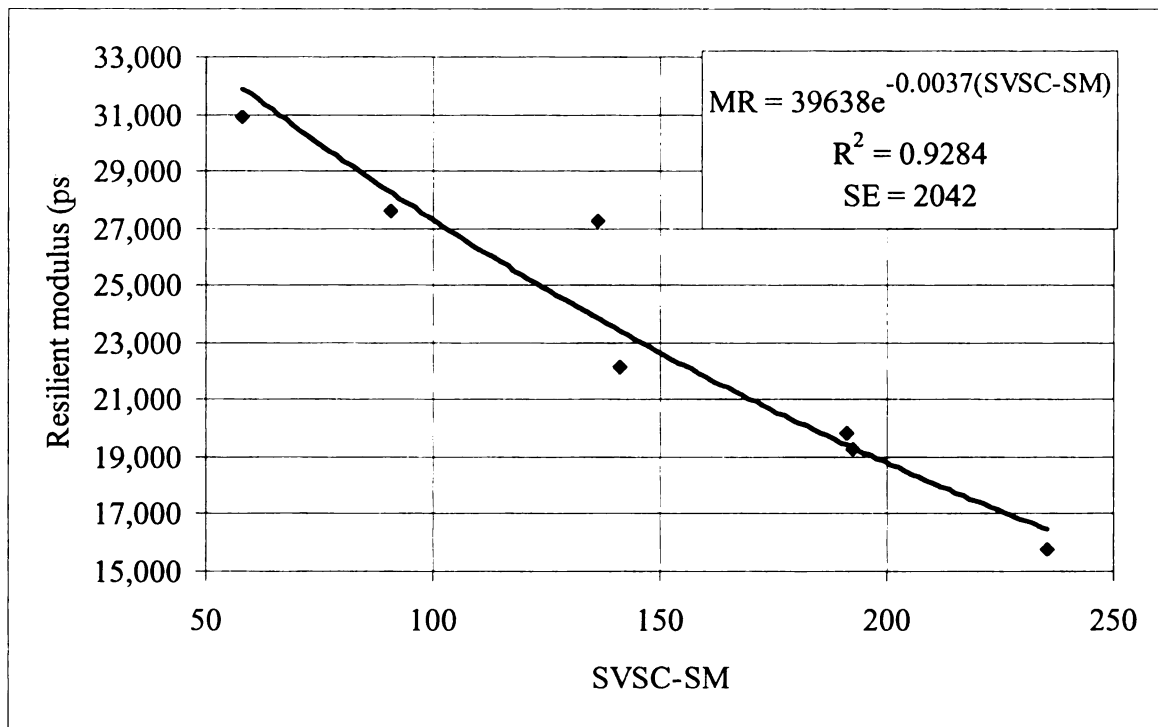


Figure 4.37 Resilient modulus versus SVSC-SM soils

It is important to note that the data used in support of Equation 4.10 includes soil samples having liquid limits values ranging from 15 to 22, coefficients of uniformity between 14.74 and 270, and moisture contents from 1.2 to 9.2 percent. The use of the equation outside these ranges is not recommended.

#### 4.5.6 Gravely Sand (SG)

Table 4.8 lists the locations, the USCS and the AASHTO soil classifications, and the sample designation number of two disturbed soil samples that were collected from various clusters and areas throughout the State of Michigan. The two samples were classified in step 1 of the analyses as SG. However, due to the large gravel particles cyclic load tests could not be performed on these samples. The AASHTO standard test procedure that was used requires that the diameter of the sample be at least four times larger than the largest particle. For this to be satisfied the sample diameter would have to be about 9 inches. Because of the limited number of samples and because this type of subgrade material is very much limited to small areas in the State of Michigan, no further analyses were conducted on the two samples.

Table 4.8 Locations of SP-SM subgrade soils

| Sample number   | Location                    | AASHTO | USCS |
|-----------------|-----------------------------|--------|------|
| M-033-S (05-05) | 750 feet South of Peters Rd | A-1-a  | SG   |
| U-012-E (12-07) | 120 feet West of Person Hwy | A-1-a  | SG   |



#### **4.6 Climatic Damage Models**

The State of Michigan is located in the AASHTO wet-freeze region. The average annual rainfall and snowfall in the State varies from one location to another. In the Lansing area, the average annual rainfall is about 32-inch and the average annual snow fall is about 56-inch. Further, the frost depth varies from about 7-feet in the Upper Peninsula to about 3-feet in the Lower Peninsula. These climatic data affect the behavior of the paving materials and roadbed soils. Because of the variability of the climatic conditions, the resilient modulus of any given soil is dynamic in nature and it changes seasonally with changing water content and below and above freezing temperatures.

For most pavement structure, the subgrade material is the weakest part of the structure. The 1993 AASHTO Design Guide calls for protecting the subgrade soils under flexible pavements by providing adequate structural number. For rigid pavement, the modulus of subgrade reaction is typically integrated with that of the base layer to yield a composite modulus of subgrade reaction. In addition, the 1993 AASHTO Design Guide includes damage assessment scenario that must be used to obtain the design modulus of the roadbed soils. Finally, the Guide does not provide pavement layer thicknesses based on frost penetration. That is the guide does not provide any protection to the roadbed soils against freezing. The new M-EPDG also includes climatic model to reduce the given subgrade modulus and hence, account for the seasonal damage.

For any pavement structure, the amount of water in the subgrade materials is a function of many variables including:

- The duration and frequency of the rainfall
- The geometry of the pavement and the flow regime of the adjacent ground

- The conditions and permeability of the surface layers and the number of unsealed cracks.
- The permeability of the subgrade materials
- The type of drainage system installed in the pavement structure
- The initial crown of the subgrade soils created during rolling
- The elevation of the ground water table

Based on the above list, a given subgrade soil located in the State of Michigan could be saturated during spring thaw season, during extended periods of rainfall (more than few hours), or during frequent rainfall. Based on this scenario, one can conclude that the subgrade soil is highly likely saturated during spring thaw, and it could be occasionally saturated during the summer and fall seasons. The subgrade soil is likely frozen during the late winter season.

Given the variability of the degree of saturation of the subgrade soil during the pavement service life and the corresponding variation in its resilient modulus, the question become what subgrade resilient modulus should be used in the design of new pavement or the rehabilitation of existing pavements. The answer depends on the type of damage model used in the analysis.

In general, two types of damage models are available; empirical and mechanistic-empirical. An example of the former is the 1993 AASHTO Design Guide. Examples of the latter is the fatigue and rut models in the MICHPAVE computer program, in VESYS computer program, in the Asphalt Institute pavement design, and in almost every other mechanistic-empirical computer program and the 1993 AASHTO Design Guide damage model presented in Equation 4.10

$$U_f = 1.18 * 10^8 * MR^{-2.32}$$

Equation 4.10

Where

$U_f$  = damage factor

$MR$  = resilient modulus of the subgrade soils

In this study, the reduction factor to reduce the resilient modulus value from its summer and fall season values was obtained using the following procedure:

- For each of the eight soil types except the SP, the proper correlation equation was used to calculate the resilient modulus at water content near the optimum water content of a standard proctor compaction. The correlation equation was also used to calculate the resilient modulus at a water content corresponding to near soil saturation (degree of saturation between 93 and 99 percent).
- For the SP soils, the reduction factor between the resilient modulus at the optimum water content and that near saturation was obtained from Holtz and Kovacs (1981).
- The damage factor of each of the eight soil types was calculated as the ratio of the two modulus values of the first two steps. The average damage factor of all eight soil types was then calculated as shown in Table 4.9.
- A standard pavement cross-section of 12 inch subbase, 6 inch base and 7 inch asphalt layer was used to calculate the service life of the pavement in terms of ESALs using the MICHPAVE computer program. The same pavement cross-section was analyzed twice, once for subgrade modulus value of 16,000 psi (an average modulus near the optimum water content) and once for an average modulus value near saturation (4000 psi). Results of the analysis yielded two expected pavement lives in term of ESALs.

The ratio of the expected ESAL at the high modulus was then divided by the ratio of ESAL at the low modulus. The results yielded a damage factor of about 8.

- Similar procedure was used in the 1993 AASHTO design guide, the damage factor was about 7.
- The average damage factors obtained from the 1993 AASHTO design procedure, the MICHPAVE computer program and the correlation equations was then calculated and is listed in Table 4.9.
- For each soil type, the average resilient modulus of all test samples was then calculated and listed in Table 4.10.
- The recommended subgrade design resilient modulus values for all eight soil types are then calculated by dividing the average resilient modulus per soil type by the average damage factor listed in Table 4.9. The values of the recommended design resilient modulus are listed in Table 4.10.

It should be noted that the recommended design resilient modulus values listed in Table 4.10 are to be used in the M-EPDG design level III. For design level II, the correlation equations should be used. And for design level I, FWD tests should be conducted and the design modulus value backcalculated and adjusted using the damage factor. The FWD procedure is not a part of this thesis. It is addressed in the final report to MDOT.

Table 4.9 Damage factor calculation

| USCS classification                                                             | Water content (%) |          |      | Resilient modulus (psi) corresponding to saturation range of |        |        | Damage factor |        |          | Average damage factor |
|---------------------------------------------------------------------------------|-------------------|----------|------|--------------------------------------------------------------|--------|--------|---------------|--------|----------|-----------------------|
|                                                                                 | Near optimum      | Moderate | High | 45-75                                                        | 75-85  | 85-100 | Laboratory    | AASHTO | MICHPAVE |                       |
| SC, CL, ML                                                                      | 15                | 22       | 30   | 36,543                                                       | 5,879  | 4,430  | 8             | NA     | NA       | NA                    |
| SC-SM                                                                           | 8.5               | 15       | 28   | 27,276                                                       | 12,000 | 9,000  | 3             |        |          |                       |
| SP-SM                                                                           | 8                 | 15       | 20   | 23,009                                                       | 11,000 | 7,000  | 3             |        |          |                       |
| SM (MI)                                                                         | 12                | 20       | 23   | 18,416                                                       | 11,480 | 5,290  | 3             |        |          |                       |
| SP1                                                                             | 11                | 20       | 25   | 29,418                                                       | 11,798 | 3,933  | 7             |        |          |                       |
| SP2                                                                             | 10                | 20       | 25   | 22,768                                                       | 9,969  | 4,000  | 6             | 7      | 8        | 7                     |
| Average damage factor                                                           |                   |          |      |                                                              |        |        | 5             |        |          |                       |
| Shaded cells represent moisture contents outside those of the sampled soil type |                   |          |      |                                                              |        |        |               |        |          |                       |

Table 4.10 Design resilient modulus values for M-E PDG design level 3

| USCS       | Average modulus (psi) | Design MR value (psi) |
|------------|-----------------------|-----------------------|
| SC, CL, ML | 26,887                | 3,841                 |
| SC-SM      | 23,258                | 3,323                 |
| SP-SM      | 21,147                | 3,021                 |
| SM         | 17,257                | 2,465                 |
| SP1        | 30,328                | 4,333                 |
| SP2        | 25,961                | 3,709                 |

## **CHAPTER 5**

### **SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS**

#### **5.1 Summary**

The resilient modulus of the roadbed soil plays a crucial role in the design of pavement systems. Currently, MDOT uses different procedures to determine the MR. Most of these procedures are applicable to M-E PDG level 3 design. Therefore, a consistent, uniform and implementable procedure that meet the requirements of M-E PDG design Levels 1, 2, and 3. To do this, the State of Michigan was divided into fifteen clusters where the physical and engineering characteristics of the soil are similar. The clusters were then divided into 99 areas to narrow down the ranges of the engineering and physical characteristics of the soils. Disturbed subgrade soil samples were collected from seventy five areas. At some locations where the disturbed samples were obtained, pocket penetrometer and vane shear tester were used to determine the penetration and shearing resistances of the soils, respectively.

The undisturbed soil samples were then tested to determine their moisture contents, grain size distributions, Atterberg limits (when applicable) and resilient modulus using cyclic load triaxial tests. Correlation equations (see Table 5.1) were then developed to estimate the MR values of the roadbed soil based on the results of the moisture content, Atterberg limits, dry unit weight, and grain size distribution data.

#### **5.2 Conclusions**

Based on the field and laboratory investigations and the data analyses, the following conclusions were drawn:

1. Michigan Department of Transportation's (MDOT) current procedure for determining the MR values is not consistent between the regions.
2. Grain size distribution on soils with more than 10 percent passing sieve number 200 should be performed by wet sieving.
3. The subgrade soils in Michigan were classified based on the USCS and the AASHTO soil classification systems.
4. In most cases, subgrade soils having similar elastic behavior under loads tend to fall within one classification (designation) of the USCS but within several AASHTO classification groups. Hence, based on the elastic behavior of the subgrade soils in Michigan, the USCS produces much better soil grouping than the AASHTO classification system.
5. Most of the subgrade soils in the State of Michigan can be divided into the following eight soil types:
  - Poorly graded sand (SP)
  - Silty sand (SM)
  - Clayey sand (SC)
  - Poorly graded sand – silty sand (SP-SM)
  - Clayey sand – silty sand (SC-SM)
  - Gravelly sand (SG)
  - Low plasticity clay (CL)
  - Low plasticity silt (ML).
6. For SC and CL subgrade soils the resilient modulus values obtained from testing undisturbed Shelby tube samples were compatible to those from disturbed samples.

7. Good correlation equations relating the resilient modulus to some of the physical characteristics of the soils were developed and are summarized in Table 5.1.
8. The correlation equations listed in Table 5.1 satisfy the M-E PDG requirements for level 2 design.
9. An average damage factor was calculated using the correlation equations, the MICHPAVE computer program and the 1993 AASHTO design procedure. The damage factor accounts for the seasonal effects on the resilient modulus values of the subgrade soils in the State of Michigan.
10. Average design resilient modulus values for the eight soil types were developed and are listed in Table 4.10 and presented in Figures 5.1 through 5.4.
11. The design resilient modulus values in Figures 5.1 through 5.4 satisfy the M-E PDG requirements for level III design.

### **5.3 Recommendations**

Based on the results and conclusions of this study, it is strongly recommended that:

- The subgrade soils in the nineteen areas where neither disturbed nor undisturbed soil samples were obtained be subjected to the full testing schemes presented in Chapter 3 of this thesis.
- Nondestructive deflection tests be conducted at the network level as to fill the gaps in the existing FWD data. Ideally, the tests should be spaced at 500 feet interval.
- The deflection data collected at the network level be used to backcalculate the resilient modulus of the various pavement layers to meet the requirements of M-E PDG level 1 design.



