FINAL REPORT

For the Florida Department of Transportation

Enhancement of Resilient Modulus Data for the Design of Pavement Structures in Florida

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by
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The opinions, findings and conclusions expressed in this publication are those of the authors and not necessarily those of the Florida Department of Transportation or the U.S. Department of Transportation. This report is prepared in cooperation with the State of Florida Department of Transportation and the U.S. Department of Transportation.

METRIC CONVERSIONS

inches = 25.4 millimeters

feet = 0.305 meters

square inches = 645.1 millimeters squared

square feet = 0.093 meters squared

cubic feet = 0.028 meters cubed

pounds = 0.454 kilograms

poundforce = 4.45 newtons

poundforce per square inch = 6.89 kilopascals

pound per cubic inch = 16.02 kilograms per meters cubed

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16. Abstract

This study is a follow-up research project on the development of a resilient modulus database for pavement design applications. The primary objective of the research was to populate and enhance the previously developed resilient modulus database for the purpose of establishing resilient modulus correlation models based on basic material physical properties. To achieve the objective, 25 subgrade materials were collected for testing from the Florida Department of Transportation (FDOT) district offices around the state. The basic physical properties of the subgrade materials were characterized by the FDOT State Materials Office and subsequently evaluated by the researchers. The subgrade materials were also transported to the laboratory in Tallahassee where resilient modulus tests were performed using the AASHTO T307-99 test method. All of the test data concerning the basic material physical properties and the resilient modulus test results were stored in an enhanced database using Microsoft Access. In addition, a comprehensive literature review was conducted to evaluate the resilient modulus of granular subgrade materials.

The resilient modulus test results were analyzed using a statistical approach (Minitab statistical software) to evaluate the effect of soil physical properties on the resilient modulus. Multiple regression analyses were also performed to find optimum resilient modulus prediction models based on the various soil types, test methods, and other test conditions. The resilient modulus values obtained from the prediction models were generally within a range of +/- 20% of the laboratory measured resilient modulus values. The research findings from this study could be adopted for future implementation of the mechanistic-empirical pavement design in Florida.

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EXECUTIVE SUMMARY

The subgrade resilient modulus is an essential engineering parameter for the mechanistic-empirical pavement design. A long-term implementation program is in effect to measure the resilient modulus in a laboratory for the design of pavement structures in Florida. However, measuring the resilient modulus of a pavement material is a complex and difficult task. In view of the complexity and difficulty in conducting the resilient modulus measurement, a database program has been initiated to catalog available resilient modulus test results and to evaluate the subgrade resilient modulus for facilitating pavement design.

This study is a follow-up research project on the development of a resilient modulus database for pavement design applications. The primary objective of the research was to populate and enhance the previously developed resilient modulus database for the purpose of establishing resilient modulus correlation models based on basic material physical properties. To achieve the objective, 25 subgrade materials were collected for testing from the Florida Department of Transportation (FDOT) district offices around the state. The basic physical properties of

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INTRODUCTION

1.1 BACKGROUND

The 1993 AASHTO Guide for the Design of Pavement Structures has incorporated the resilient modulus of component materials into the design process. Considerable attention has also been given to the development of mechanistic-empirical approaches for the design and evaluation of pavements. Both the 1993 Guide and the mechanistic based design methods use the resilient modulus of each layer in the design process.

In Florida, several research projects in the past ten years have been conducted to study the resilient modulus characteristics of Florida pavement soils. Comparative studies were conducted to evaluate the resilient modulus from laboratory cyclic triaxial tests and field experimental studies such as: field plate bearing test, falling weight deflectormeter (FWD) test, and a test-pit test that were developed to simulate field pavement layer behavior subject to dynamic traffic loadings. The resilient modulus was found to be dependent on a number of factors: soil type, test method, specimen density, specimen moisture, specimen size, confining pressure, deviator stress, etc. One soil specimen could have many different resilient modulus values depending on the states of stresses. Conducting the resilient modulus test and selecting an appropriate resilient modulus value for pavement designs are very complex processes. Research studies have also been conducted to correlate resilient modulus with basic soil physical properties, which are relatively easy to measure such as moisture, unit weight, gradation, plasticity, and classification. However, no reliable relationships between resilient modulus and these parameters have been found to this date.

More than 200 laboratory triaxial resilient modulus tests on Florida soils have been conducted in previous studies. These test results have been saved in computers in Microsoft Excel table format. In a previous project entitled "Development of an Automated Procedure for Implementing a Resilient Modulus Test for the Design of Pavement Structures in Florida", a database in Microsoft Access format was developed to catalog the available resilient modulus test data with other related data. However, the capability and usefulness of the database is limited to a certain degree due to insufficient data in the database. Thus, it seems that there is a need for a follow-up testing program to populate the database with additional resilient modulus test data and to provide a higher confidence level for the resilient modulus analysis and prediction.

1.2 STUDY OBJECTIVE

The objectives of this research study were:

1) to populate the previous developed resilient modulus database with additional resilient modulus test results,
2) to use the enhanced database for evaluating the effect of soil physical properties on the resilient modulus, and
3) to establish resilient modulus correlation models based on basic soil physical properties.

1.3 SCOPE OF STUDY

The scope of this research study included the following tasks:

- to perform a literature review on the resilient modulus concept, the test procedures, and other influencing factors,
- to collect subgrade pavement materials from field sites for laboratory testing,
- to perform laboratory resilient modulus tests using the AASHTO T307-99 test method,

- to populate and enhance the resilient modulus database,
- to evaluate the effect of soil physical properties on the resilient modulus, and
- to search for optimum resilient modulus prediction models based on basic material physical properties.

1.4 Report Organization

This report summarizes the study that examines enhancing the soil resilient modulus database and applying the database for evaluation of the soil resilient modulus. The resilient modulus database is a part of the larger effort to implement the 1986 & 1993 AASHTO design guides for pavement structures. As in the first chapter, the background and objectives are introduced. Chapter 2 reviews the resilient modulus concept, the affecting physical factors, and the correlation models. The laboratory experimental program is described in detail in Chapter 3. Chapter 4 presents the additional resilient modulus data stored in the enhanced database and the manipulation functions of the database. Chapter 5 presents the detailed analysis of the effect of basic soil properties on the resilient modulus. The development of multiple regression models for granular subgrade soils is presented in Chapter 6. The conclusions and recommendations are summarized in Chapter 7.

CHAPTER 2
LITERATURE REVIEW

2.1 RESILIENT MODULUS CONCEPT

Most pavement materials, especially soils, are not pure elastic material, but exhibit elastic-plastic behavior. That means that they act partly elastic under a static load but experience some permanent deformation. However, under repeated loads, they express other important properties. At the beginning, they perform just like they would under a static load. But after certain repetitions, the permanent deformation under each load repetition is almost completely recoverable. By this point, it can almost be considered elastic, if the repeat load is small enough compared to its strength, otherwise the soil structure would be damaged. Figure 2.1 illustrates the behavior of unbounded material under a sequence of repeating loads.

Resilient modulus (M_R or M_r) is a measurement of the elastic property of soil recognizing certain nonlinear characteristics. Resilient modulus is defined as the ratio of the axial deviator stress to the recoverable axial strain, and is presented in the following equation:

$$M_R = \sigma_d / \varepsilon_R \quad (2.1)$$

Where σ_d = axial deviator stress

ε_R = axial recoverable strain

As exhibited in Figure 2.1, there are two components to the total deformation, a resilient or recoverable portion and a permanent portion. Only the recoverable portion is included in the measurement of resilient modulus.

2.2 FACTORS AFFECTING RESILIENT MODULUS

The resilient modulus is defined as the deviator dynamic stress (due to the moving vehicular traffic) divided by the resilient axial (recoverable) strain. This concept is derived from the fact that the major component of deformation induced into a pavement structure under the traffic loading is not associated with plastic deformation or permanent deformation, but with elastic or resilient deformation. Thus, the resilient modulus is considered to be a required variable for determining the stress-strain characteristics of pavement structures subjected to a traffic loading.

The resilient modulus of unstabilized granular base and subgrade soils is highly dependent upon the stress state to which the material is subjected within the pavement in addition to other variables. As a result, constitutive models must be used to present laboratory resilient modulus test results, including the effect of the stress state, in a form suitable for use in pavement design. The resilient modulus depends on deviator stress and confining stress. Two popular and simple regression models are presented as follows:

1. When modulus is dependent on bulk stress:

$$M_r = k_1 \theta^{k_2} \quad (2\text{-}2)$$

2. When modulus is dependent on confining pressure:

$$M_r = k_3 \sigma_3^{k_4} \quad (2\text{-}3)$$

Where, θ = bulk stress, sum of the principal stresses, ($\sigma_1 + \sigma_2 + \sigma_3$)

σ_3 = confining pressure or minor principal stress

k_1, k_2, k_3, k_4 = regression constants

Many factors influence the resilient modulus of soils. The factors include soil type, soil properties, dry unit weight, water content, stain level, test procedures, and sample size. A brief review of the significant influence from these factors is discussed in the following sections.

2.2.1 Soil type

The resilient modulus is significantly influenced by the type of pavement soils. Chen et al. (1994) investigated the variability of resilient moduli due to aggregate type. The AASHTO T292-91I test procedure was used to conduct tests on six selected aggregate types of soils. Conclusions show that for a given gradation, the differences in Resilient Modulus values due to aggregate sources were found to be from 20 to 50 percent.

2.2.2 Physical Properties

The resilient modulus is also significantly correlated with soil properties such as the liquid limit, plastic limit, and grain size distribution. Thompson and Robnett (1989) concluded that the properties that tend to contribute to low resilient modulus values are low plasticity, high silt content, low clay content, and low specific gravity. From the study, regression equations were developed for predicting resilient modulus based on soil properties.

2.2.3 Dry Density

Variations in the density of the laboratory test specimen with the same water content produce variable effects on the resilient response of subgrade soils. Theoretically, Young’s modulus of a soil is proportional to its density. Trollope et al. (1962) reported that the resilient modulus of dense sand might be 50 percent higher than that of loose sand.

2.2.4 Moisture Content

The effect of the water content on the resilient response of soils was noticed a long time ago. A general relationship between dry density, water content, and resilient modulus for subgrade soils is shown in Figure 2.2 (Monismith, 1989). The effect of the Moisture Content on the resilient modulus was thoroughly reviewed by Ping and Zhang in 2004. Zhang found that the resilient modulus of coarse-grain soil was not significantly affected by the amount and manner of saturation. The reduction was approximately 20 percent, while that the resilient modulus of fine-grain soils was drastically reduced by saturation. The reduction was 50 to 75 percent depending on the degree of saturation, and the saturating method used.

2.2.5 Soil Suction

Huang and Dai studied the effect of soil suction on the mechanism characteristics of the pavement materials in 2004. They found that soil suction has a significant influence on the mechanical properties of unsaturated soils, such as effective stress, resilient modulus, and strength. It is a good indicator of the stiffness of the subgrade and is used to establish a model for predicting the resilient modulus of subgrade with varying water contents.

2.2.6 Strain Amplitude

The strain level also has a significant effect on the resilient modulus. As the strain amplitude increases, the modulus of the soil decreases. Kim et al. (1991) identified that the resilient modulus decreases with the increasing strain amplitude. The relationship of the strain amplitude versus the modulus of the compacted subgrade soils is shown in Figure 2.3.

2.2.7 Test Procedure

AASHTO T292-91I and T294-92 were two of the most extensively used test procedures in past years. A new standard specification AASHTO T307-99 based on the SHRP Protocol P46 was adopted in the year 2000. The major improvement includes higher accuracy of the measurement devices, different measurement position, different confining and loading stress, and the specimen preparation method. The T307 procedure consists of 15 sequences with different levels of confining pressure and maximum axial load. The three procedures normally produce different results. Zaman et al. (1994) found that the T294-92 test procedure gave higher resilient modulus values than those obtained by using the T292-91I test procedure. Ping and Hoang (1996) had similar results. This phenomenon was attributed to the stress sequence, which had a stiffening and strengthening effect on the specimen structure as the stress level increased. Ping and Xiong (2003) investigated the influence of the LVDT positions on the resilient modulus test results. The investigation showed that the internal LVDT position leads to a better test result than that with an external position, and the internal full-length LVDT position has the most reliable test data.

2.2.8 Size Effect

Specimen size has an influence on the resilient modulus of soils. The diameters of the specimen could be as small as 2.0 inches. However, the most common sizes are 4.0 and 6.0 inches in diameter. The ratio of height over diameter is usually 2.0.

Testing materials composed of large particles demands larger specimens. The T292-92I procedure specifies that a minimum 90% by material weight used to prepare the compacted specimen in the laboratory should have a maximum particle size finer than 1/6 of the specimen diameter. The maximum particle size of the remaining material shall be no larger than 1/4 of the specimen diameter.

Zaman et al (1994) conducted a series of resilient modulus tests on six of the most commonly encountered aggregates that are used as a base/sub-base on roads in Oklahoma. The testing materials consisted of three limestones, one sandstone, one granite, and one rhyolite. The specimens were prepared at three different levels of gradations. The maximum particle sizes varied from 0.75 inch to 1.5 inch.

Vibration and compaction methods were employed in preparing the specimens. The specimens were 4 inches and 6 inches in diameter. The test results of the 4-inch and the 6-inch samples were analyzed. In all cases, the resilient modulus for the 4-inch specimens was higher (20-50%) than those for the 6-inch specimens.

2.3 EMPIRICAL RESILIENT MODULUS MODELS

A very promising approach for obtaining resilient moduli for use in design, for at least most agencies, is to determine values of resilient modulus using generalized empirical relationships with statistically relevant, easy to measure physical properties of the material. Considering the large variation in resilient moduli along the route and important design changes in moisture with time, the use in design of empirical resilient modulus relationships is considered to be justified. A number of states have already developed generalized resilient modulus relationships for use in design, particularly for cohesive subgrade soils (K. P. George, 2004). Statistically based equations, graphs or charts would then be developed for each class of materials for the range of properties routinely used in design within the region of interest.

Previous research from Zhang (2004) had proposed several regression models that were developed for implementing the resilient modulus test for design of pavement structures in Florida. A brief review on these models is discussed as follows.

2.3.1 Seed (1962) Model

Many researchers studied the influence of the water content on the resilient modulus. Seed (1962) evaluated the influence on the undisturbed samples of the fine grained materials and found that the seasonal variation of the water content does have a significant influence on the resilient modulus. Based on the findings, the resilient modulus was evaluated using the following equations.

$$M_r = 27.06 - 0.006^{\theta} \quad \text{for } \gamma_d > 100 \text{ pcf} \tag{2.4}$$

$$M_r = 18.18 - 0.004^{\theta} \quad \text{for } \gamma_d < 100 \text{ pcf} \tag{2.5}$$

Where

M_r = Resilient modulus, ksi

θ = Volumetric water content, %

γ_d = Dry unit weight, pcf

The results from this model didn't work well, because, in this model, the resilient modulus is based on only one parameter, which contributes to inaccurate results.

2.3.2 Carmichael and Stuart (1985)

Carmichael and Stuart (1985) produced more than 3300 test data on 250 different types of fine-grained and granular materials to build the resilient modulus models. Two models were developed, one for fine-grain soils and the other for coarse-grain soils. Equation 2.6 presents the model for coarse-grain soils.

$$LogM_r = 0.523 - 0.025(Wc) + 0.544(\log\theta) + 0.173(SM) + 0.197(GR) \quad (2.6)$$

Where,

M_r = Resilient Modulus, ksi

W_c = moisture content, %

θ = bulk stress (σ_1+σ_2+σ_3), psi

SM = 1 for SM soils (Unified Soil Classification)

= 0 otherwise

GR = 1 for GR soils (GM, GW, GC or GP)

= 0 otherwise

A different equation (2.7) was derived for fine-grain soils:

$$M_r = 37.431 - 0.4566(PI) - 0.6179(W_c) - 0.1424(P_{200}) + 0.179(\sigma_3) - 0.3248(\sigma_d) + 36.722(CH) + 17.097(MH) \quad (2.7)$$

Where,

PI = plasticity index, %

P_{200} = percentage passing #200 sieve, %

σ_3 = confining stress, psi

σ_d = deviator stress, psi

CH = 1 for CH soil

= 0 otherwise (for MH, ML or CL soil)

MH = 1 for MH soil

= 0 otherwise (for CH, ML or CL soil)

W_c = Water Content, %

2.3.3 Thompson and LaGrow (1992) Model

Using the power model to express resilient modulus is a practical alternative to the slightly more accurate bilinear model. The bilinear resilient modulus model for fine-grained soils has a distinct breakpoint as shown in Figure 2.4. The resilient modulus at the breakpoint can be estimated using the following expression developed by Thompson and LaGrow (1992):

$$M_{r(opt)} = 4.46 + 0.098(\%\ clay) + 0.119(PI) \quad (2.8)$$

Where,

$M_{r(opt)}$ = breakpoint resilient modulus at optimum moisture content and 95% of AASHTO T99 maximum dry density, ksi

%clay = % particles finer than the 2 micron size

PI = plasticity index

Equation 2.8 is for cohesive soils compacted to 95% of AASHTO T99 maximum dry density at the optimum water content. Equation 2.8, although useful, has an important disadvantage that the resilient modulus is only at breakpoint. The breakpoint is often, but not always, at or close to the minimum value of the resilient modulus. Thick pavement sections apply low deviator stress to the subgrade. As a result, the breakpoint resilient modulus is likely to be too low for strong sections, resulting in unnecessary additional thickness.

2.3.4 Yau and Von Quintus (2002) Model

Yau and Von Quintus (2002) studied the methods of choosing the right data for building the resilient modulus prediction models. They found that one equation did not fit all situations for all the soils. For greater accuracy, they tried to establish the model according to different material types. The prediction models for the subgrade soils were developed based on the constitutive equation with the regression constants k_1, k_2, and k_3 as below.

$$M_r = k_1 P_a (\frac{\theta}{P_a})^{k_2} [(\frac{\tau_{oct}}{p_a}) + 1]^{k_3} \qquad (2.9)$$

The regression constants k_1, k_2, and k_3 are material-specific and are described as follows:

For coarse-grained sandy soils,

$$k_1 = 3.2868 - 0.0412 P_{3/8} + 0.0267 P_4 + 0.0137(\%Clay) + 0.0083 LL - 0.0379 \omega_{opt} - 0.0004 \gamma_s$$

$$k_2 = 0.5670 + 0.0045 P_{3/8} - 2.98 X 10^{-5} P_4 - 0.0043(\%Silt) - 0.0102(\%Clay) - 0.0041 LL$$

$$00014 \omega_{opt} - 3.41 X 10^{-5} \gamma_s - 0.4582(\frac{\gamma_s}{\gamma_{opt}}) + 0.1779(\frac{\omega_c}{\omega_{opt}})$$

$$k_3 = -3.5677 + 0.1142 P_{3/8} - 0.0839 P_4 - 0.1249 P_{200} + 0.1030(\%Silt) + 0.1191(\%Clay)$$

$$- 0.0069 LL - 0.0103 \omega_{opt} - 0.0017 \gamma_s + 4.3177(\frac{\gamma_s}{\gamma_{opt}}) - 1.1095(\frac{\omega_c}{\omega_{opt}})$$

For fine-grained silty soils,

$$k_1 = 1.0480 + 0.0177(\%Clay) + 0.0279 PI - 0.037 \omega_c$$

$$k_2 = 0.5097 - 0.0286 PI$$

$$k_3 = -0.2218 + 0.0047(\%Silt) + 0.0849 PI - 0.1399 \omega_c$$

For fine-grained clayey soils,

$$k_1 = 1.3577 + 0.0106(\%Clay) - 0.0437 \omega_c$$

$$k_2 = 0.5193 - 0.0073 P_4 + 0.0095 P_{40} - 0.0027 P_{200} - 0.003 LL - 0.0049 \omega_{opt}$$

$$k_3 = 1.4258 - 0.0288P_4 + 0.0303P_{40} - 0.0521P_{200} + 0.0251(\%Silt) + 0.0535LL - 0.0672\omega_{opt}$$

$$-0.0026\gamma_{opt} + 0.0025\gamma_s - 0.6055(\frac{\omega_c}{\omega_{opt}})$$

where,

M_r = Resilient Modulus, MPa

$P_{3/8}$ = percentage passing the 3/8" (9.5mm) sieve

P_4 = percentage passing #4 sieve

P_{40} = percentage passing #40 sieve

P_{200} = percentage passing #200 sieve

ω_c = moisture content of the specimen, %

ω_{opt} = optimum moisture content of the soil, %

γ_s = dry unit weight of the sample, kg/m^3

γ_{opt} = optimum dry unit weight, kg/m^3

LL = Liquid Limit

PI = Plastic Index

%Silt = Percent by weight of silt in the material

%Clay = Percent by weight of clay in the material

This model was established based on a granular type of material and was mainly for subgrade use.

2.3.5 Ping and Zhang (2004) Model

ChaoHan Zhang (2004) proposed a resilient modulus prediction model based on five types of granular subgrade soil commonly available in Florida. The subgrade soils contained a wide range of percent of fines passing No.200 sieve varying from 8% to 24% (A-3 and A-2-4 soils, according to the AASHTO classification). The compaction of the soil samples was determined in the laboratory using the Modified Proctor (AASHTO T-180) method. The full-length resilient modulus under 12.7 psi bulk stress (2 psi confining pressure and 6.7 psi deviator stress) was chosen as the model responses.

$$\ln(M_r) = 2.01 - 0.041 * \omega + 0.0108 * \rho + 0.0243 * (C_u) - 0.119 * (C_c) \qquad (2.10)$$

Where,

M_r = Resilient modulus @ 2 psi confining pressure, ksi

◄

ω = Gravimetric moisture content, %

ρ = Maximum dry unit weight, pcf

α = Clay percentage, %

C_c = Coefficient of Curvature (gradation)

C_u = Uniformity Coefficient (gradation)

This model had a value of the coefficient of determination (R^2 value) 54.2%.

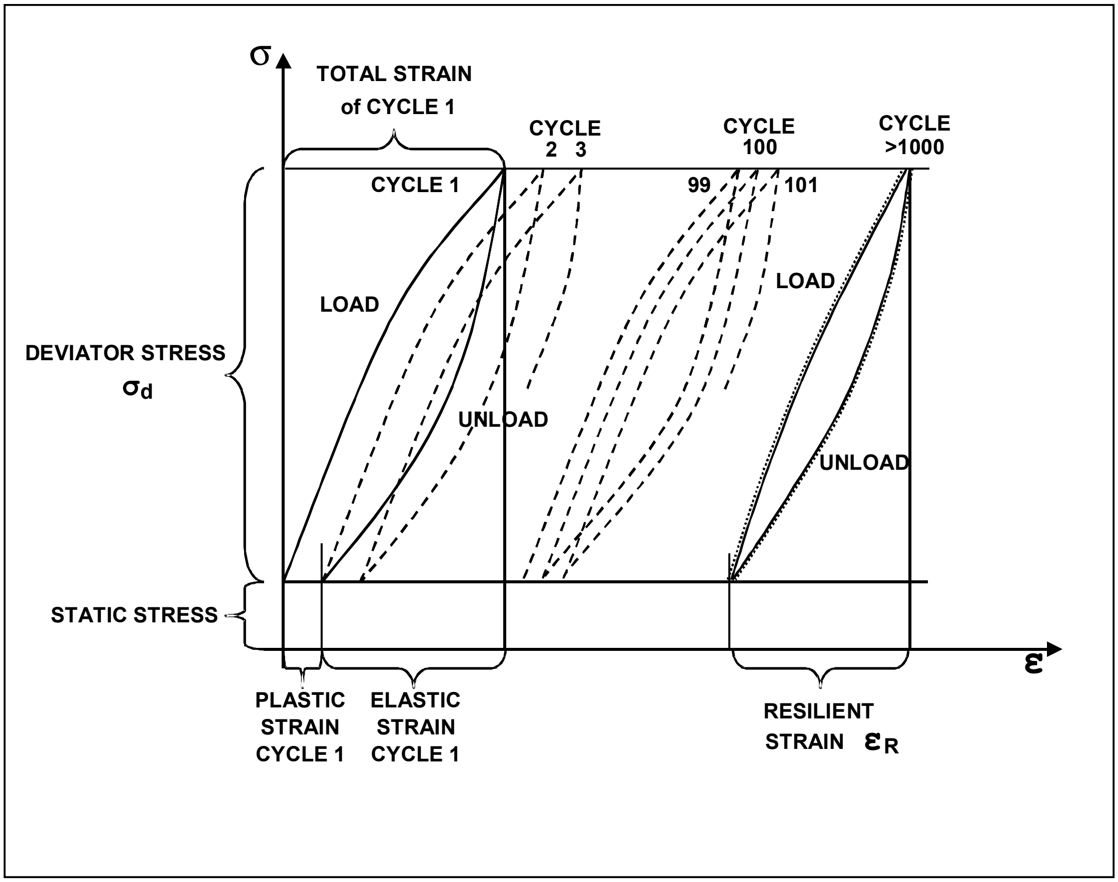


Figure 2.1 Concept of Soil Resilient Modulus

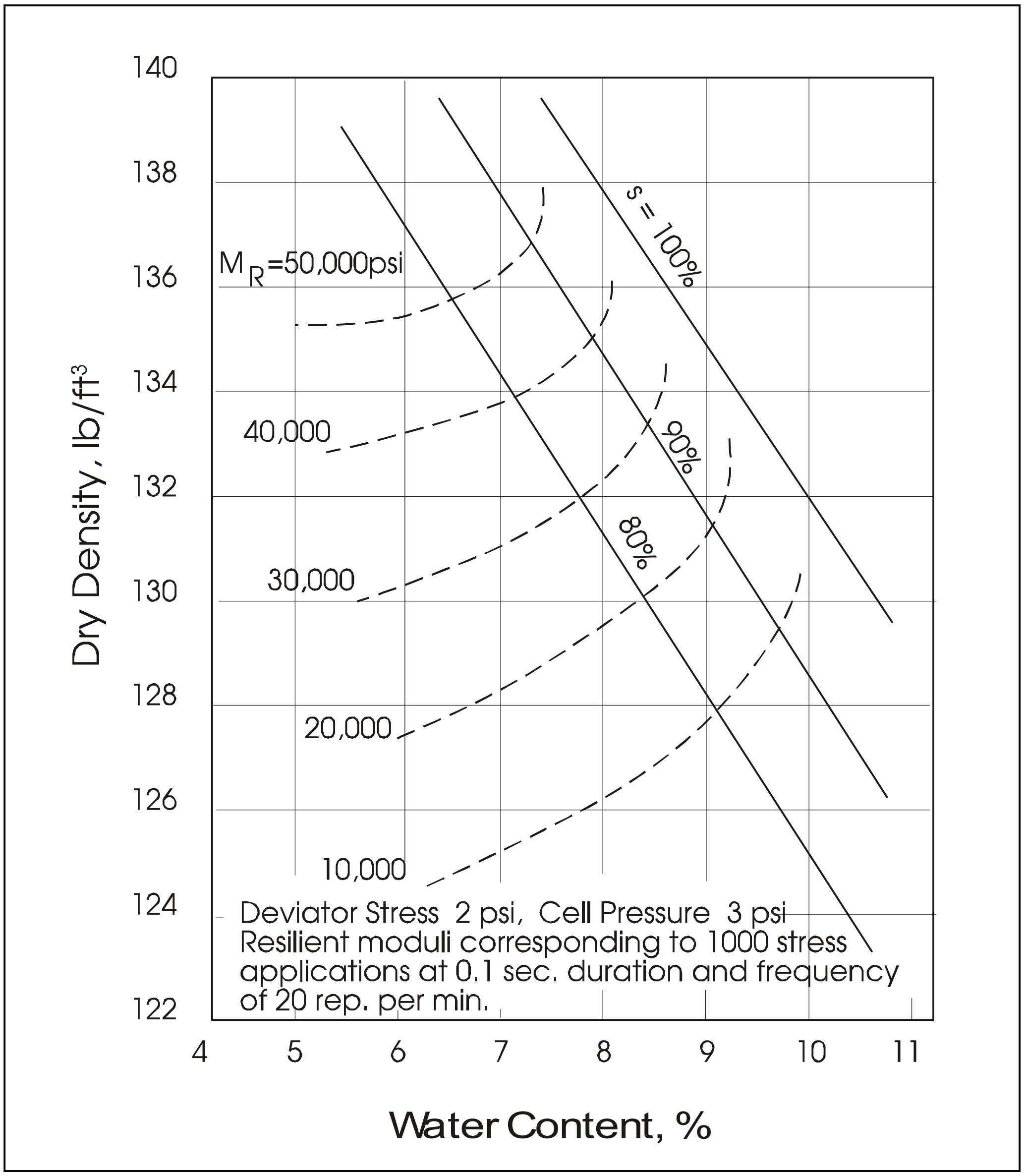


Figure 2.2 Water Content-dry Density-resilient Modulus Relationship for Subgrade Soil

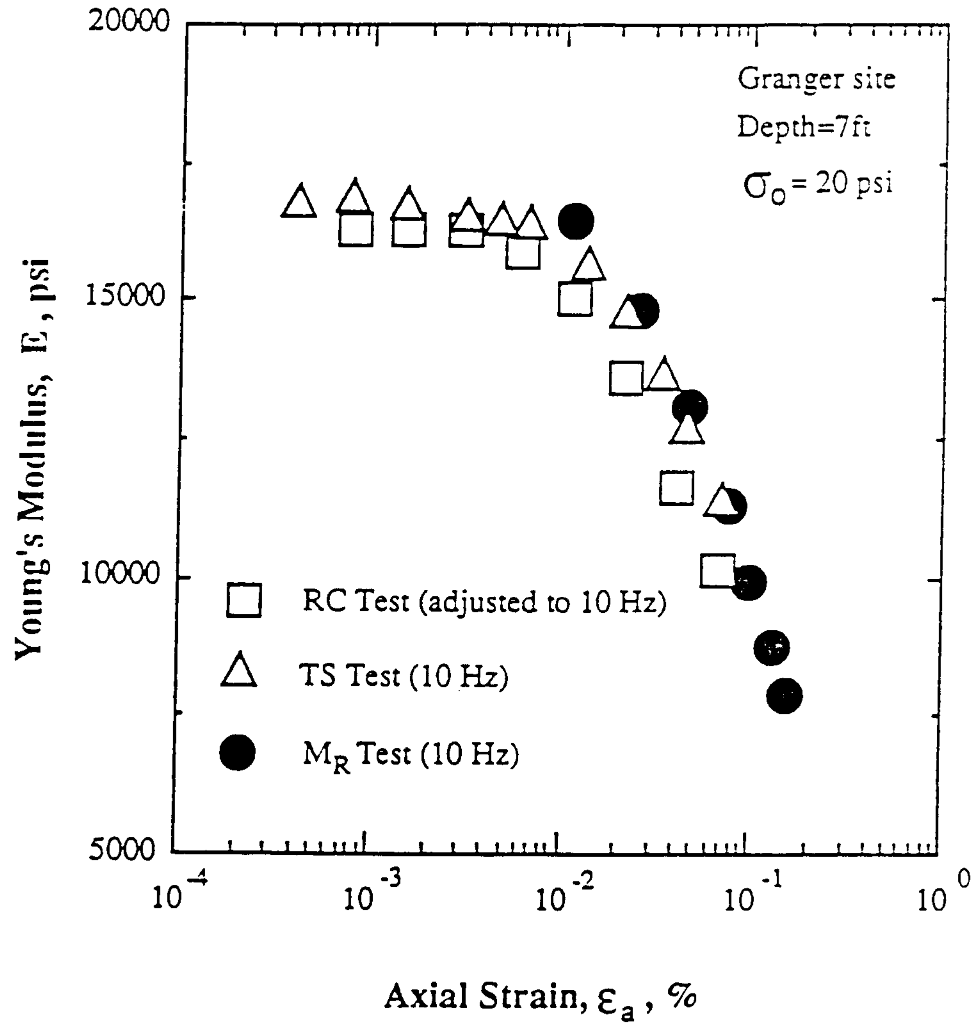


Figure 2.3 Comparison of Mr Values of Undisturbed Compacted Subgrade Soils Determined by Resonant Column, Torsional Shear and Resilient Modulus Tests (Kim and Stokoe 1991)

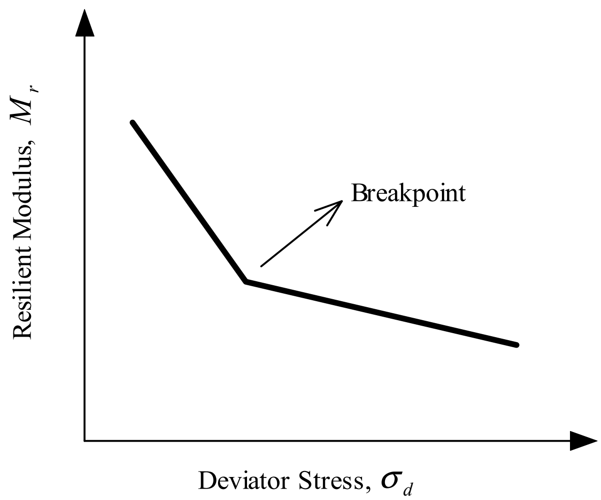


Figure 2.4 General Relationship between Resilient Modulus and Deviator Stress for Fine-grained, Cohesive Soils

CHAPTER 3
LABORATORY EXPERIMENTAL PROGRAM

3.1 GENERAL

The primary objective of the laboratory experimental program was to populate the resilient modulus database with additional resilient modulus test results. To achieve the objective, samples of soil material were collected at selected borrow pits from each of the FDOT districts and transported to the College of Engineering in Tallahassee for testing. Three subgrade soils from each district were chosen for the resilient modulus testing. The material selection process was done in cooperation with the District Materials Office, the State Materials Office, and the Pavement Design Office. The laboratory experimental program including the test materials, the resilient modulus testing program, the permeability testing program, and the engineering property analysis is described in this chapter.

3.2 TEST MATERIALS

To better characterize the resilient modulus behavior of Florida soils, three sites from each of the seven districts were chosen for soil sampling. In addition, 16 soil samples from a previous study were also included for evaluation. Thus, a total of 37 soil samples were included in this test program. The soil materials consisted of four A-1 soils, 19 A-3 soils, 11 A-2-4 soils, and three A-2-6 soils. A summary of the soil materials that were initially transported through the FDOT State Materials Office for basic properties characterization and classification is presented in Table 3.1 for information.

3.3 RESILIENT MODULUS TESTING PROGRAM

3.3.1 Test Equipment

For the resilient modulus test, all of the test protocols require the use of a triaxial chamber, in which confining pressure and deviator stress can be controlled. The test method for determining the resilient response of pavement materials is basically a triaxial compression test, in which a cyclic axial load is applied to a cylindrical test specimen. The load is measured by a load cell, while the resilient strain is measured. The test is usually conducted by applying a number of stress repetitions over a range of deviator stress levels and confining pressure levels representing variations in depth or location from the applied load. An MTS model 810 closed-loop servo-hydraulic testing system and a resilient modulus triaxial testing system were used in this study. Figure 3.1 shows the configuration of the test system schematically. The major components of these systems included the loading system, digital controller, workstation computer, triaxial cell, and linear variable differential transducer (LVDT) deformation measurements system. An illustration of the resilient modulus testing equipment is shown in Figure 3.2.

This system adopts the full-length internal LVDT position as shown in Figure 3.3. In addition to two vertical LVDTs measuring the vertical displacements, a fixture attached with four horizontal LVDTs was designed to measure the horizontal displacements for the determination of Poisson's ratio. This device was positioned in the middle half length of the specimen with four horizontal LVDTs attached at 90-degree intervals. The horizontal displacement can be obtained by averaging the measurements from the four horizontal LVDTs.

An updated controller (Model 793) with its advanced software (Multipurpose Test Ware) was used to control the test processes and acquire the test data. The raw data was acquired using the mode of the Peak/Valley, which recorded the test data at its peak and valley levels of each cycle. The output of the data acquisition system includes a graphic display of sampled dynamic load and displacement waveforms and a data file. The data in data file format was selected for further data deduction and analyses.

3.3.2 Test Method

The resilient modulus test method used in this study was AASHTO T307-99, “Determining the Resilient Modulus of Soils and Aggregate Materials”. This method was considered an improvement to the AASHTO T292-91I method. The T307-99 method covers procedures for preparing and testing untreated subgrade and untreated base/sub-base materials for determination of resilient modulus under conditions representing a simulation of the physical conditions and stress states of materials beneath the flexible pavements subjected to moving wheel loads. The original setup of LVDTs in Designation T307-99 was at an external position outside of the triaxial cell, but the location was changed to an internal position inside the cell as shown in Figure 3.3 for a better test result according to the findings from Ping & Xiong (2003).

The software used for the resilient modulus test is specifically configured according to the Standard Specification of the T307-99. A screen snapshot is illustrated in Figure 3.4. The test procedure of the T307-99 Designation was included in the CD-R database disk for reference.

3.3.3 Specimen Preparation

All subgrade materials were compacted in the laboratory to 100% of optimum moisture and maximum density using AASHTO Designation T-99 (Standard Proctor Compaction) according to the FDOT requirement. A 4-in by 8-in split mold was used to prepare the test specimen. The blow number was modified to achieve the energy condition specified in the AASHTO T-99. Two specimens were compacted at the same time to keep them in a duplicate condition. The T307-99 Designation specifies that the wet density of the laboratory-compacted specimen shall not vary by more than +/-3 percent of the target wet density and the moisture content of the laboratory-compacted specimen shall not vary by more than +/-1.0 percent for Type 1 materials or +/-0.5 percent for Type 2 materials from the target moisture content.

A typical compaction form is shown in Table 3.2 for information.