- MDOT to implement the findings of this study by adopting the data presented in Figures 5.1 through 5.4 for M-E PDG level III design.
- MDOT uses the correlation models presented in Table 5.1 for M-E PDG level II design.
- The seasonal damage factors developed in this study be implemented by all regions when using the 1993 AASHTO design guide.

Table 5.1 Summary of predictive equations for each soil type

| USCS          | Number of |       | Predictive equation                   | Variable equation                                                                      |
|---------------|-----------|-------|---------------------------------------|----------------------------------------------------------------------------------------|
|               | Clusters  | Areas |                                       |                                                                                        |
| SP1           | 6         | 8     | $MR = 89.825(SVSP1)^{2.9437}$         | $SVSP1 = \frac{\gamma_d^{1.15}}{(P_4^{1.5} - P_{40}^{0.25})^{0.5}}$                    |
| SP2           | 6         | 12    | $MR = 0.8295(SVSP2)^{3.6066}$         | $SVSP2 = \frac{\gamma_d^{1.35} * P_{200}^{-0.1}}{(P_4^{1.5} - P_{40}^{0.25})^{0.5}}$   |
| SM            | 11        | 16    | $MR = 0.0303(SVSM)^{4.1325}$          | $SVSM = \frac{\gamma_d^{0.8}}{S^{0.15}}$                                               |
|               |           |       | $MR = 45722 \exp[(-0.0258)(MI)]$      | $MI = LL^{1.1} + MC^{1.25}$                                                            |
| SC, CL,<br>ML | 10        | 28    | $MR = 650486 \exp(-0.0501(S))$        | $S = \left[ \frac{G_s * (MC/100) * \gamma_d}{G_s * \gamma_w - \gamma_d} \right] * 100$ |
| SP-SM         | 7         | 8     | $MR = 1749.6 \exp(0.0054(SVSP - SM))$ | $SVSP - SM = \frac{\gamma_d^{1.75}}{MC^{0.5} + LL^{0.6} + (P_{40} - P_{200})^{0.01}}$  |
| SC-SM         | 5         | 7     | $MR = 39638 \exp - 0.0037(SVSC - SM)$ | $SVSC - SM = C_u^{0.2} * (LL^{1.15} + MC^{1.3})$                                       |

$\gamma_d$  = dry unit weight (pcf),  $P_4$ ,  $P_{40}$ ,  $P_{200}$  = percent passing sieves number 4, 40, and 200, S = saturation (%), LL = liquid limit, MC = moisture content,  $G_s$  = specific gravity of the solid  $\approx 2.7$ ,  $\gamma_w$  = unit weight of water = 62.4 pcf,  $C_u$  = coefficient of uniformity

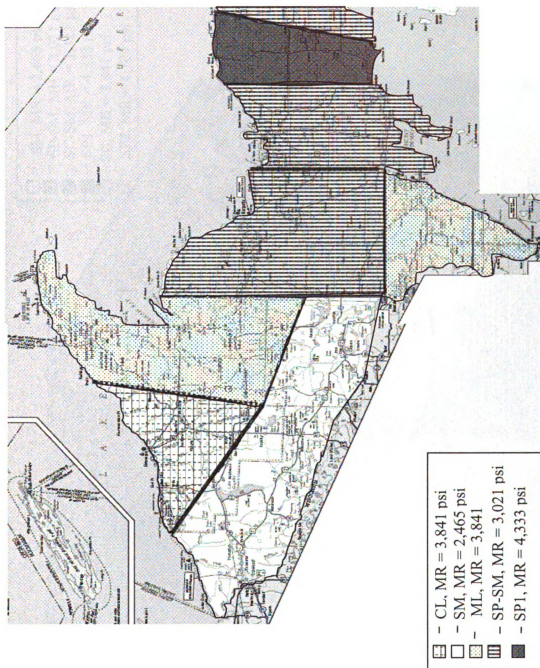
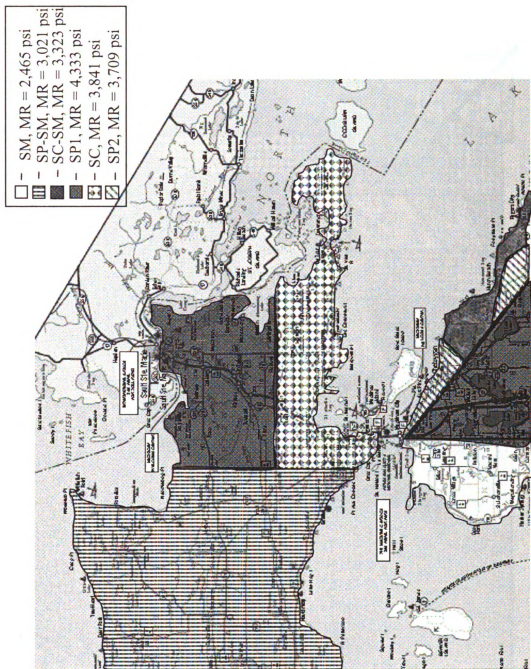


Figure 5.1 Recommended M-E PDG level 3 design modulus values for the western portion of the Upper Peninsula



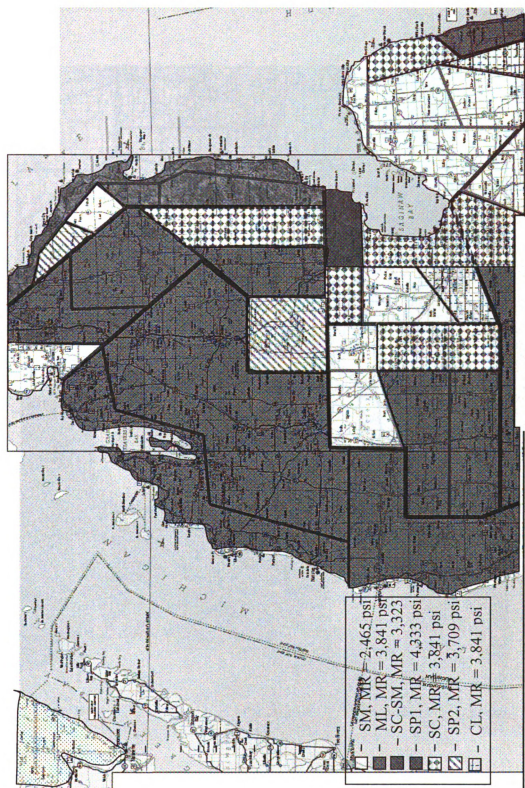


Figure 5.3 Recommended M-E PDG level 3 design modulus values for the northern portion of the Lower Peninsula

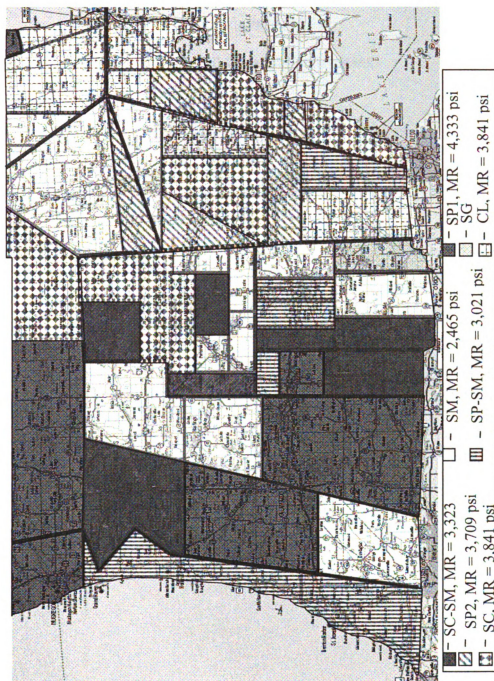


Figure 5.4 Recommended M-E PDG level 3 design modulus values for the southern portion of the Lower Peninsula

## APPENDIX A

### Soil Classification Systems



Table A.1 AASHTO soil classification system (Holtz and Kovacs 1981)

| General classification                                | Granular materials (35% or less passing 0.075 mm) |        |           |                                 |        |        | Silt-clay materials (more than 35% passing 0.075 mm) |        |              |        |        |       |
|-------------------------------------------------------|---------------------------------------------------|--------|-----------|---------------------------------|--------|--------|------------------------------------------------------|--------|--------------|--------|--------|-------|
| Group classification                                  | A-1                                               |        | A-3       | A-2                             |        |        | A-4                                                  | A-5    | A-6          | A-7    |        |       |
|                                                       | A-1-a                                             | A-1-b  |           | A-2-4                           | A-2-5  | A-2-6  |                                                      |        |              | A-2-7  | A-7-5  | A-7-6 |
| Sieve analysis, percent passing:                      |                                                   |        |           |                                 |        |        |                                                      |        |              |        |        |       |
| 2.00 mm (No. 10)                                      | 50 max                                            | -      | -         | -                               | -      | -      | -                                                    | -      | -            | -      | -      |       |
| 0.425 mm (No. 40)                                     | 30 max                                            | 50 max | 51 min    | -                               | -      | -      | -                                                    | -      | -            | -      | -      |       |
| 0.075 mm (No. 200)                                    | 15 max                                            | 25 max | 10 max    | 35 max                          | 35 max | 35 max | 36 min                                               | 36 min | 36 min       | 36 min | 36 min |       |
| Characteristics of fraction passing 0.425 mm (No. 40) |                                                   |        |           |                                 |        |        |                                                      |        |              |        |        |       |
| Liquid limit                                          | -                                                 | -      | -         | 40 max                          | 41 min | 40 max | 40 max                                               | 41 min | 40 max       | 41 min | 41 min |       |
| Plasticity index                                      | 6 max                                             | 6 max  | NP        | 10 max                          | 10 max | 11 min | 10 max                                               | 10 max | 11 min       | 11 min | 11 min |       |
| Usual types of significant constituent materials      | Stone fragments, gravel, and sand                 |        | Fine sand | Silty or clayey gravel and sand |        |        | Silty soils                                          |        | Clayey soils |        |        |       |



Figure A.1 AASHTO Atterberg limit ranges (Holtz and Kovacs 1981)

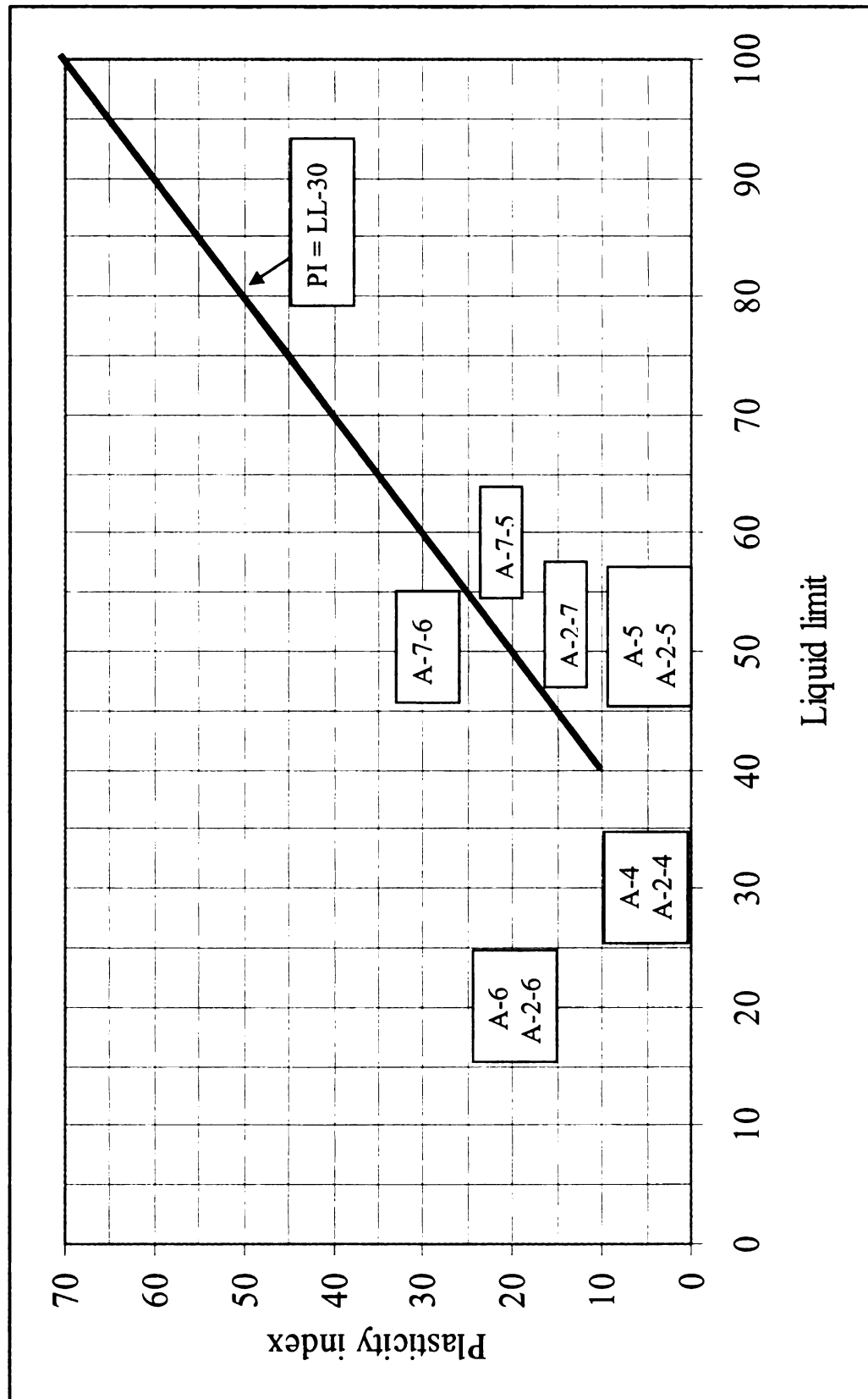


Figure A.2 Casagrande's plasticity chart (Holtz and Kovacs 1981)