3.3.4 Test Procedures

The resilient modulus test procedures basically followed the test standard from AASHTO T307-99. A deviation from the test procedure was made by using the internally-mounted LVDTs for the vertical full-length measurements instead of external LVDTs illustrated in AASHTO Designation T307-99. Four additional horizontal LVDTs were mounted to a fixture to measure the horizontal displacements for the determination of Poisson's ratio.

The test procedures are further described in the following sections.

3.3.4.1 Test Setups

Prior to testing, the compacted soil specimen was removed from the mold using an extruder. Using a vacuum membrane expander, a membrane was pulled over the specimen and perforated stones. The membrane-enclosed soil specimen with the perforated stones on the top and the bottom was placed onto the bottom platen in the triaxial chamber. The top platen was fitted in place, and the specimen membrane ends were folded over the platens and secured with O-rings. Two LVDTs were mounted on the top platen to measure the vertical resilient deformation of the entire 20.3 cm (8 in) long specimen. The other four LVDTs were secured in the horizontal fixture at the middle point of the specimen to measure the horizontal displacements. These six LVDTs were adjusted to the appropriate positions to permit enough travel distance during the testing. The assembly of the triaxial cell was completed by closing the triaxial chamber (Figure 3.3). The drainage valves to the specimen were left open.

3.3.4.2 Specimen Conditioning

Specimen conditioning was applied to simulate the stress history that exists in field conditions. The procedures for specimen conditioning are described as follows:

- Load the MTS load frame to the triaxial load cell, making sure that the load frame is firmly contacted with the triaxial load cell.
- Turn on the air compressor machine to produce a confining chamber pressure of 41.4 kPa (6 psi) for granular subgrade and embankment soils (*T307-99*).
- Zero the load reading from the control panel. Open a programmed template according to the test material. The programmed templates enable the loading device to produce a haversine wave with a fixed load duration of 0.1 second with a 0.9 second period of relaxation.
- Begin the conditioning by applying 500 repetitions of a corresponding deviator stress. Monitor the permanent axial deformation occurring during conditioning.

After completion of the specimen conditioning phase, monitor the permanent axial deformation occurring in the specimen throughout the remainder of the test. If the permanent axial strain exceeds 5 percent, the test should be terminated.

3.3.4.3 Confining Pressure and Loading Sequences

Since the laboratory resilient modulus simulates the conditions in the pavement subgrade, the stress-state should be selected to cover the expected in-service range. Resilient properties of granular specimens should be tested over the range of confining pressures expected within the subgrade layer. A template was created to monitor the test sequences. In the test sequences (Table 3.3 and Table 3.4), the confining pressures decrease while the deviator stresses increase during each confining pressure stage.

3.3.4.4 Cyclic Loading Procedures

The procedures are described as follows:

- Open a template; apply 100 repetitions (*T307-99)* of the smallest deviator stress at the highest confining stress (T307-99). The average recoverable deformation of each repetition is recorded automatically.
- Apply the same repetitions of each of the remaining deviator stresses to be used at the present confining pressure.
- Decrease (T307-99) the confining pressure to the next desired level and adjust the deviator stress to the smallest value to be applied at this confining pressure.

- Increase the deviator stress to the next desired level and continue the process until testing has been completed for all desired stress states.
- Disassemble the triaxial chamber and remove all apparatus from the specimen.

3.3.5 Raw Test Data

The raw test data were automatically generated by the software in a Data format file. The data recorded in this file included the actual axis loads in lbf (pound force) for each confining pressure, testing time, testing count and readings of the six LVDTs in inches. A typical raw data output file can be found in Table 3.5.

3.3.6 Determination of Resilient Modulus

During the resilient modulus test, after finishing the specimen conditioning stage, a series of tests with different deviator stresses at different confining pressures were performed and the data were recorded for every cycle of each test. However, only the last five cycles of each test were used for analyses following the *AASHTO T307-99* procedure.

The resilient modulus (M_r) was calculated from the load and deformation using the following equation:

$$M_r = \frac{\sigma_d}{\varepsilon_R} \qquad (3.1)$$

Where,

σ_d = the deviator stress

ε_R = the resilient or recoverable strain

3.3.7 Determination of Poisson’s Ratio

Two vertical deformations, LVDT1 and LVDT2, and four horizontal deformations, LVDT3, LVDT4, LVDT5, and LVDT6, were recorded in the raw data sheet. The Poisson's ratio (ν) is defined as the ratio of lateral strain to axial strain as the following:

$$\nu = \frac{\varepsilon_h}{\varepsilon_v} \qquad (3.2)$$

Where,

ε_h = the horizontal strain

ε_v = the vertical strain

3.4 PERMEABILITY TESTING PROGRAM

The permeability test followed the ASTM Designation D5084-90, Standard Test Method for Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter. This method is suitable for the compacted specimens that have a hydraulic conductivities less than or equal to 1E-4(cm/sec). A six-burette Triaxial/Hydraulic

Conductivity panel, FlexPanel II, from Humboldt was used to perform the test. The assembly of the test equipment is shown in Figure 3.5.

3.4.1 Test Procedure

A 4-inch-diameter and 4.584-inch-height sample was compacted at 100% of its optimum condition using the AASHTO Designation T-99 according to the FDOT requirements. The sample was first subjected to a 5 psi initial cell pressure. The backpressure was then applied to the sample by simultaneously increasing the cell pressure and the influent and effluent pressures with an increasing rate of 5 psi for a minimum of two-hour interval until the sample reached a 95% degree of saturation, at which time the specimen should be considered to be adequately saturated. The backpressure values were varied with different types of material. Usually a backpressure value greater than 80 psi is sufficient to saturate the specimen. Following the 95% saturation, the effective stress was raised from 5 psi to 7 psi, which is specified by the FDOT, for the consolidation.

The Falling-Head Test was adopted for this testing program. Three head pressures of 1 psi, 2 psi, and 3 psi were chosen according to different hydraulic conductivities of the specimens. In addition to the 7 psi effective pressure, the hydraulic conductivities under 14 psi and 21 psi effective pressure were also monitored for further use.

3.4.2 Determination of Permeability

The Constant Tailwater Pressure (Method B) was used for the data reduction. The hydraulic conductivity, *k*, can be calculated using the following formula.

$$k = \frac{aL}{A\Delta t} \ln\left(\frac{h_1}{h_2}\right) \tag{3.3}$$

Where,

K = Hydraulic Conductivity, cm/sec

a = cross-sectional area of the reservoir containing the influent liquid, m^2

L = length of the specimen, m

A = cross-sectional area of the specimen, m^2

Δt = elapsed time between the determination of h_1 and h_2,second

h_1 = head loss across the specimen at time t_1, m

h_2 = head loss across the specimen at time t_2, m

SAMPLE NAME	4 " T-99	6" T-99/LBR		6 " T-180/LBR		% Passing Sieve			Plastic Index			Gs	% Soil Type			CLASS	Soil Type
	Dens/Moist	Dens/Moist	LBR	Dens/Moist	LBR	#4	#10	#200	LL	PL	PI		SAND	SILT	CLAY		
Airport	NA	120.2/10%	52	125.8/8.2%	141	100	99.1	17.3	NP	NP	NP	2.667	83	5	12	A-2-4	2
Ball Farm 1-6	NA	111.6/15.8%	17	121.4/13.4%	109	100	98.6	34.8	37.6	24.3	13.3	2.679	65.2	7.5	27.3	A-2-6	2
Ball Farm 15-20	117.2/12.6%	119.1/11.7%	28	128.0/10.2%	78	98	95.3	23.0	32.2	18	14.2	2.672	77.2	2	20.8	A-2-6	2
Branch	NA	128.4/8.8%	43	134.7/7.2%	132			24	20	15	5				6	A-2-4	2
Blue Rock Pit	111.2/12.0%	112.7/12.3%	49@11%	109.1/12.1%	36	99.1	97.2	6.0	NP	NP	NP					A-3	2
Hills. CR 39	105.8/16.3%	106.4/16.6%	51/15%	105.1/12.7%	32/13.4%	100	100	5.0	NP	NP	NP	2.648	95	2	3	A-3	2
D1 Earth Source	107.9/12.1%	108.2/12.1%	20@11.1%	111.7/9.9%	35@8.8%	100	100	7.8	NP	NP	NP					A-3	2
Fair field	NA	116.4/13.3%	31	125.2/10.2%	108/9.2%	100	100	20.4	NP	NP	NP	2.663	80	2	18	A-2-4	2
Iron Bridge	NA	123.3/10.3%	30	132.4/8.2%	127			32	27	15	12				16	A-2-6	2
D6 MIC Project	117.8/9.3%	118.4/8.1%	48@8.9%	124.0/7.4%	129	53	31.7	5.0	NP	NP	NP					A-1-a	1
Polk Masaic Mine	104.9/14.7%	104.3/14.6%	29	105.0/10.9%	28	100	100	2.0	NP	NP	NP	2.649	98	0	2	A-3	2
Osteen (1-9)	105.1/13.2%	105.4/13.0%	17@12%	108.6/10.8%	18	100	100	3.7	NP	NP	NP					A-3	2
Spring Cemetery	NA	118.2/9.2%	100	118.4/9.3%	83			15.24	NP	NP	NP				4	A-2-4	2
Shelly Lake	106.1/13.3%	105.0/12.2%	12	105.6/10.4%	17@7.2%	100	98.7	3.4	NP	NP	NP	2.654	96.5	3	0.5	A-3	2
D1 SMR Pit	108.1/13.2%	108.8/12.1%	29	111.2/11.4%	35	100	100	4.1	NP	NP	NP	2.642				A-3	2
D4 SR 15	125.1/9.8%	125.1/9.1%	51	133.1/7.2%	143	67	52.9	12.5	NP	NP	NP					A-1-b	1
D4 SR 60	115.4/11.5%	117.0/9.2%	56	121.6/6.3%	91	100	96.2	10.3	NP	NP	NP					A-3	2
D4 SR 80	118.8/10.0%	120.5/9.6%	88	122.5/8.2%	85@9.1%	79.1	69.2	2.9	NP	NP	NP					A-3	1
D6 SR 826/NW 36	117.9/9.9%	116.9/9.5%	85@10.4%	122.3/8.8%	200	53	31.6	5.3	NP	NP	NP					A-1-a	1
D6 SR 826/NW 8	121.8/8.6%	121.1/8.8%	38	126.1/8.1%	109@7.4%	63.1	55.1	12.7	NP	NP	NP					A-1-b	1
UFRES # 1	110.7/13.3%	113.4/12.5%	47/11.7%	117.2/10.0%	85	93.5	81.2	30.0	NP	NP	NP	2.657	69	25	6	A-2-4	2
UFRES # 2	113.2/13.2%	113.4/12.5%	55/12.5%	119.5/10.9%	117	100	99.3	17.9	NP	NP	NP	2.648	82	9	9	A-2-4	2
UFRES # 3	112.8/12.8%	115.8/11.8%	47/9.7%	119.4/8.9%	126	100	100	12.2	NP	NP	NP	2.643	88	3	9	A-2-4	2
US 19	107.7/12.4%	109.0/12.1%	19/11.1%	108.5/9.5%	24	96.3	94	4.7	NP	NP	NP	2.652	95	1.5	3.5	A-3	2
Watson Pit	104.4/12.6%	104.7/14.4%	17@13.7%	105.2/11.0%	21@11.8%	100	100	2.2	NP	NP	NP					A-3	2

Table 3.1 Summary of Test Material Properties

Table 3.2 Compaction Work Sheet for Resilient Modulus Test

Compaction Work Sheet for Resilient Modulus

Standard Proctor : 5.5 lb hammer, 12" Dropping distance, 8" height, 27 blows, 5 equal layers

Soil Basic Properties

District	2	OPT MOISTURE (OMC, %)	12
Soil Location	Blue Rock Pit	4" STD MAX DENS. (DEN, pcf)	111.2
Material ID	BR001	4" Mold Volume (8-in Height) (cf)	0.05817
Lab Number	21982-S	Soil for each layer (lb) (Total 5 layers)	1.45
Soil Class	A-3	LBR	36
Soil Description	Black sand		

Optimum Water Content

Initial water content

(A) Ceramic Bowl (lb)	(B) Bowl+ Soil (lb)	(C)Bowl+Dry Soil (lb)	(D) Dry Soil (lb)	(E) Water (lb)	(F) Water Content (%)
					0.0000

Water needed to reach Optimum Water content

(G) Metal Pan (lb)	(H) Pan + Soil (lb)	(I) Soil (lb)	(J) Dry Soil (lb)	(K) Water needed (lb)	
1.433	17.7405	16.3075	16.3075	1.9569	

Water content after mixing

(A) Ceramic Bowl (lb)	(B) Bowl+ Soil (lb)	(C)Bowl+Dry Soil (lb)	(D) Dry Soil (lb)	(E) Water (lb)	(F) Water Content (%)
0.3485	0.7440	0.7015	0.3530	0.0425	12.0397

Water needed to reach Optimum Water content -0.0065 lb

Retest water content

(A) Ceramic Bowl (lb)	(B) Bowl+ Soil (lb)	(C)Bowl+Dry Soil (lb)	(D) Dry Soil (lb)	(E) Water (lb)	(F) Water Content (%)

Max. Dry Density

Sample 1 : BR001A1 **Prepared Date :** 12/18/2005 **Prepared by :** Ginger

(L) Mold + Soil (lb)	(M) Mold (lb)	(N) Soil (lb)	(O) Dry Density (pcf)	(P) Dry Density (pcf,corrected)
15.588	8.646	6.942	106.5157	NA

Water content after test

(A) Ceramic Bowl (lb)	(B) Bowl+ Soil (lb)	(C)Bowl+Dry Soil (lb)	(D) Dry Soil (lb)	(E) Water (lb)	(F) Water Content (%)
0.348	0.7970	NA	NA	NA	NA

MR Test Log **Test Date :** 12/18/2005 **Tested by :** Ginger

Test Parameter	88	Contact load	56	Stiffness	N.

RM5 doesn't work

Sample 2 : BR001B2 **Prepared Date :** 12/18/2005 **Prepared by :** Ginger

(L) Mold + Soil (lb)	(M) Mold (lb)	(N) Soil (lb)	(O) Dry Density (pcf)	(P) Dry Density (pcf,corrected)
15.7685	8.876	6.8925	105.7562	105.4042467

Water content after test

(A) Ceramic Bowl (lb)	(B) Bowl+ Soil (lb)	(C)Bowl+Dry Soil (lb)	(D) Dry Soil (lb)	(E) Water (lb)	(F) Water Content (%)
0.363	0.7705	0.7255	0.3625	0.0450	12.4138

MR Test Log **Test Date :** 12/18/2005 **Tested by :** Ginger

Test Parameter	89	Contact load	68		

Use A1 paremeter to start and it doesn't work. D gain too much cause unstable. RM didn't change much from Seq. 1~13.

Didn't adjust Seq. 6-10. Overshooting at Seq. 13-15.

Table 3.3 AASHTO T307-99 Test Procedures for Granular Materials

Test	AASHTO T307-99					
Material	Subgrade			Base/Subbase		
Procedure	Confining Pressure	Deviator Stress	No. of Load Applications	Confining Pressure	Deviator Stress	No. of Load Applications
Unit	kPa	kPa		kPa	kPa	
Specimen Condition	41.4	27.6	500-1000	103.4	103.4	500-1000
15 Testing Sequences	41.4	13.8	100	20.7	20.7	100
	41.4	27.6	100	20.7	41.4	100
	41.4	41.4	100	20.7	62.1	100
	41.4	55.2	100	34.5	34.5	100
	41.4	68.9	100	34.5	68.9	100
	27.6	13.8	100	34.5	103.4	100
	27.6	27.6	100	68.9	68.9	100
	27.6	41.4	100	68.9	137.9	100
	27.6	55.2	100	68.9	206.8	100
	27.6	68.9	100	103.4	68.9	100
	13.8	13.8	100	103.4	103.4	100
	13.8	27.6	100	103.4	206.8	100
	13.8	41.4	100	137.9	103.4	100
	13.8	55.2	100	137.9	137.9	100
	13.8	68.9	100	137.9	275.8	100

Table 3.4 AASHTO T307-99 Test Sequence for Subgrade Soil

Sequence No.	Confining Pressure		Max. Axial Stress		Cycle Stress		Constant Stress		No. of Load Applications
	kPa	psi	kPa	psi	kPa	psi	kPa	psi	500
0	41.4	6	27.6	4	24.8	3.6	2.8	0.4	100
1	41.4	6	13.8	2	12.4	1.8	1.4	0.2	100
2	41.4	6	27.6	4	24.8	3.6	2.8	0.4	100
3	41.4	6	41.4	6	37.3	5.4	4.1	0.6	100
4	41.4	6	55.2	8	49.7	7.2	5.5	0.8	100
5	41.4	6	68.9	10	62	9	6.9	1	100
6	27.6	4	13.8	2	12.4	1.8	1.4	0.2	100
7	27.6	4	27.6	4	24.8	3.6	2.8	0.4	100
8	27.6	4	41.4	6	37.3	5.4	4.1	0.6	100
9	27.6	4	55.2	8	49.7	7.2	5.5	0.8	100
10	27.6	4	68.9	10	62	9	6.9	1	100
11	13.8	2	13.8	2	12.4	1.8	1.4	0.2	100
12	13.8	2	27.6	4	24.8	3.6	2.8	0.4	100
13	13.8	2	41.4	6	37.3	5.4	4.1	0.6	100
14	13.8	2	55.2	8	49.7	7.2	5.5	0.8	100
15	13.8	2	68.9	10	62	9	6.9	1	100

Note: Load sequences 14 and 15 are not to be used for materials designated as Type 1.

Table 3.5 Output Data File for Resilient Modulus Test

MTS793|MPT|ENU|1|2|.|/|:|1|0|0|A								
Data Acquisition						Time:	644.14624	Sec
Ch 1 Force 2	Time	RM 1	RM 2	Ch 1 Count	RM 3	RM 4	RM 5	RM 6
lbf	Sec	in	in	segments	in	in	in	In
-25.439482	639.1687	0.016026491	0.018307414	1773	-0.002104864	0.006599932	0.007711109	-0.004444718
-2.4227951	639.70996	0.014676962	0.0173329	1774	-0.002269359	0.006599932	0.007754751	-0.004538715
-25.241348	640.16992	0.015999636	0.01828053	1776	-0.002111578	0.006593218	0.007704395	-0.004454789
-2.243341	640.43628	0.014670248	0.017306017	1777	-0.002266002	0.006589861	0.007754751	-0.004535358
-25.420183	641.16919	0.016026491	0.018287253	1779	-0.002114935	0.006596575	0.007697681	-0.004448075
-2.3185654	641.68262	0.014670248	0.017339621	1780	-0.002266002	0.006596575	0.007754751	-0.004532001
-25.165346	642.16943	0.015992921	0.01828053	1782	-0.002111578	0.006593218	0.007697681	-0.004454789
-2.3031259	642.7356	0.014650105	0.017346341	1783	-0.002262645	0.006593218	0.007758108	-0.004532001
-25.239399	643.17114	0.016006349	0.018307414	1785	-0.002108221	0.006596575	0.007707752	-0.004451432
-2.2212422	643.2251	0.014690391	0.017366504	1786	-0.002276073	0.006576433	0.007748037	-0.004542072

Table 3.6 Compaction Work Sheet for Permeability Test

Compaction Work Sheet for Permeability

Standard Proctor : 5 lb hammer, 12" Dropping distance, 4.584" height, 25 blows, 3 equal layers

District	5	OPT MOISTURE (OMC, %)	11.8
Soil Location	UFRES-3	4" STD MAX DENS. (DEN, pcf)	115.8
Material ID	UF003	4" Mold Volume (5-in Height) (cf)	1/30
Lab Number	21889-S	Soil for each layer (lb) (Total 5 layers)	1.44
Soil Class	A-2-4	LBR	126
Soil Description			

Sample 1 : UF003D **Prepared Date :** 9/22/2005 **Prepared by :** Mike

(A) Ceramic Bowl (lb)	(B) Bowl+ Soil (lb)	(C)Bowl+Dry Soil (lb)	(D) Dry Soil (lb)	(E) Water (lb)	(F) Water Content (%)
0.29	0.558	0.531	0.241	0.0270	11.2033
(G) Metal Pan (lb)	(H) Pan + Soil (lb)	(I) Soil (lb)	(J) Dry Soil (lb)	(K) Water needed (lb)	
1.4575		5.0155	4.5102	0.0269	
Retset Water Content after Mixing					
(A) Ceramic Bowl (lb)	(B) Bowl+ Soil (lb)	(C)Bowl+Dry Soil (lb)	(D) Dry Soil (lb)	(E) Water (lb)	(F) Water Content (%)
0.2895	0.5105	0.4865	0.197	0.0240	12.1827
(L) Mold + Soil (lb)	(M) Mold (lb)	(N) Soil (lb)	(O) Dry Density (pcf)		
8.8275	4.5045	4.323	115.6060		

Gs	2.643
e (Void Ratio) = (Gs * rw - rd)/ rd	0.426597012
S (Degree of Saturation) = wGs/e	0.754786927
Required backpressure for 97% degree of saturation	70 psi

Remark

use 110 psi to get 98% saturation

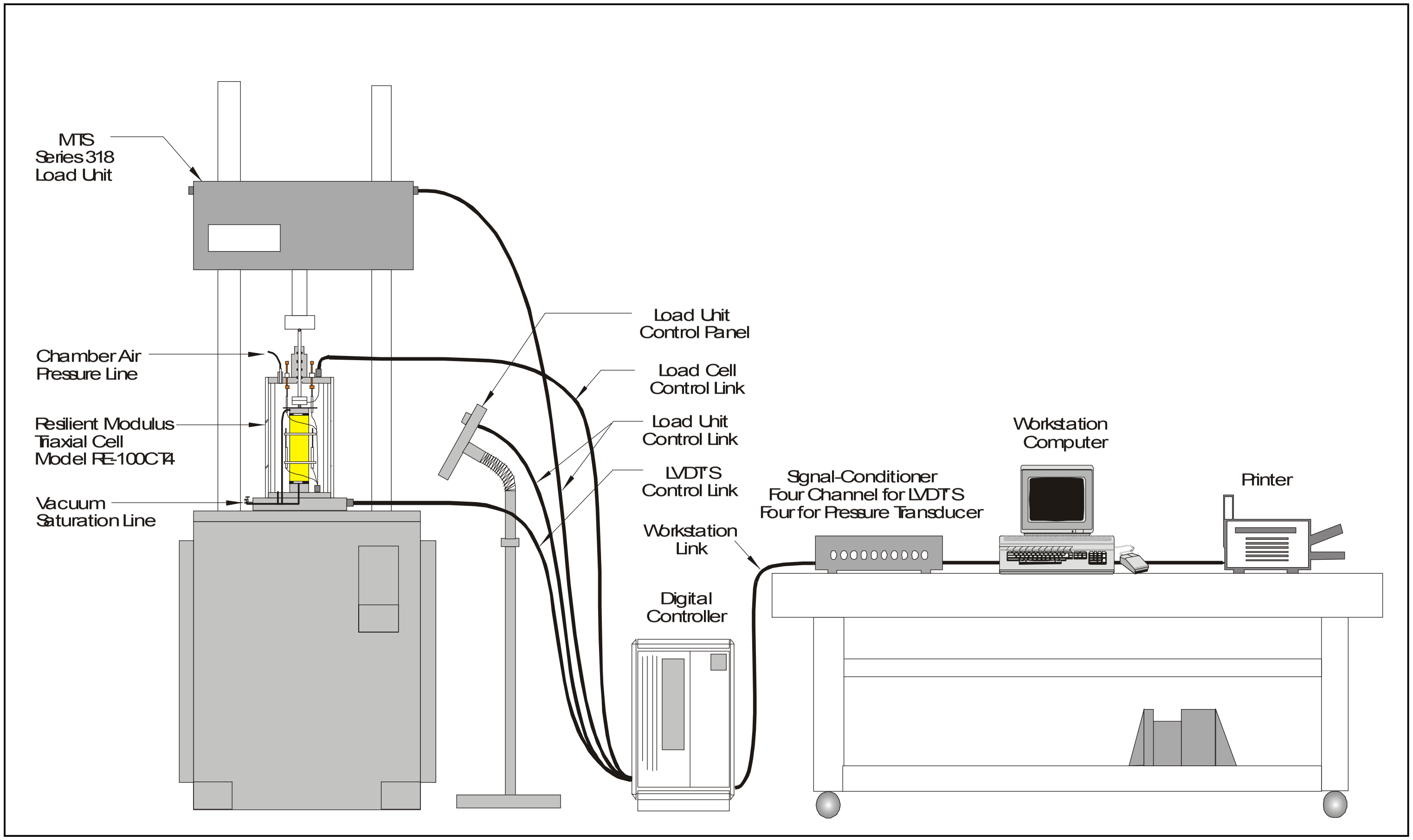


Figure 3.1 Sketch of Resilient Modulus Testing Equipment

Figure 3.2 Resilient Modulus Test Setup

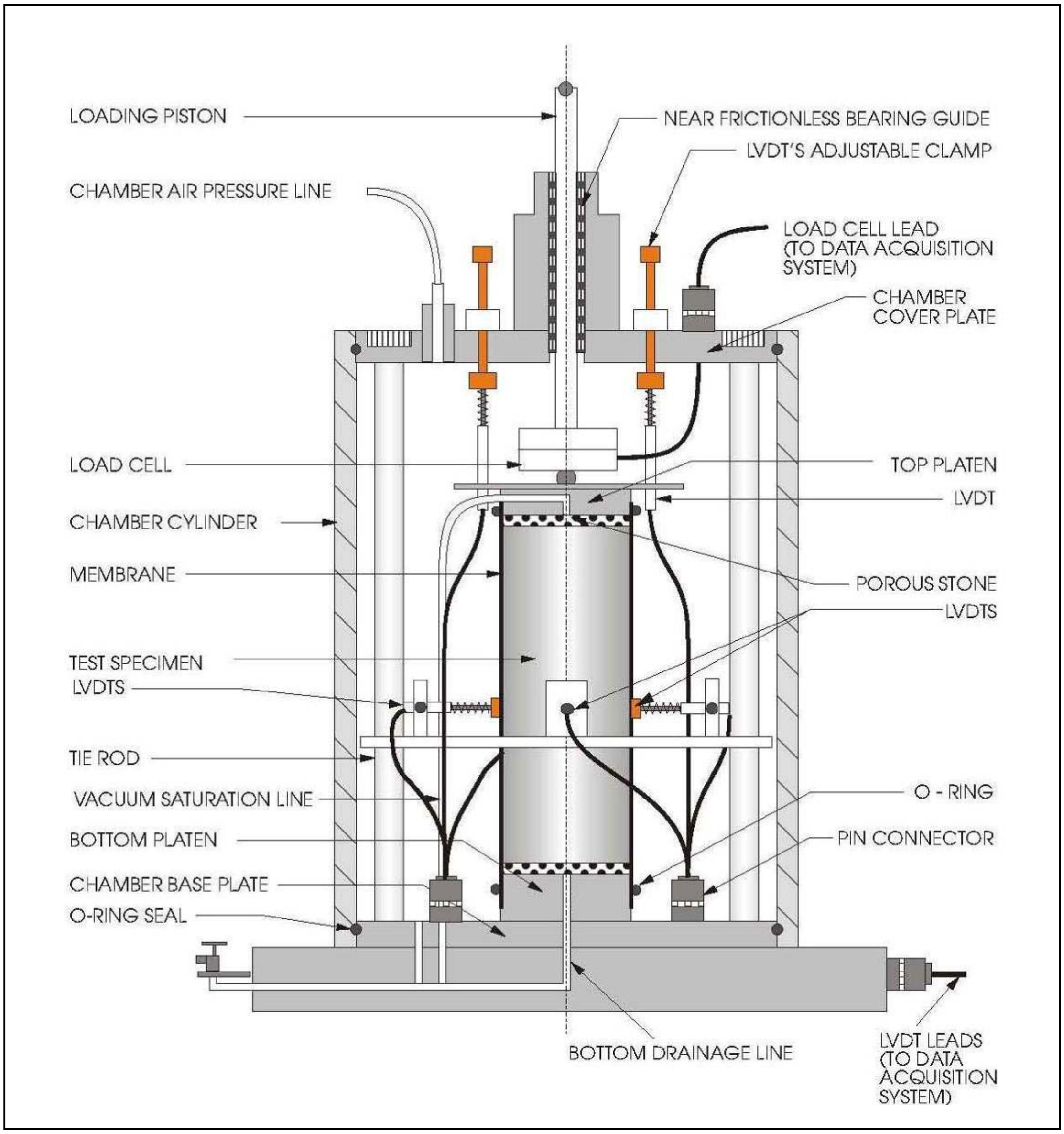


Figure 3.3 Triaxial Cell Assembly for Resilient Modulus Test

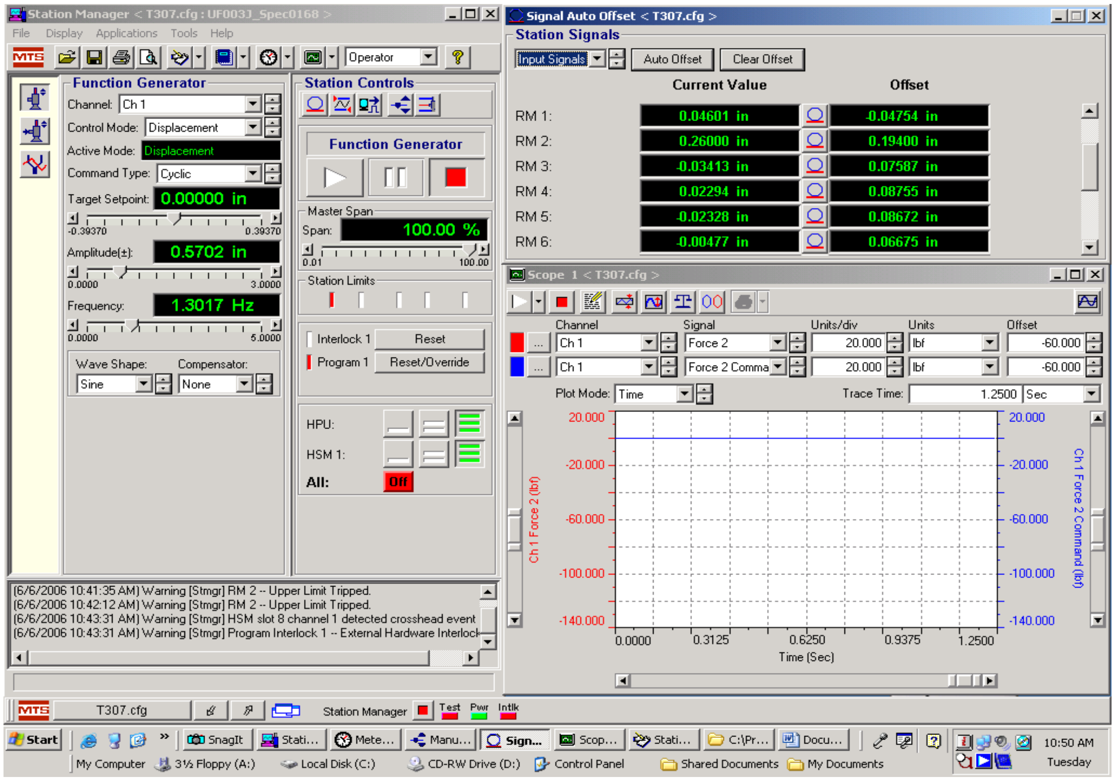


Figure 3.4 Resilient Modulus Testing Software

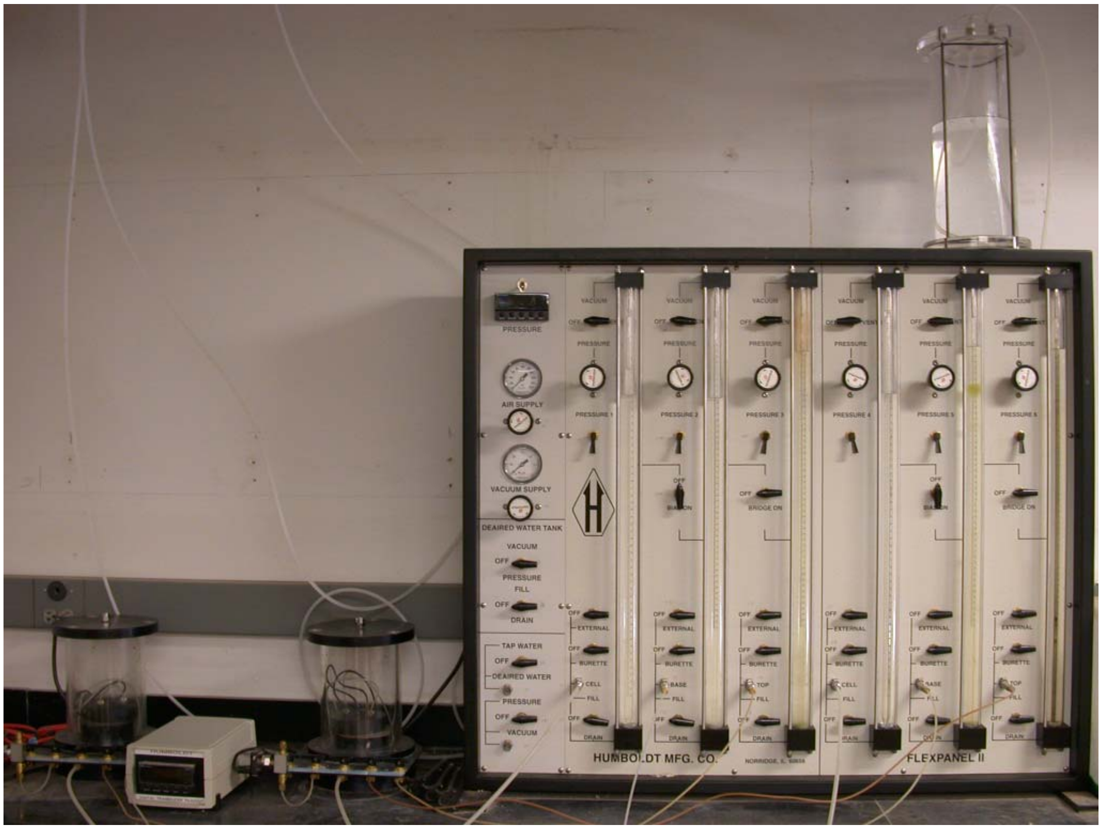


Figure 3.5 Permeability Testing Equipment

CHAPTER 4
PRESENTATION OF EXPERIMENTAL RESULTS

4.1 GENERAL

The resilient modulus and permeability test results are presented in this chapter. A total of 168 resilient modulus tests and 19 permeability tests were performed and the data were recorded in a Microsoft Excel file format for each test. The Excel data file for each resilient modulus test was then stored in a database using Microsoft Access. Detailed presentations of the test data are described in the following sections. In particular, the focus is on the presentation of the resilient modulus test results using the AASHTO Designation T307-99 test method.

4.2 RESILIENT MODULUS TEST RESULTS

Each resilient modulus test included 15 sets of modulus data corresponding to the various combinations of confining pressure and deviator stress when tested using the T307-99 method. The test results were presented in an MS Excel file, which included the resilient modulus data for each test sequence and two regression models, one for the resilient modulus versus bulk stress and the other one for the resilient modulus versus confining stress. A typical summary sheet of the test data is presented in Table 4.1. A typical regression relationship between the resilient modulus and bulk stress is illustrated in Figure 4.1, while Figure 4.2 demonstrates a typical regression relationship between the resilient modulus and confining pressure. A complete set of test data files was stored in the enhanced resilient modulus database “MRAnalyzer” CD-ROM disk. The individual file name indexes are summarized and attached in Appendix A.

A summary of the resilient modulus test results together with other engineering properties is presented in Table 4.2. Some test data were left out due to the problems encountered during testing in the laboratory. The average resilient modulus values at 2 psi confining pressure as well as at 11 psi bulk stress were obtained for each soil material. The resilient modulus values under the conditions of optimum moisture content (within +/- 0.5% for Type 2 materials, and +/- 1.0% for Type 1 materials) and maximum wet unit weight (within 97% range) were then selected and averaged to represent the average resilient modulus value at their optimum condition for each soil material.

It should be noted that the resilient modulus test data were obtained based on the full-length, internal LVDT measurement. According to a previous study (Ping and Hoang, 1996), the resilient modulus obtained from the external-mounted LVDT measurements will result in slightly lower values than those obtained from the internal-mounted LVDT measurements. The average resilient modulus ratio between the values obtained from the external and the internal LVDT measurements ranged from 0.87 at 3 psi confining pressure to 0.69 at 20 psi confining pressure for A-3 soils. For A-2-4 soils, the average resilient modulus ratio could be higher. If the resilient modulus test data were obtained conforming to the AASHTO T-307 test procedure with external LVDT measurements, a 10% reduction of the resilient modulus test results should be applied to correct the difference between the external-mounted LVDT measurements and the internal-mounted LVDT measurements at 2 psi confining pressure.

4.3 POISSON'S RATIO TEST RESULTS

The experimental setup of the resilient modulus test in the triaxial chamber was capable of measuring the horizontal deformations of the specimen under various stress conditions. The average value of the four measured horizontal deformations (ε_h) and the measured vertical deformations (ε_v) were used to calculate the Poisson's ratio following Equation 3.2. The Poisson's ratios were recorded in the raw data sheet for each test file. Some of the Poisson's ratios were found to be unstable in this study. A wide range of values were measured for some identical specimens under various test sequences. A discussion of the Poisson’s ratio data is given in Chapter 5.

4.4 PERMEABILITY TEST RESULTS

A total of 19 permeability tests were performed in this study. A typical data summary sheet for the permeability test is presented in Table 4.3. A summary of all the permeability test results is presented in Table 4.4. The file name indexes are also included in Table 4.4 for reference. In addition to the Excel files, the test results were also saved in the database.

The test materials contained a wide range of percent of fines (% passing sieve No. 200) varying from 2.0% to 34.8%. One permeability test for a subgrade material with 2.0% fines obtained from Polk Masaic Mine (FDOT District 1) failed and was not reported in the table. For some A-3 soils (D1 Earth Source, D4 SR 60, and D2 Watson Pit) with permeability values greater than 1E-4 cm/sec and less than 1E-3 cm/sec, the water ran through the burettes with a faster speed during the test resulting in a shorter time to monitor the water flow.

With an additional seven permeability tests from a previous project, a total of 25 permeability test data were available for further analysis.

4.5 DEVELOPMENT OF DATABASE

A new database “MRAnalyzer.mdb” was established to enhance the manipulation of an early version of the resilient modulus database “soillab.mdb”. The original table structures and all of the T-292 and T-294 resilient modulus test data were kept and imported to the new database. To separate the T307-99 test results from the T-292 and T-294, all of the T307-99 test result data including the 15 test sequences for each test were saved in a table “MRTestT307Data” in the database. The average resilient modulus values at the 2 psi confining pressure, along with the test conditions for each test, were then saved into the table “MRTestT307” for further analysis. Results of the 168 resilient modulus tests were added into the database “MRAnalyzer.mdb”. A complete set of the resilient modulus test data is presented in the database.

The new database “MRAnalyzer.mdb” was designed to easily access the resilient modulus test data and to correlate the resilient modulus with the soil material properties and other data analyses. In addition to storing the resilient modulus test data, the Poisson’s ratio data were saved in the table “MRTestT307PRData” for further analysis. The relationships among the tables in the database are presented in Figure 4.3

for information. Some tables in the database were created by querying fields from other relational tables to make a new connection for analysis purposes. A relational table listing all of its fields is presented in Appendix C.

4.6 APPLICATION OF DATABASE

To prevent any loss of the test data, the database was locked for viewing purpose only. Users can not add, delete, or edit the data from the application. A summary of the Main SwitchBoard was presented upon the opening of the database. Users without access authorization can only view the data. Figure 4.4 shows the on-open Main SwitchBoard. Three main functions included in the Main SwitchBoard are Data Presentation, Data Analysis, and Data Report. A help menu was also provided in the database.

4.6.1 Data Presentation

The resilient modulus test data were stored in two different tables. The average resilient modulus values at 2 psi confining pressure from the T307-99 test method were stored in a table “tblMRTestT307”, while those from the T-292 and T-294 test methods were placed in another table “tblMRTestT292T294”. Figure 4.5 shows the application interface for the “View Test Data” functions. The 15 resilient modulus test data for each sequence using the T307-

99 are shown in Figure 4.6, while Figure 4.7 illustrates the relationship between the resilient modulus and confining pressure and Figure 4.8 demonstrates the relationship between the resilient modulus and bulk stress. Figure 4.9 presents the 15 resilient modulus test data for each sequence using the T-292 and T-294 test procedures. Each main table has a sub table to store the 15 sequences of test data points. The sub tables are named “tblMRTestT307Data” and “tblMRTestT292T294Data”. A total of 349 sets of resilient modulus test data, which included 181 sets of the T292T294 data and 168 sets of the T307 data, were presented in the database. Among those data sets, the T307 had a total of 123 sets of reliable data, while the T292 had a total of 164 sets of reliable data and the T294 had only 17 sets of reliable data. Among those reliable data sets, some were tested at their optimum conditions and some were not. The total number of the reliable data sets representing the optimum conditions was 167. The number of the average resilient modulus data sets at the optimum condition was 79 in total, which included 33 data sets from T307 and 46 data sets from T292. A summary table listing the numbers of the tests and the numbers of materials for all situations is provided in Table 4.5. A step-by-step user’s guide through the “MRAnalyzer.mdb” data application is presented in Appendix C for reference.

4.6.2 Data Analysis

The analysis of relationships between resilient modulus and other soil properties can be performed interactively using the application. The comparative analyses are further performed and discussed in Chapter 5. A sub-menu of the “Data Analysis” window displays the available functions for retrieving resilient modulus and permeability test data with other soil parameters. The interfaces are illustrated in Figure 4.10, Figure 4.11, and Figure 4.12.

A step-by-step data analysis guide through the “MRAnalyzer.mdb” application is presented in Appendix C.

4.6.3 Data Report

The “MRAnalyzer.mdb” application can be used to produce the test report according to user’s request. Two default reports of the table structure and the permeability test summary table were included in the database. Figure 4.13 shows the available report functions. A typical database test report is presented in Figure 4.14. However, users can build their own test reports according to their needs using the “report” function in the database.

A step-by-step user’s guide through the “MRAnalyzer.mdb” application is attached in Appendix C.

Table 4.1 Typical Data Summary Sheet for Resilient Modulus Test

RESILIENT MODULUS TEST RESULTS

SOILS LABORATORY, FAMU-FSU COLLEGE OF ENGINEERING

SAMPLE ID:	BR001	TEST NO:	G1
PROJECT ID:		SPECIMEN PREPARATION DATE:	3/17/2006
LAB NO:	21982-S	SPECIMEN DIAMETER, TOP, (in):	4
SOIL CLASS:	A-3	SPECIMEN DIAMETER, MIDDLE, (in):	4
LBR	36	SPECIMEN DIAMETER, BOTTOM, (in):	4
STD OPT MOIST (%):	12	SPECIMEN HEIGHT (in):	8
STD MAX DRY DEN (pcf):	111.2	COMPACTION MC, (%):	12
		COMPACTION DRY DEN, (pcf):	108.2
		MC AFTER TESTING, (%):	11.9
		TESTED BY:	Ed
		TEST DATE:	3/19/2006

PRECONDITION INFORMATION	
CONFINING STRESS (psi):	6
MAX. AXIAL STRESS (psi):	4
REPETITIONS:	500

REMARKS:

TEST SEQ. #	CONFINING STRESS	MAX. AXIAL STRESS	CONTACT STRESS	CYCLIC STRESS	BULK STRESS	RESILIENT STRAIN	RESILIENT MODULUS
	psi	psi	psi	psi	psi	in/in	psi
1	6	1.985086067	0.166794	1.818292	19.98509	8.2369E-05	22074.9523
2	6	3.972475191	0.2459177	3.726557	21.97248	0.00016524	22551.7332
3	6	5.986175064	0.2259307	5.760244	23.98618	0.00026726	21553.1254
4	6	8.020435191	0.2843707	7.736065	26.02044	0.00035954	21516.753
5	6	10.18190621	0.3853204	9.796586	28.18191	0.0004498	21779.8506
6	4	1.978941513	0.1655548	1.813387	13.97894	0.00012015	15092.1989
7	4	3.90490957	0.3673043	3.537605	15.90491	0.00022494	15727.0088
8	4	6.006731783	0.2856185	5.721113	18.00673	0.00035181	16262.1495
9	4	8.00892914	0.369064	7.639865	20.00893	0.00044299	17246.2202
10	4	10.22354363	0.4662066	9.757337	22.22354	0.0005393	18092.6819
11	2	1.985037882	0.1798429	1.805195	7.985038	0.00016852	10711.8962
12	2	3.994491672	0.3399264	3.654565	9.994492	0.00030925	11817.6759
13	2	6.043062994	0.356429	5.686634	12.04306	0.00044921	12659.1732
14	2	7.983940924	0.4412571	7.542684	13.98394	0.0005587	13500.498
15	2	7.983940924	0.4412571	7.542684	13.98394	0.0005587	13500.498

Table 4.2 Summary of Resilient Modulus Test Results

Summary of Resilient Modulus Test Results (1)

Index No.	FDOT Lab. #	Soil Class	Passing #200	Clay	4" T-99 OMC	4" T-99 MDD	6" T-180 LBR	FSU Sample ID	FSU Test #	Compaction Method	Test Method	Test Date	Regression Model		Avg. MR (2psi Confining Pressure)	MR (11 psi Bulk Stress)
			%	%	%	pcf							$MR=k1\theta^{k2}$	R^2	psi	psi
1	21157	A-2-4			12.1	110.8	14	21157	S1	4" T-180	T307	5/11/2004	$y = 3275x^{0.4869}$	0.8782	11824.26	10526.05
2								21157	S2	4" T-180	T307	5/12/2004	$y = 3275.8x^{0.5044}$	0.9517	11109.71	10979.84
3	21158	A-2-4			13.0	110.2	17	21158	S1	4" T-180	T307	6/10/2004	$y = 6287.6x^{0.3791}$	0.9083	15702.64	15605.47
4								21158	S2	4" T-180	T307	6/14/2004	$y = 5189.6x^{0.4213}$	0.9458	14341.78	14251.90
5	21159	A-2-4			12.9	108.5	13	21159	S1	4" T-180	T307	6/11/2004	$y = 3259.4x^{0.5882}$	0.9182	12668.44	13356.26
6								21159	S2	4" T-180	T307	6/14/2004	$y = 4402.3x^{0.4627}$	0.9296	12944.87	13351.56
7	21383	A-2-4	11		11.6	109.4	54	21383	S1	4" T-180	T307	5/17/2004	$y = 2229.4x^{0.611}$	0.9190	9719.78	9648.92
8								21383	S2	4" T-180	T307	5/18/2004	$y = 3684.9x^{0.464}$	0.9535	11295.85	11210.68
9	21384	A-3	9		12.8	106.9	57	21384	S1	4" T-180	T307	5/13/2004	$y = 3158.3x^{0.5004}$	0.8584	9584.94	10484.95
10								21384	S2	4" T-180	T307	5/14/2004	$y = 3088.5x^{0.5378}$	0.9226	11454.44	11215.24
11	21385	A-3	10		11.3	111.6	46	21385	S1	4" T-180	T307	5/19/2004	$y = 1325.2x^{0.7729}$	0.9464	8689.06	8456.17
12								21385	S2	4" T-180	T307	5/20/2004	$y = 2458.7x^{0.5928}$	0.8723	10211.72	10186.93
13	21386	A-3	6		11.9	108.2	42	21386	S1	4" T-180	T307	5/24/2004	$y = 3268.4x^{0.5492}$	0.9013	12172.44	12197.42
14								21386	S2	4" T-180	T307	5/25/2004	$y = 3400.5x^{0.5329}$	0.8709	12172.02	12203.96
15	21387	A-3	7		11.7	107.7	39	21387	S1	4" T-180	T307	5/26/2004	$y = 2419.2x^{0.6205}$	0.9322	10875.24	10711.64
16								21387	S2	4" T-180	T307	5/27/2004	$y = 2625.5x^{0.5904}$	0.8981	10811.63	10815.59
17	21388	A-3	7		12.0	107.4	52	21388	S1	4" T-180	T307	6/2/2004	$y = 3099.9x^{0.5741}$	0.9616	12552.25	12280.36
18								21388	S2	4" T-180	T307	6/2/2004	$y = 3614x^{0.5282}$	0.9488	13102.18	12824.83
19	21389	A-3	6		12.9	107.6	49	21389	S1	4" T-180	T307	6/3/2004	$y = 2427.5x^{0.621}$	0.9383	11051.35	10761.28
20								21389	S2	4" T-180	T307	6/3/2004	$y = 2426.4x^{0.6195}$	0.9163	11154.86	10717.79
21	21390	A-3	5		13.0	104.5	27	21390	S1	4" T-180	T307	6/4/2004	$y = 3660.9x^{0.5928}$	0.7643	14532.02	15167.90
22								21390	S2	4" T-180	T307	6/7/2004	$y = 2885.2x^{0.6375}$	0.9067	13316.35	13306.50
23	21391	A-3	6		14.5	104.1	33	21391	S1	4" T-180	T307	6/8/2004	$y = 4640.8x^{0.4435}$	0.9195	13479.30	13441.59
24								21391	S2	4" T-180	T307	6/9/2004	$y = 4348.4x^{0.4751}$	0.9843	13953.58	13586.11
25	NA	A-2-4	14		11.2	118.8		LS001	A1	4" T-180	T307	1/24/2005	$y = 2830.1x^{0.6311}$	0.9846	13698.93	12853.60
26								LS001	A2	4" T-180	T307	1/27/2005	$y = 3308.8x^{0.6214}$	0.9535	15591.43	14682.23
27								LS001	B1	4" T-180	T307	1/27/2005	$y = 15406x^{0.2291}$	0.9904	27775.34	26685.35
28								LS001	B2	4" T-180	T307	1/28/2005	$y = 4562.2x^{0.5294}$	0.9643	17125.91	16236.32
29								LS001	B3	4" T-180	T307	1/28/2005	$y = 2807x^{0..6692}$	0.8269	15721.12	13968.26
30								LS001	B4	4" T-180	T307	1/28/2005	$y = 2599.4x^{0..7268}$	0.9568	16092.70	14851.06

Table 4.2 Summary of Resilient Modulus Test Results (Continued)

Summary of Resilient Modulus Test Results (2)

Index No.	FDOT Lab. #	Soil Class	Pass# 200	Clay	4" T-99 OMC	4" T-99 MDD	6" T-180 LBR	FSU Sample ID	FSU Test #	Compaction Method	Test Method	Test Date	Regression Model		Avg. MR (2psi Confining Pressure)	MR (11 psi Bulk Stress)
			%	%	%	pcf							$MR=k1\theta^{k2}$	R^2	psi	psi
31								SC001	C1	4" T-99	T307	11/17/2005	$y = 2795.9x^{0..5608}$	0.9495	9920.73	10728.39
32	21665-7	A-2-4	15	4	9.2	118.2	83	SC001	D1	4" T-99	T307	11/18/2005	$y = 2340.7x^{0..5801}$	0.9739	8672.81	9407.14
33								SC001	E1	4" T-99	T307	2/3/2006	$y = 2383.4x^{0..5511}$	0.9832	8384.70	8935.29
34								SC001	F1	4" T-99	T307	2/3/2006	$y = 2357.7x^{0..5944}$	0.9435	9640.03	9806.01
35								BH001	C1	4" T-99	T307	11/18/2005	$y = 9752.3x^{0..3848}$	0.5244	21985.44	24537.76
36								BH001	D2	4" T-99	T307	11/18/2005	$y = 6444.4x^{0..6256}$	0.7156	25260.62	28885.36
37	21671-3	A-2-4	24	6	8.8	128.4	132	BH001	E1	4" T-99	T307	12/7/2005	$y = 12551x^{0.3171}$	0.4444	25285.21	26847.51
38								BH001	F1	4" T-99	T307	12/7/2005	$y = 11636x^{0.3637}$	0.4793	26110.14	27832.89
39								BH001	G1	4" T-99	T307	3/22/2006	$y = 3592.1x^{0.577}$	0.7335	13997.09	14329.53
40								BH001	H1	4" T-99	T307	3/22/2006	$y = 5283.8x^{0.4985}$	0.6085	16384.36	17461.46
41								IB001	C1	4" T-99	T307	11/22/2005	$y = 3897.9x^{0..3678}$	0.7348	9906.53	9415.75
42	21668-70	A-2-6	32	16	10.3	123.3	127	IB001	D1	4" T-99	T307	11/22/2005	$y = 3555.2x^{0.3946}$	0.7027	9714.83	9157.94
43								IB001	E1	4" T-99	T307	2/7/2006	$y = 3779.6x^{0.3762}$	0.6927	10268.80	9315.75
44								IB001	F1	4" T-99	T307	2/7/2006	$y = 4163.2x^{0.3269}$	0.6658	9597.77	9117.14
45								AP001	C1	4" T-99	T307	10/8/2005	$y = 6422.4x^{0.1784}$	0.9280	9030.66	9851.03
46								AP001	D1	4" T-99	T307	10/11/2005	$y = 6182.3x^{0.1969}$	0.9869	8920.96	9912.89
47								AP001	E3	4" T-99	T307	10/17/2005	$y = 9381.7x^{0..2483}$	0.8467	14870.32	17016.07
48								AP001	F1	4" T-99	T307	10/18/2005	$y = 8619.1x^{0.19}$	0.7359	12803.80	13593.35
49	21851-S	A-2-4	17.3	12	10.0	120.2	141	AP001	G1	4" T-99	T307	10/19/2005	$y = 7622.2x^{0.2362}$	0.9352	12222.71	13429.42
50								AP001	H1	4" T-99	T307	10/19/2005	$y = 7276x^{0.2395}$	0.8708	11707.96	12921.30
51								AP001	I1	4" T-99	T307	11/10/2005	$y = 4399.8x^{0.4801}$	0.9405	14227.72	13912.51
52								AP001	J1	4" T-99	T307	11/10/2005	$y = 2197.3x^{0.6222}$	0.9864	10204.52	9768.86
53								AP001	K3	4" T-99	T307	2/1/2006	$y = 1466.6x^{0.727}$	0.9467	8556.71	8383.09
54								AP001	L1	4" T-99	T307	2/1/2006	$y = 2798.1x^{0.5892}$	0.9616	12301.34	11493.49
55								FF001	A1	4" T-99	T307	10/21/2005	$y = 9924.8x^{0.1717}$	0.6890	14398.16	14980.59
56								FF001	B1	4" T-99	T307	10/21/2005	$y = 9166.8x^{0.1492}$	0.7736	12573.50	13109.72
57								FF001	C1	4" T-99	T307	10/22/2005	$y = 9111.3x^{0.1682}$	0.8042	12972.98	13637.75
58								FF001	D2	4" T-99	T307	10/22/2005	$y = 7899x^{0.1297}$	0.7506	10072.80	10780.55
59	21852-S	A-2-4	20.4	18	13.3	116.4	108	FF001	D3	4" T-99	T307	10/22/2005	$y = 6154x^{0.2441}$	0.8649	9805.70	11049.98
60								FF001	E1	4" T-99	T307	11/15/2005	$y = 4451.9x^{0.4948}$	0.9852	15360.27	14582.32
61								FF001	F1	4" T-99	T307	11/16/2005	$y = 5360x^{0.4034}$	0.9843	14171.94	14101.41
62								FF001	G1	4" T-99	T307	2/9/2006	$y = 4053.2x^{0.4608}$	0.9794	12647.55	12236.91
63								FF001	H1	4" T-99	T307	2/9/2006	$y = 2079.6x^{0.6683}$	0.9539	10558.48	10326.25

Table 4.2 Summary of Resilient Modulus Test Results (Continued)

Summary of Resilient Modulus Test Results (3)

Index No.	FDOT Lab. #	Soil Class	Pass# 200	Clay	4" T-99 OMC	4" T-99 MDD	6" T-180 LBR	FSU Sample ID	FSU Test #	Compaction Method	Test Method	Test Date	Regression Model		Avg. MR (2psi Confining Pressure)	MR (11 psi Bulk Stress)
			%	%	%	pcf							$MR=k1\theta^{k2}$	R^2	psi	psi
64	21887-S	A-2-4	30	6	13.3	110.7	85	UF001	A1	4" T-99	T307	8/11/2005	$y = 7557.2x^{0.2359}$	0.9636	11638.61	13305.32
65								UF001	A2	4" T-99	T307	8/11/2005	$y = 7872.2x^{0.2254}$	0.8665	11459.25	13515.31
66								UF001	A3	4" T-99	T307	8/12/2005	$y = 8337.9x^{0.2354}$	0.8604	12466.88	14662.25
67								UF001	B1	4" T-99	T307	8/18/2005	$y = 7566.3x^{0.1656}$	0.5734	9297.67	11254.81
68								UF001	E1	4" T-99	T307	11/3/2005	$y = 4740.1x^{0.5021}$	0.9719	15400.10	15800.50
69								UF001	F1	4" T-99	T307	11/4/2005	$y = 4968.8x^{0.4585}$	0.9370	14793.94	14918.67
70								UF001	G1	4" T-99	T307	2/23/2006	$y = 2310.7x^{0.6491}$	0.9536	11773.98	10957.50
71								UF001	H1	4" T-99	T307	2/23/2006	$y = 3052x^{0.5494}$	0.9563	12110.20	11395.30
72								UF001	I1	4" T-99	T307	3/30/2006	$y =2518.1x^{0.6484}$	0.9299	12485.31	11920.98
73								UF001	J1	4" T-99	T307	3/30/2006	$y = 3851.7x^{0.4919}$	0.9269	12552.16	12528.92
74	21888-S	A-2-4	17.9	9	13.2	113.2	117	UF002	A1	4" T-99	T307	8/23/2005	$y = 7565.3x^{0.2128}$	0.8138	11489.63	12601.86
75								UF002	B1	4" T-99	T307	8/24/2005	$y = 6714.7x^{0.198}$	0.9033	9518.29	10794.99
76								UF002	E1	4" T-99	T307	11/8/2005	$y = 5516.4x^{0.4133}$	0.8813	14053.88	14861.52
77								UF002	F1	4" T-99	T307	11/8/2005	$y = 5024.2x^{0.4496}$	0.9108	14126.66	14766.48
78								UF002	G1	4" T-99	T307	2/24/2006	$y = 1677.1x^{0.6264}$	0.9640	8166.11	7531.60
79								UF002	H1	4" T-99	T307	2/24/2006	$y = 2256x^{0.5618}$	0.9312	9422.55	8677.48
80								UF002	I1	4" T-99	T307	3/23/2006	$y = 2137.9x^{0.6234}$	0.9593	9913.28	9532.17
81								UF002	J1	4" T-99	T307	3/23/2006	$y = 1500.9x^{0.7373}$	0.9883	NA	8793.68
82	21889-S	A-2-4	12.2	9	12.8	112.8	126	UF003	A1	4" T-99	T307	9/7/2005	$y = 10090x^{0.1158}$	0.8489	12959.91	13319.39
83								UF003	B1	4" T-99	T307	9/14/2005	$y = 6644.8x^{0.195}$	0.6365	9853.72	10606.05
84								UF003	C1	4" T-99	T307	9/15/2005	$y = 6109.7x^{0.2017}$	0.9308	8941.19	9909.89
85								UF003	E1	4" T-99	T307	11/9/2005	$y = 4964.7x^{0.4748}$	0.9048	14657.57	15500.52
86								UF003	F1	4" T-99	T307	11/9/2005	$y = 3978.9x^{0.5391}$	0.9266	13806.40	14493.65
87								UF003	G1	4" T-99	T307	2/17/2006	$y = 1632.1x^{0.723}$	0.9189	NA	9240.04
88								UF003	H1	4" T-99	T307	2/17/2006	$y = 2565.7x^{0.5677}$	0.9324	10956.79	10009.32
89								UF003	I1	4" T-99	T307	3/31/2006	$y = 2012x^{0.628}$	0.9543	9345.17	9070.32
90								UF003	J1	4" T-99	T307	3/31/2006	$y = 1843.9x^{0.6077}$	0.9627	7718.29	7917.57
91	21881-S	A-2-6	34.8	27.3	15.8	111.6	109	BF001	A1	4" T-99	T307	10/28/2005	$y = 7263.4x^{0.2492}$	0.9601	12163.71	13202.46
92								BF001	B5	4" T-99	T307	10/28/2005	$y = 10511x^{0.339}$	0.3311	20526.57	23696.06
93								BF001	C1	4" T-99	T307	11/4/2005	$y = 6292.2x^{0..3769}$	0.2584	12912.14	15534.72
94								BF001	D1	4" T-99	T307	11/4/2005	$y = 4645x^{0.4555}$	0.3046	11465.57	13846.50
95								BF001	F1	4" T-99	T307	1/31/2006	$y =2447x^{0.6143}$	0.4460	9620.44	10674.84
96								BF001	G1	4" T-99	T307	1/31/2006	$y = 5654x^{0.3716}$	0.3540	11742.24	13782.80
97								BF001	H1	4" T-99	T307	2/10/2006	$y =5845.5x^{0.4259}$	0.5674	15186.16	16231.21
98								BF001	I1	4" T-99	T307	2/10/2006	$y = 7581x^{0.3493}$	0.5470	16656.40	17518.02

Table 4.2 Summary of Resilient Modulus Test Results (Continued)

Summary of Resilient Modulus Test Results (4)

Index No.	FDOT Lab. #	Soil Class	Pass #200	Clay	4" T-99 OMC	4" T-99 MDD	6" T-180 LBR	FSU Sample ID	FSU Test #	Compaction Method	Test Method	Test Date	Regression Model		Avg. MR (2psi Confining Pressure)	MR (11 psi Bulk Stress)
			%	%	%	pcf							$MR=k1\theta^{k2}$	R^2	psi	psi
99	21897-S	A-2-6	23	20.8	12.6	117.2	78	BF002	A5	4" T-99	T307	10/31/2005	$y = 4970.4x^{0.5513}$	0.9585	18226.59	18642.80
100								BF002	B3	4" T-99	T307	11/1/2005	$y = 11119x^{0.3018}$	0.3430	20775.60	22927.57
101								BF002	C1	4" T-99	T307	11/5/2005	$y = 17436x^{0.2182}$	0.2511	26456.72	29422.44
102								BF002	D1	4" T-99	T307	11/5/2005	$y = 9562.1x^{0.3599}$	0.5006	20500.39	22664.73
103								BF002	E1	4" T-99	T307	12/10/2005	$y = 4404.8x^{0.5642}$	0.9204	19363.47	17040.41
104								BF002	F1	4" T-99	T307	12/10/2005	$y = 3447.1x^{0.6616}$	0.9288	19000.81	16843.77
105								BF002	G1	4" T-99	T307	2/14/2006	$y = 5300.5x^{0.3486}$	0.9188	12747.75	12227.74
106								BF002	H1	4" T-99	T307	2/15/2006	$y = 2895.8x^{0.4823}$	0.7454	10328.97	9205.18
107	21906-S	A-3	2	2	14.7	104.9	28	MM001	A1	4" T-99	T307	11/23/2005	$y = 6171.6x^{0.4042}$	0.9460	15555.33	16267.80
108								MM001	B1	4" T-99	T307	11/23/2005	$y =3937.9x^{0.5518}$	0.9479	13983.70	14787.85
109								MM001	D1	4" T-99	T307	2/18/2006	$y =6209.2x^{0.4119}$	0.9248	16757.58	16671.91
110								MM001	E1	4" T-99	T307	2/18/2006	$y =5232.5x^{0.4744}$	0.9320	16360.34	16320.97
111	21905-S	A-3	5	3	16.3	105.8	32	CR3901	A1	4" T-99	T307	11/30/2005	$y = 3945.1x^{0.5486}$	0.8302	13504.41	14701.65
112								CR3901	B1	4" T-99	T307	11/30/2005	$y = 3061x^{0.6142}$	0.9177	12434.46	13350.17
113								CR3901	C1	4" T-99	T307	12/8/2005	$y = 3596.1x^{0.5807}$	0.9423	14514.80	14473.33
114								CR3901	D1	4" T-99	T307	12/9/2005	$y = 3234.2x^{0.5558}$	0.9764	12415.16	12262.33
115	21910-S	A-3	3.4	0.5	13.3	106.1	17	SL001	A1	4" T-99	T307	12/1/2005	$y = 4144.2x^{0.5612}$	0.9389	14253.63	15917.33
116								SL001	B1	4" T-99	T307	12/1/2005	$y = 5522x^{0.4944}$	0.9719	16804.97	18070.12
117								SL001	C1	4" T-99	T307	3/7/2006	$y = 3313.1x^{0.5728}$	0.8915	12244.30	13084.11
118								SL001	D1	4" T-99	T307	3/7/2006	$y = 3287.3x^{0.5709}$	0.9228	12964.63	12923.21
119	21909-S	A-3	4.7	3.5	12.4	107.7	24	US1901	A1	4" T-99	T307	12/2/2005	$y = 4083.3x^{0.534}$	0.9628	14279.10	14693.15
120								US1901	B1	4" T-99	T307	12/2/2005	$y = 3028.2x^{0.6222}$	0.9603	13028.12	13462.91
121								US1901	C1	4" T-99	T307	3/6/2006	$y = 2118.3x^{0.6694}$	0.9574	10301.73	10546.19
122								US1901	D1	4" T-99	T307	3/6/2006	$y = 2458.8x^{0.6269}$	0.9451	10697.28	11055.34
123	21980-S	A-3	4.1	NA	13.2	108.1	35	SMR001	A1	4" T-99	T307	12/14/2005	$y = 2910.9x^{0.5604}$	0.9330	10700.56	11158.96
124								SMR001	B1	4" T-99	T307	12/16/2005	$y = 2587.6x^{0.5528}$	0.9424	9861.58	9740.45
125								SMR001	C1	4" T-99	T307	3/8/2006	$y = 2512.7x^{0.5922}$	0.8903	10356.94	10395.69
126								SMR001	D1	4" T-99	T307	3/8/2006	$y = 2349.5x^{0.605}$	0.9422	9834.75	10023.47
127	21982-S	A-3	6	NA	12.0	111.2	36	BR001	A1	4" T-99	T307	12/18/2005	$y = 3520.8x^{0.6086}$	0.9631	15273.10	15150.71
128								BR001	B2	4" T-99	T307	12/18/2005	$y = 3128x^{0.6558}$	0.9813	15403.00	15073.43
129								BR001	D1	4" T-99	T307	2/28/2006	$y =1795.7x^{0.6823}$	0.9552	9448.40	9220.96
130								BR001	E1	4" T-99	T307	2/28/2006	$y =1360x^{0.6337}$	0.9686	6480.59	6215.41
131								BR001	F1	4" T-99	T307	3/19/2006	$y = 3711.4x^{0.5567}$	0.9570	13872.77	14102.01
132								BR001	G1	4" T-99	T307	3/19/2006	$y = 3115.6x^{0.5782}$	0.9744	12172.31	12464.50

Table 4.2 Summary of Resilient Modulus Test Results(Continued)

Summary of Resilient Modulus Test Results (5)

Index No.	FDOT Lab. #	Soil Class	Pass #200	Clay	4" T-99 OMC	4" T-99 MDD	6" T-180 LBR	FSU Sample ID	FSU Test #	Compaction Method	Test Method	Test Date	Regression Model		Avg. MR (2psi Confining Pressure)	MR (11 psi Bulk Stress)
			%	%	%	pcf							$MR=k1\theta^{k2}$	R^2	psi	psi
133								ES001	A1	4" T-99	T307	12/20/2005	$y = 2851x^{0.6789}$	0.9332	14708.48	14521.07
134	21981-S	A-3	7.8	NA	12.1	107.9	35	ES001	B1	4" T-99	T307	12/21/2005	$y = 3740.9x^{0.5993}$	0.9664	15290.76	15742.83
135								ES001	D1	4" T-99	T307	3/9/2006	$y = 3385.6x^{0.5827}$	0.9522	13419.28	13691.63
136								ES001	E1	4" T-99	T307	3/9/2006	$y = 2703.1x^{0.6279}$	0.9479	11793.63	12182.95
137								WT001	A1	4" T-99	T307	12/22/2005	$y = 3821.1x^{0.5715}$	0.9767	14660.32	15043.34
138	21983-S	A-3	2.2	NA	12.6	104.4	21	WT001	B1	4" T-99	T307	1/4/2006	$y = 3375.3x^{0.6281}$	0.9787	14729.72	15219.88
139								WT001	D1	4" T-99	T307	3/10/2006	$y =2925.3x^{0.6378}$	0.9828	13916.47	13501.15
140								WT001	E1	4" T-99	T307	3/13/2006	$y = 3551.9x^{0.5833}$	0.9595	13922.86	14384.84
141								OS001	A1	4" T-99	T307	1/5/2006	$y = 4029.9x^{0.5562}$	0.9695	14939.11	15293.85
142	21984-S	A-3	3.7	NA	13.2	105.1	18	OS001	B1	4" T-99	T307	1/6/2006	$y = 4774.2x^{0.5357}$	0.9736	17551.20	17249.43
143								OS001	C1	4" T-99	T307	3/13/2006	$y = 3930.1x^{0.5242}$	0.9752	14204.49	13813.43
144								OS001	D1	4" T-99	T307	3/13/2006	$y = 3337.8x^{0.5819}$	0.9782	13192.43	13472.45
145								SR8001	A1	4" T-99	T307	1/9/2006	$y = 3395.6x^{0.5238}$	0.9152	12046.25	11923.34
146	21991-S	A-3	2.9	NA	10	118.8	85	SR8001	B1	4" T-99	T307	1/9/2006	$y = 4696.1x^{0.5457}$	0.9185	17448.12	17379.02
147								SR8001	C2	4" T-99	T307	1/27/2006	$y = 5018.2x^{0.5633}$	0.8101	17064.25	19371.55
148								SR8001	D1	4" T-99	T307	1/27/2006	$y = 4602.9x^{0.5419}$	0.8975	15856.62	16879.60
149								SR6001	A1	4" T-99	T307	1/11/2006	$y = 4355.9x^{0.502}$	0.9691	14807.15	14516.34
150	21990-S	A-3	10.3	NA	11.5	115.4	91	SR6001	B1	4" T-99	T307	1/11/2006	$y = 3980.4x^{0.5566}$	0.9665	16080.68	15120.49
151								SR6001	D1	4" T-99	T307	3/14/2006	$y = 1747.7x^{0.7633}$	0.9877	10699.96	10898.38
152								SR6001	E1	4" T-99	T307	3/15/2006	$y =3901.9x^{0.5383}$	0.945	14070.68	14185.93
153								SR1501	A1	4" T-99	T307	1/17/2006	$y = 5903.8x^{0.4406}$	0.8860	17840.62	16981.23
154	21989-S	A-1-b	12.5	NA	9.8	125.1	143	SR1501	B1	4" T-99	T307	1/18/2006	$y = 3625.8x^{0.6114}$	0.9365	16914.28	15707.65
155								SR1501	C1	4" T-99	T307	2/21/2006	$y =6732.5x^{0.447}$	0.9275	20613.95	19664.32
156								SR1501	D1	4" T-99	T307	2/21/2006	$y = 3450.7x^{0.603}$	0.9543	15837.47	14650.99
157								SR82601	A1	4" T-99	T307	1/20/2006	$y = 4642.4x^{0.5601}$	0.8735	18980.80	17783.88
158	21992-S	A-1-a	5.3	NA	9.9	117.9	200	SR82601	B1	4" T-99	T307	1/20/2006	$y = 4359.2x^{0.5628}$	0.8249	17796.31	16807.48
159								SR82601	C1	4" T-99	T307	2/22/2006	$y = 2030.9x^{0.6897}$	0.961	10935.86	10615.42
160								SR82601	D1	4" T-99	T307	2/22/2006	$y = 3211.8x^{0.6499}$	0.9276	16301.41	15259.83
161								SR82602	A1	4" T-99	T307	1/24/2006	$y = 4426.1x^{0.4985}$	0.9066	15429.55	14627.01
162	21993-S	A-1-b	12.7	NA	8.6	121.8	109	SR82602	B1	4" T-99	T307	1/24/2006	$y = 4435.8x^{0.5151}$	0.9418	16163.56	15254.34
163								SR82602	D1	4" T-99	T307	3/16/2006	$y = 3373.1x^{0.4844}$	0.9539	10944.60	10776.55
164								SR82602	E1	4" T-99	T307	3/16/2006	$y = 2203.7x^{0.6623}$	0.9319	11452.26	10786.16
165								MIC001	A1	4" T-99	T307	1/25/2006	$y = 4420.2x^{0.51}$	0.8967	16009.32	15015.93
166	21994-S	A-1-a	5	NA	9.3	117.8	129	MIC001	B2	4" T-99	T307	1/25/2006	$y = 2624.5x^{0.7701}$	0.9126	19467.12	16635.01
167								MIC001	D1	4" T-99	T307	3/17/2006	$y = 2796.9x^{0.6727}$	0.892	15017.01	14035.30
168								MIC001	E1	4" T-99	T307	3/17/2006	$y =3771.8x^{0.5876}$	0.8973	15120.12	15433.73

Table 4.3 Typical Data Summary Sheet for Permeability Test

Civil Engineering Department	**Flexible Wall Permeability Test**	
Florida State University	ASTM - D 5084	Page 1 of 1

Sample No. :	BF002E	Liquid Limit	32	Sample Length (cm):	11.64
Lab. Test No.	1	Plastic Index	14	Sample Diameter (in.):	4.00
Soil Description :		Opti. Moisture Content :	11.7 %	Sample Area (cm2):	81.00
Soil Location :	Ball Farm 16-20	Max. Dry Density :	119.1 pcf	Burette Cross Section Area(cm2):	0.20
Soil Class :	A-2-6	LBR :	78	Sample Prepared :	11/30/2005
Grad Pass #200	23 %	Compacted Moisture Content	11.7 %	Test Date :	12/21/2005
% Clay	20.8 %	Compacted Density	118.9 pcf	Tested by :	Ginger

Remark :