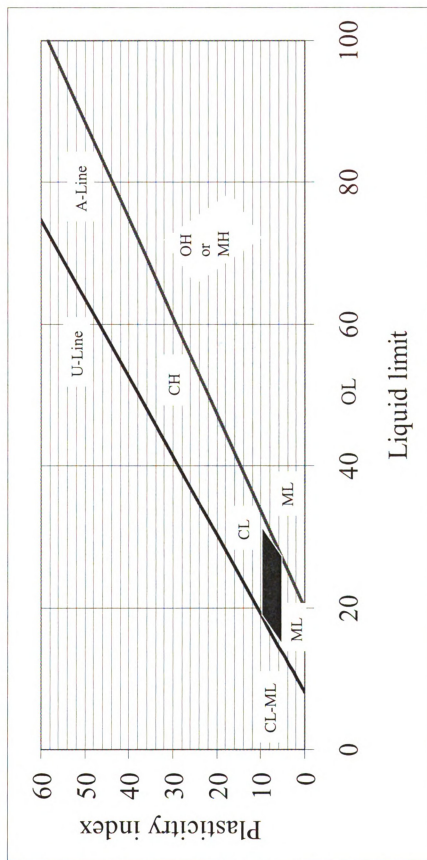


Figure A.3 USCS coarse grained soil classification (Holtz and Kovacs 1981)

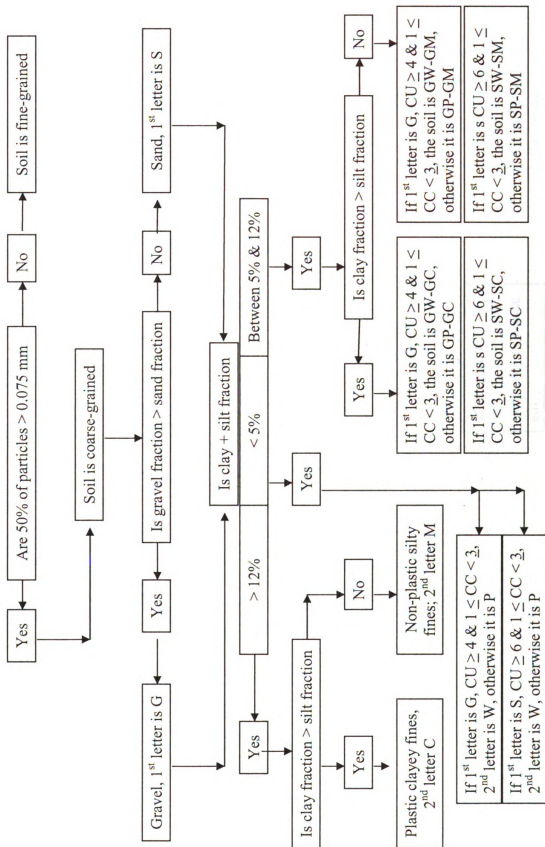


Figure A.4 USCS fine grained soil classification (Holtz and Kovacs 1981)

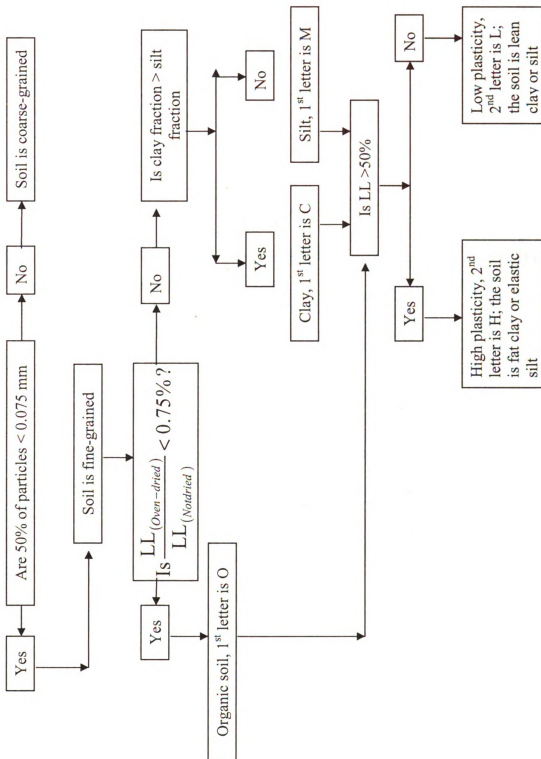


Table A.2 Possible AASHTO soil classifications per USCS group (Holtz and Kovacs 1981)

| USCS group | Possible AASHTO classification                                 |
|------------|----------------------------------------------------------------|
| SP         | A-3, A-1-b, A-1-a, A-2-4, A-2-5, A-2-6, A-2-7                  |
| SG         | A-3, A-1-b, A-1-a, A-2-4, A-2-5, A-2-6, A-2-8                  |
| SM         | A-1-b, A-2-4, A-2-5, A-2-7, A-2-6, A-4, A-5, A-6, A-7-5, A-7-6 |
| SC         | A-2-6, A-2-7, A-2-4, A-2-6, A-4, A-7-6, A-7-5                  |
| CL         | A-6, A-7-6, A-4                                                |
| ML         | A-4, A-5, A-6, A-7-5                                           |
| SP-SM      | A-3, A-1-a, A-1-b, A-2-4, A-2-4, A-2-6, A-2-7                  |
| SC-SM      | A-4, A-5, A-2-4, A-2-5, A-1-a, A-1-b                           |

Table A.3 Possible USCS classification per AASHTO group (Holtz and Kovacs 1981)

| AASHTO group | Possible USCS classification           |
|--------------|----------------------------------------|
| A-1-a        | GW, GP, SW, SP, GM, SM                 |
| A-1-b        | SW, SP, GM, SM, GP                     |
| A-3          | SP, SW, GP                             |
| A-2-4        | GM, SM, GC, SC, GW, GP, SW, SP         |
| A-2-5        | GM, SM, GW, GP, SW, SP                 |
| A-2-6        | GC, SC, GM, SM, GW, GP, SW, SP         |
| A-2-7        | GM, GC, SM, SC, GW, GP, SW, SP         |
| A-4          | ML, OL, CL, SM, SC, GM, GC             |
| A-5          | OH, MH, ML, OL, SM, GM                 |
| A-6          | CL, ML, OL, SC, GC, GM, SM             |
| A-7-5        | OH, MH, ML, OL, CH, GM, SM, GC, SC     |
| A-7-6        | CH, CL, ML, OL, SC, OH, MH, GC, GM, SM |

## APPENDIX B

### Laboratory resilient modulus results

Table B.1 Laboratory resilient modulus results

| Sample number   | Soil Type |       | Cycle number | Cyclic stress (psi)       |                            |                                 |                                                   |                           |                            |                                 |                                                   |
|-----------------|-----------|-------|--------------|---------------------------|----------------------------|---------------------------------|---------------------------------------------------|---------------------------|----------------------------|---------------------------------|---------------------------------------------------|
|                 |           |       |              | 10                        |                            |                                 |                                                   | 15                        |                            |                                 |                                                   |
|                 | AASHTO    | USCS  |              | Average cyclic load (lbs) | Average deformation (mils) | Average resilient modulus (psi) | Average MR (psi) at load cycles 500, 800 and 1000 | Average cyclic load (lbs) | Average deformation (mils) | Average resilient modulus (psi) | Average MR (psi) at load cycles 500, 800 and 1000 |
| M-045-S (01-01) | A-6       | CL    | 100          | 31.6                      | 2.304                      | 35,043                          | 36,543                                            | 49.0                      | 3.740                      | 31,266                          | 31,503                                            |
|                 |           |       | 200          | 32.1                      | 2.202                      | 36,823                          |                                                   | 50.3                      | 3.774                      | 31,862                          |                                                   |
|                 |           |       | 500          | 32.2                      | 2.262                      | 36,639                          |                                                   | 50.1                      | 3.663                      | 31,747                          |                                                   |
|                 |           |       | 800          | 32.5                      | 2.205                      | 37,056                          |                                                   | 50.1                      | 3.817                      | 31,297                          |                                                   |
|                 |           |       | 1000         | 32.8                      | 2.227                      | 35,934                          |                                                   | 50.4                      | 3.872                      | 31,465                          |                                                   |
| U-002-E (02-01) | A-4       | SM    | 100          | 32.5                      | 3.729                      | 13,894                          | 15,352                                            | 50.3                      | 5.850                      | 12,872                          | 13,818                                            |
|                 |           |       | 200          | 32.9                      | 3.592                      | 14,285                          |                                                   | 50.1                      | 5.727                      | 13,150                          |                                                   |
|                 |           |       | 500          | 32.7                      | 3.442                      | 15,044                          |                                                   | 50.4                      | 5.551                      | 13,686                          |                                                   |
|                 |           |       | 800          | 32.7                      | 3.325                      | 15,708                          |                                                   | 50.4                      | 5.496                      | 13,826                          |                                                   |
|                 |           |       | 1000         | 33.3                      | 3.415                      | 15,305                          |                                                   | 49.9                      | 5.364                      | 13,942                          |                                                   |
| M-028-W (02-02) | A-4       | ML    | 100          | 32.0                      | 1.741                      | 48,422                          | 53,824                                            | 50.7                      | 2.777                      | 45,310                          | 41,516                                            |
|                 |           |       | 200          | 32.5                      | 1.650                      | 50,092                          |                                                   | 51.0                      | 2.801                      | 44,090                          |                                                   |
|                 |           |       | 500          | 32.7                      | 1.569                      | 53,892                          |                                                   | 51.3                      | 2.969                      | 42,510                          |                                                   |
|                 |           |       | 800          | 32.7                      | 1.600                      | 53,350                          |                                                   | 51.3                      | 3.047                      | 41,331                          |                                                   |
|                 |           |       | 1000         | 33.0                      | 1.598                      | 54,230                          |                                                   | 51.3                      | 3.087                      | 40,707                          |                                                   |
| M-028-W (02-03) | A-1-b     | SP-SM | 100          | 33.9                      | 2.675                      | 19,996                          | 19,195                                            | 51.4                      | 4.042                      | 16,997                          | 17,845                                            |
|                 |           |       | 200          | 33.8                      | 2.698                      | 20,013                          |                                                   | 51.4                      | 3.956                      | 16,510                          |                                                   |
|                 |           |       | 500          | 33.7                      | 2.821                      | 19,057                          |                                                   | 52.6                      | 3.873                      | 17,649                          |                                                   |
|                 |           |       | 800          | 33.8                      | 2.796                      | 19,502                          |                                                   | 51.7                      | 3.733                      | 17,942                          |                                                   |
|                 |           |       | 1000         | 34.0                      | 2.792                      | 19,025                          |                                                   | 51.5                      | 3.774                      | 17,945                          |                                                   |
| U-002-E (02-04) | A-4       | ML    | 100          | 32.8                      | 2.499                      | 31,653                          | 37,012                                            | 50.0                      | 3.944                      | 29,991                          | 33,191                                            |
|                 |           |       | 200          | 32.8                      | 2.471                      | 33,225                          |                                                   | 49.8                      | 3.855                      | 30,881                          |                                                   |
|                 |           |       | 500          | 33.7                      | 2.322                      | 36,319                          |                                                   | 50.0                      | 3.724                      | 31,614                          |                                                   |
|                 |           |       | 800          | 33.1                      | 2.219                      | 36,874                          |                                                   | 50.1                      | 3.560                      | 33,569                          |                                                   |
|                 |           |       | 1000         | 33.1                      | 2.207                      | 37,843                          |                                                   | 50.5                      | 3.516                      | 34,390                          |                                                   |
| U-002-E (03-01) | A-3       | SP-SM | 100          | 33.3                      | 2.393                      | 22,822                          | 22,830                                            | 51.0                      | 4.295                      | 18,193                          | 19,629                                            |
|                 |           |       | 200          | 33.9                      | 2.412                      | 23,466                          |                                                   | 50.2                      | 4.135                      | 18,644                          |                                                   |
|                 |           |       | 500          | 33.9                      | 2.441                      | 23,426                          |                                                   | 51.6                      | 4.005                      | 19,685                          |                                                   |
|                 |           |       | 800          | 34.1                      | 2.522                      | 22,465                          |                                                   | 52.0                      | 4.114                      | 19,323                          |                                                   |
|                 |           |       | 1000         | 34.6                      | 2.560                      | 22,598                          |                                                   | 51.7                      | 3.990                      | 19,880                          |                                                   |

Table B.1 (cont'd)