Test Date	CHAMBER READINGS			INFLOW BURETTE					OUTFLOW BURETTE					TEST TIME (sec)	Change in Height (inflow)	Change in Height (outflow)	Head @ T_i	Head @ Tf	GRADIENT	PERMEABILITY (cm/sec.)
	CELL PRESSURE (psi)	BACK PRESSURE (psi)	B VALUE	PRESSURE (PSI)	Ht. H_2O INITIAL	Ht. H_2O FINAL	PORE PRESSURE INITIAL	PORE PRESSURE FINAL	PRESSURE (psi)	Ht. H_2O INITIAL	Ht. H_2O FINAL	PORE PRESSURE INITIAL	PORE PRESSURE FINAL							
12/21/2005	97	90	0.98	92	2.60	4.25	93.6	93.5	90	7.97	6.33	91.2	91.3	408	-1.65	1.64	167.52692	151.07692	13.69	3.64E-06
				92	4.25	5.54	93.5	93.4	90	6.33	5.20	91.3	91.4	288	-1.29	1.13	151.07692	138.97692	12.46	4.17E-06
				92	5.54	6.70	93.4	93.4	90	5.20	4.08	91.4	91.4	314	-1.16	1.12	138.97692	127.57692	11.45	3.92E-06
				92	6.70	7.94	93.4	93.3	90	4.08	2.90	91.4	91.5	375	-1.24	1.18	127.57692	115.47692	10.44	3.82E-06
																			average=	3.89E-06
12/21/2005	97	90	0.98	92	2.34	3.68	93.7	93.5	90	7.57	6.36	91.3	91.4	340	-1.34	1.21	166.82692	154.07692	13.78	3.36E-06
				92	3.68	5.06	93.5	93.5	90	6.36	4.95	91.4	91.5	377	-1.38	1.41	154.07692	140.12692	12.64	3.62E-06
				92	5.06	6.30	93.5	93.4	90	4.95	3.90	91.5	91.6	379	-1.24	1.05	140.12692	128.67692	11.55	3.23E-06
				92	6.30	7.60	93.4	93.3	90	3.90	2.67	91.6	91.6	443	-1.3	1.23	128.67692	116.02692	10.51	3.36E-06
																			average=	3.39E-06
12/21/2005	97	90	0.98	92	2.30	3.74	93.7	93.6	90	7.80	6.36	91.3	91.4	351	-1.44	1.44	168.17692	153.77692	13.83	3.66E-06
				92	3.74	5.00	93.6	93.5	90	6.36	5.10	91.4	91.4	331	-1.26	1.26	153.77692	141.17692	12.67	3.71E-06
				92	5.00	6.40	93.5	93.4	90	5.10	3.72	91.4	3.0	420	-1.4	1.38	141.17692	127.27692	11.53	3.55E-06
				92	6.40	7.80	93.4	93.3	90	3.72	2.36	3.0	91.5	471	-1.4	1.36	127.27692	113.47692	10.34	3.50E-06
																			average=	3.61E-06
12/22/2005	104	90	0.98	92	2.20	3.60	113.8	113.7	90	7.68	6.28	111.4	111.5	87	-1.4	1.4	168.07692	154.07692	13.84	1.44E-05
				92	3.60	5.00	113.7	113.5	110	6.28	4.92	111.5	111.6	100	-1.4	1.36	-1252.69228	-1266.49228	-108.21	-1.57E-06
				92	5.00	6.40	113.5	113.3	110	4.92	3.57	111.5	111.6	114	-1.4	1.35	-1266.49228	-1280.24228	-109.40	-1.36E-06
				92	6.40	7.70	113.3	113.2	110	3.57	2.32	111.6	111.7	123	-1.3	1.25	-1280.24228	-1292.99228	-110.53	-1.16E-06
																			average=	2.57E-06
12/23/2005	111	90	0.98	92	3.23	5.40	93.6	93.5	90	6.77	6.26	91.3	91.4	919	-2.17	0.51	158.37692	144.97692	13.03	1.38E-06
				112	5.40	6.70	93.5	93.4	90	6.26	5.98	91.4	91.4	626	-1.3	0.28	1551.74612	1543.84612	132.97	1.17E-07
																			average=	7.50E-07

11/30/2005 Sample prepared and started back pressure
11/30~12/20 Increasing 5 psi every 2 hours until B-value reaches to 0.98
12/20/2005 Consolidation about 3mm,
12/21/2005 Start perm test with 2 psi head at 7 psi confining pressure
12/22/2005 Start perm test with 2 psi head at 14 psi confining pressure
12/23/2005 Consolidation about 4~5mm, continue perm test with 2 psi head at 21 psi confining pressure

Table 4.4 Summary of Permeability Test Results

SampleID	Test No	Project	TestApproach	CompactedDUW	Initial S	Final S	Permeability(cm/sec)	ConfiningPressure	ExcelFileName
A24-12%		DesignHighWater	Panel	NA	NA	NA	0.000305	7	NA
A24-20%		DesignHighWater	Panel	NA	NA	NA	0.000104	7	NA
A24-24%		DesignHighWater	Panel	NA	NA	NA	0.000065	7	NA
A24-30%		DesignHighWater	Panel	NA	NA	NA	0.0000201	7	NA
AP001		MRDB2	Panel	124.2	75	96	0.00000645	7	PM-03-AP001A.XLS
BF001	E	MRDB2	Panel	112.5	87	99	0.000000207	7	PM-03-BF002E.XLS
BF002	G	MRDB2	Panel	118.9	78	98	0.00000361	7	PM-03-BF002E.XLS
BH001		MRDB2	Panel	131.2	83	96	0.000000742	7	PM-03-BH001A.XLS
BR001	C	MRDB2	Panel	106.5		98	0.000164	7	PM-02-BR001C.XLS
ES001	C	MRDB2	Panel	109.3		97	0.000547	7	PM-01-ES001C.XLS
FF001		MRDB2	Panel	123.3	90	96	0.00000165	7	PM-03-FF001-1.XLS
IB001		MRDB2	Panel	133.8	86	96	0.00000056	7	PM-03-IB001A.XLS
Levy		DesignHighWater	Constant Head	107.7	57	98	0.00552		NA
LS001		MRDB2	Panel	121.2	70	85	0.000188	6	PM-03-LS001-1.XLS
MIC001	C	MRDB2	Panel	114.2		100	0.000472	7	PM-06-MIC001C.XLS
SC001	B	MRDB2	Panel	118.8	64	98	0.000276	6	PM-02-SC001B.XLS
SR6001	C	MRDB2	Panel	114.7		98	0.000245	7	PM-04-SR6001C.XLS
SR70-A24		DesignHighWater	Panel	117.6	65		0.00025		NA
SR70-A3		DesignHighWater	Constant Head	109.7	61	98	0.00206		NA
SR82602	C	MRDB2	Panel	116.9		100	0.000185	7	PM-06-SR82602C.XLS
UF001	D	MRDB2	Panel	110.9	72	99	0.0000521	7	PM-05-UF001D.XLS
UF002	D	MRDB2	Panel	113.4	78	99	0.0000221	7	PM-05-UF002D.XLS
UF003	D	MRDB2	Panel	115.6	75	98	0.0000133	7	PM-05-UF003D.XLS
US1901	E	MRDB2	Panel	108.6	65	99	0.000305		PM-01-US1901C.XLS
WT001	C	MRDB2	Panel	105.1		98	0.000654	7	PM-02-WT001C.XLS

Table 4.5 Summary of Useful Test Data Points for Various Conditions and Test Methods

Test Condition	Test Method			
	T-292	T-294	T-307	Total
Individual Test	164	17	168	349
Reliable Individual Test	164	17	123	304
Reliable Individual Test @ Optimum Condition	61	17	88	166
Reliable Average Test @ Optimum Condition	46	17	33	96

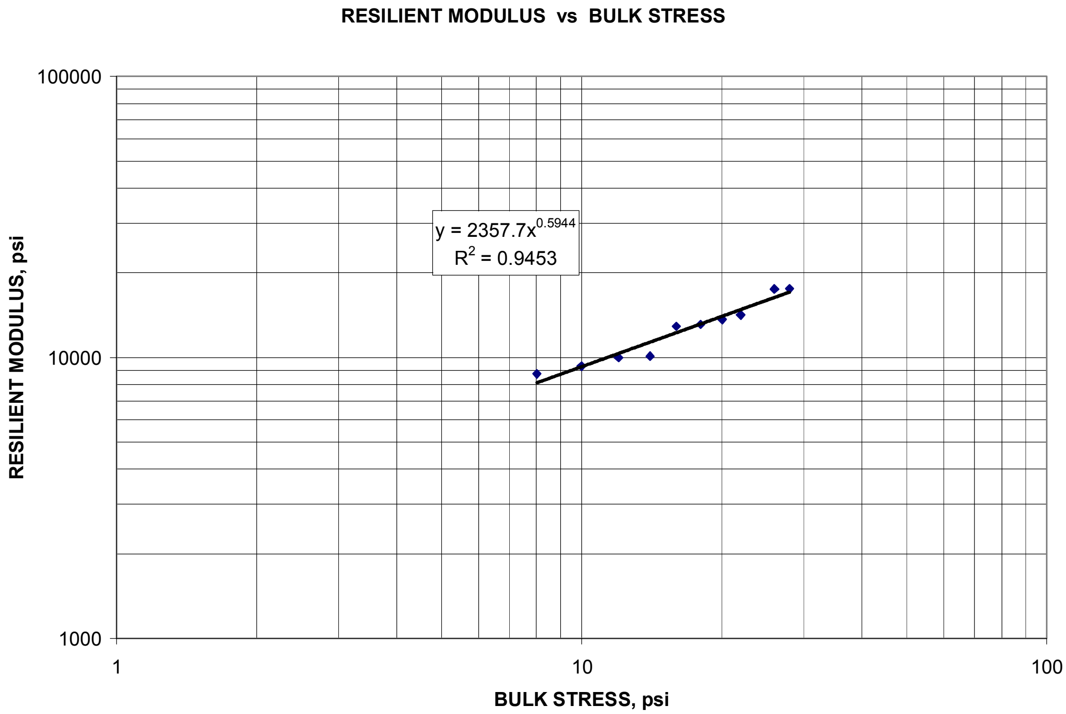


Figure 4.1 Regression Model for Resilient Modulus versus Bulk Stress

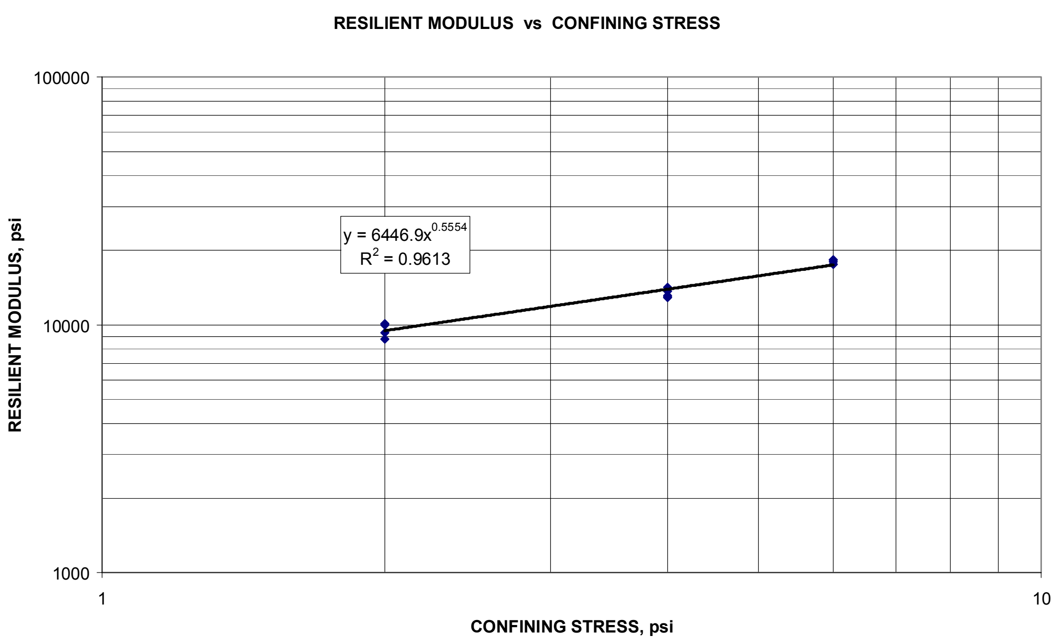


Figure 4.2 Regression Model for Resilient Modulus versus Confining Stress (pressure)

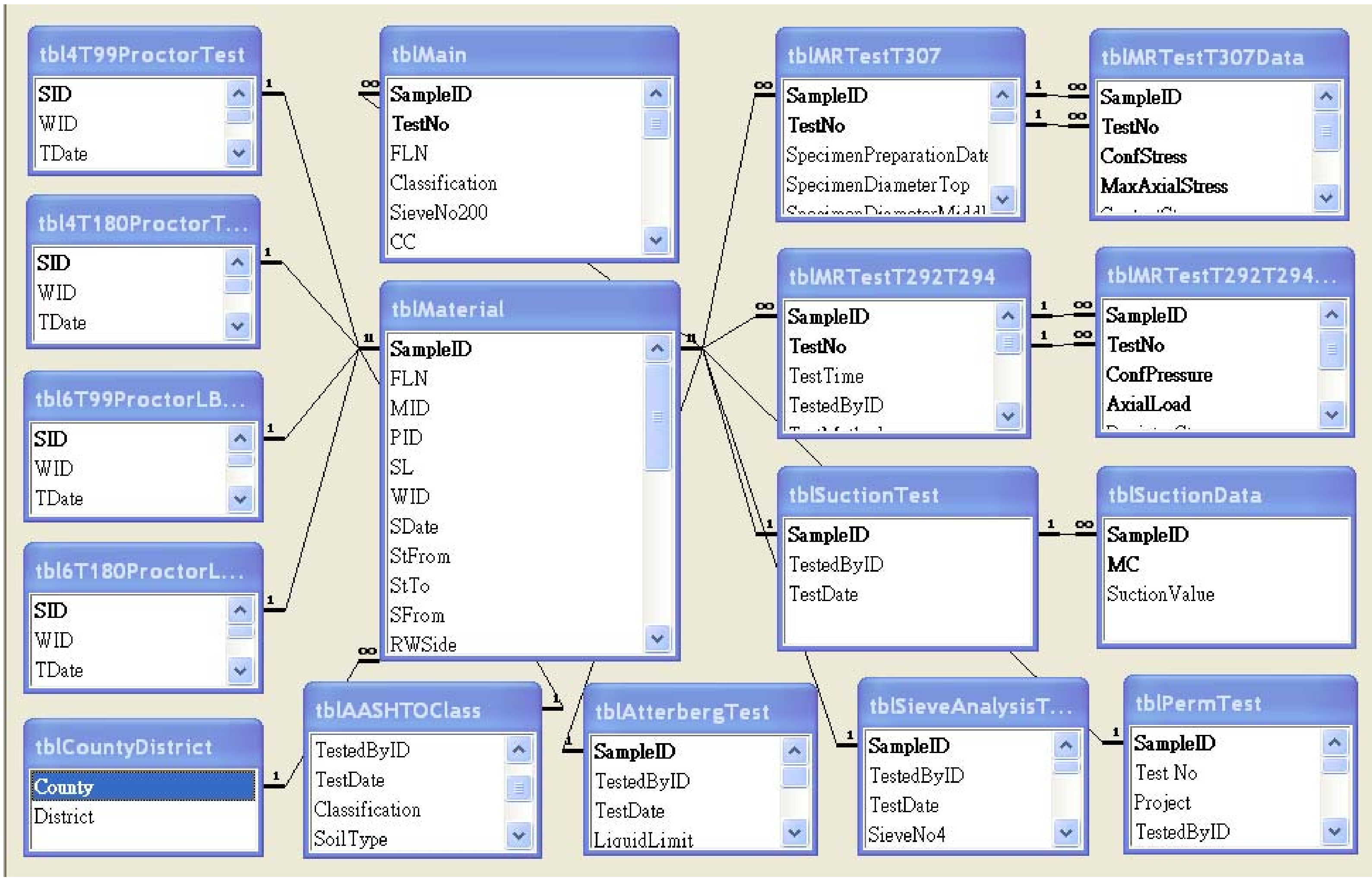


Figure 4.3 Table Relationships for Resilient Modulus Database

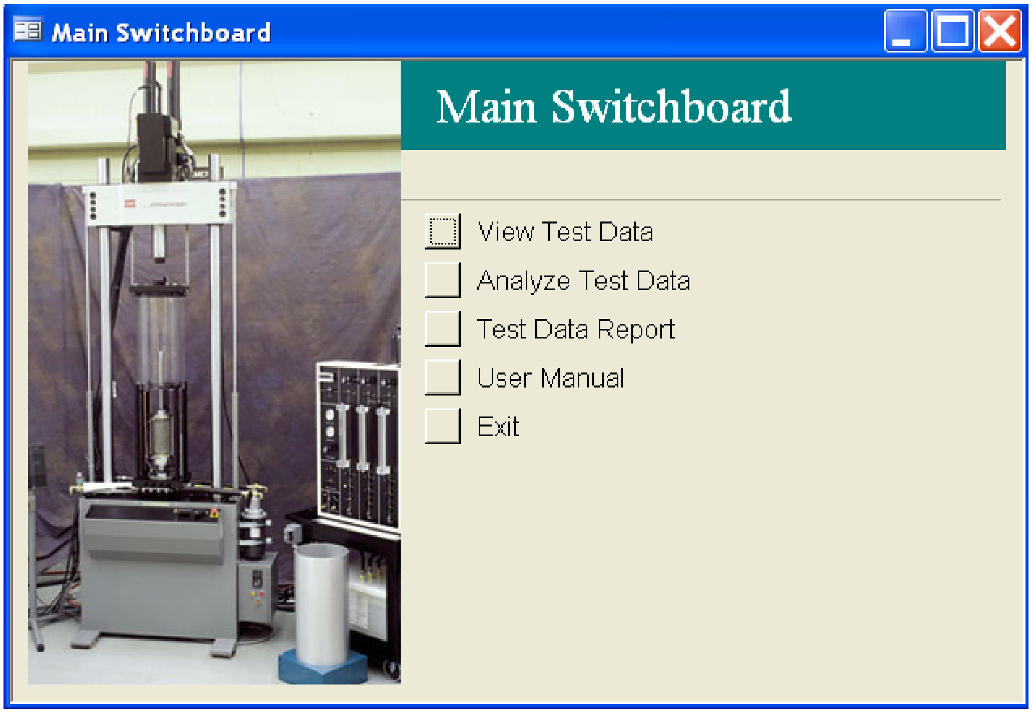


Figure 4.4 Main Page of Database Application

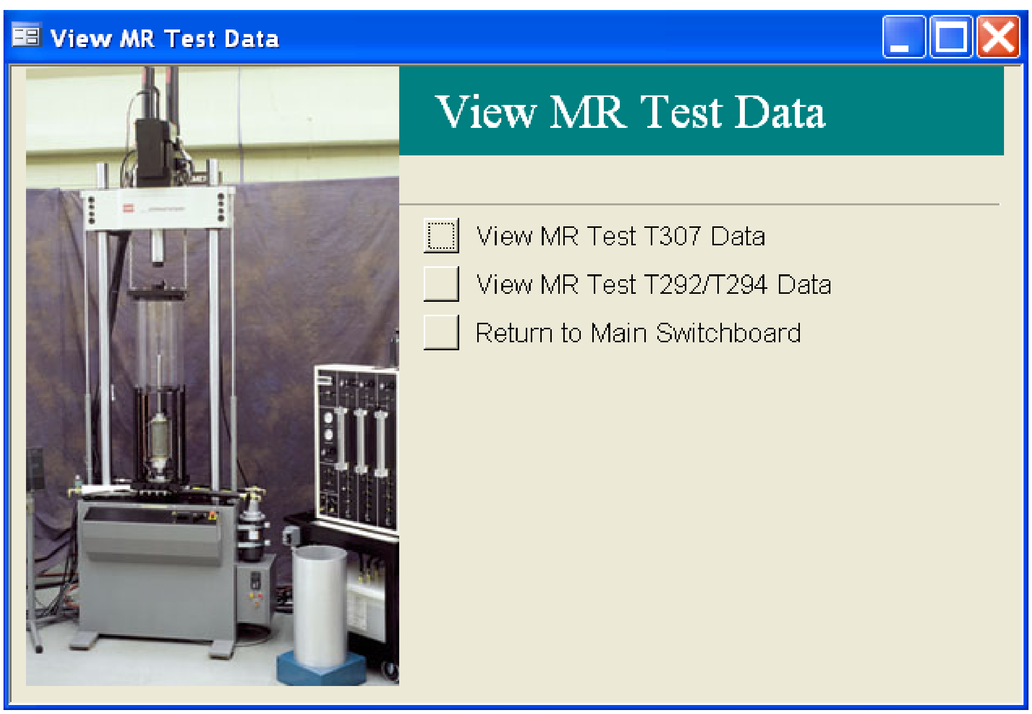
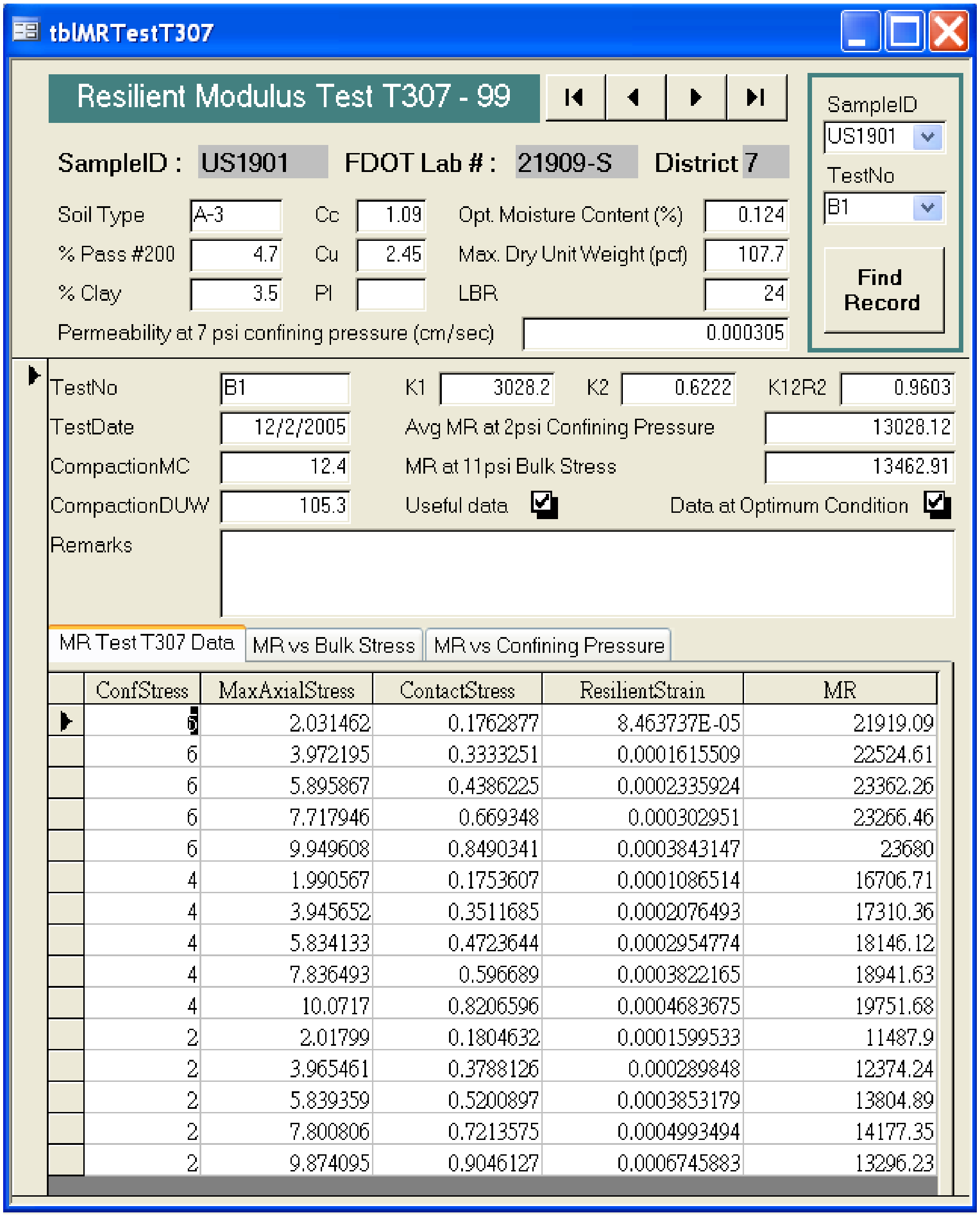


Figure 4.5 View MR Test Data Page of Database Application


tblMRTestT307

Resilient Modulus Test T307 - 99

SampleID : US1901 FDOT Lab # : 21909-S District 7

Soil Type	A-3	Cc	1.09	Opt. Moisture Content (%)	0.124
% Pass #200	4.7	Cu	2.45	Max. Dry Unit Weight (pcf)	107.7
% Clay	3.5	PI		LBR	24

Permeability at 7 psi confining pressure (cm/sec) 0.000305

SampleID US1901

TestNo B1

Find Record

TestNo	B1	K1	3028.2	K2	0.6222	K12R2	0.9603
TestDate	12/2/2005	Avg MR at 2psi Confining Pressure					13028.12
CompactionMC	12.4	MR at 11psi Bulk Stress					13462.91
CompactionDUW	105.3	Useful data	☑		Data at Optimum Condition		☑

Remarks

MR Test T307 Data | MR vs Bulk Stress | MR vs Confining Pressure

ConfStress	MaxAxialStress	ContactStress	ResilientStrain	MR
6	2.031462	0.1762877	8.463737E-05	21919.09
6	3.972195	0.3333251	0.0001615509	22524.61
6	5.895867	0.4386225	0.0002335924	23362.26
6	7.717946	0.669348	0.000302951	23266.46
6	9.949608	0.8490341	0.0003843147	23680
4	1.990567	0.1753607	0.0001086514	16706.71
4	3.945652	0.3511685	0.0002076493	17310.36
4	5.834133	0.4723644	0.0002954774	18146.12
4	7.836493	0.596689	0.0003822165	18941.63
4	10.0717	0.8206596	0.0004683675	19751.68
2	2.01799	0.1804632	0.0001599533	11487.9
2	3.965461	0.3788126	0.000289848	12374.24
2	5.839359	0.5200897	0.0003853179	13804.89
2	7.800806	0.7213575	0.0004993494	14177.35
2	9.874095	0.9046127	0.0006745883	13296.23

Figure 4.6 Resilient Modulus Test Data from Test T307-99 Page of Database Application

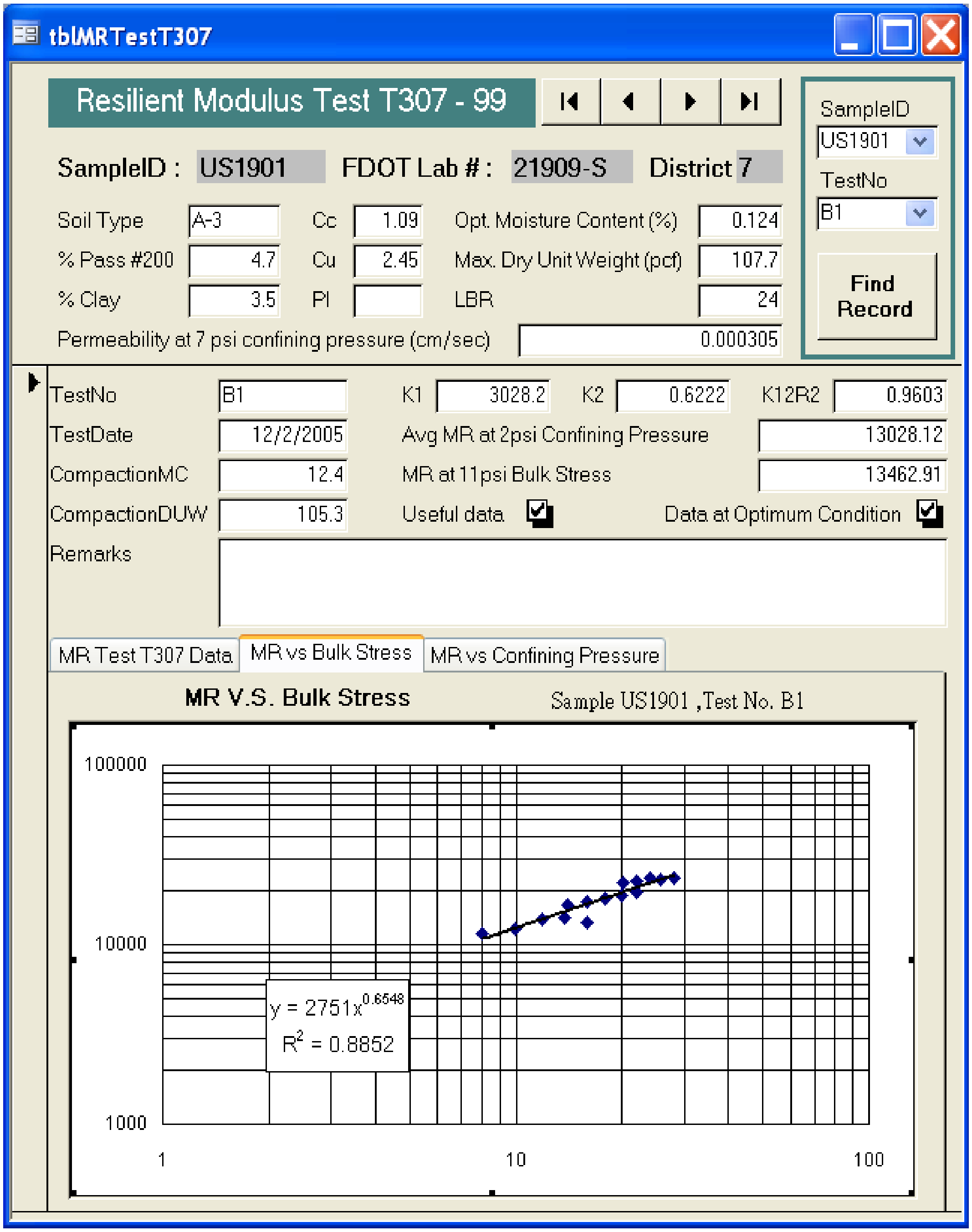


Figure 4.7 Resilient Modulus versus Bulk Stress Page of Database Application

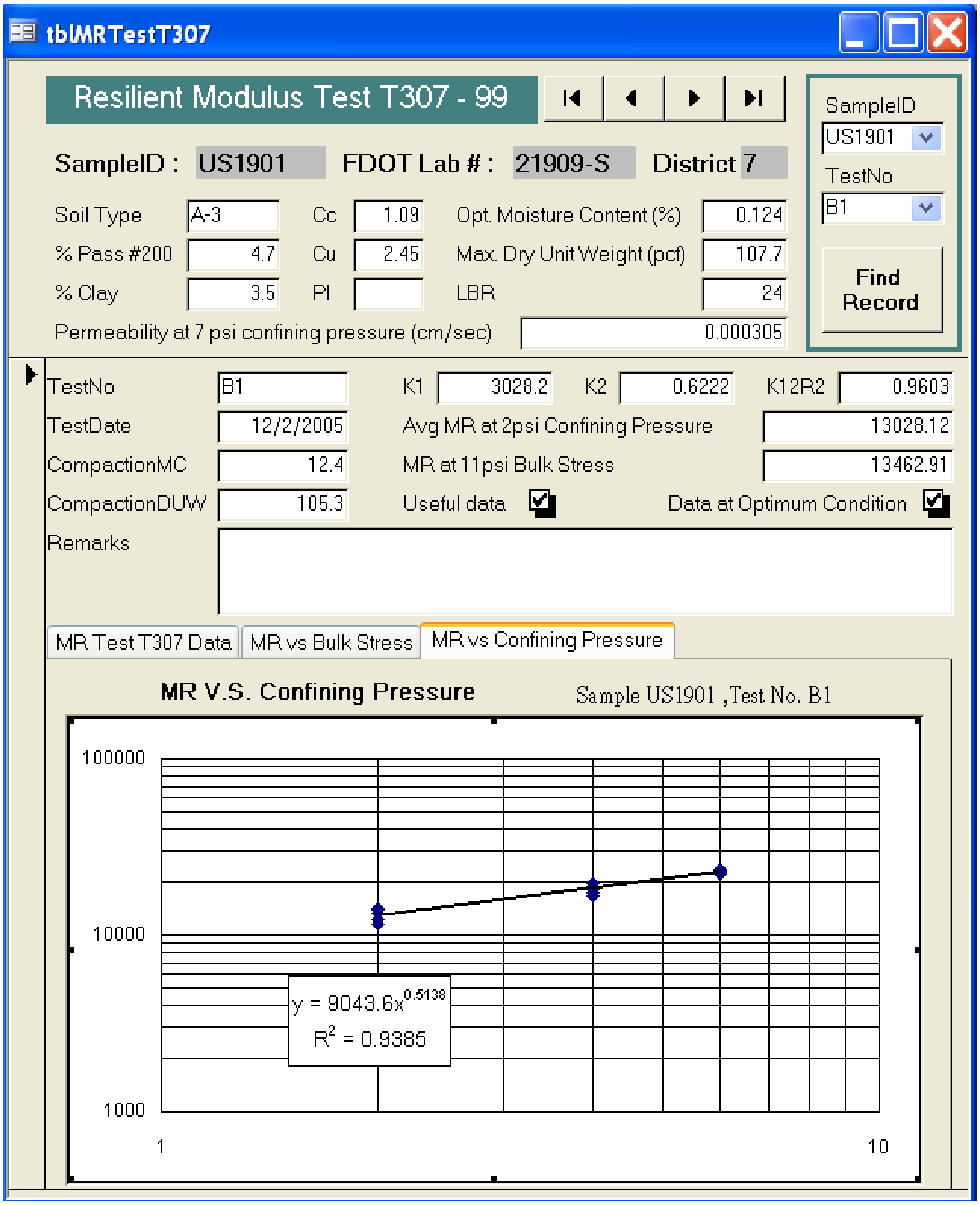
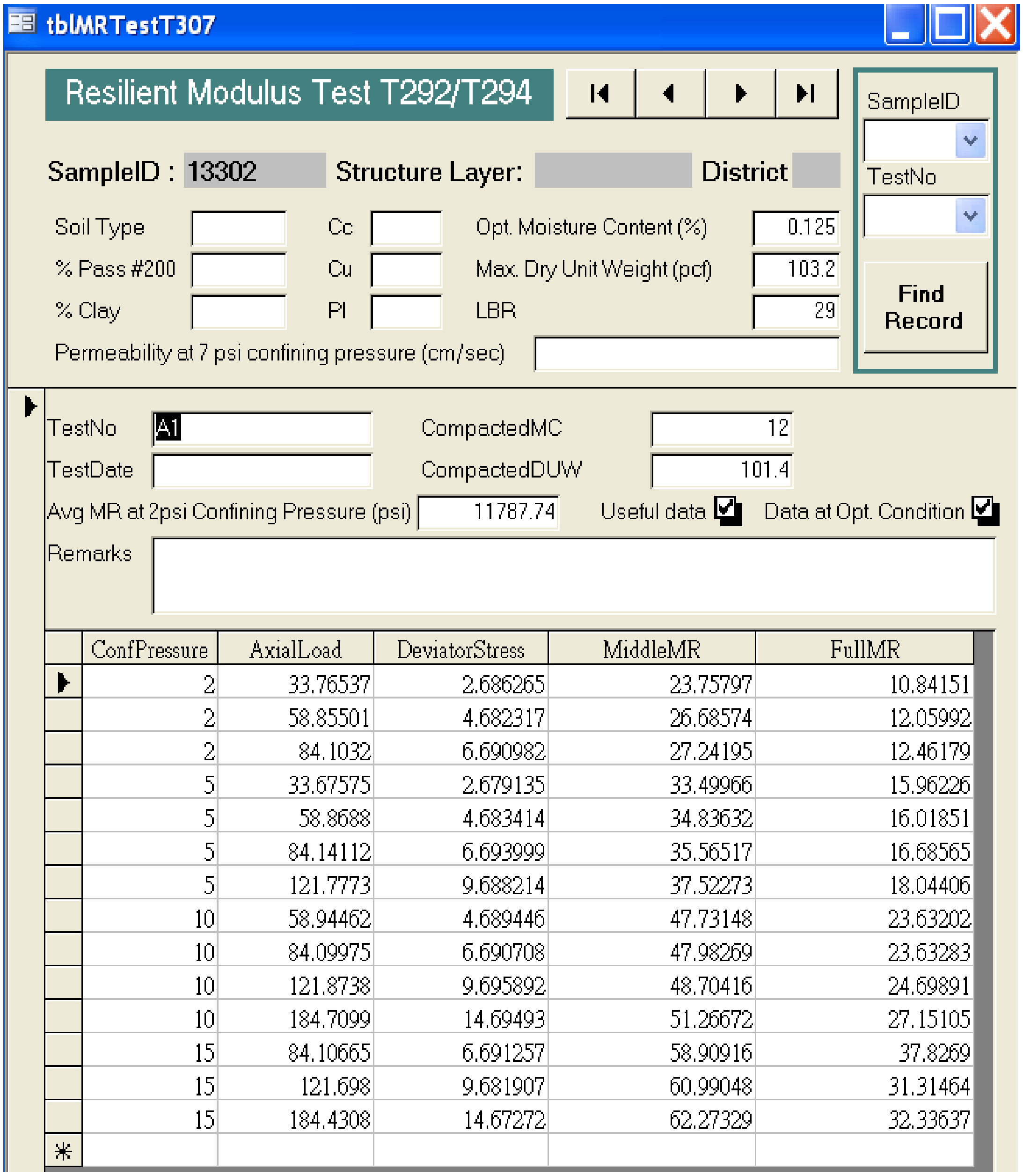


Figure 4.8 Resilient Modulus versus Confining Pressure Page of Database Application



tblMRTestT307

Resilient Modulus Test T292/T294

SampleID : 13302 Structure Layer: District

Soil Type | Cc | Opt. Moisture Content (%) 0.125

% Pass #200 | Cu | Max. Dry Unit Weight (pcf) 103.2

% Clay | PI | LBR 29

Permeability at 7 psi confining pressure (cm/sec)

SampleID

TestNo

Find Record

TestNo A1 | CompactedMC 12

TestDate | CompactedDUW 101.4

Avg MR at 2psi Confining Pressure (psi) 11787.74 | Useful data ☑ | Data at Opt. Condition ☑

Remarks

ConfPressure	AxialLoad	DeviatorStress	MiddleMR	FullMR
2	33.76537	2.686265	23.75797	10.84151
2	58.85501	4.682317	26.68574	12.05992
2	84.1032	6.690982	27.24195	12.46179
5	33.67575	2.679135	33.49966	15.96226
5	58.8688	4.683414	34.83632	16.01851
5	84.14112	6.693999	35.56517	16.68565
5	121.7773	9.688214	37.52273	18.04406
10	58.94462	4.689446	47.73148	23.63202
10	84.09975	6.690708	47.98269	23.63283
10	121.8738	9.695892	48.70416	24.69891
10	184.7099	14.69493	51.26672	27.15105
15	84.10665	6.691257	58.90916	37.8269
15	121.698	9.681907	60.99048	31.31464
15	184.4308	14.67272	62.27329	32.33637

Figure 4.9 Resilient Modulus from Test T292/T294 Page of Database Application

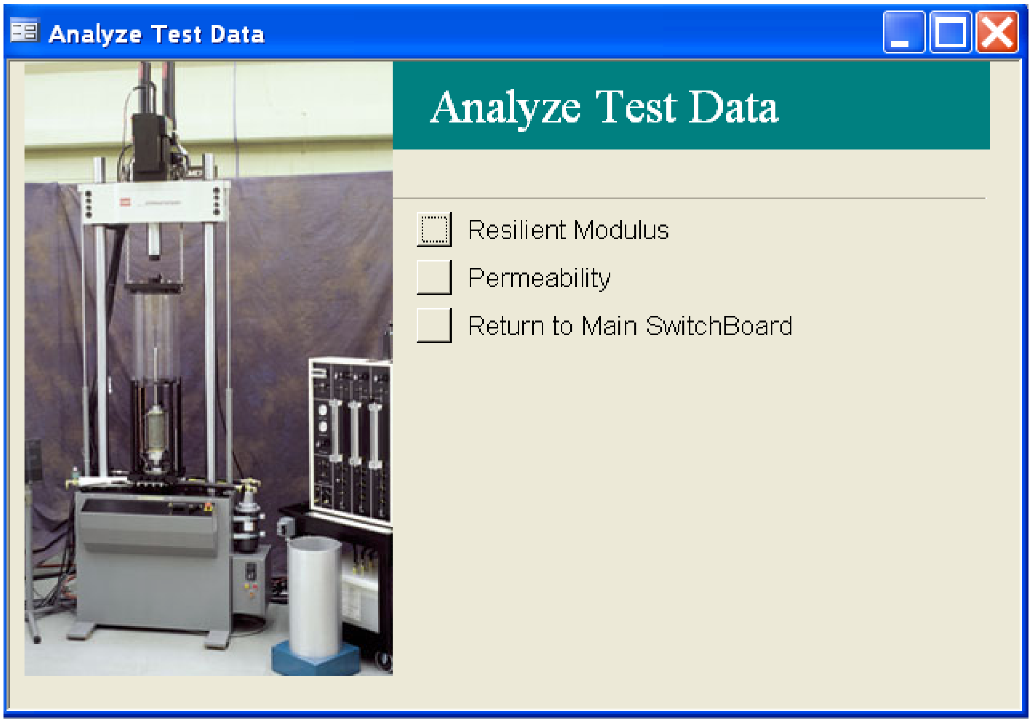


Figure 4.10 Analyze Test Data Page of Database Application

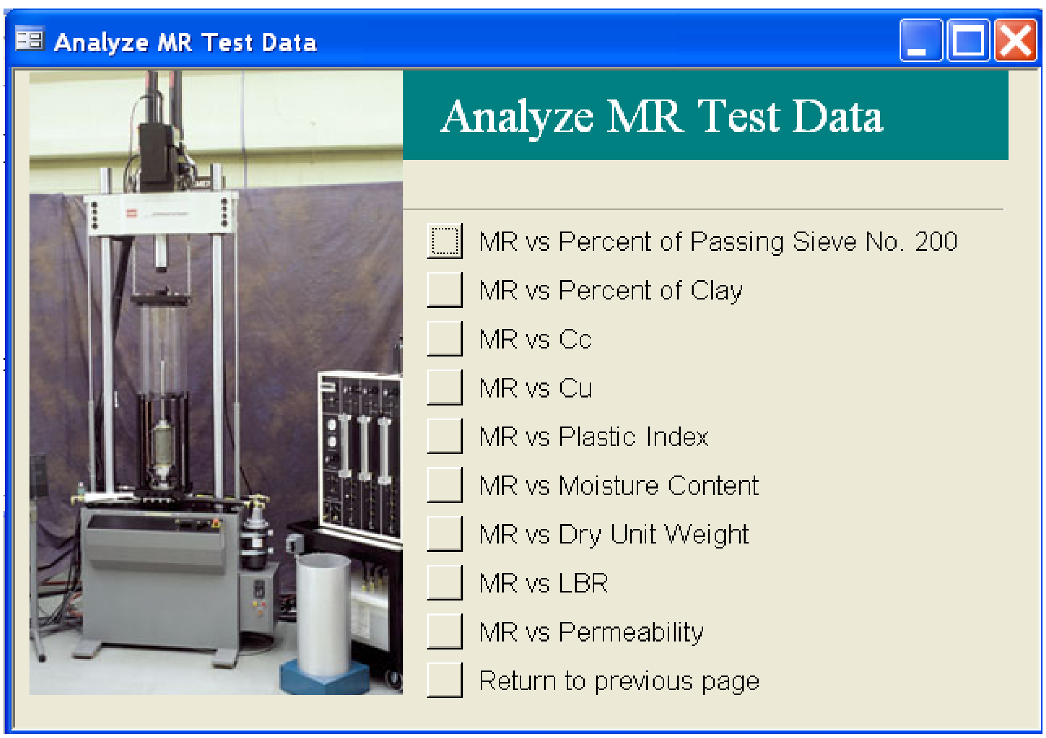


Figure 4.11 Analyze Resilient Modulus Test Data Page of Database Application

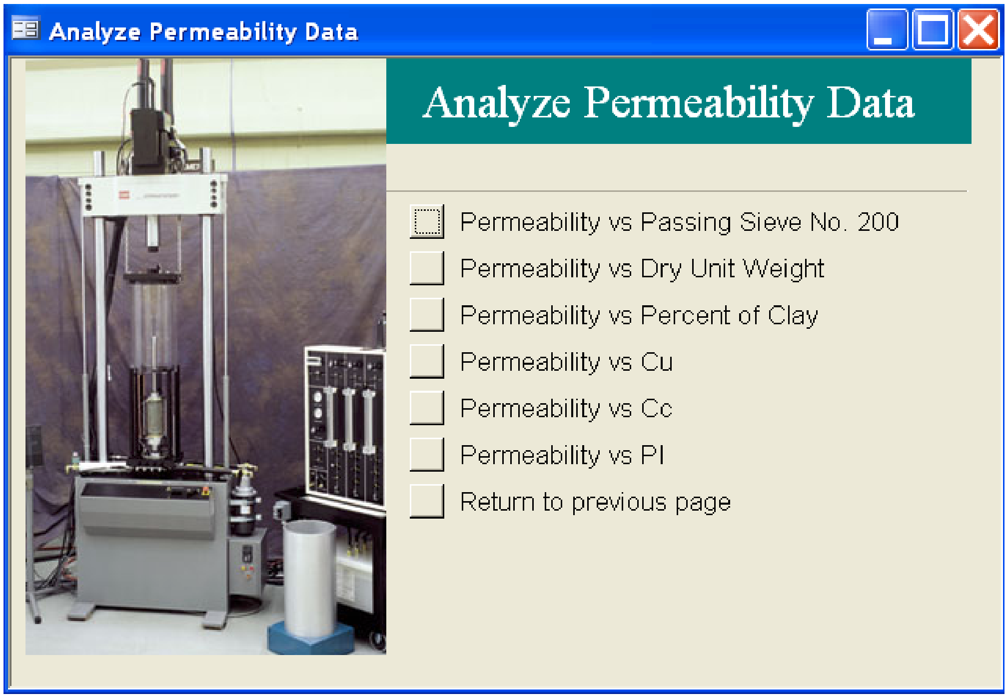


Figure 4.12 Analyze Permeability Test Data Page of Database Application

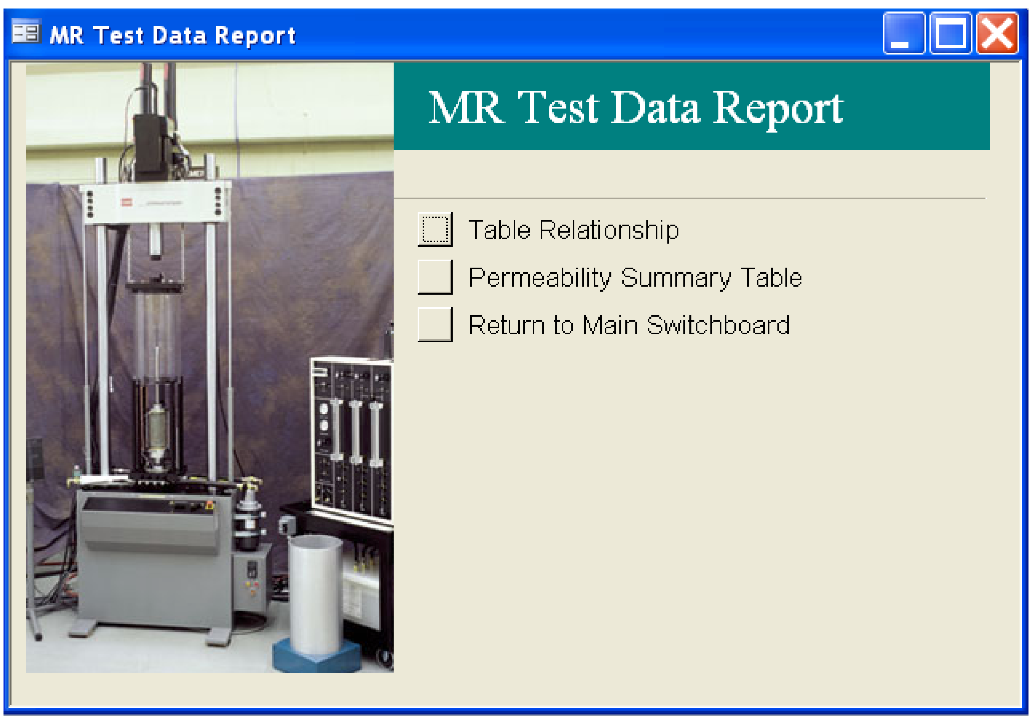


Figure 4.13 MR Test Data Report Page of Database Application

Permeability Test Result Summary

There are total 25 Tests

Sample ID	FDOT Lab No.	Passing Sieve No. 200 (%)	Compacted DUW (pcf)	Initial Degree Of Satuation(%)	Permeability (cm/sec)	TestApproach
A24-12%		12			0.000305	Panel
A24-20%		20			0.000104	Panel
A24-24%		24			0.000065	Panel
A24-30%		30			0.0000201	Panel
AP001	21851-S	17.3	124.2	75	0.00000645	Panel
BF001	21881-S	34.8	112.5	87	0.000000207	Panel
BF002	21897-S	22.8	118.9	78	0.00000361	Panel
BH001	21671~21673	24	131.2	83	0.000000742	Panel
BR001	21982-S	6	106.5		0.000164	Panel
ES001	21981-S	7.8	109.3		0.000547	Panel
FF001	21852-S	20.4	123.3	90	0.00000165	Panel
IB001	21668~21670	32	133.8	86	0.00000056	Panel
Levy		4	107.7	57	0.00552	Constant Head
LS001	21697-S	14	121.2	70	0.000188	Panel
MIC001	21994-S	5	114.2		0.000472	Panel
SC001	21665~21667	15.24	118.8	64	0.000276	Panel
SR6001	21990-S	10.3	114.7		0.000245	Panel
SR70-A24		14	117.6	65	0.00025	Panel
SR70-A3		8	109.7	61	0.00206	Constant Head
SR82602	21993-S	12.7	116.9		0.000185	Panel
UF001	21887-S	30	110.9	72	0.0000521	Panel
UF002	21888-S	17.9	113.4	78	0.0000221	Panel
UF003	21889-S	12.2	115.6	75	0.0000133	Panel
US1901	21909-S	4.7	108.6	65	0.000305	Panel
WT001	21984-S	2.2	105.1		0.000654	Panel

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Figure 4.14 Database Application View Permeability Test Summary Report Page

CHAPTER 5
ANALYSES OF EXPERIMENTAL RESULTS

5.1 GENERAL

The laboratory test results are further analyzed in this chapter. In order to have accurate analytical results, the data with a reasonable size of population were first grouped together according to the various test methods and material types. These data groups were then checked carefully for possible anomalies. The final analyses were performed based on the selected data for different material types and test conditions. The resilient modulus prediction model proposed by Zhang (2004) was verified by comparing the laboratory measured resilient modulus with the resilient modulus value obtained from the model. An improved resilient modulus prediction model was also proposed based on the available data in the database.

5.2 SELECTION PROCESS OF RESILIENT MODULUS TEST DATA

A total of 349 sets of resilient modulus test data with 117 various types of soil materials were stored in the database. The database included the resilient modulus test data from the AASHTO T307-99, T292-91I, and T294-92 test methods. The T307-99 and T292-91I test data were chosen for further analysis, but the T294-92 data were excluded due to an insufficient data population size. Xiong (2003) suggested that the T292-91I test procedure is more reliable for simulating soil conditions in the pavement, which is under a low in-situ confining stress. Both the T292-91I and T307-99 test procedures are performed under an identical lowest confining pressure at 2 psi, which simulates closely with the low in-situ confining stress in the pavement and allows the resilient modulus values with an identical condition to give further comparison and analysis. In addition, it should be noted that the test conditions from T292-91I were performed on the samples compacted at the modified Proctor condition (AASHTO T-180), while the test data from the T307-99 procedure were obtained using the standard Proctor compacted condition (AASHTO T-99). This variation in the test condition gave a higher resilient modulus value for the T292-91I test than that from the T307-99 test on an identical type of material. There were 164 test data points from the T292-94 test and 168 data points from the T307-99 test, and that amounted to a total of 332 resilient modulus test data points. In this study, the majority of the material types are the A-2-4, A-2-6, and A-3 soils. Only those three types of soils were selected for further analysis.

5.3 TEST DATA ANOMALIES

Many factors could affect the resilient modulus test results. For some tests, the results were reliable and could be used for further analyses, while the others were not and should be excluded form the analyses. Yau and Von Quintus (2002) conducted an evaluation regarding those influencing factors on the resilient moudulus. The factors included sampling technique, sample preparation method, testing equipment, testing method, testing program configuration, testing environmental conditions (noise, vibration, etc.) and the errors that could occur during the testing program either by the operator or the machine itself. Some of the errors included an incorrect calibration of the load cell, signal noise interference, incorrect conditioning/stress sequence, leaks in the membrane, incorrect stress levels, unstable Linear Variable Differential Transducer (LVDT) clamps attached to the specimen, exceeding the LVDT linear range limits, incorrect LVDT readings due to fractioned contact, and specimen disturbance at the higher stress states. Any data anomaly could occur due to the above referenced errors. The determination of anomalies in the database was based on the observations during the testing. The anomalies were screened out to ensure data quality and to identify any bias between different data sets.

The data selected for analysis fall into two groups. Group I data consist of all the test data from the previous projects using the T292-91I test method, while Group II data consist of the data from the T307-99 test performed in the current project. Since there was no evidence showing any anomaly in the data from the T292-91I test, it is assumed that all the data obtained from the previous projects are reliable data and eligible for further analysis. The processing of anomaly identification only applied to the data obtained from the T307-99 test method in this project.

A detailed description of the anomalies is summarized in Appendix D. The possible causes along with the type of anomalies are summarized in Table 5.1. The tests flagged as the anomalies are summarized and presented in Table 5.2. The test data were reduced to a total of 123 data points for the T307-99 test and 164 data points for the T292-91I test.

5.4 REPRESENTATIVE DATA FOR ANALYSIS

In the beginning of the testing program, the soil samples were prepared using the Modified Proctor compaction. Subsequently, the FDOT placed a request to prepare the samples using the 100% maximum dry unit weight of the 4-inch T-99 (Standard Proctor compaction) test. The compaction efforts of preparing the soil samples were then adjusted to adapt to the requested change of compaction procedure (T-99). The test data from the specimens that contained the moisture within +/- 1.0 percent of the optimum moisture content and the laboratory compacted wet unit weight within +/- 3.0 percent of the maximum wet unit weight of the AASHTO T-99 were used to represent the resilient modulus data for analysis at the optimum condition. The representative data points at the optimum condition were 89 sets for the T307-99 test and 61 sets for the T292-91I test.

The resilient modulus values at the 2 psi confining pressure and 6 psi deviator stress for a similar type of soil material were obtained from the representative data sets and then merged to get the average resilient modulus value for the soil material. The representative data points for the average resilient modulus at the optimum condition were 33 sets for the T307-99 test and 46 sets for the T292-91I test. The averaged resilient modulus values at the optimum condition are summarized in Table 5.3 and Table 5.4 for each type of soil materials.

The representative data sets at the optimum condition were used for the analysis of relationships between the resilient modulus and basic soil properties including those factors such as water content and unit weight of the material. The representative data selected for analysis were further categorized into different groups according to their classification. Three major categories, i.e., A-3, A-2-4, and A-2-6 soils, were chosen for further detailed analysis.

A summary of the data sets available for various material types and test methods in the database is listed in Table 5.5. A summary of the available data points on each material property for different test methods in the database is presented in Table 5.6.

5.5 Analysis of Resilient Modulus Test Results

Two groups of resilient modulus test data were selected for analysis. One group of data involved the resilient modulus test data based on the strain measurements using the internal LVDTs at the full length following the T307-99 test method, and the other group of data involved those test data from the T292-91I test with the strain measurements under the identical LVDT position as in the T307-99 test. Both test methods include test sequences that are under the identical LVDTs measurement position and stress path. The test sequences were run from a higher confining pressure to a lower confining pressure. A comparison of the test sequences and stress conditions from the two methods is provided in Table 5.7. It should be noted that the specimens used in the design highwater project were prepared using the Modified

Proctor compaction, which gave slightly higher unit weight values than the other specimens compacted under the Standard Proctor compaction.

The following sections focus on the effect of the basic soil physical properties on the resilient modulus.

5.5.1 Effect of Moisture Content

A total of 231 data points are presented in Figure 5.1 to show the relationship between the resilient modulus and moisture content. There are 110 data points from the T307-99 and 121 points from the T292-91I. The moisture content of the wet, optimum, and dry compacted conditions are all presented in the figure. The T292-91I had a wide range of the moisture content, and showed a trend of the resilient modulus decreasing with an increase in the moisture content for the A-2-4 soils. Most of the resilient modulus values were within the range from 24,000 psi to 10,000 psi for the T292-91I test, and within the range from 17,000 psi to 8,500 psi for the T307-99 test data.

At the optimum condition as shown in Figure 5.2, the resilient modulus values from the T292-91I revealed a trend that the resilient modulus decreased with an increase in the moisture content, while the data from the T307-99 showed no significant trend. The average resilient modulus values

(Tables 5.3 and 5.4) at the optimum condition are presented in Figure 5.3 with 73 data points for illustration.

5.5.2 Effect of Dry Unit Weight

A total of 229 data points are presented in Figure 5.4 to show the relationship between the resilient modulus and dry unit weight. There are 110 data points from the T307-99 test and 119 from the T292-91I test. The data showed that the resilient modulus increased with an increase in the dry unit weight for both A-2-4 and A-2-6 soils. For the A-3 soils, the effect of dry unit weight on the resilient modulus became insignificant.

At the optimum condition (Figure 5.5), the resilient modulus increased with an increase in the maximum dry unit weight for the A-2-4 and A-3 soils. However, the data from the T307-99 showed no definite trend for this effect. The average resilient modulus values are illustrated in Figure 5.6.

5.5.3 Effect of Percent Fines

A total of 95 test data points are presented in Figure 5.7 to show the relationship between the resilient modulus and percent of fines passing the #200 sieve. The average resilient modulus versus percent of fines passing the #200 sieve for each soil is illustrated in Figure 5.8. The scattered data show a lack of correlation between the resilient modulus and percent of fines.

5.5.4 Effect of Percent of Clay

A total of 52 test data points are presented in Figure 5.9 to demonstrate the relationship between the resilient modulus and percent of clay content. The average resilient modulus versus percent of clay content for each soil is illustrated in Figure 5.10. For the A-2-4 soils, the percent of clay content had a slight effect on the resilient modulus, i.e., the resilient modulus increased with an increase in the percent of clay content.

5.5.5 Effect of LBR

A total of 132 test data points are presented in Figure 5.11 to show the relationship between the resilient modulus and LBR. The average resilient modulus versus LBR for each soil is illustrated in Figure 5.12. No relationship existed between the resilient modulus and LBR values for the A-3 soils. For the T292-91I test data, it appeared that the resilient modulus increased with an increase in the LBR for the A-2-4 soils. For the T307-99 test data, A-2-4 soils did not show any definite trend. The LBR may not be a reliable indicator for predicting resilient modulus values.

5.5.6 Effect of Coefficient of Curvature

A total of 52 test data points are presented in Figure 5.13 to demonstrate the relationship between resilient modulus and coefficient of curvature (C_c). The average resilient modulus versus coefficient of curvature (C_c) for each soil is presented in Figure 5.14. The data are very scattered and the resilient modulus values are not correlated very well with the coefficient of curvature for either the A-2-4 or A-3 soils. For well-graded sandy soils, the coefficient of curvature should be between about 1 and 3. With the coefficient of curvature ranging from 0.6 to 1.5 for the A-3 soils in this study, the A-3 soils are classified as poorly-graded granular materials.

5.5.7 Effect of Uniformity Coefficient

A total of 52 test data points are presented in Figure 5.15 to demonstrate the relationship between resilient modulus and uniformity coefficient (C_u). The average resilient modulus versus uniformity coefficient (C_u) for each soil is illustrated in Figure 5.16. The data are very scattered and no definite correlation exists between the uniformity coefficient and resilient modulus. For well-graded sandy soils, the uniformity coefficient should be greater than 6.

Again, the data indicate that most A-3 soils are poorly-graded.

5.5.8 Effect of Plasticity Index

A total of 14 data points of the A-2-6 soil, that are cohesive with plastic index values, are presented in Figure 5.17 to demonstrate the relationship between resilient modulus and plasticity index. The average resilient modulus versus plasticity index for each soil is illustrated in Figure 5.18. There are not enough data points to evaluate the effect of plasticity index on resilient modulus. Most Florida pavement soils are granular materials, such as the A-3 and A-2-4 soils.

5.5.9 Effect of Permeability

A total of 63 test data points are presented in Figure 5.19 to demonstrate the relationship between resilient modulus and permeability. The average resilient modulus versus permeability for each soil is illustrated in Figure 5.20. The data are very scattered and no definite correlations exist between the resilient modulus and permeability values. The data show that the A-3 soils have higher permeability values than the A-2-4 and A-2-6 soils.

5.5.10 Poisson's Ratio Test Results

The Poisson's ratio can be obtained from the resilient modulus test. Some Poisson's ratio data were found to be unstable in this study. A wide range of values were found with the same specimen under various test sequences. The ranges of the Poisson's ratio values for each soil material are presented in Figure 5.21. Figure 5.22 shows the average Poisson's ratio value for the A-3, A-2-4, and A-2-6 soils. In general, Poisson's ratio value increased with an increase in the deviator stress. There is no significant correlation between the Poisson's ratio and confining stress.

5.6 LABORATORY PERMEABILITY TEST RESULTS

The permeability test results are summarized in Table 5.8. There are 25 tests in total with seven tests from a previous project "Design High Water" and 18 tests from the current database project. Typical relationships between permeability and moisture content, and between dry unit weight and moisture content, are illustrated in Figure 5.23. Typical ranges of permeability values are presented in Figure 5.24 for some soil and rock formation.

The relationships between the permeability and the percent of fines are shown in Figure 5.25. The trend shows that the permeability value decreases with an increase in percent of fines. The permeability test results show that the percent of fines is a good indicator of predicting the soil permeability. The relationships between the permeability and the percent of clay content are illustrated in Figure 5.26. A similar trend is shown that the permeability value decreases with an increase in the percent of fines or the percent of clay. The same trend is also observed for the relationship between permeability and dry unit weight shown in Figure 5.27.

A regression equation may be drawn based on the correlation relationships between the permeability and the percent of fines and the percent of clay. The soil permeability may be correlated with the percent of fines using the following regression equation:

$$K = 0.0018e^{-0.2681(P200)} \qquad (5.1)$$

Where,

K = Coefficient of permeability, cm/sec
$P200$ = Percent of fines passing sieve No.200, percent

The regression equation for the relationship between the soil permeability and percent of clay content may be presented as follows:

$$K = 0.0003e^{-0.2877(Clay)} \qquad (5.2)$$

Where,

K = Coefficient of permeability, cm/sec
Clay = Percent of clay content, percent

The relationships between permeability and the coefficient of curvature, uniformity coefficient, and plastic index are shown in Figure 5.28, Figure 5.29, and Figure 5.30. The data shown in Figure 5.28 indicate that the permeability value decreases with an increase in the coefficient of curvature. No other significant correlations are observed in Figure 5.29 and Figure 5.30.

5.7 Resilient Modulus Prediction Model Proposed by Zhang

Among the prediction models reviewed in Chapter 2, the model proposed by Zhang (2004) was selected to evaluate the resilient modulus rest results in this study. The prediction equation (Equation 2.10) is presented again as follows:

$$\ln(M_r) = 2.01 - 0.041*(\omega) + 0.0108*(\rho) + 0.0243*(C_u) - 0.119*(C_c) \tag{5.3}$$

Where,

M_r = Resilient modulus in ksi, at 2 psi confining pressure

C_c = Coefficient of Curvature

C_u = Uniformity Coefficient

ω = Gravimetric moisture content in percentage (0~100)

ρ = Dry unit weight in pcf

This model was established based on selected Florida granular materials. The four variables were water content, dry unit weight, uniformity coefficient, and coefficient of curvature of gradation, and were used to correlate with the resilient modulus test results in a previous study. The sample population had a reasonable range of percent of fines passing No.200 sieve varying from 8% to 24%. It should be noted that the compaction characteristics were determined in the laboratory using the Modified Proctor (AASHTO T-180) method instead of the Standard Proctor (AASHTO T-99) method as in the current project. This factor should be taken into consideration when comparing the laboratory resilient modulus test results with the resilient modulus obtained from the prediction model.

The resilient modulus values derived from the Equation 5.3 were recorded in the database “MRAnalyzer.mdb” under the table designated as Table “tblZhang”. Upon review of the data, the resilient modulus test data for the test No. Mdf-Dry-1 of the SR70-A24 material was not reasonable and should be excluded from analysis. It was also found that all A-1 materials had a significantly different predicted resilient modulus from the laboratory resilient modulus. Since the prediction model proposed by Zhang was developed using only the A-2-4 and A-3 materials, any materials other than these two basic types should not be included for analysis. A summary of the comparisons between the laboratory resilient modulus and the predicted values is presented in Table 5.9. A summary is also presented in Table 5.10 to show the differences between the laboratory resilient modulus and predicted resilient modulus values for those materials that are not represented well by Equation 5.3.

The laboratory resilient modulus versus the predicted resilient modulus is shown in Figure 5.31. The comparison between the laboratory resilient modulus and the predicted resilient modulus at the optimum condition is shown in Figure 5.32. For the 86 data points in Figure 5.31, 66 data points (77%) fall within the range of +/- 3,000 psi from the measured resilient modulus. For the 52 data points in Figure 5.32 at the optimum condition, 42 data points (81%) fall within the range of +/-3,000 psi from the measured resilient modulus. In terms of the ratio between the predicted resilient modulus and the laboratory resilient modulus, 69 out of 86 data points are within the range between 1.25 and 0.75 (+/- 25%) as shown in Figure 5.33.

The ratios of the predicted resilient modulus over the laboratory resilient modulus versus various parameters are illustrated in Figure 5.33, Figure 5.34, Figure 5.35, Figure 5.36, Figure 5.37, and Figure 5.38. A comparison of the ratios versus various parameters is presented in Figure 5.39. From Zhang’s model, the most significant parameter is the dry unit weight, which has more influence than the other three parameters. This effect may be observed from Figure 5.39.

Table 5.1 Anomaly Type Index

Cause of Anomalies	Anomaly Type
R-square value of the regression model between resilient modulus and bulk stress is less than 0.5	1
Tests were not done under right confining pressure	2
Deformation exceeded the designed limits	3
Not the first test on the sample	4
Test results were not repeatable	5
Contact load was higher than the normal value of 70 ~ 80 lbs	6
Sample was not prepared at the optimum condition of T-99	7
Other Contributors	8

Table 5.2 Anomalies Suspected for Test Samples

Sample ID	Test No.	Anomaly Type	Remarks
AP001	C1	1,2	
AP001	D1	1,2	
AP001	E3	1,2,4	
AP001	F1	1,2,6	
AP001	G1	1,2	
AP001	H1	1,2	
AP001	K3	4	
BF001	A1	1,2	
BF001	B5	2,4,5	
BF002	A5	2,4	
BF002	B3	1,2,4,6	
BR001	B2	4,7	LVDTs didn't work properly
BR001	D1	2	
BR001	E1	2	
FF001	A1	1,2,8	LVDT3, and 5 did not work properly
FF001	B1	1,2	
FF001	C1	1,2	
FF001	D2	1,2,4	
FF001	D3	1,2,4	
LS001	B1	7	
MIC001	B2	4,7	
MM001	B1	2,7	
SC001	D2	2,4	
SC001	E1	7,8	Stopped at Seq. 14
SR1501	A1	7,8	LVDT2 did not work properly
SR6001	D1	8	Machine shut down at the last sequence.
SR8001	A1	5	
SR8001	C2	2,5	
SR82601	C1	5	
UF001	A1	1,2,7	
UF001	A2	1,2,4,7	
UF001	A3	1,2,4,7	
UF001	B1	1,2	
UF002	A1	1,2	
UF002	B1	1,2	
UF002	J1	8	Test terminated at Seq. 10
UF003	A1	1,2,7	
UF003	B1	1,2,7,8	Lost data on Sequence 1
UF003	C1	1,2,8	Lost data on Sequences 1, 14, 15
UF003	G1	7,8	Deviator stress was out of accepted range
UF003	I1	3	
UF003	J1	3	
US1901	C1	5	
US1901	D1	5	
WT001	B1	3	

Table 5.3 Average Resilient Modulus @ 2 psi Using Test Method T307-99 (33 data points)

SampleID	FLN	Classification	SieveNo200	CC	CU	Clay	PlasticIndex	OptOMC	OptMDUW	6T180LBR	Permeability(cm/s)	TestMethod	AvgMRAt2CP(psi)
21157	21157-S	A-2-4						0.121	110.8	14		T307	11466.99
21158	21158-S	A-2-4						0.13	110.2	17		T307	15022.21
21159	21159-S	A-2-4						0.129	108.5	13		T307	12806.66
21383	21383-S	A-2-4	11					0.116	109.4	54		T307	10507.81
21384	21384-S	A-3	9					0.128	106.9	57		T307	10519.69
21385	21385-S	A-3	10					0.113	111.6	46		T307	9450.39
21386	21386-S	A-3	6					0.119	108.2	42		T307	12172.44
21387	21387-S	A-3	7					0.117	107.7	39		T307	10843.43
21388	21388-S	A-3	7					0.12	107.4	52		T307	12827.21
21389	21389-S	A-3	6					0.129	107.6	49		T307	11103.10
21390	21390-S	A-3	5					0.13	104.5	27		T307	13924.18
21391	21391-S	A-3	6					0.145	104.1	33		T307	13716.44
AP001	21851-S	A-2-4	17.3			12		0.1	120.2	141	0.00000645	T307	12244.52
BF001	21881-S	A-2-6	34.8			27.3	13.3	0.158	111.6	109	0.000000207	T307	11435.098
BF002	21897-S	A-2-6	22.8			20.8	14.2	0.126	117.2	78	0.00000361	T307	14666.28
BH001	21671~21673	A-2-4	24			6	5	0.088	128.4	132	0.000000742	T307	24660.35
BR001	21982-S	A-3	6	1.07	2.98			0.12	111.2	36	0.000164	T307	13022.54
ES001	21981-S	A-3	7.8	0.86	2.31			0.121	107.9	35	0.000547	T307	13803.04
FF001	21852-S	A-2-4	20.4			18		0.133	116.4	108	0.00000165	T307	13184.56
IB001	21668~21670	A-2-6	32			16	12	0.103	123.3	127	0.00000056	T307	9871.98
MM001	21906-S	A-3	2.3	0.97	2.18	2		0.147	104.9	28		T307	16224.42
OS001	21984-S	A-3	3.7	1.07	2.1			0.132	105.1	18		T307	14971.81
SC001	21665~21667	A-2-4	15.24			4		0.092	118.2	83	0.000276	T307	9920.73
SL001	21910-S	A-3	3.4	1.04	1.85	0.5		0.133	106.1	17		T307	12604.46
SMR001	21980-S	A-3	4.1	1.26	2.67			0.132	108.1	35		T307	10188.46
SR1501	21989-S	A-1-b	12.5	0.51	137.5	4.5		0.098	125.1	143		T307	20613.95
SR6001	21990-S	A-3	10.3	1.44	4			0.115	115.4	91	0.000245	T307	14986.17
SR8001	21991-S	A-3	2.9	0.61	6.6			0.1	118.8	85		T307	16652.37
UF001	21887-S	A-2-4	30	1.26	4.52	6		0.133	110.7	85	0.0000521	T307	13326.08
UF002	21888-S	A-2-4	17.9	13.44	36	9		0.132	113.2	117	0.0000221	T307	11136.50
UF003	21889-S	A-2-4	12.2	4.89	11.5	9		0.128	111.8	126	0.0000133	T307	13140.25
US1901	21909-S	A-3	4.7	1.09	2.45	3.5		0.124	107.7	24	0.000305	T307	13653.61
WT001	21984-S	A-3	2.2	0.9	1.64			0.126	104.4	21	0.000654	T307	14166.55

Table 5.4 Average Resilient Modulus @ 2 psi Using Test Method T292-91I (46 data points)

SampleID	FLN	Classification	SieveNo200	CC	CU	Clay	OptOMC	OptMDUW	6T180LBR	Permeability(cm/s)	TestMethod	AvgMRAt2CP(psi)
13302	20973						0.125	103.2	29		T292	11787.74
23302	20972						0.12	103.1	29		T292	11194.63
33302	20971	A-2-6					0.15	113	125		T292	7368.41
43302	20974						0.158	111.4	70		T292	8166.97
A1AES		A-3					0.124	108.71	16		T292	10600.67
A1ASS		A-2-4					0.101	116.48	47		T292	14945.33
A1BES		A-3					0.108	107.89	19		T292	17752
A1BSS		A-3					0.12	104.06	43		T292	15222
A24-12%		A-2-4	12	1.31	3	3	0.121	110.6	30	0.000305	T292	13078.83
A24-20%		A-2-4	20	1.6	3.78	8	0.1	124.4	146	0.000104	T292	15545.33
A24-24%		A-2-4	24	5.06	14.74	5	0.107	116.3	69	0.000065	T292	13282.83
A24-30%		A-2-4	30				0.12	116	72	0.0000201	T292	14989.67
A2AES		A-3					0.108	110.18	30		T292	16306.33
A2ASS		A-2-4					0.105	118.96	64		T292	16157.67
A2BES		A-3					0.133	105.02	33		T292	15442.67
A2BSS		A-3					0.108	105.66	49		T292	15899.67
B3ASS		A-3					0.117	113.17	38		T292	14751
B4ASS		A-2-4					0.112	112.09	46		T292	17500.67
B5CES		A-3					0.128	104.7	53		T292	13631.33
B5CSS		A-2-4					0.135	100.5	49		T292	11420.67
B6CES		A-3					0.124	101.71	68		T292	14773
B6CSS		A-3					0.143	100.89	43		T292	10769.67
C2GES		A-2-4					0.097	116.29	81		T292	14902.67
C2GSS		A-2-4					0.069	128.57	145		T292	21638
C3GSS		A-3					0.113		121		T292	16116.67
D3MES		A-3					0.096	106.3	21		T292	15865
D3MSS		A-3					0.089	118.2	70		T292	21217.67
D4MES		A-3					0.095	113.42	29		T292	20599.33
D4MSS		A-4					0.097	117.82	45		T292	20514
E1SES		A-2-4					0.084	108.52	20		T292	16941.67
E1SSS		A-2-4					0.063	119.28	79		T292	19891.67
E2SES		A-3					0.127	107.31	31		T292	18157.67
E2SSS		A-2-4					0.08	118.2	93		T292	18422.33
E3OES		A-3					0.127	107.31	18		T292	15212.00
E3OSS		A-3					0.09	118.2	56		T292	23326
E4OES		A-3					0.128	103.37	60		T292	11808.67
E4OSS		A-3					0.089	121	85		T292	19229.33
I 75-Alachua		A-2-4					0.099	124.16			T292	19711
Levy		A-3	4				0.1	106.5	22	0.00552	T292	15355.17
Oolite		A-1					0.076	132.6	194		T292	16166.00
SR 200-Ocala		A-2-4					0.089	120.4			T292	15483.67
SR 30A-Panama City		A-2-4					0.085	125.11			T292	16335.00
SR 369-Crawfordville		A-3					0.1	115.05			T292	10695.67
SR 50-Brooksville		A-3					0.106	113.45			T292	15848.33
SR70-A24		A-2-4	14	58.28	290	10	0.105	122	124	0.00025	T292	23312.67
SR70-A3		A-3	8	0.9	3.83	6	0.115	112	45	0.00206	T292	17050.83

Table 5.5 Data Points for Different Material Type and Different Test Method in Database

	T292			T294			T307			Total		
Material Type	Total	Reliable	Optimum	Total	Reliable	Optimum	Total	Reliable	Optimum	Total	Reliable	Optimum
Limerock	23	23								23	23	
A-1	6	6	2				16	13	1	22	19	3
A-1-a							8	6		8	6	
A-1-b							8	7	1	8	7	1
A-2-4	63	63	23	7	7	7	70	42	33	140	112	63
A-2-6	2	2	2				20	16	10	22	18	12
A-3	59	59	25	8	8	8	62	52	44	129	119	77
A-4	5	5	3	2	2	2				7	7	5
A-6	3	3	2							3	3	2
NA	3	3	3							3	3	3
Total	164	164	60	17	17	17	168	123	88	349	304	165
*Total selected for analysis		124	50					110	87		234	137

* The data from test method T292-91 and T307-99, and from the material type A-2-4, A-2-6, and A-3 are selected for analysis.