| Sample number   | Soil Type |       | Cycle number | Cyclic stress (psi)       |                            |                                 |                                                   |                           |                            |                                 |                                                   |
|-----------------|-----------|-------|--------------|---------------------------|----------------------------|---------------------------------|---------------------------------------------------|---------------------------|----------------------------|---------------------------------|---------------------------------------------------|
|                 |           |       |              | 10                        |                            |                                 |                                                   | 15                        |                            |                                 |                                                   |
|                 | AASHTO    | USCS  |              | Average cyclic load (lbs) | Average deformation (mils) | Average resilient modulus (psi) | Average MR (psi) at load cycles 500, 800 and 1000 | Average cyclic load (lbs) | Average deformation (mils) | Average resilient modulus (psi) | Average MR (psi) at load cycles 500, 800 and 1000 |
| M-028-W (03-02) | A-3       | SP    | 100          | 33.1                      | 2.429                      | 22,556                          | 23,003                                            | 50.3                      | 3.861                      | 20,301                          | 22,536                                            |
|                 |           |       | 200          | 33.3                      | 2.428                      | 22,706                          |                                                   | 50.9                      | 3.783                      | 21,157                          |                                                   |
|                 |           |       | 500          | 34.1                      | 2.460                      | 23,286                          |                                                   | 51.3                      | 3.731                      | 21,613                          |                                                   |
|                 |           |       | 800          | 33.9                      | 2.374                      | 23,167                          |                                                   | 51.3                      | 3.644                      | 22,811                          |                                                   |
|                 |           |       | 1000         | 33.8                      | 2.483                      | 22,555                          |                                                   | 52.0                      | 3.582                      | 23,185                          |                                                   |
| M-028-W (03-03) | A-3       | SP-SM | 100          | 32.7                      | 3.357                      | 15,294                          | 16,911                                            | 49.8                      | 5.258                      | 14,150                          | 15,956                                            |
|                 |           |       | 200          | 33.4                      | 3.283                      | 16,085                          |                                                   | 50.3                      | 5.113                      | 14,855                          |                                                   |
|                 |           |       | 500          | 33.0                      | 3.059                      | 16,876                          |                                                   | 50.5                      | 4.774                      | 15,866                          |                                                   |
|                 |           |       | 800          | 33.8                      | 3.094                      | 16,885                          |                                                   | 50.9                      | 4.876                      | 15,840                          |                                                   |
|                 |           |       | 1000         | 33.9                      | 3.175                      | 16,971                          |                                                   | 50.9                      | 4.722                      | 16,162                          |                                                   |
| U-002-E (03-03) | A-2-4     | SM    | 100          | 31.7                      | 3.230                      | 15,364                          | 15,984                                            | 50.3                      | 5.163                      | 14,590                          | 15,833                                            |
|                 |           |       | 200          | 32.2                      | 3.208                      | 15,857                          |                                                   | 50.5                      | 5.056                      | 15,302                          |                                                   |
|                 |           |       | 500          | 32.7                      | 3.167                      | 16,240                          |                                                   | 50.3                      | 4.973                      | 15,412                          |                                                   |
|                 |           |       | 800          | 32.7                      | 3.251                      | 15,919                          |                                                   | 51.1                      | 4.873                      | 15,966                          |                                                   |
|                 |           |       | 1000         | 32.6                      | 3.286                      | 15,793                          |                                                   | 51.0                      | 4.793                      | 16,120                          |                                                   |
| I-075-N (03-04) | A-3       | SP    | 100          | 33.8                      | 2.198                      | 25,827                          | 26,140                                            | 51.4                      | 3.419                      | 24,035                          | 24,401                                            |
|                 |           |       | 200          | 33.8                      | 2.255                      | 25,821                          |                                                   | 51.9                      | 3.423                      | 24,209                          |                                                   |
|                 |           |       | 500          | 34.0                      | 2.203                      | 25,887                          |                                                   | 51.7                      | 3.456                      | 24,040                          |                                                   |
|                 |           |       | 800          | 34.3                      | 2.156                      | 26,592                          |                                                   | 52.3                      | 3.402                      | 24,474                          |                                                   |
|                 |           |       | 1000         | 34.2                      | 2.263                      | 25,940                          |                                                   | 52.3                      | 3.348                      | 24,689                          |                                                   |
| U-023-S (04-01) | A-3       | SP    | 100          | 33.6                      | 2.390                      | 23,852                          | 23,060                                            | 51.5                      | 3.757                      | 21,584                          | 21,735                                            |
|                 |           |       | 200          | 33.9                      | 2.392                      | 24,136                          |                                                   | 51.7                      | 3.775                      | 21,768                          |                                                   |
|                 |           |       | 500          | 33.7                      | 2.472                      | 23,456                          |                                                   | 51.5                      | 3.807                      | 21,526                          |                                                   |
|                 |           |       | 800          | 33.8                      | 2.440                      | 22,395                          |                                                   | 51.7                      | 3.700                      | 21,852                          |                                                   |
|                 |           |       | 1000         | 33.7                      | 2.508                      | 23,330                          |                                                   | 51.7                      | 3.814                      | 21,828                          |                                                   |
| M-068-W (04-02) | A-2-4     | SC-SM | 100          | 34.1                      | 2.034                      | 29,159                          | 30,958                                            | 51.3                      | 3.595                      | 22,151                          | 24,764                                            |
|                 |           |       | 200          | 33.0                      | 2.006                      | 28,338                          |                                                   | 52.3                      | 3.505                      | 23,435                          |                                                   |
|                 |           |       | 500          | 34.1                      | 1.883                      | 30,987                          |                                                   | 52.1                      | 3.377                      | 24,481                          |                                                   |
|                 |           |       | 800          | 34.4                      | 1.861                      | 30,960                          |                                                   | 51.6                      | 3.383                      | 24,598                          |                                                   |
|                 |           |       | 1000         | 34.6                      | 1.980                      | 30,927                          |                                                   | 51.9                      | 3.299                      | 25,212                          |                                                   |



Table B.1 (cont'd)

| Sample number   | Soil Type |       | Cycle number | Cyclic stress (psi)       |                            |                                 |                                                   |                           |                            |                                 |                                                   |
|-----------------|-----------|-------|--------------|---------------------------|----------------------------|---------------------------------|---------------------------------------------------|---------------------------|----------------------------|---------------------------------|---------------------------------------------------|
|                 |           |       |              | 10                        |                            |                                 |                                                   | 15                        |                            |                                 |                                                   |
|                 | AASHTO    | USCS  |              | Average cyclic load (lbs) | Average deformation (mils) | Average resilient modulus (psi) | Average MR (psi) at load cycles 500, 800 and 1000 | Average cyclic load (lbs) | Average deformation (mils) | Average resilient modulus (psi) | Average MR (psi) at load cycles 500, 800 and 1000 |
| M-068-W (04-03) | A-3       | SP    | 100          | 29.4                      | 5.139                      | 8,572                           | 9,979                                             | 46.6                      | 8.078                      | 8,440                           | 10,013                                            |
|                 |           |       | 200          | 30.7                      | 4.944                      | 9,491                           |                                                   | 47.1                      | 7.723                      | 8,966                           |                                                   |
|                 |           |       | 500          | 31.3                      | 4.879                      | 9,725                           |                                                   | 48.6                      | 7.368                      | 9,822                           |                                                   |
|                 |           |       | 800          | 31.7                      | 4.685                      | 10,215                          |                                                   | 48.8                      | 7.052                      | 10,308                          |                                                   |
|                 |           |       | 1000         | 31.6                      | 4.806                      | 9,996                           |                                                   | 48.5                      | 7.166                      | 9,910                           |                                                   |
| M-065-S (04-04) | A-2-4     | SM    | 100          | 31.7                      | 4.463                      | 10,722                          | 11,943                                            | 48.7                      | 6.850                      | 10,728                          | 11,909                                            |
|                 |           |       | 200          | 31.5                      | 4.383                      | 10,903                          |                                                   | 49.7                      | 6.524                      | 11,210                          |                                                   |
|                 |           |       | 500          | 32.1                      | 4.101                      | 11,945                          |                                                   | 50.0                      | 6.427                      | 11,637                          |                                                   |
|                 |           |       | 800          | 32.3                      | 4.157                      | 11,833                          |                                                   | 50.3                      | 6.268                      | 11,995                          |                                                   |
|                 |           |       | 1000         | 32.5                      | 4.190                      | 12,050                          |                                                   | 49.6                      | 6.038                      | 12,096                          |                                                   |
| M-032-W (04-05) | A-4       | SC-SM | 100          | 32.5                      | 2.880                      | 17,806                          | 19,255                                            | 50.5                      | 4.474                      | 16,758                          | 18,161                                            |
|                 |           |       | 200          | 32.3                      | 2.805                      | 17,979                          |                                                   | 50.7                      | 4.478                      | 17,269                          |                                                   |
|                 |           |       | 500          | 32.9                      | 2.739                      | 18,915                          |                                                   | 50.6                      | 4.283                      | 18,002                          |                                                   |
|                 |           |       | 800          | 33.2                      | 2.725                      | 19,303                          |                                                   | 50.9                      | 4.267                      | 18,269                          |                                                   |
|                 |           |       | 1000         | 33.1                      | 2.708                      | 19,546                          |                                                   | 50.7                      | 4.208                      | 18,211                          |                                                   |
| U-131-N (05-01) | A-2-4     | SM    | 100          | 32.1                      | 2.263                      | 23,769                          | 24,651                                            | 51.4                      | 3.311                      | 24,414                          | 25,604                                            |
|                 |           |       | 200          | 32.2                      | 2.284                      | 23,491                          |                                                   | 51.3                      | 3.281                      | 24,858                          |                                                   |
|                 |           |       | 500          | 33.3                      | 2.257                      | 24,948                          |                                                   | 51.4                      | 3.239                      | 26,201                          |                                                   |
|                 |           |       | 800          | 33.6                      | 2.314                      | 24,548                          |                                                   | 50.9                      | 3.247                      | 25,241                          |                                                   |
|                 |           |       | 1000         | 33.8                      | 2.266                      | 24,456                          |                                                   | 51.9                      | 3.298                      | 25,370                          |                                                   |
| U-127-N (05-04) | A-3       | SP    | 100          | 34.1                      | 1.757                      | 35,135                          | 37,158                                            | 52.6                      | 2.846                      | 29,879                          | 29,949                                            |
|                 |           |       | 200          | 34.3                      | 1.708                      | 36,388                          |                                                   | 51.9                      | 2.861                      | 29,921                          |                                                   |
|                 |           |       | 500          | 34.5                      | 1.687                      | 37,843                          |                                                   | 52.9                      | 2.866                      | 30,325                          |                                                   |
|                 |           |       | 800          | 35.3                      | 1.727                      | 36,438                          |                                                   | 51.9                      | 2.901                      | 29,588                          |                                                   |
|                 |           |       | 1000         | 35.2                      | 1.766                      | 37,194                          |                                                   | 52.6                      | 2.850                      | 29,935                          |                                                   |
| M-072-W (05-06) | A-6       | SC    | 100          | 30.6                      | 3.211                      | 22,916                          | 26,492                                            | 48.9                      | 4.652                      | 24,395                          | 27,193                                            |
|                 |           |       | 200          | 31.3                      | 3.095                      | 24,442                          |                                                   | 49.0                      | 4.593                      | 25,076                          |                                                   |
|                 |           |       | 500          | 31.7                      | 2.941                      | 26,104                          |                                                   | 49.8                      | 4.403                      | 26,622                          |                                                   |
|                 |           |       | 800          | 31.9                      | 2.888                      | 27,204                          |                                                   | 49.8                      | 4.321                      | 27,183                          |                                                   |
|                 |           |       | 1000         | 31.2                      | 2.958                      | 26,168                          |                                                   | 50.2                      | 4.252                      | 27,774                          |                                                   |

Table B.1 (cont'd)

| Sample number   | Soil Type |       | Cycle number | Cyclic stress (psi)       |                            |                                 |                                                   |                           |                            |                                 |                                                   |
|-----------------|-----------|-------|--------------|---------------------------|----------------------------|---------------------------------|---------------------------------------------------|---------------------------|----------------------------|---------------------------------|---------------------------------------------------|
|                 |           |       |              | 10                        |                            |                                 |                                                   | 15                        |                            |                                 |                                                   |
|                 | AASHTO    | USCS  |              | Average cyclic load (lbs) | Average deformation (mils) | Average resilient modulus (psi) | Average MR (psi) at load cycles 500, 800 and 1000 | Average cyclic load (lbs) | Average deformation (mils) | Average resilient modulus (psi) | Average MR (psi) at load cycles 500, 800 and 1000 |
| M-132-N (06-01) | A-3       | SP    | 100          | 33.8                      | 2.004                      | 27,798                          | 31,741                                            | 52.1                      | 3.079                      | 26,746                          | 28,997                                            |
|                 |           |       | 200          | 33.9                      | 2.055                      | 29,008                          |                                                   | 52.7                      | 3.027                      | 27,574                          |                                                   |
|                 |           |       | 500          | 34.1                      | 1.984                      | 30,874                          |                                                   | 52.6                      | 2.977                      | 28,591                          |                                                   |
|                 |           |       | 800          | 34.4                      | 1.960                      | 31,899                          |                                                   | 53.2                      | 2.989                      | 29,341                          |                                                   |
|                 |           |       | 1000         | 34.0                      | 1.857                      | 32,449                          |                                                   | 52.0                      | 2.917                      | 29,059                          |                                                   |
| I-075-N (06-02) | A-3       | SP    | 100          | 33.4                      | 1.616                      | 26,603                          | 32,450                                            | 51.6                      | 2.882                      | 26,762                          | 31,187                                            |
|                 |           |       | 200          | 33.3                      | 1.535                      | 28,072                          |                                                   | 51.9                      | 2.855                      | 28,300                          |                                                   |
|                 |           |       | 500          | 33.8                      | 1.461                      | 32,068                          |                                                   | 52.3                      | 2.552                      | 31,485                          |                                                   |
|                 |           |       | 800          | 34.5                      | 1.499                      | 32,023                          |                                                   | 52.1                      | 2.508                      | 31,026                          |                                                   |
|                 |           |       | 1000         | 34.4                      | 1.417                      | 33,260                          |                                                   | 52.7                      | 2.450                      | 31,049                          |                                                   |
| U-031-N (06-03) | A-3       | SP    | 100          | 34.1                      | 1.933                      | 30,572                          | 31,867                                            | 52.5                      | 2.814                      | 29,633                          | 29,636                                            |
|                 |           |       | 200          | 33.8                      | 1.884                      | 31,084                          |                                                   | 52.1                      | 2.832                      | 29,692                          |                                                   |
|                 |           |       | 500          | 34.6                      | 1.808                      | 32,659                          |                                                   | 52.6                      | 2.897                      | 29,123                          |                                                   |
|                 |           |       | 800          | 35.0                      | 1.908                      | 31,347                          |                                                   | 52.9                      | 2.861                      | 30,084                          |                                                   |
|                 |           |       | 1000         | 35.4                      | 1.937                      | 31,594                          |                                                   | 52.6                      | 2.842                      | 29,701                          |                                                   |
| I-196-N (06-05) | A-2-4     | SP-SM | 100          | 33.5                      | 2.456                      | 22,276                          | 23,030                                            | 51.9                      | 3.650                      | 21,630                          | 21,985                                            |
|                 |           |       | 200          | 33.7                      | 2.428                      | 23,097                          |                                                   | 51.7                      | 3.641                      | 21,694                          |                                                   |
|                 |           |       | 500          | 34.2                      | 2.386                      | 23,190                          |                                                   | 51.5                      | 3.618                      | 22,017                          |                                                   |
|                 |           |       | 800          | 33.6                      | 2.395                      | 22,525                          |                                                   | 51.7                      | 3.675                      | 21,801                          |                                                   |
|                 |           |       | 1000         | 33.9                      | 2.371                      | 23,375                          |                                                   | 52.1                      | 3.637                      | 22,136                          |                                                   |
| M-020-W (07-02) | A-3       | SP    | 100          | 33.6                      | 2.112                      | 26,636                          | 31,489                                            | 51.2                      | 3.135                      | 25,897                          | 31,766                                            |
|                 |           |       | 200          | 33.8                      | 2.001                      | 29,046                          |                                                   | 51.6                      | 3.012                      | 27,403                          |                                                   |
|                 |           |       | 500          | 34.3                      | 1.969                      | 30,442                          |                                                   | 51.8                      | 2.891                      | 28,918                          |                                                   |
|                 |           |       | 800          | 34.0                      | 1.902                      | 31,795                          |                                                   | 52.5                      | 2.649                      | 33,296                          |                                                   |
|                 |           |       | 1000         | 34.1                      | 1.893                      | 32,230                          |                                                   | 52.7                      | 2.550                      | 33,084                          |                                                   |
| M-020-W (07-02) | A-3       | SP    | 100          | 32.8                      | 2.029                      | 27,192                          | 30,272                                            | 50.6                      | 3.326                      | 23,445                          | 24,896                                            |
|                 |           |       | 200          | 33.6                      | 2.032                      | 28,722                          |                                                   | 50.5                      | 3.436                      | 23,201                          |                                                   |
|                 |           |       | 500          | 33.8                      | 1.969                      | 30,147                          |                                                   | 51.7                      | 3.361                      | 25,035                          |                                                   |
|                 |           |       | 800          | 34.0                      | 1.971                      | 30,271                          |                                                   | 51.7                      | 3.315                      | 24,950                          |                                                   |
|                 |           |       | 1000         | 33.9                      | 1.965                      | 30,399                          |                                                   | 51.6                      | 3.408                      | 24,702                          |                                                   |

Table B.1 (cont'd)

| Sample number   | Soil Type |      | Cycle number | Cyclic stress (psi)       |                            |                                 |                                                   |                           |                            |                                 |                                                   |
|-----------------|-----------|------|--------------|---------------------------|----------------------------|---------------------------------|---------------------------------------------------|---------------------------|----------------------------|---------------------------------|---------------------------------------------------|
|                 |           |      |              | 10                        |                            |                                 |                                                   | 15                        |                            |                                 |                                                   |
|                 | AASHTO    | USCS |              | Average cyclic load (lbs) | Average deformation (mils) | Average resilient modulus (psi) | Average MR (psi) at load cycles 500, 800 and 1000 | Average cyclic load (lbs) | Average deformation (mils) | Average resilient modulus (psi) | Average MR (psi) at load cycles 500, 800 and 1000 |
| M-020-W (07-02) | A-3       | SP   | 100          | 33.7                      | 2.016                      | 28,992                          | 29,446                                            | 51.2                      | 3.080                      | 25,785                          | 28,593                                            |
|                 |           |      | 200          | 33.9                      | 2.064                      | 28,380                          |                                                   | 51.3                      | 3.000                      | 27,443                          |                                                   |
|                 |           |      | 500          | 33.9                      | 1.961                      | 29,237                          |                                                   | 51.4                      | 2.948                      | 28,001                          |                                                   |
|                 |           |      | 800          | 34.0                      | 2.042                      | 29,357                          |                                                   | 51.6                      | 2.893                      | 28,741                          |                                                   |
|                 |           |      | 1000         | 34.3                      | 1.984                      | 29,743                          |                                                   | 51.7                      | 2.938                      | 29,037                          |                                                   |
| M-020-W (07-02) | A-3       | SP   | 100          | 33.2                      | 1.883                      | 19,618                          | 19,693                                            | 51.0                      | 3.025                      | 16,754                          | 20,257                                            |
|                 |           |      | 200          | 33.1                      | 1.884                      | 19,462                          |                                                   | 51.0                      | 2.949                      | 18,301                          |                                                   |
|                 |           |      | 500          | 33.6                      | 1.901                      | 20,010                          |                                                   | 52.1                      | 2.779                      | 19,917                          |                                                   |
|                 |           |      | 800          | 33.8                      | 1.922                      | 19,736                          |                                                   | 52.0                      | 2.722                      | 20,529                          |                                                   |
|                 |           |      | 1000         | 33.6                      | 1.876                      | 19,334                          |                                                   | 51.7                      | 2.723                      | 20,325                          |                                                   |
| M-020-W (07-02) | A-3       | SP   | 100          | 31.7                      | 2.516                      | 20,521                          | 24,320                                            | 49.5                      | 4.178                      | 17,679                          | 24,552                                            |
|                 |           |      | 200          | 32.8                      | 2.321                      | 22,926                          |                                                   | 50.3                      | 3.959                      | 19,876                          |                                                   |
|                 |           |      | 500          | 33.1                      | 2.329                      | 24,360                          |                                                   | 51.4                      | 3.364                      | 23,953                          |                                                   |
|                 |           |      | 800          | 33.3                      | 2.344                      | 24,091                          |                                                   | 51.3                      | 3.310                      | 24,799                          |                                                   |
|                 |           |      | 1000         | 33.8                      | 2.284                      | 24,508                          |                                                   | 51.4                      | 3.307                      | 24,904                          |                                                   |
| M-020-E (07-03) | A-3       | SP   | 100          | 33.9                      | 1.963                      | 29,497                          | 32,696                                            | 52.6                      | 3.106                      | 27,496                          | 28,182                                            |
|                 |           |      | 200          | 34.0                      | 1.935                      | 30,737                          |                                                   | 52.2                      | 2.999                      | 27,797                          |                                                   |
|                 |           |      | 500          | 34.4                      | 1.881                      | 32,158                          |                                                   | 51.9                      | 2.992                      | 28,321                          |                                                   |
|                 |           |      | 800          | 34.3                      | 1.941                      | 31,958                          |                                                   | 52.3                      | 3.019                      | 27,995                          |                                                   |
|                 |           |      | 1000         | 34.2                      | 1.810                      | 33,972                          |                                                   | 51.9                      | 3.081                      | 28,230                          |                                                   |
| U-127-N (07-05) | A-6       | SC   | 100          | 42.5                      | 11.329                     | 3,466                           | 3,984                                             | 72.2                      | 15.047                     | 4,432                           | 5,481                                             |
|                 |           |      | 200          | 43.7                      | 10.944                     | 3,698                           |                                                   | 73.5                      | 7.386                      | 4,716                           |                                                   |
|                 |           |      | 500          | 44.3                      | 10.593                     | 3,897                           |                                                   | 75.1                      | 6.798                      | 5,246                           |                                                   |
|                 |           |      | 800          | 44.4                      | 10.260                     | 4,015                           |                                                   | 75.4                      | 6.602                      | 5,455                           |                                                   |
|                 |           |      | 1000         | 44.2                      | 10.170                     | 4,041                           |                                                   | 75.4                      | 12.596                     | 5,742                           |                                                   |
| U-127-N (07-05) | A-6       | SC   | 100          | 52.0                      | 2.068                      | 47,427                          | 54,737                                            | 82.9                      | 3.013                      | 49,924                          | 53,030                                            |
|                 |           |      | 200          | 51.7                      | 1.926                      | 50,103                          |                                                   | 82.3                      | 2.944                      | 50,430                          |                                                   |
|                 |           |      | 500          | 52.8                      | 1.878                      | 53,735                          |                                                   | 81.6                      | 2.806                      | 51,951                          |                                                   |
|                 |           |      | 800          | 51.5                      | 1.860                      | 54,842                          |                                                   | 82.5                      | 2.821                      | 53,516                          |                                                   |
|                 |           |      | 1000         | 52.3                      | 1.860                      | 55,634                          |                                                   | 82.0                      | 2.761                      | 53,623                          |                                                   |



Table B.1 (cont'd)

| Sample number   | Soil Type |      | Cycle number | Cyclic stress (psi)       |                            |                                 |                                                   |                           |                            |                                 |                                                   |
|-----------------|-----------|------|--------------|---------------------------|----------------------------|---------------------------------|---------------------------------------------------|---------------------------|----------------------------|---------------------------------|---------------------------------------------------|
|                 |           |      |              | 10                        |                            |                                 |                                                   | 15                        |                            |                                 |                                                   |
|                 | AASHTO    | USCS |              | Average cyclic load (lbs) | Average deformation (mils) | Average resilient modulus (psi) | Average MR (psi) at load cycles 500, 800 and 1000 | Average cyclic load (lbs) | Average deformation (mils) | Average resilient modulus (psi) | Average MR (psi) at load cycles 500, 800 and 1000 |
| U-127-N (07-05) | A-6       | SC   | 100          | 46.3                      | 6.202                      | 7,133                           | 7,323                                             | 75.8                      | 10.783                     | 6,642                           | 6,925                                             |
|                 |           |      | 200          | 46.7                      | 6.185                      | 7,244                           |                                                   | 76.7                      | 10.605                     | 6,765                           |                                                   |
|                 |           |      | 500          | 46.7                      | 6.248                      | 7,223                           |                                                   | 77.2                      | 10.557                     | 6,875                           |                                                   |
|                 |           |      | 800          | 47.2                      | 6.196                      | 7,353                           |                                                   | 77.5                      | 10.534                     | 6,936                           |                                                   |
|                 |           |      | 1000         | 47.9                      | 6.195                      | 7,395                           |                                                   | 77.9                      | 10.543                     | 6,965                           |                                                   |
| U-127-N (07-05) | A-6       | SC   | 100          | 44.7                      | 9.544                      | 4,319                           | 4,713                                             | 74.4                      | 14.108                     | 4,852                           | 5,358                                             |
|                 |           |      | 200          | 45.8                      | 9.458                      | 4,487                           |                                                   | 75.7                      | 13.880                     | 5,081                           |                                                   |
|                 |           |      | 500          | 46.2                      | 9.290                      | 4,651                           |                                                   | 75.8                      | 13.294                     | 5,339                           |                                                   |
|                 |           |      | 800          | 46.5                      | 9.278                      | 4,718                           |                                                   | 75.7                      | 13.131                     | 5,338                           |                                                   |
|                 |           |      | 1000         | 46.4                      | 9.113                      | 4,770                           |                                                   | 76.4                      | 13.119                     | 5,398                           |                                                   |
| U-127-N (07-05) | A-6       | SC   | 100          | 30.4                      | 2.658                      | 31,474                          | 36,054                                            | 47.9                      | 4.349                      | 28,993                          | 27,729                                            |
|                 |           |      | 200          | 30.9                      | 2.535                      | 33,999                          |                                                   | 48.7                      | 4.299                      | 30,151                          |                                                   |
|                 |           |      | 500          | 31.5                      | 2.333                      | 36,628                          |                                                   | 49.1                      | 4.290                      | 27,523                          |                                                   |
|                 |           |      | 800          | 31.6                      | 2.285                      | 36,290                          |                                                   | 49.0                      | 4.221                      | 27,851                          |                                                   |
|                 |           |      | 1000         | 32.5                      | 2.231                      | 35,243                          |                                                   | 50.2                      | 4.333                      | 27,814                          |                                                   |
| M-061-E (07-06) | A-2-4     | SM   | 100          | 28.0                      | 7.229                      | 10,631                          | 11,483                                            | 41.8                      | 12.878                     | 11,660                          | 12,907                                            |
|                 |           |      | 200          | 28.6                      | 7.191                      | 10,855                          |                                                   | 42.3                      | 12.581                     | 11,834                          |                                                   |
|                 |           |      | 500          | 29.3                      | 6.855                      | 11,362                          |                                                   | 43.2                      | 12.189                     | 13,155                          |                                                   |
|                 |           |      | 800          | 29.6                      | 6.630                      | 11,709                          |                                                   | 44.2                      | 11.636                     | 12,831                          |                                                   |
|                 |           |      | 1000         | 28.8                      | 6.826                      | 11,377                          |                                                   | 44.2                      | 11.476                     | 12,736                          |                                                   |
| M-061-E (08-02) | A-2-4     | SM   | 100          | 33.1                      | 1.937                      | 29,999                          | 32,231                                            | 51.2                      | 2.807                      | 30,104                          | 31,763                                            |
|                 |           |      | 200          | 32.9                      | 1.864                      | 30,417                          |                                                   | 51.7                      | 2.743                      | 30,517                          |                                                   |
|                 |           |      | 500          | 33.8                      | 1.897                      | 32,344                          |                                                   | 52.1                      | 2.713                      | 31,551                          |                                                   |
|                 |           |      | 800          | 33.8                      | 1.930                      | 32,106                          |                                                   | 51.9                      | 2.701                      | 31,719                          |                                                   |
|                 |           |      | 1000         | 34.0                      | 1.875                      | 32,242                          |                                                   | 52.3                      | 2.728                      | 32,020                          |                                                   |
| U-010-W (08-04) | A-6       | SC   | 100          | 41.4                      | 10.662                     | 3,592                           | 4,134                                             | 70.9                      | 14.499                     | 4,516                           | 5,268                                             |
|                 |           |      | 200          | 42.3                      | 10.310                     | 3,829                           |                                                   | 71.7                      | 13.972                     | 4,771                           |                                                   |
|                 |           |      | 500          | 42.9                      | 9.824                      | 4,076                           |                                                   | 72.8                      | 13.214                     | 5,099                           |                                                   |
|                 |           |      | 800          | 43.2                      | 9.691                      | 4,164                           |                                                   | 73.7                      | 12.850                     | 5,323                           |                                                   |
|                 |           |      | 1000         | 42.9                      | 9.608                      | 4,163                           |                                                   | 73.8                      | 12.675                     | 5,382                           |                                                   |