Table 5.6 Data Points Available on Each Material Property for Different Test Method in Database

	T292			T294			T307			Total		
Property	Total	Reliable	Optimum	Total	Reliable	Optimum	Total	Reliable	Optimum	Total	Reliable	Optimum
Moisture Content	138	138(121)*	60(50)*	17	17	17	168	123(110)*	88(87)*	323	278(231)*	165(137)*
Dry Unit Weight	136	136(119)*	59(49)*	16	16	16	168	123(110)*	88(87)*	320	275(229)*	163(135)*
% Clay	32	32	10(10)*				104	68	43(42)*	136	100	53(52)*
% Fines	48	48	14(14)*				162	117	82(81)*	210	165	96(95)*
LBR	151	151	55(45)*	17	17	17	168	123	88(87)*	336	291	160(132)*
Plastic Index							26	22	14(14)*	26	22	14(14)*
Cu	32	32	10(10)*				95	68	43(42)*	127	100	53(52)*
Cc	32	32	10(10)*				95	68	43(42)*	127	100	53(52)*
Permeability	48	48	16(14)*				112	72	49(49)*	160	120	65(63)*

*The number in parentheses indicates that the data population from material type A-2-4, A-2-6, and A-3 only.

Table 5.7 Comparison of the Test Procedures for Test Method T292-91I and T307-99

Test		AASHTO T 292-91I			AASHTO T307-99		
Material		Subgrade			Subgrade		
Procedure		Confining Pressure	Deviator Stress	Load Number	Confining Pressure	Deviator Stress	Load Number
Unit		psi	psi		psi	psi	
Specimen Condition		15	12	1000	6	4	500
Testing Sequence	1	15	7	50	6	2	100
	2	15	10	50	6	4	100
	3	15	15	50	6	6	100
	4	10	5	50	6	8	100
	5	10	7	50	6	10	100
	6	10	10	50	4	2	100
	7	10	15	50	4	4	100
	8	5	3	50	4	6	100
	9	5	5	50	4	8	100
	10	5	7	50	4	10	100
	11	5	10	50	2	2	100
	12	2	3	50	2	4	100
	13	2	5	50	2	6	100
	14	2	7	50	2	8	100
	15				2	10	100

Table 5.8 Summary of Permeability Test Results

Sample ID	Class	% Fines	% Clay	CC	CU	PI	OptOMC (%)	OptMDUW(pcf)	Permeability (cm/s)	Test Method	Project
A24-12%	A-2-4	12	3	1.31	3		12.1	110.6	0.000305	Flex Panel	DesignHighWater
A24-20%	A-2-4	20	8	1.6	3.78		10	124.4	0.000104	Flex Panel	DesignHighWater
A24-24%	A-2-4	24	5	5.06	14.74		10.7	116.3	0.000065	Flex Panel	DesignHighWater
A24-30%	A-2-4	30					12	116	0.0000201	Flex Panel	DesignHighWater
AP001	A-2-4	17.3	12				10	120.2	0.00000645	Flex Panel	MRDB2
BF001	A-2-6	34.8	27.3			13.3	15.8	111.6	0.000000207	Flex Panel	MRDB2
BF002	A-2-6	22.8	20.8			14.2	12.6	117.2	0.00000361	Flex Panel	MRDB2
BH001	A-2-4	24	6			5	8.8	128.4	0.000000742	Flex Panel	MRDB2
BR001	A-3	6		1.07	2.98		12	111.2	0.000164	Flex Panel	MRDB2
ES001	A-3	7.8		0.86	2.31		12.1	107.9	0.000547	Flex Panel	MRDB2
FF001	A-2-4	20.4	18				13.3	116.4	0.00000165	Flex Panel	MRDB2
IB001	A-2-6	32	16			12	10.3	123.3	0.00000056	Flex Panel	MRDB2
Levy	A-3	4					10	106.5	0.00552	Constant Head	DesignHighWater
LS001	A-2-4	14		1.58	4.5		9.6	124.8	0.000188	Flex Panel	MRDB2
MIC001	A-1-a	5		2.51	35.29		9.3	117.8	0.000472	Flex Panel	MRDB2
MM001	A-3	2.3	2	0.97	2.18		14.7	104.9		Flex Panel	MRDB2
SC001	A-2-4	15.24	4				9.2	118.2	0.000276	Flex Panel	MRDB2
SR6001	A-3	10.3		1.44	4		11.5	115.4	0.000245	Flex Panel	MRDB2
SR70-A24	A-2-4	14	10	58.28	290		10.5	122	0.00025	Flex Panel	DesignHighWater
SR70-A3	A-3	8	6	0.9	3.83		11.5	112	0.00206	Constant Head	DesignHighWater
SR82602	A-1-b	12.7	2	0.29	85		8.6	121.8	0.000185	Flex Panel	MRDB2
UF001	A-2-4	30	6	1.26	4.52		13.3	110.7	0.0000521	Flex Panel	MRDB2
UF002	A-2-4	17.9	9	13.44	36		13.2	113.2	0.0000221	Flex Panel	MRDB2
UF003	A-2-4	12.2	9	4.89	11.5		12.8	111.8	0.0000133	Flex Panel	MRDB2
US1901	A-3	4.7	3.5	1.09	2.45		12.4	107.7	0.000305	Flex Panel	MRDB2
WT001	A-3	2.2		0.9	1.64		12.6	104.4	0.000654	Flex Panel	MRDB2

Table 5.9 Summary Table for Resilient Modulus Values/Ratios Derived from Zhang's Regression Model

Classification	Total Tests	MRLab-MRZhang (Average)	MRLab/MRZhang (Average)	MRLab-MRZhang (Maximum)	MRLab/MRZhang (Maximum)	MRLab-MRZhang (Minimum)	MRLab/MRZhang (Minimum)
A-1-a	6	-12929.56	0.56	-10876.15	0.64	-14675.50	0.51
A-1-b	7	-263523.92	0.07	-122139.59	0.12	-455042.50	0.03
A-2-4	42	-38.44	1.04	6690.92	1.90	-6964.30	0.63
A-3	44	410.61	1.05	5181.15	1.43	-3999.27	0.74

Table 5.10 Summary Table for Materials that do not fit Zhang's Model

SampleID	TestNo	Classification	% Fines	CC	CU	MC	DUW	MRLab	MRZhang	MRLab-MRZhang	MRLab/MRZhang
MIC001	A1	A-1-a	5	2.51	35.29	9.4	112.1	16009.32	29788.87	-13779.55	0.54
MIC001	D1	A-1-a	5	2.51	35.29	9.4	111.8	15017.01	29692.51	-14675.50	0.51
MIC001	E1	A-1-a	5	2.51	35.29	10.2	112.3	15120.12	28889.98	-13769.86	0.52
SR1501	B1	A-1-b	12.5	0.51	137.5	10	118	16914.28	471046.1	-454131.78	0.04
SR1501	C1	A-1-b	12.5	0.51	137.5	10.5	120.8	20613.95	475656.4	-455042.50	0.04
SR1501	D1	A-1-b	12.5	0.51	137.5	10.8	118.7	15837.47	459305.7	-443468.19	0.03
SR82601	A1	A-1-a	5.3	2.67	37.5	9.9	111	18980.8	29856.95	-10876.15	0.64
SR82601	B1	A-1-a	5.3	2.67	37.5	9.9	110	17796.31	29536.23	-11739.92	0.60
SR82601	D1	A-1-a	5.3	2.67	37.5	11	112.6	16301.41	29037.78	-12736.37	0.56
SR82602	A1	A-1-b	12.7	0.29	85	8.7	114.8	15429.55	137569.1	-122139.59	0.11
SR82602	B1	A-1-b	12.7	0.29	85	8.7	115.9	16163.56	139213.2	-123049.66	0.12
SR82602	D1	A-1-b	12.7	0.29	85	8.4	112.1	10944.6	135269.2	-124324.57	0.08
SR82602	E1	A-1-b	12.7	0.29	85	8.9	113.1	11452.26	133963.4	-122511.15	0.09
SR70-A24	Mdf-Dry-1	A-2-4	14	58.28	290	8.41	120.3	41732.66	21673.88	20058.78	1.93

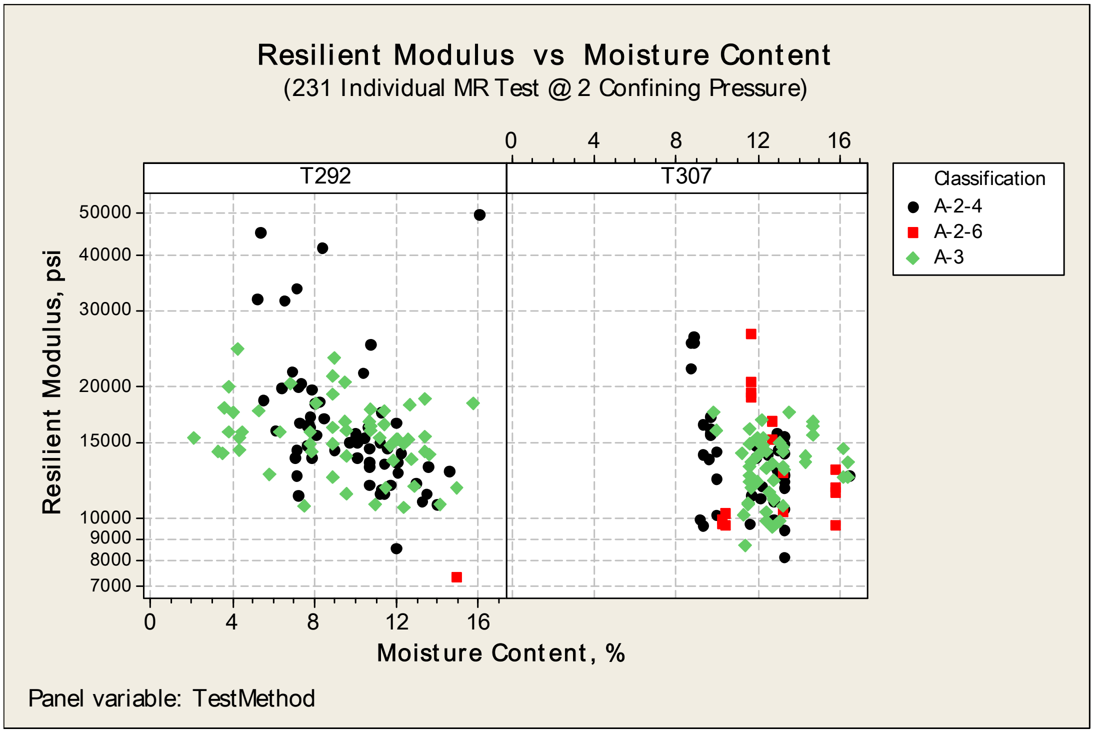


Figure 5.1 Resilient Modulus versus Moisture Content for 231 data points

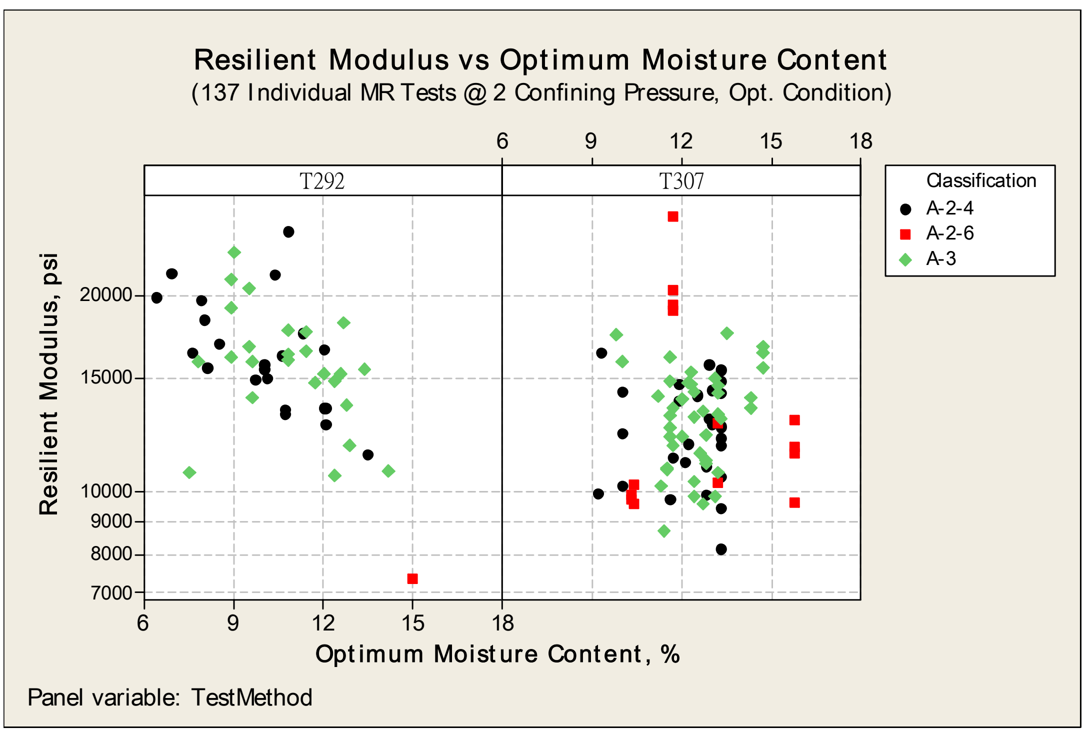


Figure 5.2 Resilient Modulus versus Optimum Moisture Content for 137 data points

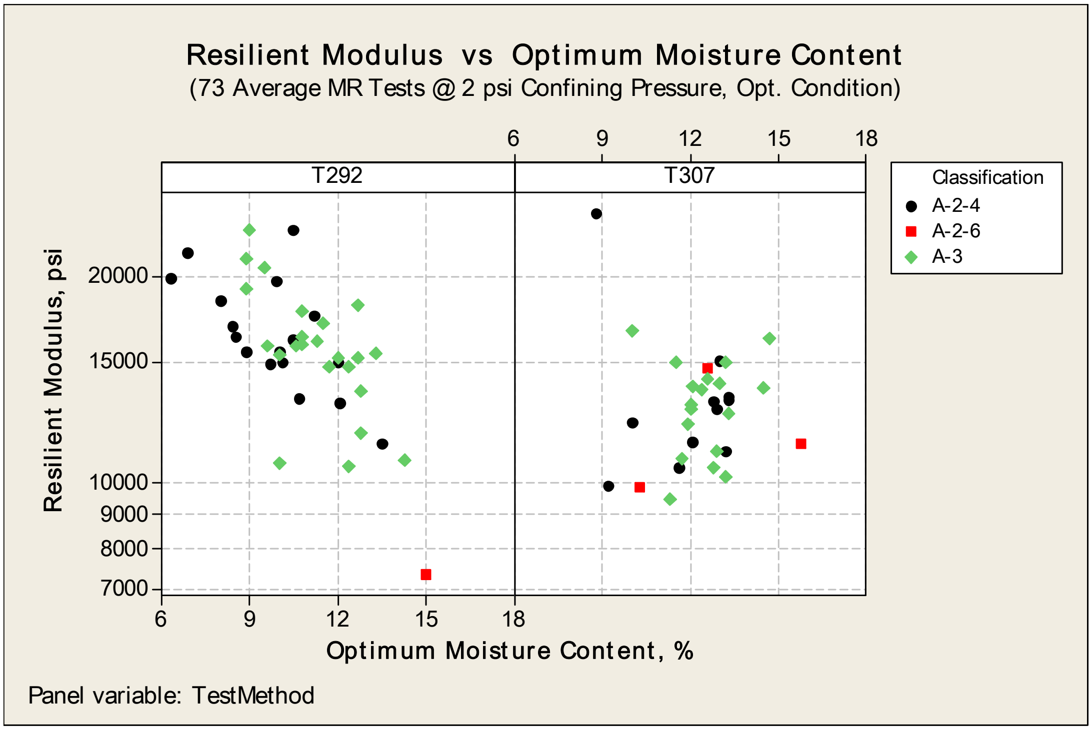


Figure 5.3 Average Resilient Modulus versus Optimum Moisture Content for 73 data points

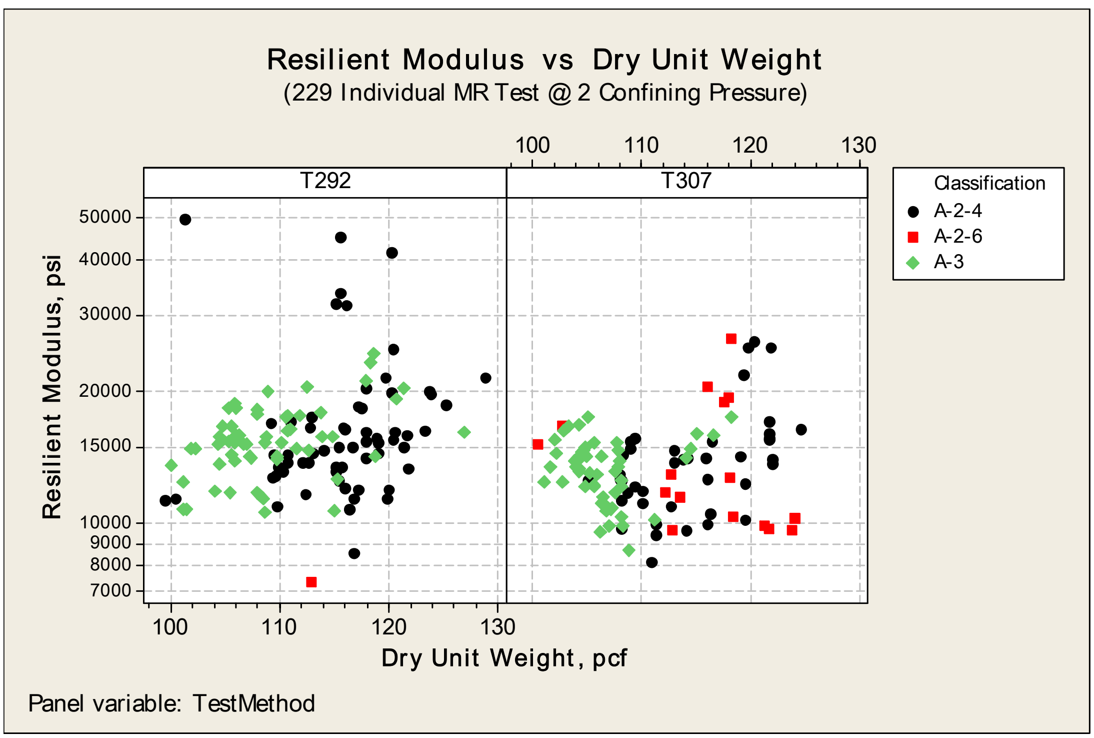


Figure 5.4 Resilient Modulus versus Dry Unit Weight for 229 data points

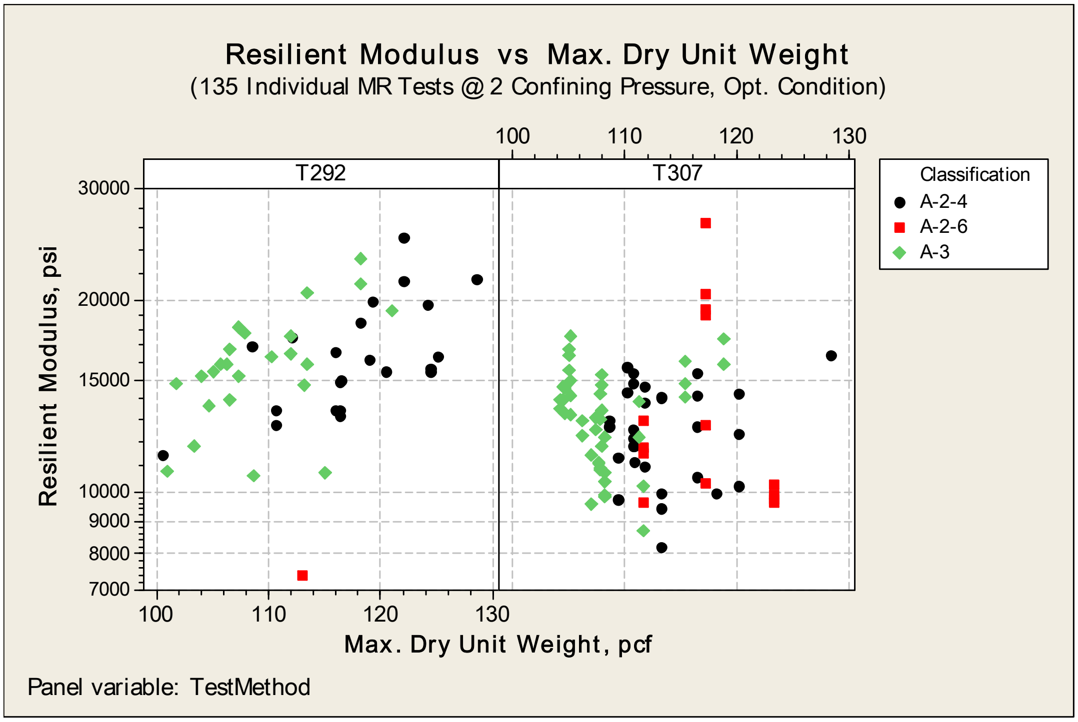


Figure 5.5 Resilient Modulus versus Dry Unit Weight @ Optimum Condition for 135 data points

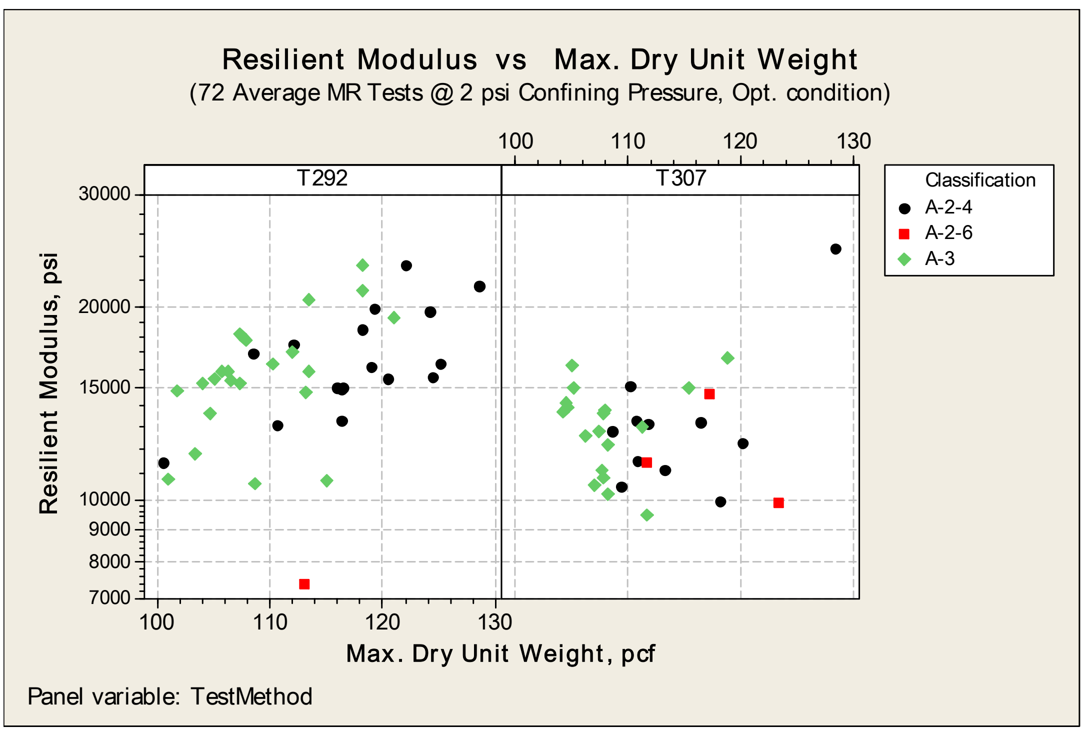


Figure 5.6 Average Resilient Modulus versus Dry Unit Weight @ Optimum Condition for 72 data points

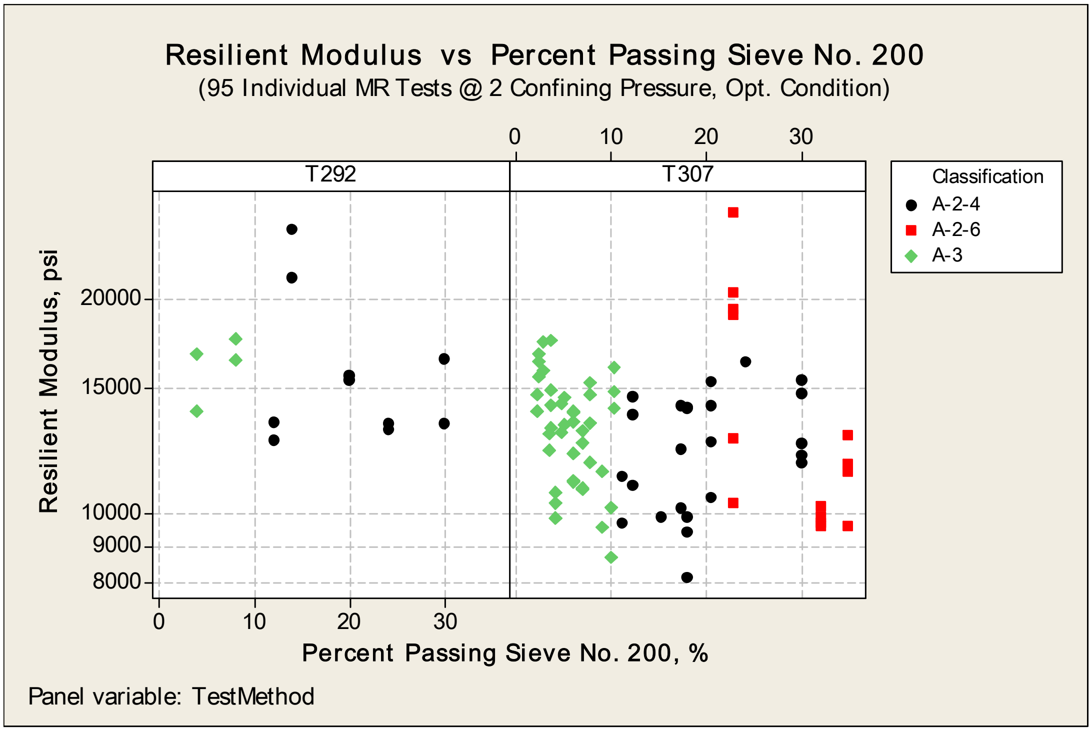


Figure 5.7 Resilient Modulus versus Percent of Fines @ Optimum Condition for 95 data points

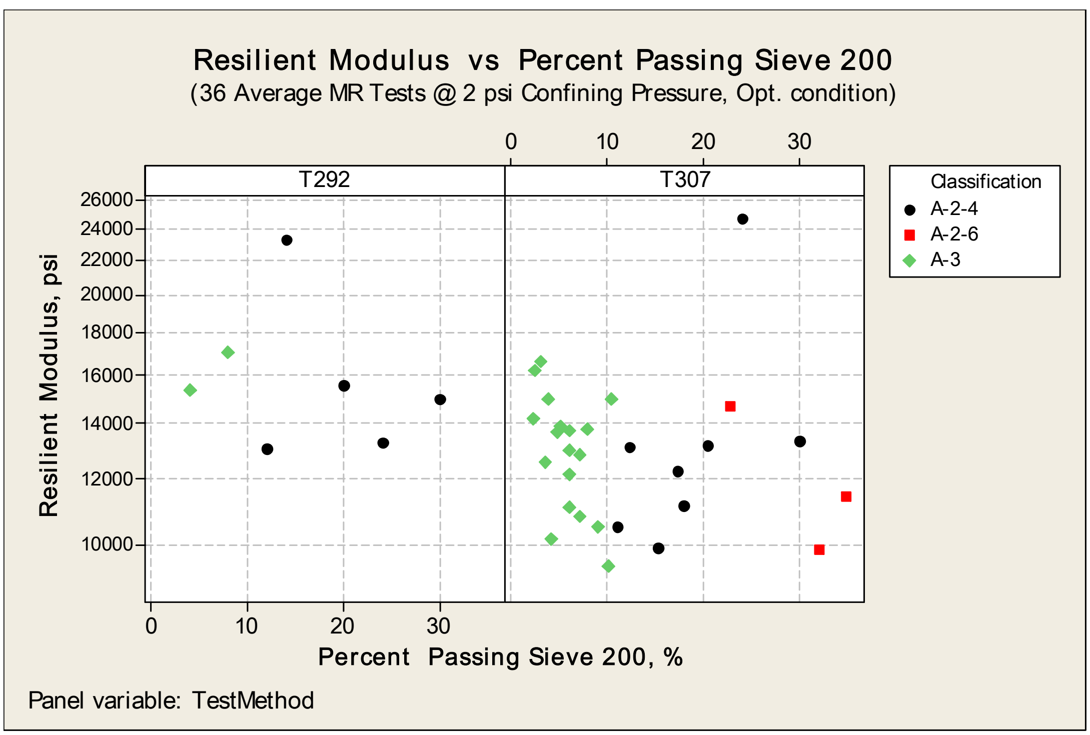


Figure 5.8 Average Resilient Modulus versus Percent of Fines @ Optimum Condition for 36 data points

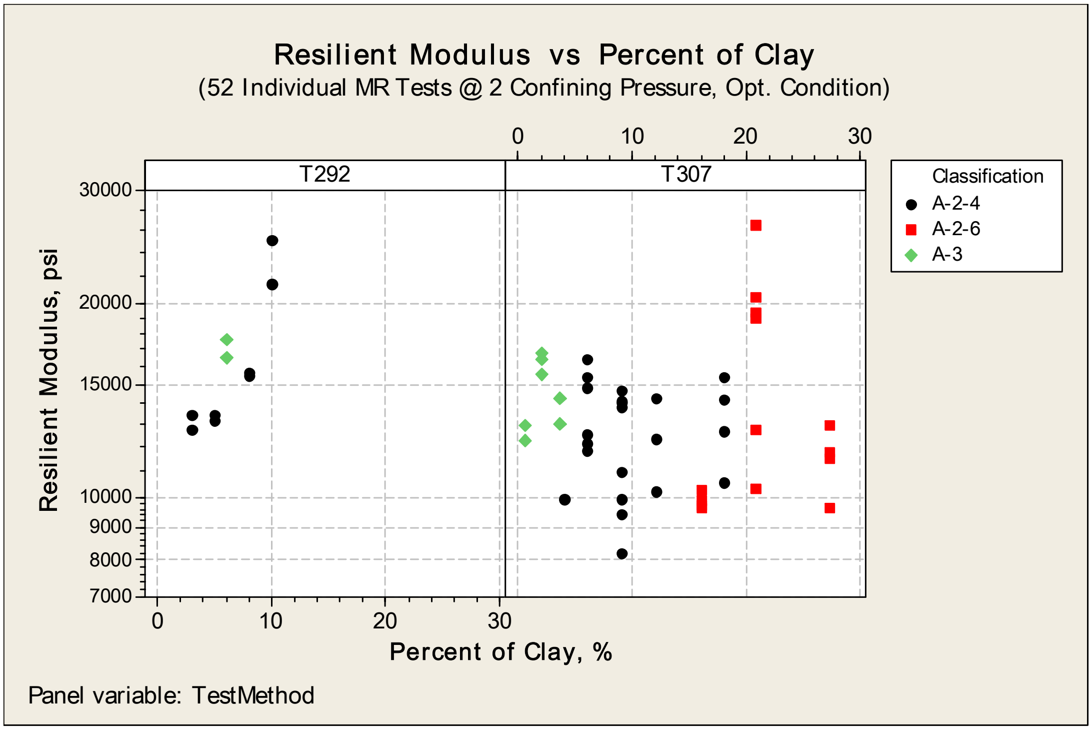


Figure 5.9 Resilient Modulus versus Percent of Clay @ Optimum Condition for 52 data points

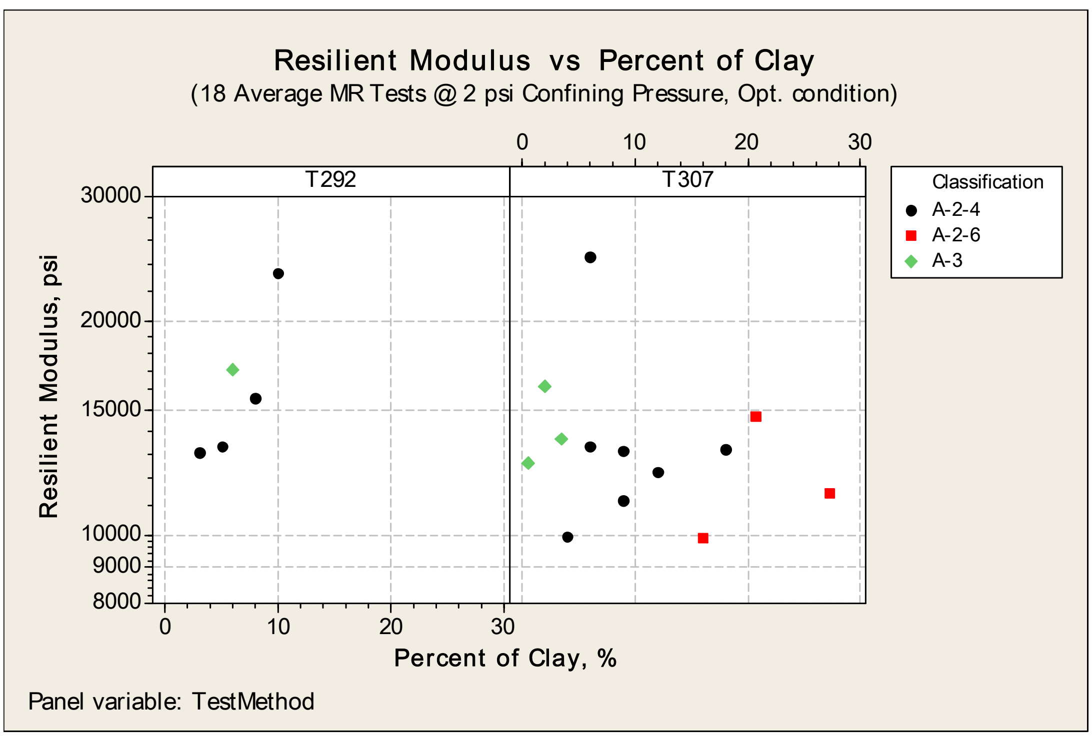


Figure 5.10 Average Resilient Modulus versus Percent of Clay @ Optimum Condition for 18 data points

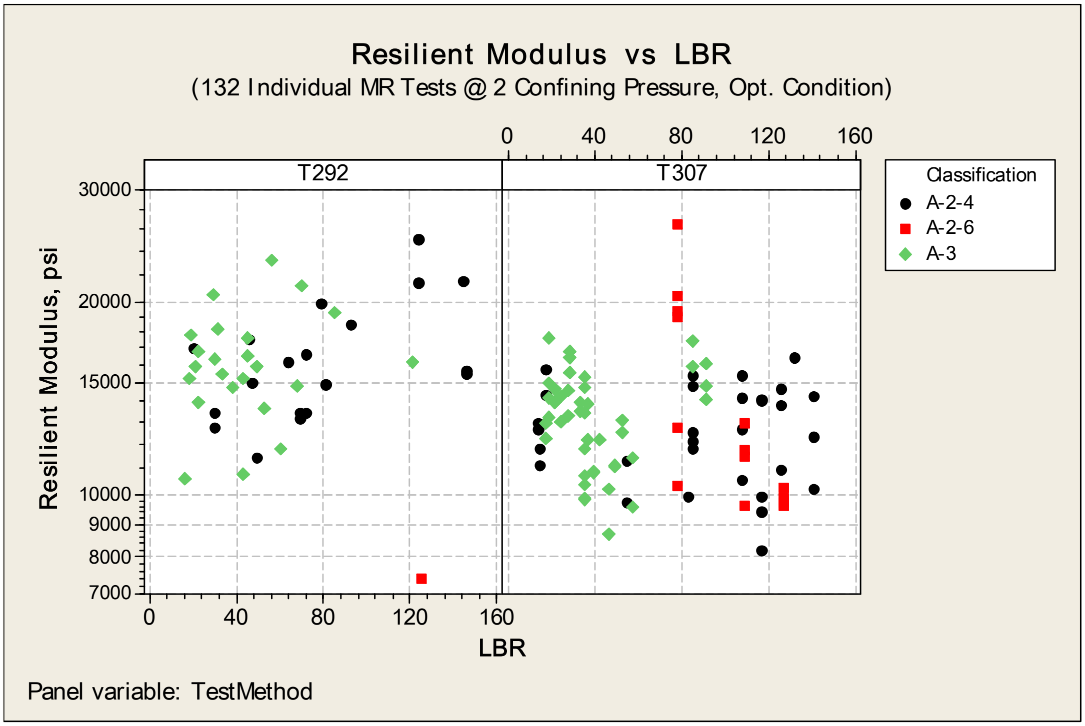


Figure 5.11 Resilient Modulus versus LBR @ Optimum Condition for 132 data points

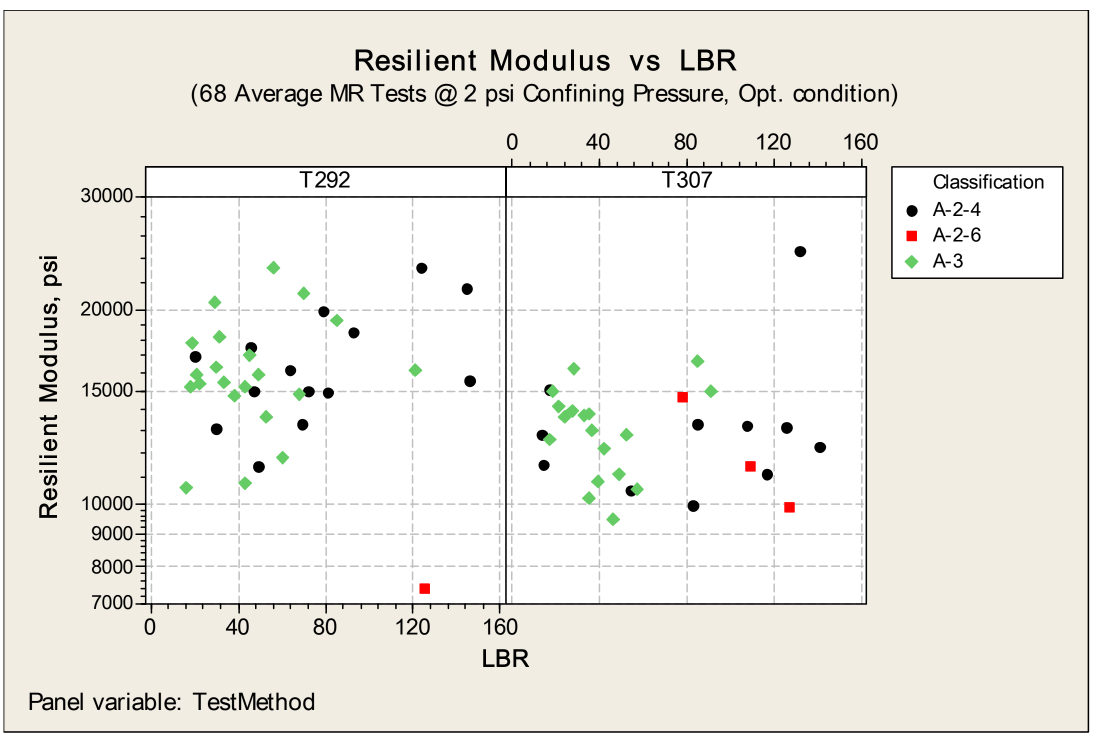


Figure 5.12 Average Resilient Modulus versus LBR @ Optimum Condition for 68 data points