Table B.1 (cont'd)

| Sample number   | Soil Type |       | Cycle number | Cyclic stress (psi)       |                            |                                 |                                                   |                           |                            |                                 |                                                   |
|-----------------|-----------|-------|--------------|---------------------------|----------------------------|---------------------------------|---------------------------------------------------|---------------------------|----------------------------|---------------------------------|---------------------------------------------------|
|                 |           |       |              | 10                        |                            |                                 |                                                   | 15                        |                            |                                 |                                                   |
|                 | AASHTO    | USCS  |              | Average cyclic load (lbs) | Average deformation (mils) | Average resilient modulus (psi) | Average MR (psi) at load cycles 500, 800 and 1000 | Average cyclic load (lbs) | Average deformation (mils) | Average resilient modulus (psi) | Average MR (psi) at load cycles 500, 800 and 1000 |
| U-010-W (08-04) | A-6       | SC    | 100          | 43.2                      | 7.759                      | 5,212                           | 5,873                                             | 71.7                      | 13.897                     | 4,831                           | 5,106                                             |
|                 |           |       | 200          | 44.4                      | 7.585                      | 5,439                           |                                                   | 72.2                      | 13.671                     | 4,937                           |                                                   |
|                 |           |       | 500          | 45.6                      | 7.430                      | 5,791                           |                                                   | 73.0                      | 13.508                     | 5,049                           |                                                   |
|                 |           |       | 800          | 45.9                      | 7.266                      | 5,946                           |                                                   | 73.6                      | 13.342                     | 5,130                           |                                                   |
|                 |           |       | 1000         | 46.1                      | 7.252                      | 5,884                           |                                                   | 73.4                      | 13.283                     | 5,138                           |                                                   |
| I-075-N (08-06) | A-2-4     | SC-SM | 100          | 32.4                      | 3.493                      | 14,265                          | 15,798                                            | 51.1                      | 4.992                      | 15,346                          | 16,577                                            |
|                 |           |       | 200          | 32.9                      | 3.499                      | 14,932                          |                                                   | 50.9                      | 4.807                      | 15,758                          |                                                   |
|                 |           |       | 500          | 33.3                      | 3.406                      | 15,448                          |                                                   | 51.4                      | 4.785                      | 16,290                          |                                                   |
|                 |           |       | 800          | 33.3                      | 3.297                      | 15,986                          |                                                   | 51.2                      | 4.676                      | 16,606                          |                                                   |
|                 |           |       | 1000         | 33.1                      | 3.263                      | 15,960                          |                                                   | 51.3                      | 4.594                      | 16,836                          |                                                   |
| U-131-S (09-01) | A-3       | SP    | 100          | 33.8                      | 2.123                      | 26,881                          | 28,793                                            | 52.3                      | 3.220                      | 26,018                          | 27,732                                            |
|                 |           |       | 200          | 33.9                      | 2.126                      | 27,797                          |                                                   | 52.8                      | 3.183                      | 26,982                          |                                                   |
|                 |           |       | 500          | 34.5                      | 2.127                      | 29,155                          |                                                   | 52.8                      | 3.200                      | 27,204                          |                                                   |
|                 |           |       | 800          | 34.3                      | 2.052                      | 29,674                          |                                                   | 52.6                      | 3.078                      | 27,868                          |                                                   |
|                 |           |       | 1000         | 34.6                      | 2.152                      | 27,550                          |                                                   | 53.2                      | 3.081                      | 28,124                          |                                                   |
| I-096-W (09-02) | A-2-4     | SC-SM | 100          | 33.5                      | 2.694                      | 20,127                          | 22,163                                            | 52.0                      | 4.254                      | 18,607                          | 19,597                                            |
|                 |           |       | 200          | 33.8                      | 2.624                      | 21,049                          |                                                   | 51.6                      | 4.205                      | 18,942                          |                                                   |
|                 |           |       | 500          | 33.7                      | 2.566                      | 21,588                          |                                                   | 51.5                      | 4.164                      | 19,295                          |                                                   |
|                 |           |       | 800          | 34.0                      | 2.530                      | 22,509                          |                                                   | 52.0                      | 4.085                      | 19,756                          |                                                   |
|                 |           |       | 1000         | 33.8                      | 2.473                      | 22,392                          |                                                   | 51.2                      | 3.999                      | 19,740                          |                                                   |
| U-131-S (09-03) | A-3       | SP    | 100          | 33.9                      | 1.997                      | 28,736                          | 30,368                                            | 51.1                      | 3.381                      | 23,393                          | 28,022                                            |
|                 |           |       | 200          | 34.3                      | 2.019                      | 29,283                          |                                                   | 51.9                      | 3.341                      | 24,843                          |                                                   |
|                 |           |       | 500          | 34.9                      | 1.990                      | 30,848                          |                                                   | 52.1                      | 3.006                      | 27,525                          |                                                   |
|                 |           |       | 800          | 34.0                      | 1.948                      | 30,648                          |                                                   | 52.4                      | 3.010                      | 27,615                          |                                                   |
|                 |           |       | 1000         | 34.4                      | 1.983                      | 29,608                          |                                                   | 52.6                      | 2.953                      | 28,925                          |                                                   |
| U-131-S (09-05) | A-1-b     | SP    | 100          | 34.0                      | 2.036                      | 36,835                          | 38,498                                            | 52.5                      | 2.817                      | 33,838                          | 35,390                                            |
|                 |           |       | 200          | 33.9                      | 2.070                      | 37,497                          |                                                   | 52.0                      | 2.833                      | 34,449                          |                                                   |
|                 |           |       | 500          | 34.5                      | 1.978                      | 38,818                          |                                                   | 52.5                      | 2.776                      | 35,389                          |                                                   |
|                 |           |       | 800          | 34.9                      | 1.943                      | 38,902                          |                                                   | 52.5                      | 2.796                      | 35,440                          |                                                   |
|                 |           |       | 1000         | 34.8                      | 2.007                      | 37,773                          |                                                   | 52.5                      | 2.856                      | 35,340                          |                                                   |

Table B.1 (cont'd)

| Sample number   | Soil Type |       | Cycle number | Cyclic stress (psi)       |                            |                                 |                                                   |                           |                            |                                 |                                                   |
|-----------------|-----------|-------|--------------|---------------------------|----------------------------|---------------------------------|---------------------------------------------------|---------------------------|----------------------------|---------------------------------|---------------------------------------------------|
|                 |           |       |              | 10                        |                            |                                 |                                                   | 15                        |                            |                                 |                                                   |
|                 | AASHTO    | USCS  |              | Average cyclic load (lbs) | Average deformation (mils) | Average resilient modulus (psi) | Average MR (psi) at load cycles 500, 800 and 1000 | Average cyclic load (lbs) | Average deformation (mils) | Average resilient modulus (psi) | Average MR (psi) at load cycles 500, 800 and 1000 |
| M-044-E (09-07) | A-2-4     | SM    | 100          | 33.4                      | 2.943                      | 17,969                          | 18,434                                            | 51.4                      | 4.275                      | 18,433                          | 19,654                                            |
|                 |           |       | 200          | 33.5                      | 2.928                      | 18,261                          |                                                   | 52.0                      | 4.175                      | 19,068                          |                                                   |
|                 |           |       | 500          | 33.9                      | 2.948                      | 18,534                          |                                                   | 51.6                      | 4.086                      | 19,511                          |                                                   |
|                 |           |       | 800          | 33.7                      | 2.841                      | 18,744                          |                                                   | 51.6                      | 4.043                      | 19,663                          |                                                   |
|                 |           |       | 1000         | 34.0                      | 3.046                      | 18,023                          |                                                   | 51.9                      | 4.041                      | 19,788                          |                                                   |
| M-024-S (09-09) | A-2-4     | SM    | 100          | 33.1                      | 3.415                      | 15,148                          | 15,156                                            | 50.4                      | 5.279                      | 14,639                          | 15,854                                            |
|                 |           |       | 200          | 33.1                      | 3.421                      | 15,097                          |                                                   | 50.5                      | 5.143                      | 15,004                          |                                                   |
|                 |           |       | 500          | 33.6                      | 3.458                      | 15,204                          |                                                   | 50.6                      | 4.889                      | 15,786                          |                                                   |
|                 |           |       | 800          | 32.9                      | 3.427                      | 14,945                          |                                                   | 50.8                      | 4.853                      | 15,880                          |                                                   |
|                 |           |       | 1000         | 33.3                      | 3.378                      | 15,318                          |                                                   | 51.0                      | 4.891                      | 15,897                          |                                                   |
| I-069-E (09-10) | A-3       | SP    | 100          | 34.0                      | 1.985                      | 29,263                          | 28,663                                            | 52.2                      | 3.321                      | 25,428                          | 26,095                                            |
|                 |           |       | 200          | 34.1                      | 2.074                      | 29,172                          |                                                   | 52.2                      | 3.248                      | 25,709                          |                                                   |
|                 |           |       | 500          | 34.4                      | 2.071                      | 28,746                          |                                                   | 52.3                      | 3.163                      | 26,255                          |                                                   |
|                 |           |       | 800          | 34.3                      | 2.079                      | 29,232                          |                                                   | 51.9                      | 3.231                      | 25,802                          |                                                   |
|                 |           |       | 1000         | 34.8                      | 2.160                      | 28,012                          |                                                   | 52.4                      | 3.192                      | 26,227                          |                                                   |
| I-069-N (10-01) | A-3       | SP-SM | 100          | 33.5                      | 3.483                      | 14,917                          | 15,873                                            | 51.2                      | 4.732                      | 16,473                          | 17,394                                            |
|                 |           |       | 200          | 33.5                      | 3.542                      | 14,864                          |                                                   | 51.1                      | 4.694                      | 16,512                          |                                                   |
|                 |           |       | 500          | 33.1                      | 3.344                      | 15,551                          |                                                   | 51.3                      | 4.485                      | 17,528                          |                                                   |
|                 |           |       | 800          | 33.8                      | 3.457                      | 15,312                          |                                                   | 50.8                      | 4.533                      | 17,144                          |                                                   |
|                 |           |       | 1000         | 34.0                      | 3.162                      | 16,756                          |                                                   | 51.7                      | 4.526                      | 17,509                          |                                                   |
| I-096-W (10-03) | A-2-6     | SC    | 100          | 32.9                      | 2.180                      | 41,549                          | 43,824                                            | 50.1                      | 3.266                      | 40,469                          | 37,712                                            |
|                 |           |       | 200          | 33.4                      | 2.210                      | 42,092                          |                                                   | 50.5                      | 3.275                      | 41,776                          |                                                   |
|                 |           |       | 500          | 33.8                      | 2.175                      | 43,219                          |                                                   | 51.5                      | 3.167                      | 42,767                          |                                                   |
|                 |           |       | 800          | 34.1                      | 2.196                      | 44,499                          |                                                   | 49.2                      | 3.779                      | 34,806                          |                                                   |
|                 |           |       | 1000         | 34.1                      | 2.203                      | 43,754                          |                                                   | 48.7                      | 2.686                      | 35,563                          |                                                   |
| I-069-N (10-04) | A-2-4     | SM    | 100          | 33.4                      | 2.846                      | 18,890                          | 19,190                                            | 51.4                      | 4.400                      | 18,049                          | 18,963                                            |
|                 |           |       | 200          | 33.5                      | 2.771                      | 19,221                          |                                                   | 51.8                      | 4.330                      | 18,293                          |                                                   |
|                 |           |       | 500          | 33.5                      | 2.839                      | 19,530                          |                                                   | 51.0                      | 4.232                      | 18,653                          |                                                   |
|                 |           |       | 800          | 33.4                      | 2.862                      | 19,049                          |                                                   | 51.5                      | 4.107                      | 18,952                          |                                                   |
|                 |           |       | 1000         | 33.9                      | 2.802                      | 18,990                          |                                                   | 51.6                      | 4.076                      | 19,284                          |                                                   |



Table B.1 (cont'd)

| Sample number   | Soil Type |       | Cycle number | Cyclic stress (psi)       |                            |                                 |                                                   |                           |                            |                                 |                                                   |
|-----------------|-----------|-------|--------------|---------------------------|----------------------------|---------------------------------|---------------------------------------------------|---------------------------|----------------------------|---------------------------------|---------------------------------------------------|
|                 |           |       |              | 10                        |                            |                                 |                                                   | 15                        |                            |                                 |                                                   |
|                 | AASHTO    | USCS  |              | Average cyclic load (lbs) | Average deformation (mils) | Average resilient modulus (psi) | Average MR (psi) at load cycles 500, 800 and 1000 | Average cyclic load (lbs) | Average deformation (mils) | Average resilient modulus (psi) | Average MR (psi) at load cycles 500, 800 and 1000 |
| I-069-N (10-05) | A-2-4     | SM    | 100          | 25.4                      | 8.607                      | 4,273                           | 5,295                                             | 37.6                      | 15.895                     | 3,469                           | 5,646                                             |
|                 |           |       | 200          | 25.9                      | 8.326                      | 4,542                           |                                                   | 41.3                      | 12.494                     | 4,766                           |                                                   |
|                 |           |       | 500          | 27.0                      | 7.715                      | 5,123                           |                                                   | 43.1                      | 11.611                     | 5,377                           |                                                   |
|                 |           |       | 800          | 27.2                      | 7.630                      | 5,241                           |                                                   | 43.7                      | 11.104                     | 5,712                           |                                                   |
|                 |           |       | 1000         | 27.6                      | 7.381                      | 5,521                           |                                                   | 43.8                      | 11.027                     | 5,850                           |                                                   |
| I-096-W (10-09) | A-2-4     | SM    | 100          | 30.1                      | 5.580                      | 8,027                           | 9,518                                             | 47.9                      | 7.602                      | 9,168                           | 11,394                                            |
|                 |           |       | 200          | 30.9                      | 5.176                      | 8,832                           |                                                   | 48.1                      | 7.430                      | 9,504                           |                                                   |
|                 |           |       | 500          | 31.2                      | 5.002                      | 9,361                           |                                                   | 49.5                      | 6.721                      | 10,908                          |                                                   |
|                 |           |       | 800          | 31.0                      | 4.917                      | 9,419                           |                                                   | 49.5                      | 6.363                      | 11,495                          |                                                   |
|                 |           |       | 1000         | 31.6                      | 4.875                      | 9,775                           |                                                   | 49.8                      | 6.307                      | 11,778                          |                                                   |
| I-069-N (11-01) | A-3       | SP-SM | 100          | 32.9                      | 1.119                      | 30,534                          | 30,733                                            | 51.7                      | 1.595                      | 29,788                          | 28,147                                            |
|                 |           |       | 200          | 33.8                      | 1.119                      | 32,960                          |                                                   | 52.0                      | 1.567                      | 30,484                          |                                                   |
|                 |           |       | 500          | 34.0                      | 1.063                      | 30,406                          |                                                   | 52.0                      | 2.994                      | 28,203                          |                                                   |
|                 |           |       | 800          | 34.0                      | 1.119                      | 30,967                          |                                                   | 52.2                      | 2.974                      | 28,154                          |                                                   |
|                 |           |       | 1000         | 34.8                      | 1.119                      | 30,827                          |                                                   | 51.9                      | 2.995                      | 28,083                          |                                                   |
| I-094-W (11-02) | A-3       | SP    | 100          | 33.6                      | 1.694                      | 36,073                          | 44,521                                            | 51.2                      | 3.205                      | 25,752                          | 27,372                                            |
|                 |           |       | 200          | 33.3                      | 1.627                      | 37,965                          |                                                   | 52.2                      | 3.144                      | 26,314                          |                                                   |
|                 |           |       | 500          | 34.1                      | 1.487                      | 45,141                          |                                                   | 52.8                      | 3.102                      | 27,442                          |                                                   |
|                 |           |       | 800          | 32.6                      | 1.432                      | 42,908                          |                                                   | 51.9                      | 3.136                      | 26,857                          |                                                   |
|                 |           |       | 1000         | 34.1                      | 1.453                      | 45,513                          |                                                   | 52.6                      | 3.020                      | 27,817                          |                                                   |
| M-060-W (11-03) | A-2-4     | SC-SM | 100          | 31.9                      | 2.614                      | 19,615                          | 19,812                                            | 50.2                      | 4.354                      | 17,216                          | 16,639                                            |
|                 |           |       | 200          | 31.3                      | 2.561                      | 19,255                          |                                                   | 50.7                      | 4.426                      | 17,262                          |                                                   |
|                 |           |       | 500          | 32.0                      | 2.553                      | 19,808                          |                                                   | 50.8                      | 4.481                      | 16,817                          |                                                   |
|                 |           |       | 800          | 32.4                      | 2.561                      | 19,861                          |                                                   | 50.7                      | 4.560                      | 16,601                          |                                                   |
|                 |           |       | 1000         | 32.2                      | 2.563                      | 19,768                          |                                                   | 50.9                      | 4.669                      | 16,498                          |                                                   |
| I-069-S (11-05) | A-4       | SC-SM | 100          | 33.7                      | 2.252                      | 23,451                          | 27,303                                            | 52.3                      | 3.358                      | 24,923                          | 25,645                                            |
|                 |           |       | 200          | 33.8                      | 2.220                      | 24,393                          |                                                   | 52.6                      | 3.317                      | 25,291                          |                                                   |
|                 |           |       | 500          | 34.0                      | 2.095                      | 25,903                          |                                                   | 52.5                      | 3.274                      | 25,489                          |                                                   |
|                 |           |       | 800          | 34.2                      | 2.014                      | 26,908                          |                                                   | 51.6                      | 3.267                      | 25,632                          |                                                   |
|                 |           |       | 1000         | 34.3                      | 1.931                      | 29,098                          |                                                   | 52.2                      | 3.245                      | 25,814                          |                                                   |

Table B.1 (cont'd)

| Sample number   | Soil Type |       | Cycle number | Cyclic stress (psi)       |                            |                                 |                                                   |                           |                            |                                 |                                                   |
|-----------------|-----------|-------|--------------|---------------------------|----------------------------|---------------------------------|---------------------------------------------------|---------------------------|----------------------------|---------------------------------|---------------------------------------------------|
|                 |           |       |              | 10                        |                            |                                 | 15                                                |                           |                            |                                 |                                                   |
|                 | AASHTO    | USCS  |              | Average cyclic load (lbs) | Average deformation (mils) | Average resilient modulus (psi) | Average MR (psi) at load cycles 500, 800 and 1000 | Average cyclic load (lbs) | Average deformation (mils) | Average resilient modulus (psi) | Average MR (psi) at load cycles 500, 800 and 1000 |
| I-094-W (12-01) | A-2-4     | SC-SM | 100          | 33.3                      | 1.963                      | 28,024                          | 27,636                                            | 51.3                      | 3.519                      | 22,990                          | 23,872                                            |
|                 |           |       | 200          | 32.5                      | 2.028                      | 27,129                          |                                                   | 52.0                      | 3.594                      | 23,024                          |                                                   |
|                 |           |       | 500          | 34.1                      | 2.041                      | 28,985                          |                                                   | 51.8                      | 3.438                      | 23,554                          |                                                   |
|                 |           |       | 800          | 33.6                      | 2.129                      | 26,615                          |                                                   | 52.0                      | 3.414                      | 24,001                          |                                                   |
|                 |           |       | 1000         | 33.9                      | 2.113                      | 27,308                          |                                                   | 52.4                      | 3.534                      | 24,060                          |                                                   |
| I-094-W (12-03) | A-3       | SP-SM | 100          | 33.6                      | 2.783                      | 19,527                          | 18,139                                            | 50.8                      | 4.851                      | 15,566                          | 15,977                                            |
|                 |           |       | 200          | 33.6                      | 2.766                      | 19,827                          |                                                   | 50.9                      | 4.881                      | 15,796                          |                                                   |
|                 |           |       | 500          | 33.4                      | 2.814                      | 18,886                          |                                                   | 50.4                      | 4.789                      | 16,090                          |                                                   |
|                 |           |       | 800          | 33.9                      | 3.021                      | 17,820                          |                                                   | 50.8                      | 4.831                      | 15,893                          |                                                   |
|                 |           |       | 1000         | 34.1                      | 3.066                      | 17,711                          |                                                   | 50.8                      | 4.798                      | 15,947                          |                                                   |
| U-012-E (12-04) | A-2-4     | SP-SM | 100          | 33.3                      | 2.862                      | 18,848                          | 19,234                                            | 50.8                      | 4.340                      | 18,416                          | 18,343                                            |
|                 |           |       | 200          | 33.3                      | 2.930                      | 19,047                          |                                                   | 51.3                      | 4.323                      | 18,683                          |                                                   |
|                 |           |       | 500          | 33.6                      | 2.781                      | 19,237                          |                                                   | 51.2                      | 4.264                      | 18,191                          |                                                   |
|                 |           |       | 800          | 34.1                      | 2.881                      | 19,210                          |                                                   | 51.4                      | 4.312                      | 18,324                          |                                                   |
|                 |           |       | 1000         | 34.1                      | 2.766                      | 19,255                          |                                                   | 51.3                      | 4.266                      | 18,515                          |                                                   |
| I-094-W (12-06) | A-2-4     | SM    | 100          | 33.9                      | 2.675                      | 19,996                          | 19,425                                            | 51.4                      | 4.042                      | 19,797                          | 21,382                                            |
|                 |           |       | 200          | 33.8                      | 2.698                      | 20,013                          |                                                   | 51.4                      | 3.956                      | 20,110                          |                                                   |
|                 |           |       | 500          | 33.7                      | 2.821                      | 19,357                          |                                                   | 52.6                      | 3.873                      | 21,249                          |                                                   |
|                 |           |       | 800          | 33.8                      | 2.796                      | 19,802                          |                                                   | 51.7                      | 3.733                      | 21,552                          |                                                   |
|                 |           |       | 1000         | 34.0                      | 2.792                      | 19,115                          |                                                   | 51.5                      | 3.774                      | 21,346                          |                                                   |
| M-024-S (13-01) | A-4       | SM    | 100          | 34.4                      | 3.172                      | 17,093                          | 17,950                                            | 51.9                      | 5.000                      | 15,746                          | 16,175                                            |
|                 |           |       | 200          | 34.0                      | 3.101                      | 17,359                          |                                                   | 50.0                      | 4.846                      | 15,814                          |                                                   |
|                 |           |       | 500          | 34.8                      | 3.149                      | 17,853                          |                                                   | 51.5                      | 4.878                      | 16,213                          |                                                   |
|                 |           |       | 800          | 34.6                      | 3.049                      | 17,891                          |                                                   | 51.6                      | 4.844                      | 16,042                          |                                                   |
|                 |           |       | 1000         | 35.1                      | 3.052                      | 18,106                          |                                                   | 51.8                      | 4.844                      | 16,271                          |                                                   |
| M-059-W (13-02) | A-3       | SP    | 100          | 33.6                      | 2.042                      | 28,216                          | 24,863                                            | 51.7                      | 3.362                      | 23,959                          | 23,810                                            |
|                 |           |       | 200          | 33.5                      | 2.112                      | 27,648                          |                                                   | 51.9                      | 3.351                      | 24,234                          |                                                   |
|                 |           |       | 500          | 33.9                      | 2.186                      | 26,464                          |                                                   | 52.1                      | 3.478                      | 23,699                          |                                                   |
|                 |           |       | 800          | 33.9                      | 2.368                      | 24,623                          |                                                   | 51.7                      | 3.453                      | 23,882                          |                                                   |
|                 |           |       | 1000         | 33.8                      | 2.439                      | 23,502                          |                                                   | 51.9                      | 3.436                      | 23,849                          |                                                   |



Table B.1 (cont'd)

| Sample number   | Soil Type |       | Cycle number | Cyclic stress (psi)       |                            |                                 |                                                   |                           |                            |                                 |                                                   |
|-----------------|-----------|-------|--------------|---------------------------|----------------------------|---------------------------------|---------------------------------------------------|---------------------------|----------------------------|---------------------------------|---------------------------------------------------|
|                 |           |       |              | 10                        |                            |                                 |                                                   | 15                        |                            |                                 |                                                   |
|                 | AASHTO    | USCS  |              | Average cyclic load (lbs) | Average deformation (mils) | Average resilient modulus (psi) | Average MR (psi) at load cycles 500, 800 and 1000 | Average cyclic load (lbs) | Average deformation (mils) | Average resilient modulus (psi) | Average MR (psi) at load cycles 500, 800 and 1000 |
| I-094-W (13-04) | A-3       | SP    | 100          | 32.8                      | 2.693                      | 20,399                          | 21,470                                            | 51.2                      | 4.441                      | 17,533                          | 18,859                                            |
|                 |           |       | 200          | 32.5                      | 2.615                      | 20,565                          |                                                   | 50.7                      | 4.353                      | 17,856                          |                                                   |
|                 |           |       | 500          | 33.2                      | 2.592                      | 21,384                          |                                                   | 50.8                      | 4.245                      | 18,355                          |                                                   |
|                 |           |       | 800          | 33.5                      | 2.589                      | 21,598                          |                                                   | 50.8                      | 4.133                      | 18,836                          |                                                   |
|                 |           |       | 1000         | 33.4                      | 2.648                      | 21,427                          |                                                   | 51.2                      | 4.040                      | 19,387                          |                                                   |
| U-023-N (13-07) | A-3       | SP-SM | 100          | 34.0                      | 2.515                      | 22,197                          | 22,629                                            | 51.6                      | 3.907                      | 20,649                          | 20,593                                            |
|                 |           |       | 200          | 33.8                      | 2.443                      | 23,009                          |                                                   | 51.4                      | 3.846                      | 20,641                          |                                                   |
|                 |           |       | 500          | 34.0                      | 2.573                      | 22,214                          |                                                   | 51.2                      | 3.961                      | 20,201                          |                                                   |
|                 |           |       | 800          | 33.9                      | 2.428                      | 22,768                          |                                                   | 52.4                      | 3.910                      | 20,900                          |                                                   |
|                 |           |       | 1000         | 34.7                      | 2.477                      | 22,904                          |                                                   | 52.2                      | 3.952                      | 20,678                          |                                                   |
| M-010-E (13-08) | A-6       | CL    | 100          | 29.7                      | 4.124                      | 16,710                          | 17,012                                            | 45.5                      | 6.531                      | 16,006                          | 16,345                                            |
|                 |           |       | 200          | 30.1                      | 4.182                      | 16,898                          |                                                   | 46.1                      | 6.637                      | 15,991                          |                                                   |
|                 |           |       | 500          | 30.2                      | 4.256                      | 16,855                          |                                                   | 46.3                      | 6.562                      | 16,218                          |                                                   |
|                 |           |       | 800          | 30.7                      | 4.226                      | 16,995                          |                                                   | 46.5                      | 6.433                      | 16,417                          |                                                   |
|                 |           |       | 1000         | 30.5                      | 4.202                      | 17,186                          |                                                   | 46.6                      | 6.492                      | 16,399                          |                                                   |
| M-010-E (13-08) | A-6       | CL    | 100          | 48.6                      | 3.375                      | 14,374                          | 15,561                                            | 77.7                      | 7.441                      | 9,934                           | 9,553                                             |
|                 |           |       | 200          | 49.6                      | 3.334                      | 15,053                          |                                                   | 78.1                      | 7.453                      | 9,867                           |                                                   |
|                 |           |       | 500          | 49.6                      | 3.271                      | 15,423                          |                                                   | 78.2                      | 7.743                      | 9,627                           |                                                   |
|                 |           |       | 800          | 49.8                      | 3.258                      | 15,631                          |                                                   | 78.2                      | 7.779                      | 9,528                           |                                                   |
|                 |           |       | 1000         | 49.8                      | 3.257                      | 15,629                          |                                                   | 78.3                      | 7.849                      | 9,504                           |                                                   |
| M-010-E (13-08) | A-6       | CL    | 100          | 51.5                      | 1.331                      | 31,968                          | 44,641                                            | 83.3                      | 1.796                      | 36,929                          | 41,989                                            |
|                 |           |       | 200          | 51.8                      | 1.291                      | 36,534                          |                                                   | 82.8                      | 1.731                      | 38,488                          |                                                   |
|                 |           |       | 500          | 52.7                      | 1.218                      | 43,564                          |                                                   | 82.5                      | 1.808                      | 40,155                          |                                                   |
|                 |           |       | 800          | 52.3                      | 1.211                      | 45,089                          |                                                   | 82.2                      | 1.629                      | 42,399                          |                                                   |
|                 |           |       | 1000         | 51.8                      | 1.152                      | 45,271                          |                                                   | 82.4                      | 1.793                      | 43,414                          |                                                   |
| M-010-E (13-08) | A-6       | CL    | 100          | 39.6                      | 7.658                      | 8,407                           | 9,713                                             | 46.6                      | 8.078                      | 8,440                           | 8,280                                             |
|                 |           |       | 200          | 41.3                      | 7.157                      | 9,399                           |                                                   | 47.1                      | 7.723                      | 8,966                           |                                                   |
|                 |           |       | 500          | 42.2                      | 6.971                      | 9,004                           |                                                   | 48.6                      | 7.368                      | 8,822                           |                                                   |
|                 |           |       | 800          | 43.5                      | 6.473                      | 9,818                           |                                                   | 48.8                      | 7.052                      | 8,108                           |                                                   |
|                 |           |       | 1000         | 44.0                      | 6.376                      | 10,317                          |                                                   | 48.5                      | 7.166                      | 7,910                           |                                                   |