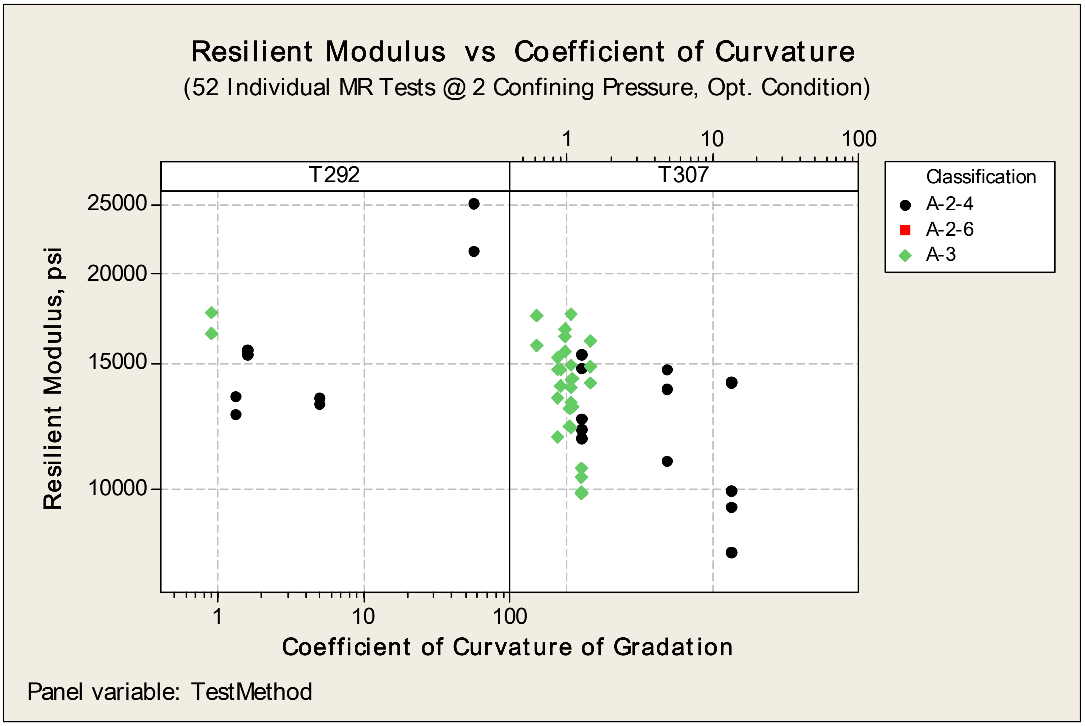


Figure 5.13 Resilient Modulus versus Coefficient of Curvature (C_c) @ Optimum Condition for 52 data points

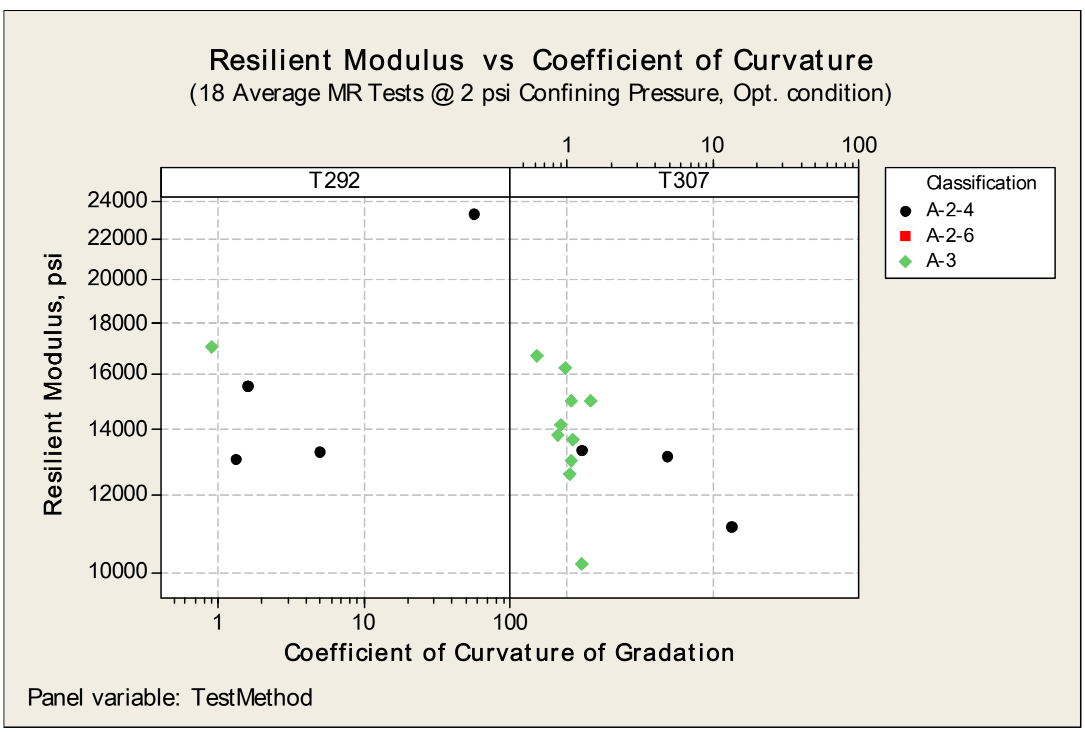


Figure 5.14 Average Resilient Modulus versus Coefficient of Curvature (C_c) @ Optimum Condition for 18 data points

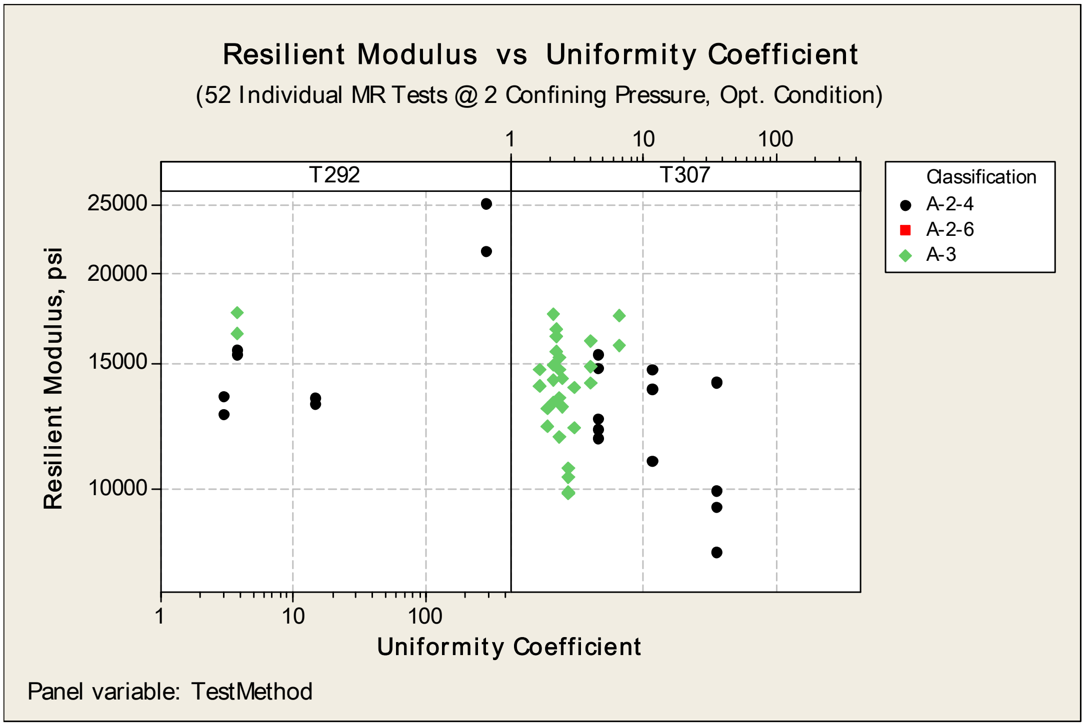


Figure 5.15 Resilient Modulus versus Uniformity Coefficient (C_u) @ Optimum Condition for 52 data points

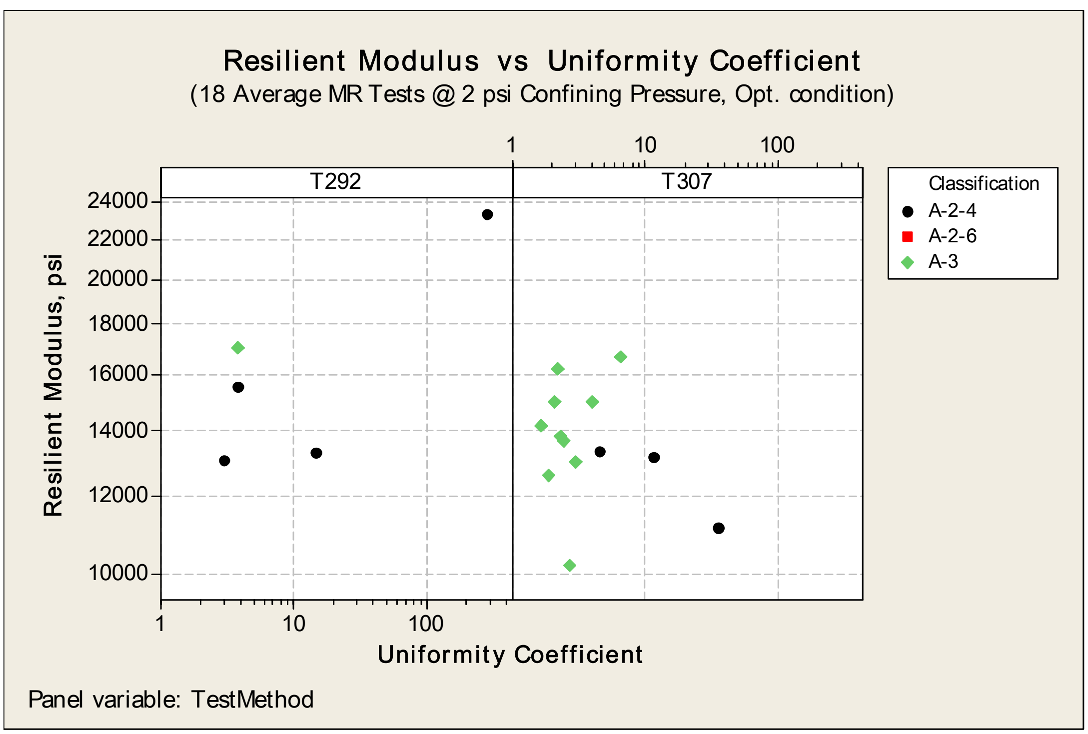


Figure 5.16 Average Resilient Modulus versus Uniformity Coefficient (C_u) @ Optimum Condition for 18 data points

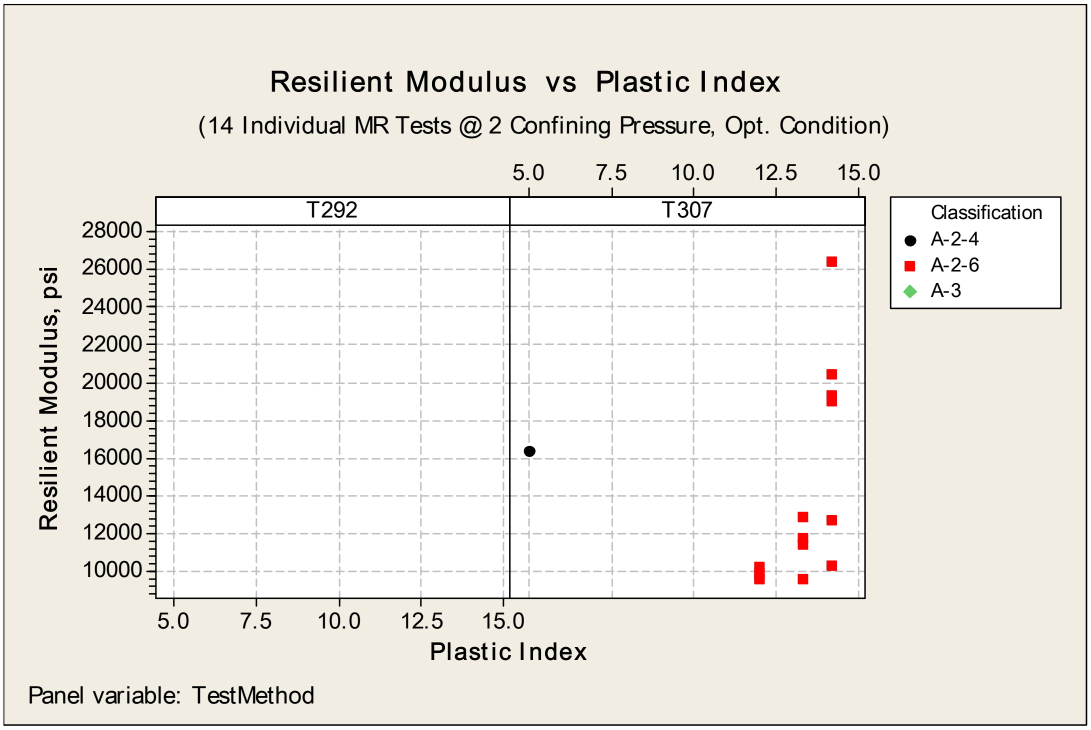


Figure 5.17 Resilient Modulus versus Plastic Index @ Optimum Condition for 14 data points

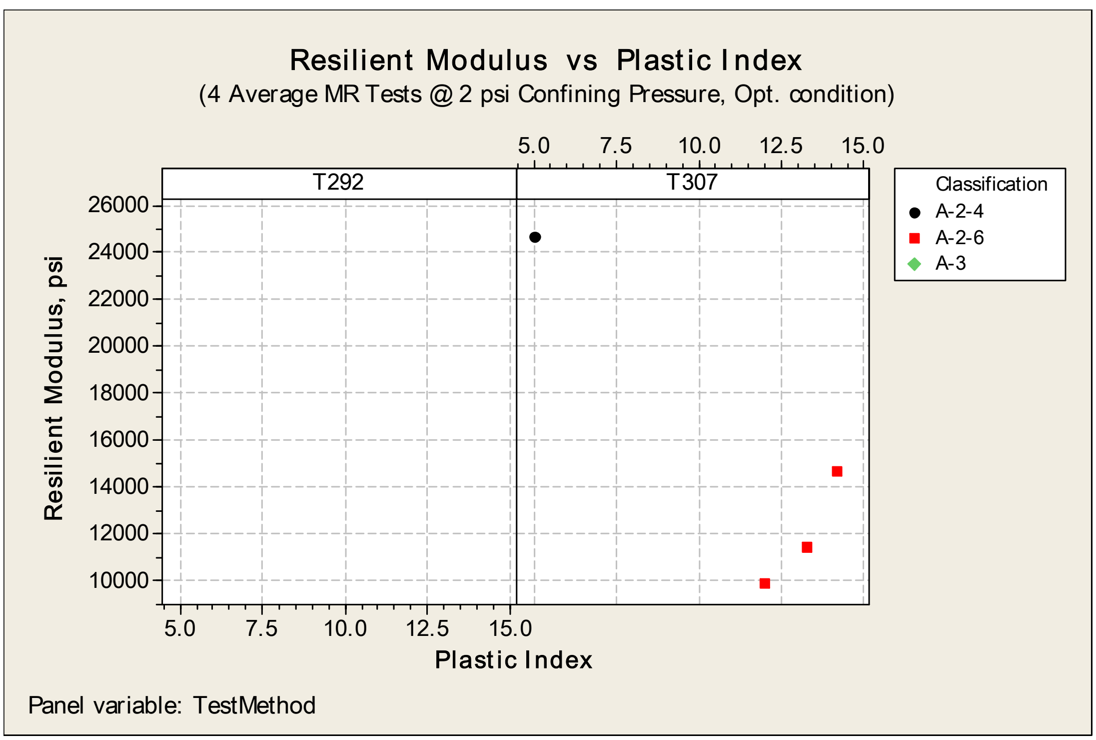


Figure 5.18 Average Resilient Modulus versus Plastic Index @ Optimum Condition for 4 data points

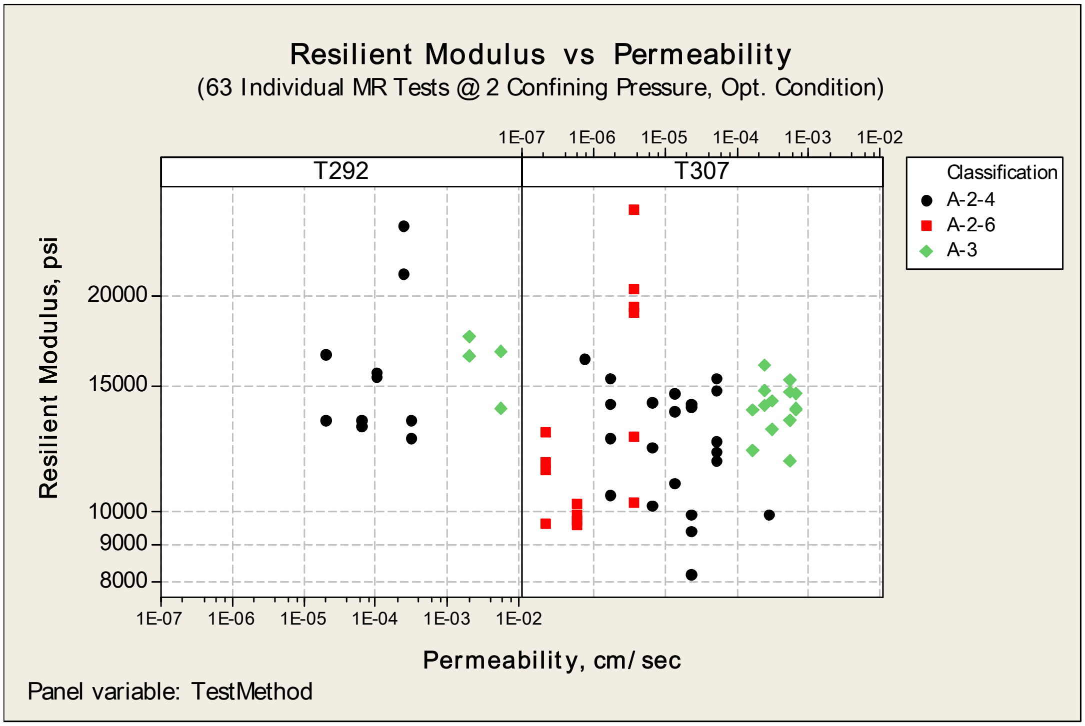


Figure 5.19 Resilient Modulus versus Permeability @ Optimum Condition for 63 data points

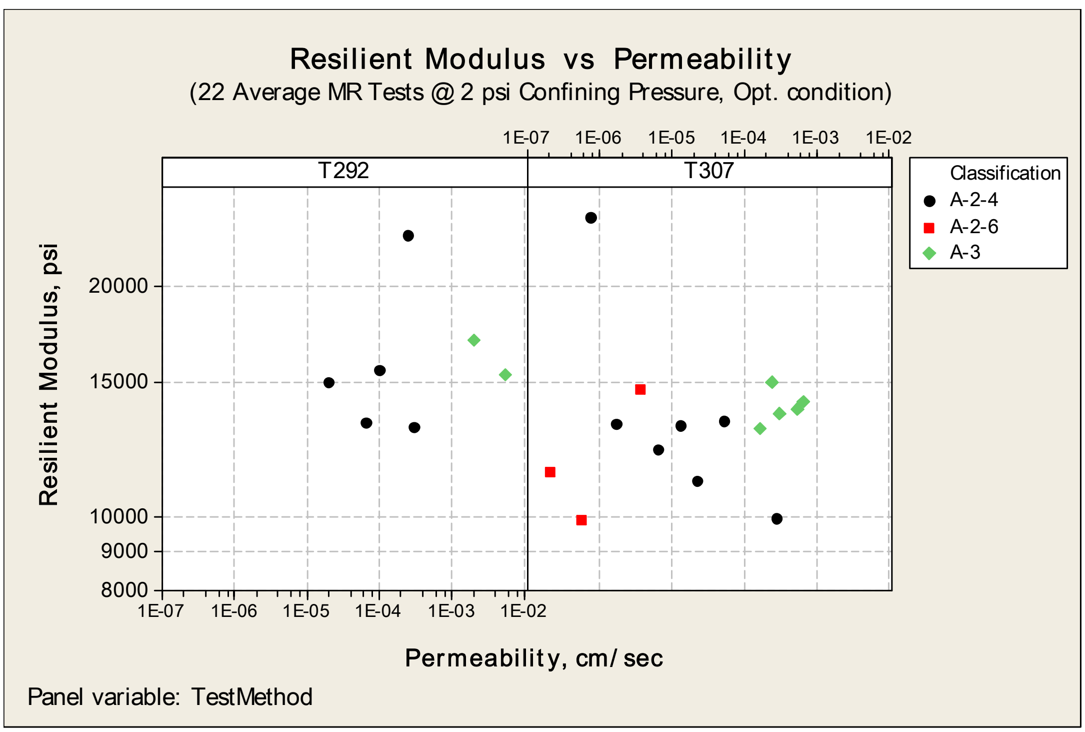


Figure 5.20 Average Resilient Modulus versus Permeability @ Optimum Condition for22 data points

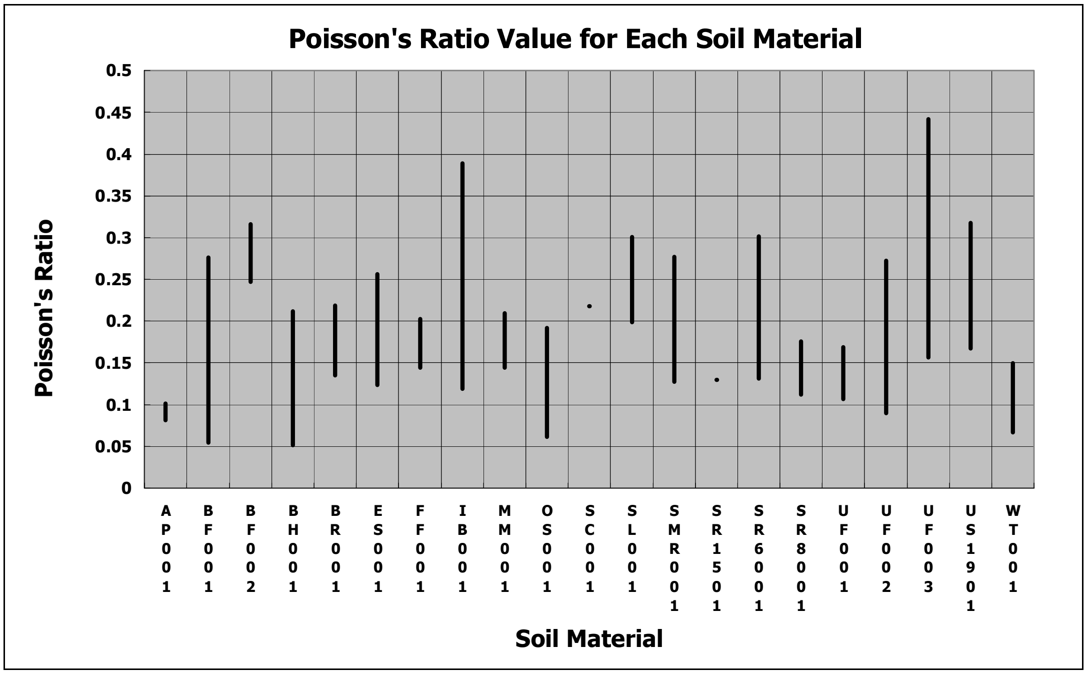


Figure 5.21 Poisson's Ratio Value for each Soil Material

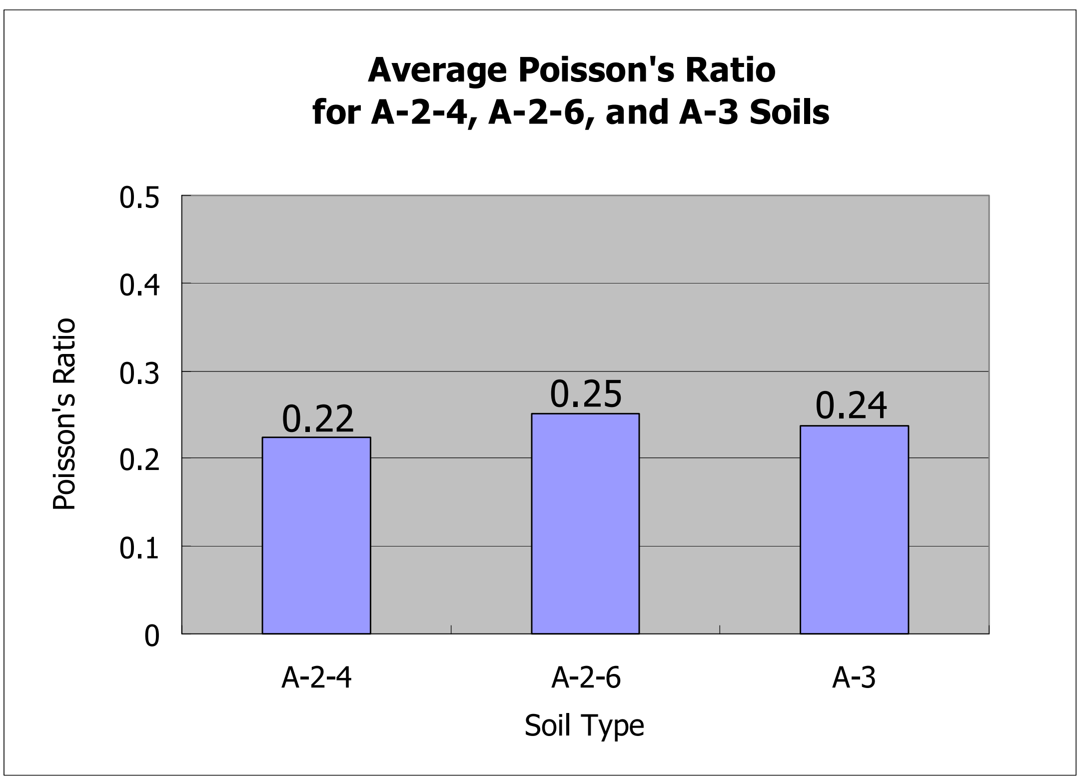


Figure 5.22 Average Poisson's Ratio for A-3, A-2-4, and A-2-6 Soils

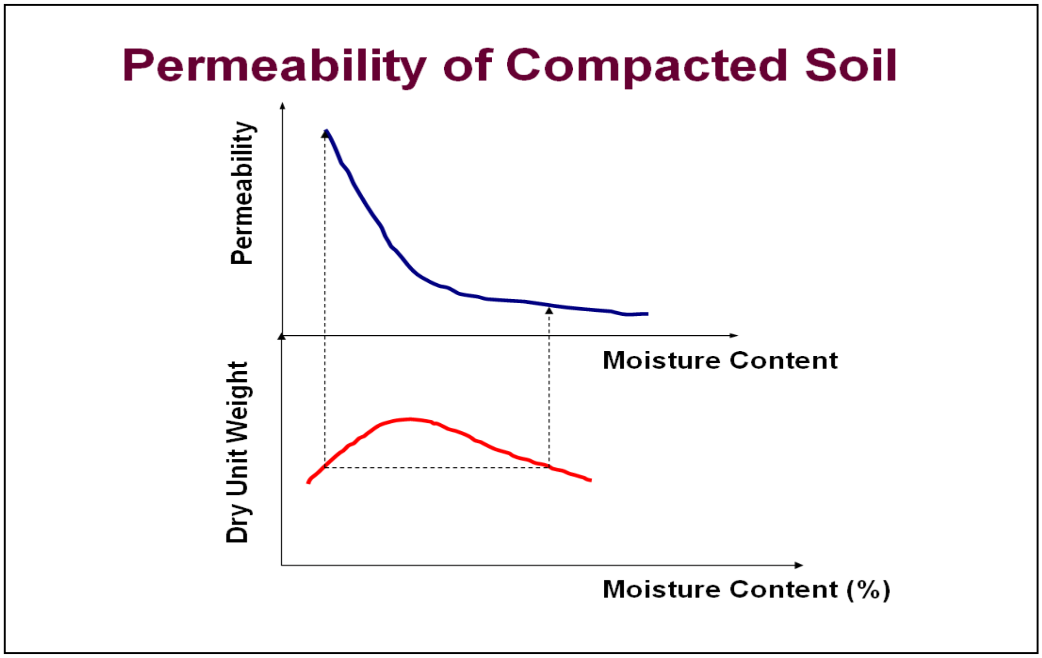


Figure 5.23 Typical Relationships between Permeability and Moisture Content, Dry Unit Weight

Typical Permeability of Soils

Soil or rock formation	Range of k (cm/s)
Gravel	1 - 5
Clean sand	10^{-3} - 10^{-2}
Clean sand and gravel mixtures	10^{-3} - 10^{-1}
Medium to coarse sand	10^{-2} - 10^{-1}
Very fine to fine sand	10^{-4} - 10^{-3}
Silty sand	10^{-5} - 10^{-2}
Homogeneous clays	10^{-9} - 10^{-7}
Shale	10^{-11} - 10^{-7}
Sandstone	10^{-8} - 10^{-4}
Limestone	10^{-7} - 10^{-4}
Fractured rocks	10^{-6} - 10^{-2}

Figure 5.24 Typical Range for the Permeability Coefficient on Different Material Types