Table B.1 (cont'd)

| Sample number   | Soil Type |      | Cycle number | Cyclic stress (psi)       |                            |                                 |                                                   |                           |                            |                                 |                                                   |
|-----------------|-----------|------|--------------|---------------------------|----------------------------|---------------------------------|---------------------------------------------------|---------------------------|----------------------------|---------------------------------|---------------------------------------------------|
|                 |           |      |              | 10                        |                            |                                 |                                                   | 15                        |                            |                                 |                                                   |
|                 | AASHTO    | USCS |              | Average cyclic load (lbs) | Average deformation (mils) | Average resilient modulus (psi) | Average MR (psi) at load cycles 500, 800 and 1000 | Average cyclic load (lbs) | Average deformation (mils) | Average resilient modulus (psi) | Average MR (psi) at load cycles 500, 800 and 1000 |
| I-075-S (14-01) | A-7-6     | SC   | 100          | 30.3                      | 2.283                      | 11,369                          | 18,221                                            | 48.9                      | 3.899                      | 14,813                          | 17,842                                            |
|                 |           |      | 200          | 31.0                      | 2.259                      | 13,560                          |                                                   | 48.7                      | 3.804                      | 15,893                          |                                                   |
|                 |           |      | 500          | 31.3                      | 2.074                      | 17,389                          |                                                   | 48.9                      | 3.721                      | 16,938                          |                                                   |
|                 |           |      | 800          | 31.7                      | 1.971                      | 18,449                          |                                                   | 49.6                      | 3.586                      | 18,253                          |                                                   |
|                 |           |      | 1000         | 32.0                      | 2.067                      | 18,825                          |                                                   | 49.6                      | 3.573                      | 18,336                          |                                                   |
| I-075-S (14-01) | A-7-6     | SC   | 100          | 51.3                      | 2.172                      | 32,901                          | 32,510                                            | 82.3                      | 2.390                      | 32,808                          | 29,860                                            |
|                 |           |      | 200          | 51.2                      | 1.994                      | 36,098                          |                                                   | 82.8                      | 2.299                      | 31,287                          |                                                   |
|                 |           |      | 500          | 52.3                      | 1.815                      | 31,799                          |                                                   | 82.7                      | 2.045                      | 29,226                          |                                                   |
|                 |           |      | 800          | 52.3                      | 1.481                      | 32,377                          |                                                   | 82.4                      | 1.858                      | 30,295                          |                                                   |
|                 |           |      | 1000         | 51.7                      | 1.417                      | 33,354                          |                                                   | 82.3                      | 1.668                      | 30,060                          |                                                   |
| I-075-S (14-01) | A-7-6     | SC   | 100          | 35.0                      | 10.936                     | 5,114                           | 7,187                                             | 61.1                      | 14.155                     | 6,907                           | 8,386                                             |
|                 |           |      | 200          | 35.9                      | 9.896                      | 5,982                           |                                                   | 61.6                      | 13.624                     | 7,285                           |                                                   |
|                 |           |      | 500          | 36.6                      | 9.349                      | 7,441                           |                                                   | 62.5                      | 12.617                     | 7,928                           |                                                   |
|                 |           |      | 800          | 36.7                      | 8.808                      | 7,284                           |                                                   | 63.5                      | 12.002                     | 8,545                           |                                                   |
|                 |           |      | 1000         | 37.3                      | 8.616                      | 6,835                           |                                                   | 64.1                      | 11.896                     | 8,685                           |                                                   |
| U-024-S (14-04) | A-3       | SP   | 100          | 32.7                      | 2.313                      | 21,994                          | 22,765                                            | 51.7                      | 3.526                      | 19,968                          | 21,913                                            |
|                 |           |      | 200          | 33.0                      | 2.337                      | 22,227                          |                                                   | 52.0                      | 3.540                      | 20,296                          |                                                   |
|                 |           |      | 500          | 33.5                      | 2.305                      | 22,633                          |                                                   | 52.3                      | 3.336                      | 21,874                          |                                                   |
|                 |           |      | 800          | 33.6                      | 2.300                      | 22,813                          |                                                   | 52.1                      | 3.396                      | 21,707                          |                                                   |
|                 |           |      | 1000         | 33.6                      | 2.297                      | 22,849                          |                                                   | 52.4                      | 3.329                      | 22,159                          |                                                   |
| M-153-E (14-06) | A-7-6     | SC   | 100          | 42.5                      | 10.621                     | 3,715                           | 3,732                                             | 65.6                      | 19.895                     | 3,023                           | 3,015                                             |
|                 |           |      | 200          | 42.7                      | 10.593                     | 3,736                           |                                                   | 65.4                      | 19.906                     | 3,021                           |                                                   |
|                 |           |      | 500          | 42.8                      | 10.681                     | 3,717                           |                                                   | 66.4                      | 20.023                     | 3,036                           |                                                   |
|                 |           |      | 800          | 42.9                      | 10.628                     | 3,745                           |                                                   | 66.4                      | 20.120                     | 3,014                           |                                                   |
|                 |           |      | 1000         | 43.1                      | 10.729                     | 3,733                           |                                                   | 66.0                      | 20.123                     | 2,995                           |                                                   |
| M-153-E (14-06) | A-7-6     | SC   | 100          | 29.2                      | 13.397                     | 3,483                           | 4,430                                             | 65.6                      | 19.995                     | 4,023                           | 3,915                                             |
|                 |           |      | 200          | 30.3                      | 12.818                     | 3,798                           |                                                   | 65.4                      | 19.996                     | 3,821                           |                                                   |
|                 |           |      | 500          | 32.1                      | 12.062                     | 4,285                           |                                                   | 66.4                      | 20.017                     | 3,936                           |                                                   |
|                 |           |      | 800          | 32.8                      | 11.875                     | 4,471                           |                                                   | 66.4                      | 21.120                     | 3,814                           |                                                   |
|                 |           |      | 1000         | 33.0                      | 11.708                     | 4,535                           |                                                   | 66.0                      | 21.123                     | 3,995                           |                                                   |

Table B.1 (cont'd)

| Sample number   | Soil Type |      | Cycle number | Cyclic stress (psi)       |                            |                                 |                                                   |                           |                            |                                 |                                                   |
|-----------------|-----------|------|--------------|---------------------------|----------------------------|---------------------------------|---------------------------------------------------|---------------------------|----------------------------|---------------------------------|---------------------------------------------------|
|                 |           |      |              | 10                        |                            |                                 |                                                   | 15                        |                            |                                 |                                                   |
|                 | AASHTO    | USCS |              | Average cyclic load (lbs) | Average deformation (mils) | Average resilient modulus (psi) | Average MR (psi) at load cycles 500, 800 and 1000 | Average cyclic load (lbs) | Average deformation (mils) | Average resilient modulus (psi) | Average MR (psi) at load cycles 500, 800 and 1000 |
| M-153-E (14-06) | A-7-6     | SC   | 100          | 33.8                      | 2.378                      | 38,348                          | 40,902                                            | 51.2                      | 3.050                      | 42,427                          | 44,483                                            |
|                 |           |      | 200          | 34.4                      | 2.254                      | 39,970                          |                                                   | 51.5                      | 2.964                      | 42,728                          |                                                   |
|                 |           |      | 500          | 34.5                      | 2.223                      | 40,365                          |                                                   | 51.4                      | 3.004                      | 43,684                          |                                                   |
|                 |           |      | 800          | 34.0                      | 2.119                      | 41,453                          |                                                   | 51.5                      | 2.965                      | 44,394                          |                                                   |
|                 |           |      | 1000         | 33.7                      | 2.120                      | 40,889                          |                                                   | 52.2                      | 2.876                      | 45,372                          |                                                   |
| M-053-S (14-07) | A-3       | SP   | 100          | 33.6                      | 2.237                      | 25,772                          | 25,738                                            | 51.5                      | 3.727                      | 21,646                          | 22,296                                            |
|                 |           |      | 200          | 33.6                      | 2.150                      | 25,870                          |                                                   | 51.7                      | 3.731                      | 21,643                          |                                                   |
|                 |           |      | 500          | 33.9                      | 2.249                      | 26,465                          |                                                   | 51.9                      | 3.688                      | 22,217                          |                                                   |
|                 |           |      | 800          | 34.0                      | 2.258                      | 25,493                          |                                                   | 52.0                      | 3.646                      | 22,403                          |                                                   |
|                 |           |      | 1000         | 33.7                      | 2.315                      | 25,255                          |                                                   | 51.8                      | 3.622                      | 22,268                          |                                                   |
| I-094-W (14-09) | A-7-6     | CL   | 100          | 49.1                      | 5.308                      | 8,870                           | 9,955                                             | 77.2                      | 9.347                      | 7,782                           | 8,080                                             |
|                 |           |      | 200          | 49.1                      | 5.217                      | 9,211                           |                                                   | 77.2                      | 9.253                      | 7,846                           |                                                   |
|                 |           |      | 500          | 49.2                      | 4.966                      | 9,690                           |                                                   | 77.1                      | 9.107                      | 7,995                           |                                                   |
|                 |           |      | 800          | 48.8                      | 4.777                      | 9,943                           |                                                   | 77.8                      | 9.010                      | 8,089                           |                                                   |
|                 |           |      | 1000         | 49.2                      | 4.675                      | 10,234                          |                                                   | 77.8                      | 8.918                      | 8,156                           |                                                   |
| I-094-W (14-09) | A-7-6     | CL   | 100          | 51.2                      | 2.114                      | 45,953                          | 73,344                                            | 81.9                      | 2.609                      | 57,985                          | 70,094                                            |
|                 |           |      | 200          | 51.1                      | 1.853                      | 52,917                          |                                                   | 82.8                      | 2.466                      | 61,580                          |                                                   |
|                 |           |      | 500          | 52.2                      | 1.602                      | 67,009                          |                                                   | 82.5                      | 2.327                      | 67,663                          |                                                   |
|                 |           |      | 800          | 52.7                      | 1.426                      | 75,719                          |                                                   | 82.2                      | 2.190                      | 70,504                          |                                                   |
|                 |           |      | 1000         | 51.2                      | 1.383                      | 77,304                          |                                                   | 81.8                      | 2.205                      | 72,116                          |                                                   |
| I-094-W (14-09) | A-7-6     | CL   | 100          | 33.0                      | 1.604                      | 53,229                          | 60,217                                            | 50.7                      | 2.211                      | 57,722                          | 60,303                                            |
|                 |           |      | 200          | 32.7                      | 1.585                      | 55,517                          |                                                   | 51.7                      | 2.228                      | 59,950                          |                                                   |
|                 |           |      | 500          | 33.8                      | 1.530                      | 60,326                          |                                                   | 51.7                      | 2.152                      | 60,448                          |                                                   |
|                 |           |      | 800          | 34.1                      | 1.462                      | 60,280                          |                                                   | 51.8                      | 2.104                      | 60,142                          |                                                   |
|                 |           |      | 1000         | 34.2                      | 1.459                      | 60,046                          |                                                   | 52.3                      | 2.044                      | 60,318                          |                                                   |
| M-053-S (15-02) | A-2-4     | SM   | 100          | 33.3                      | 2.923                      | 18,400                          | 18,342                                            | 51.1                      | 4.424                      | 18,022                          | 18,060                                            |
|                 |           |      | 200          | 33.2                      | 2.914                      | 18,486                          |                                                   | 51.0                      | 4.470                      | 18,018                          |                                                   |
|                 |           |      | 500          | 33.4                      | 2.921                      | 18,171                          |                                                   | 51.4                      | 4.471                      | 17,918                          |                                                   |
|                 |           |      | 800          | 33.4                      | 2.963                      | 18,372                          |                                                   | 51.3                      | 4.416                      | 18,113                          |                                                   |
|                 |           |      | 1000         | 33.4                      | 2.894                      | 18,483                          |                                                   | 51.0                      | 4.372                      | 18,149                          |                                                   |

Table B.1 (cont'd)

| Sample number   | Soil Type |      | Cycle number | Cyclic stress (psi)       |                            |                                 |                                                   |                           |                            |                                 |                                                   |
|-----------------|-----------|------|--------------|---------------------------|----------------------------|---------------------------------|---------------------------------------------------|---------------------------|----------------------------|---------------------------------|---------------------------------------------------|
|                 |           |      |              | 10                        |                            |                                 |                                                   | 15                        |                            |                                 |                                                   |
|                 | AASHTO    | USCS |              | Average cyclic load (lbs) | Average deformation (mils) | Average resilient modulus (psi) | Average MR (psi) at load cycles 500, 800 and 1000 | Average cyclic load (lbs) | Average deformation (mils) | Average resilient modulus (psi) | Average MR (psi) at load cycles 500, 800 and 1000 |
| M-090-E (15-04) | A-4       | CL   | 100          | 34.6                      | 1.494                      | 65,657                          | 67,841                                            | 51.5                      | 2.170                      | 60,204                          | 62,065                                            |
|                 |           |      | 200          | 34.2                      | 1.492                      | 65,191                          |                                                   | 51.9                      | 2.192                      | 61,455                          |                                                   |
|                 |           |      | 500          | 34.6                      | 1.487                      | 67,087                          |                                                   | 51.7                      | 2.159                      | 61,666                          |                                                   |
|                 |           |      | 800          | 34.6                      | 1.510                      | 68,335                          |                                                   | 51.7                      | 2.128                      | 62,105                          |                                                   |
|                 |           |      | 1000         | 34.5                      | 1.398                      | 68,102                          |                                                   | 52.0                      | 2.212                      | 62,423                          |                                                   |
| M-025-S (15-05) | A-3       | SP   | 100          | 34.0                      | 1.585                      | 37,971                          | 40,152                                            | 52.6                      | 2.503                      | 35,506                          | 35,481                                            |
|                 |           |      | 200          | 34.0                      | 1.601                      | 38,716                          |                                                   | 52.2                      | 2.445                      | 35,369                          |                                                   |
|                 |           |      | 500          | 34.1                      | 1.588                      | 39,705                          |                                                   | 51.7                      | 2.500                      | 35,195                          |                                                   |
|                 |           |      | 800          | 34.9                      | 1.643                      | 40,506                          |                                                   | 52.3                      | 2.468                      | 35,680                          |                                                   |
|                 |           |      | 1000         | 35.0                      | 1.595                      | 40,246                          |                                                   | 52.0                      | 2.437                      | 35,567                          |                                                   |
| M-019-S (15-07) | A-2-4     | SM   | 100          | 34.3                      | 2.740                      | 19,702                          | 22,233                                            | 51.3                      | 4.328                      | 18,630                          | 19,500                                            |
|                 |           |      | 200          | 35.7                      | 2.770                      | 20,960                          |                                                   | 51.9                      | 4.203                      | 18,904                          |                                                   |
|                 |           |      | 500          | 35.0                      | 2.584                      | 21,859                          |                                                   | 51.7                      | 4.118                      | 19,310                          |                                                   |
|                 |           |      | 800          | 35.2                      | 2.539                      | 22,379                          |                                                   | 51.4                      | 4.096                      | 19,441                          |                                                   |
|                 |           |      | 1000         | 34.6                      | 2.572                      | 22,462                          |                                                   | 53.2                      | 4.183                      | 19,750                          |                                                   |



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