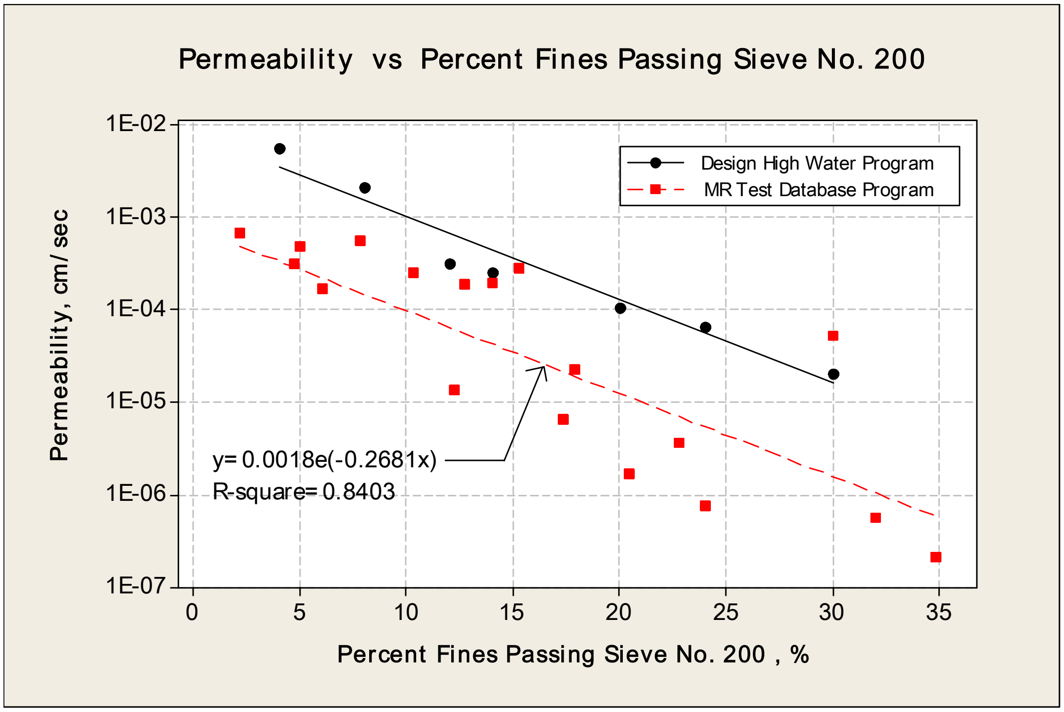


Figure 5.25 Permeability versus Percent of Fines

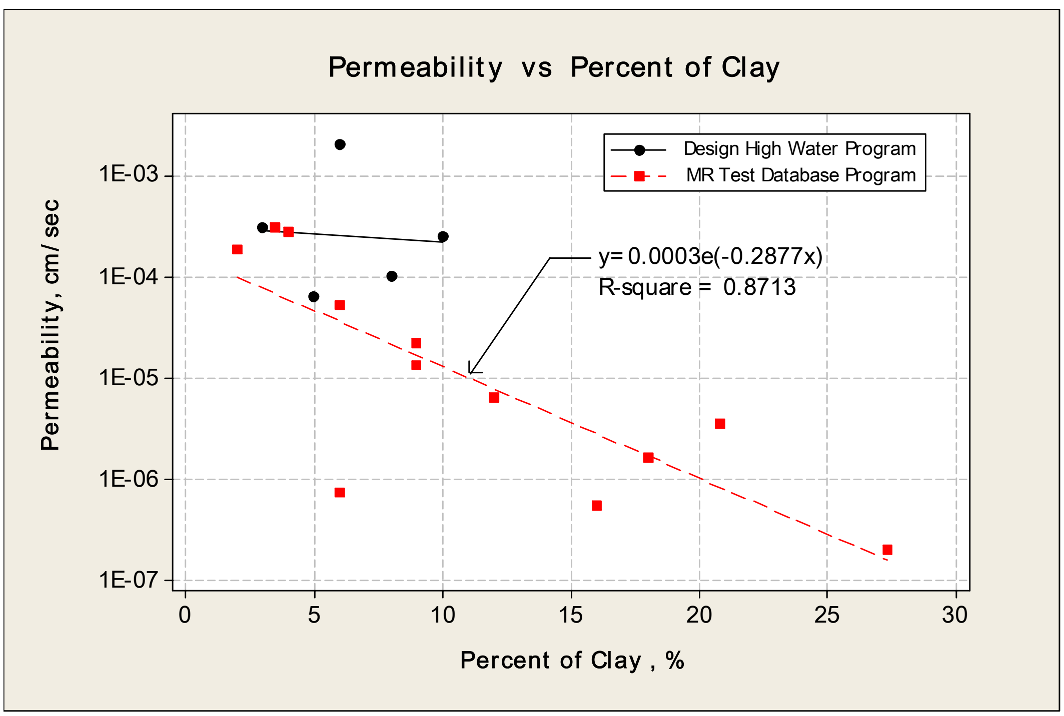


Figure 5.26 Permeability versus Percent of Clay

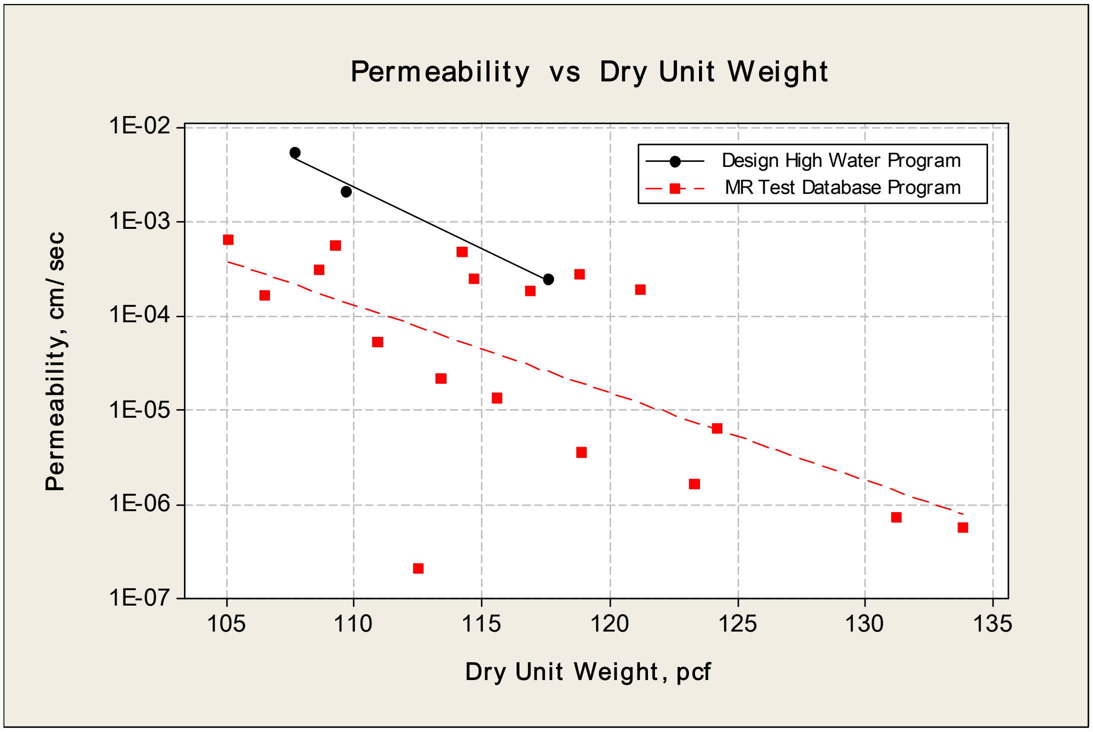


Figure 5.27 Permeability versus Dry Unit Weight

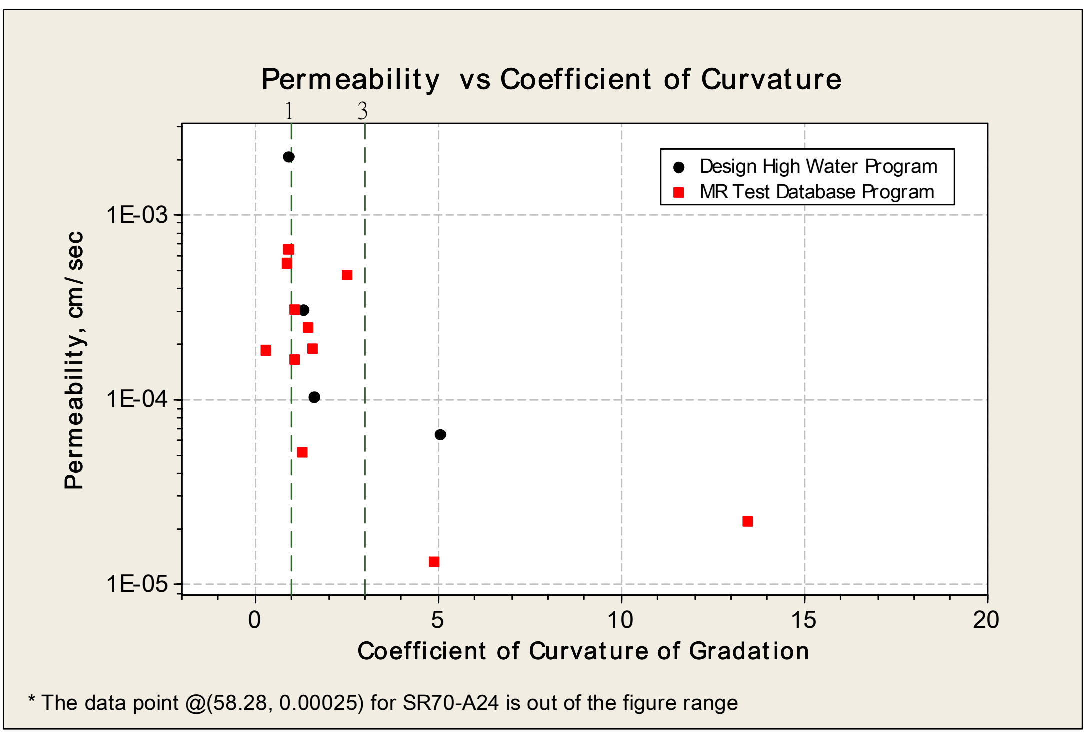


Figure 5.28 Permeability versus Coefficient of Curvature

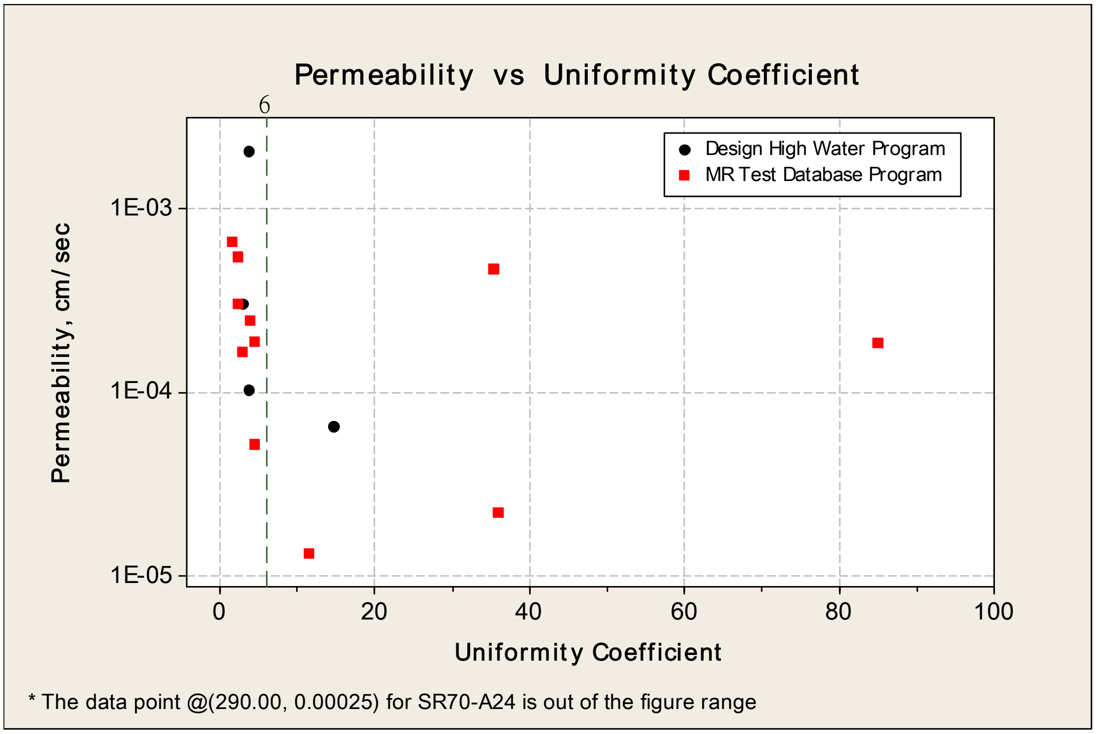


Figure 5.29 Permeability vs Uniformity Coefficient

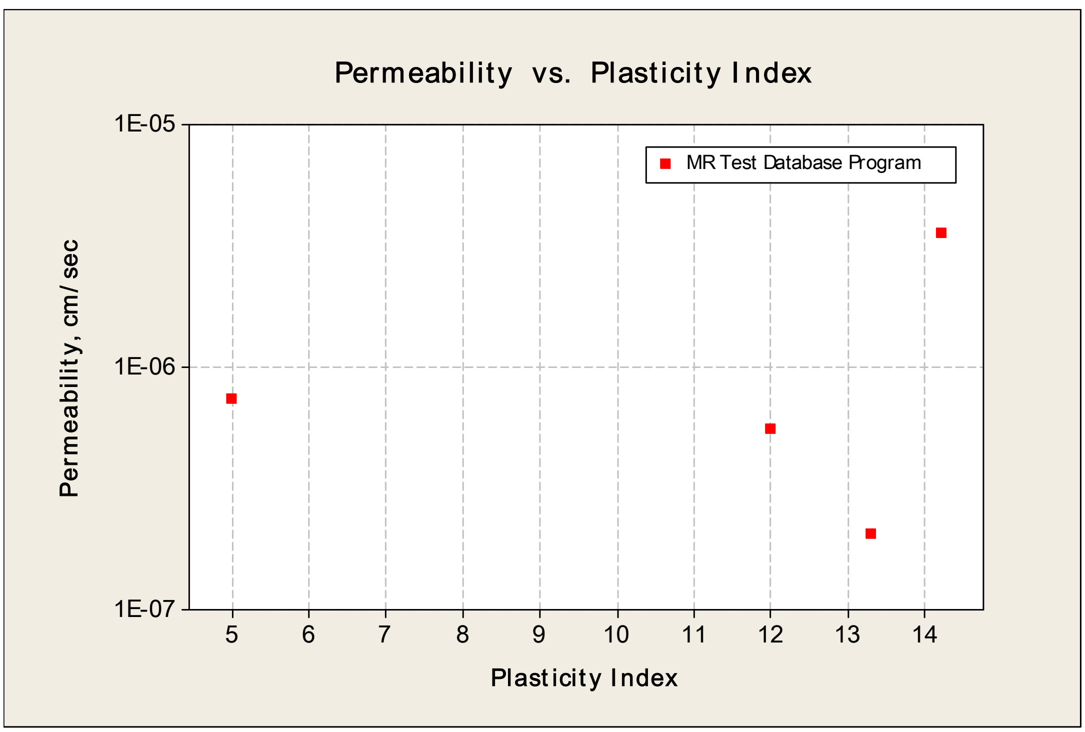


Figure 5.30 Permeability vs Plasticity Index

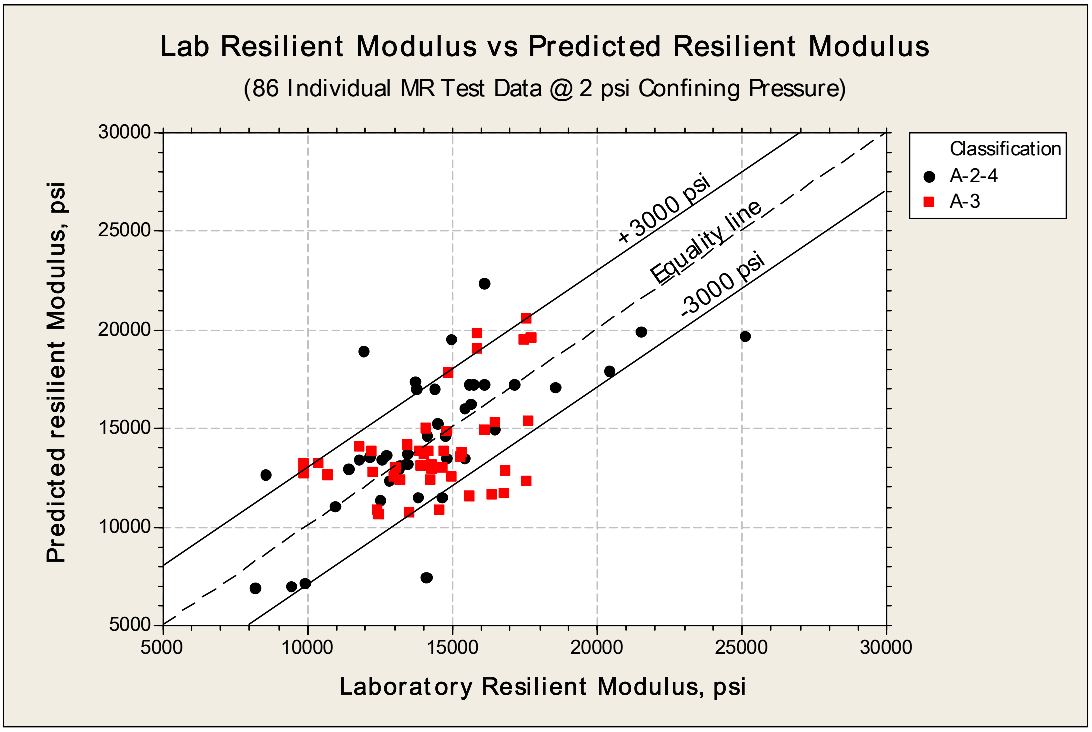


Figure 5.31 Lab Measured Resilient Modulus versus Predicted Resilient Modulus (Zhang's Model)

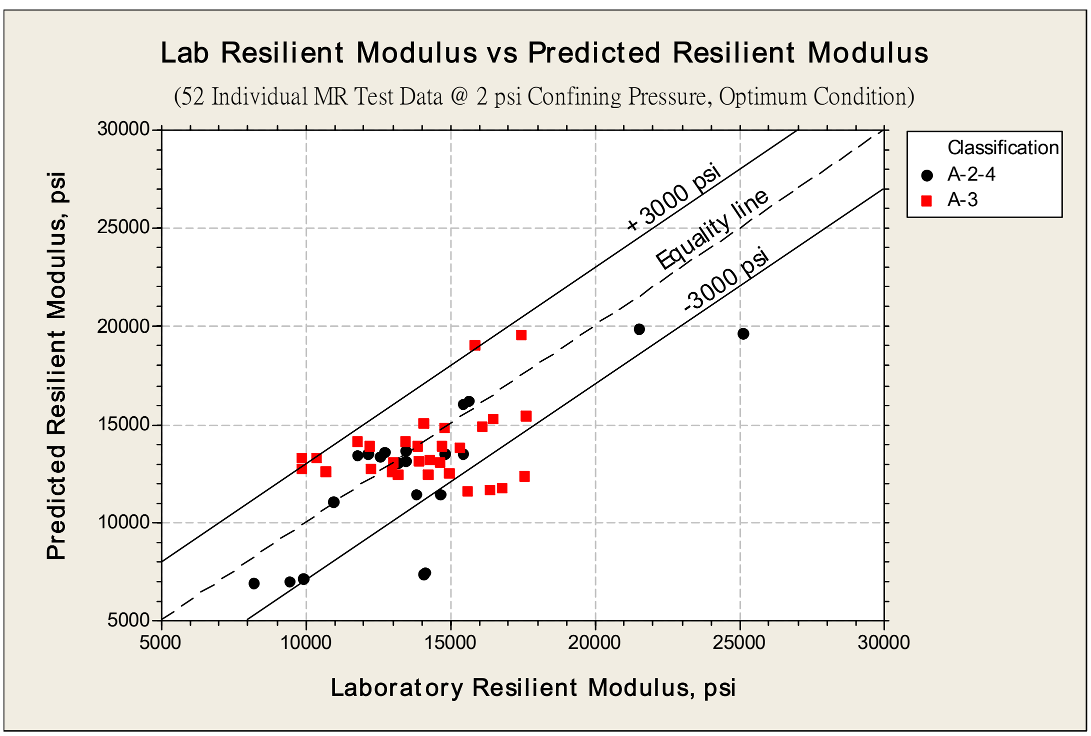


Figure 5.32 Lab Measured Resilient Modulus versus Predicted Resilient Modulus @ Optimum Condition (Zhang's Model)

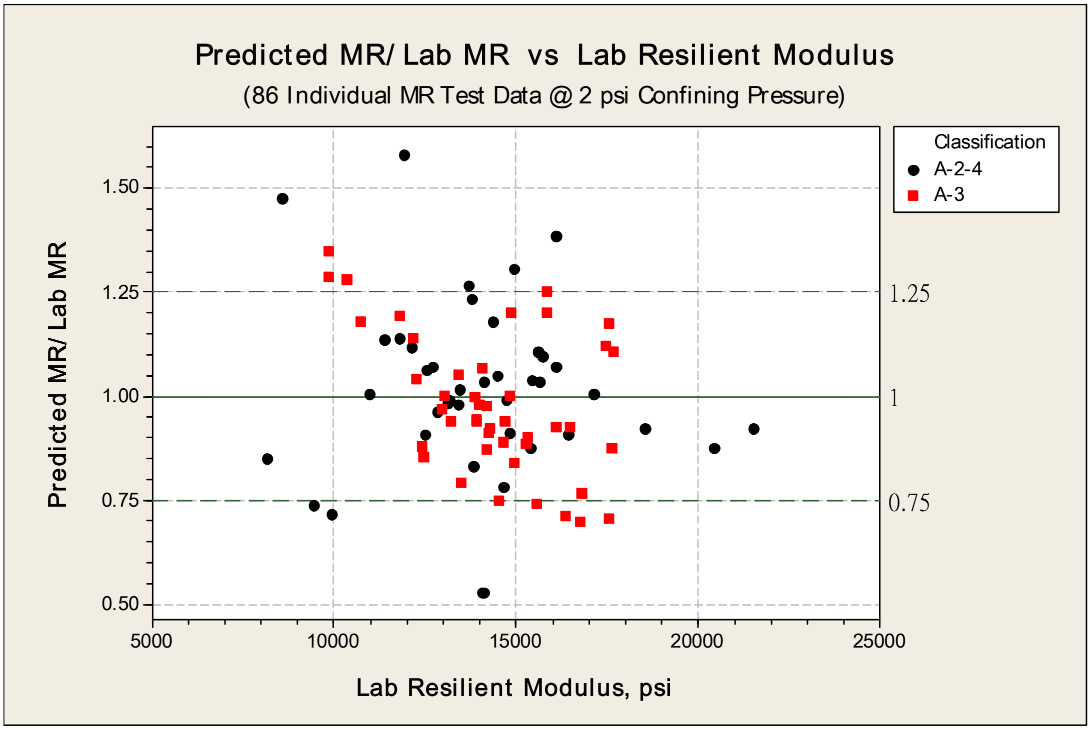


Figure 5.33 Ratio of Predicted MR over Lab MR versus Lab MR (Zhang's Model)

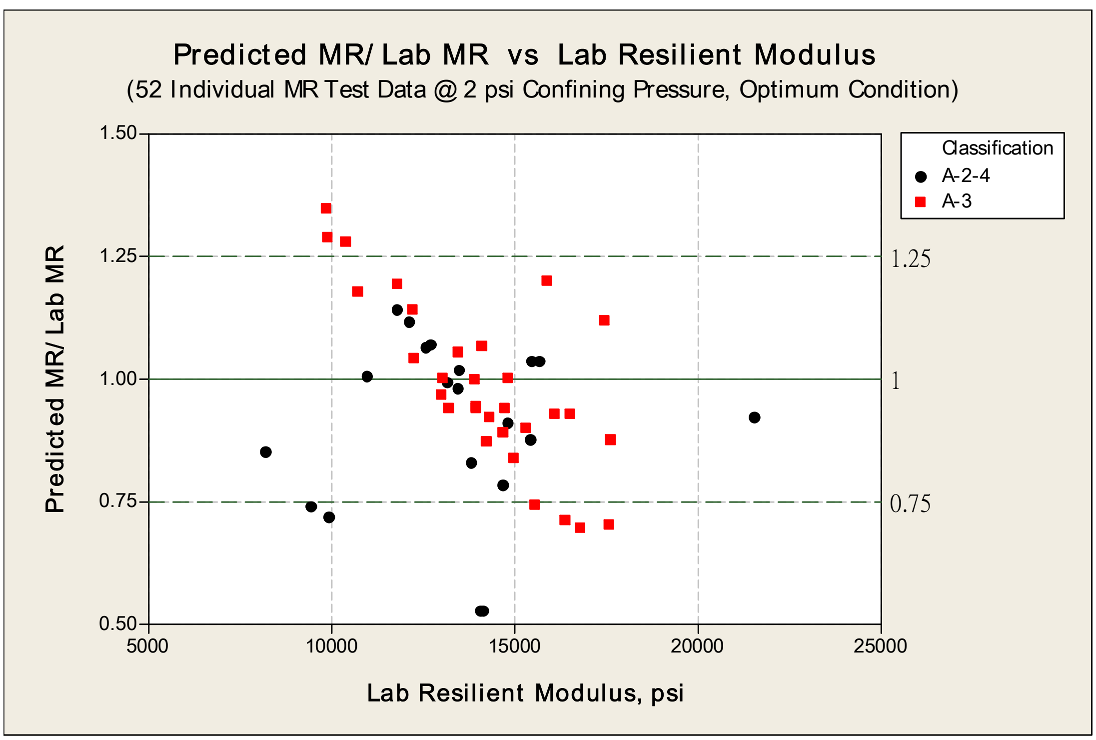


Figure 5.34 Ratio of Predicted MR over Lab MR versus Lab MR @ Optimum Condition (Zhang's Model)

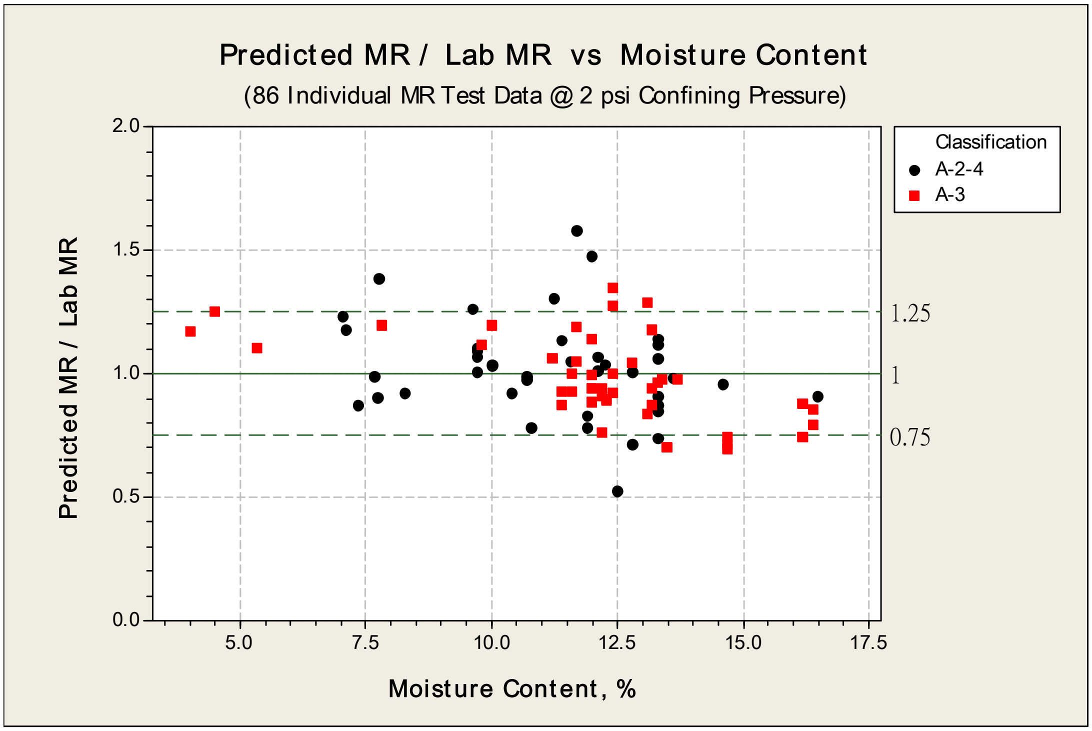


Figure 5.35 Ratio of Predicted MR over Lab MR versus Moisture Content (Zhang's Model)

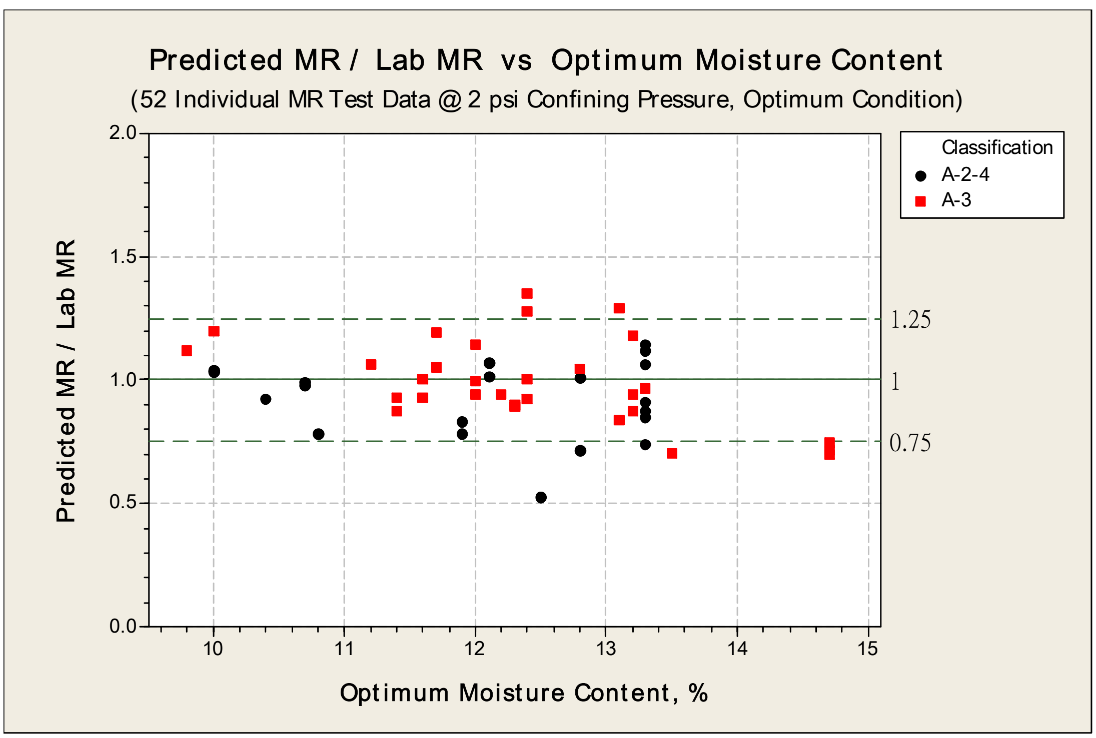


Figure 5.36 Ratio of Predicted MR over Lab MR versus Moisture Content at Optimum Condition (Zhang's Model)

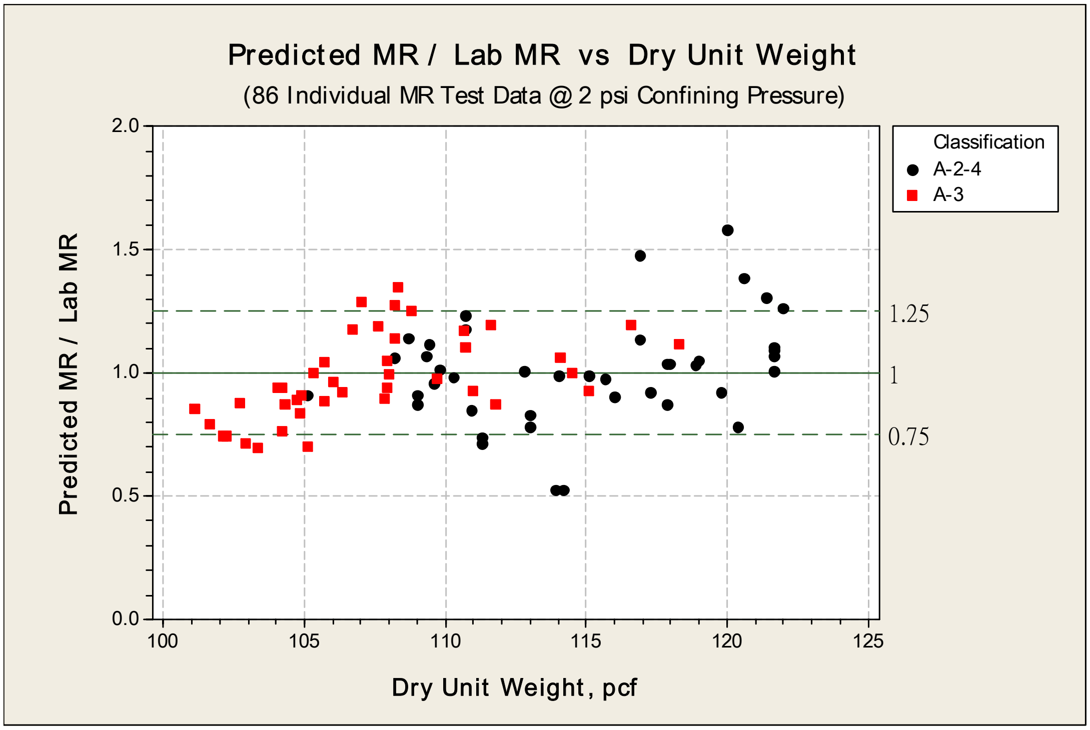


Figure 5.37 Ratio of Predicted MR over Lab MR versus Dry Unit Weight (Zhang's Model)

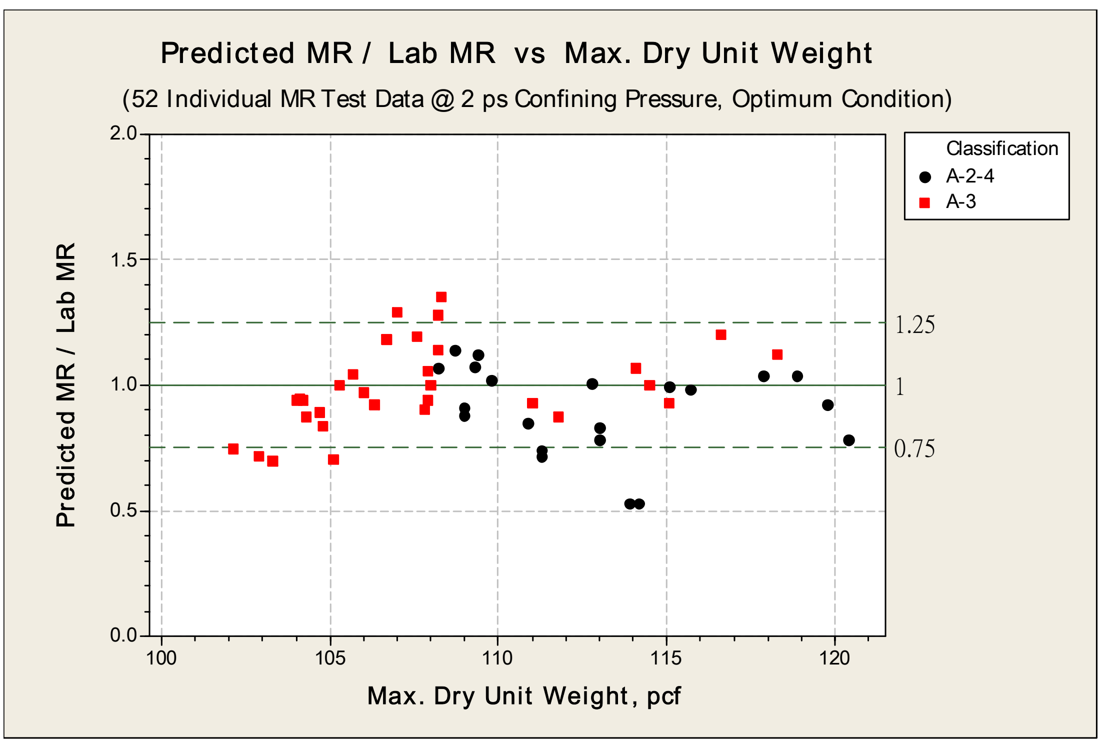


Figure 5.38 Ratio of Predicted MR over Lab MR versus Dry Unit Weight at Optimum Condition (Zhang's Model)

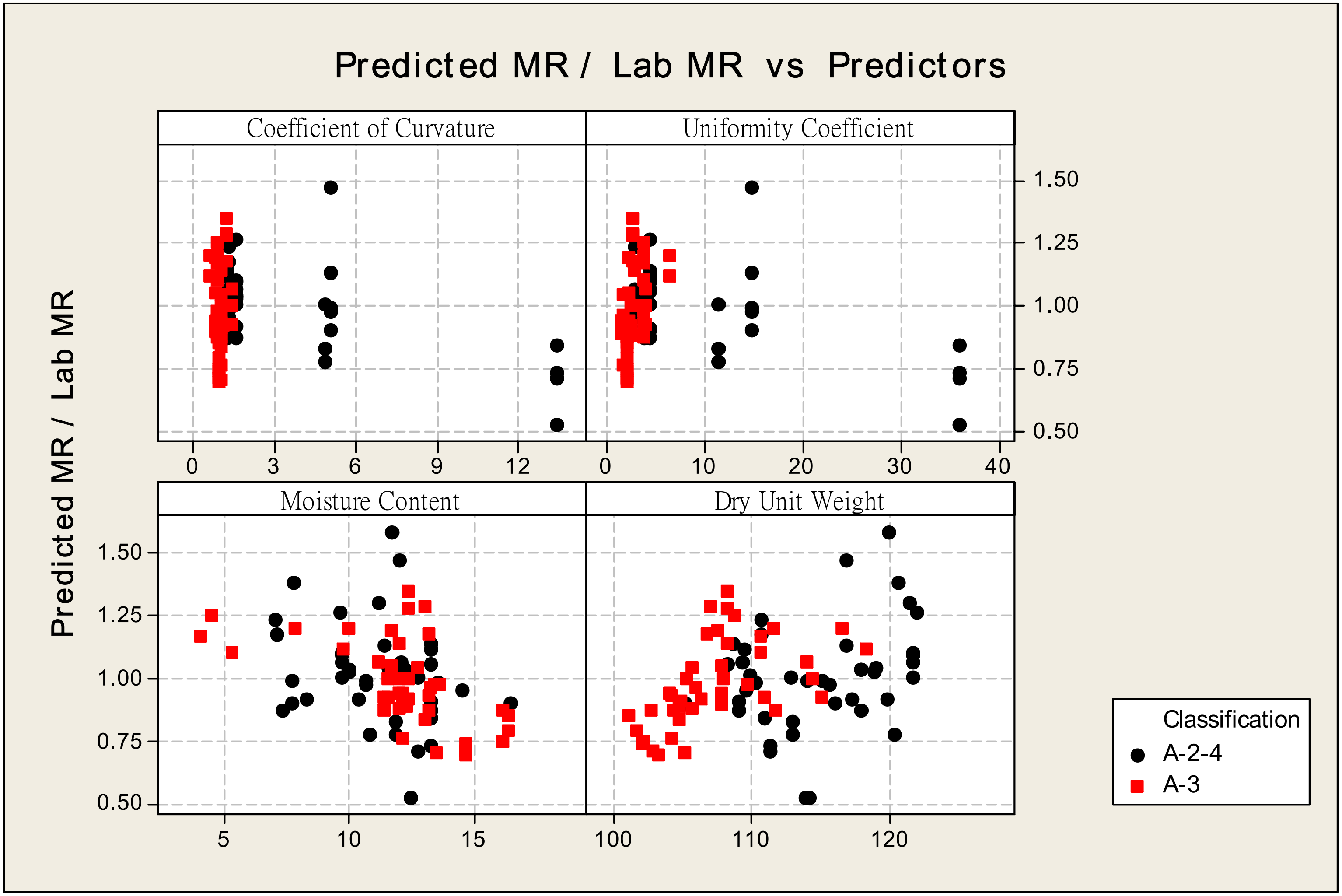


Figure 5.39 Comparison of the Ratio of Predicted MR over Lab MR versus Various Predictors (Zhang's Model)

CHAPTER 6
RESILIENT MODULUS PREDICTION MODELS

6.1 GENERAL

The general purpose of multiple regression analysis is to learn more about the relationship between several independent or predictor variables and a dependent or criterion variable. In general, multiple regression allows the researcher to ask (and hopefully answer) the general question “what is the best predictor of …?”.

In the multivariate case, when there is more than one independent variable, the regression line cannot be visualized in a two dimensional space, but can be computed just as easily. In general then, multiple regression procedures will estimate a linear equation of the form:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_k x_k + \varepsilon \qquad (6.1)$$

The smaller the variability of the residual values around the regression line relative to the overall variability, the better is our prediction. The R-square value is an indicator of how well the model fits the data (e.g., an R-square value close to 1.0 indicates that most of the variability with the variables specified in the model have been accounted for). More information about multiple regression analysis may be found in Appendix E.

6.2 Selection of MR Regression Variables

The purpose of a regression model is to use some parameters to predict another value (called response). In the laboratory resilient modulus test, it is difficult and time consuming to conduct a test to obtain resilient modulus values, but it is easier to obtain basic soil properties such as the percentage of fines, the gradation curve, and moisture content, etc. If more parameters are added in the multiple regression model, the resulting prediction model will be more accurate.

The selection of the predicting parameters was based on the availability of the basic soil properties in the database. The resilient modulus values under the stress state of 2 psi confining stress and 6 psi deviator stress were selected for analysis. Nine basic soil properties were available for analysis, and they are moisture content, dry unit weight, percent of fines, percent of clay content, LBR, coefficient of curvature, uniformity coefficient, plasticity index, and permeability. The parameter plasticity index was removed from analysis due to the limited data points. The selected eight parameters were evaluated employing the method of the backward, stepwise regression analysis to identify the important variables. A detailed procedure of the stepwise analysis is further described in Section 6.4, and the analyzed results are attached in Appendix E. The results were then adjusted according to the observations in section 5.5.

6.3 Model Sample Population

The analysis from the section 5.5 showed that the correlations between resilient modulus and some soil properties might have different trends for A-3 and A-2-4 soils. Therefore, one prediction model was developed to include the combination of the A-3 and A-2-4 soils, and two separate models were also considered for the A-3 and A-2-4 soils, respectively. The available number of data points on each variable for the A-3 and A-2-4 soils was presented in Table 6.1. The final data population was determined based on the selected parameters.

6.4 Statistical Analysis Tool

The multiple regression analyses were performed using the statistical software, Minitab Release 14, to correlate the physical properties of the soils with the resilient modulus. To identify the important parameters, the stepwise regression analyses were performed for the purpose of identifying a useful subset of the predictors. The Minitab provides three commonly used procedures: standard stepwise regression (adds and removes variables), forward selection (adds variables), and backward elimination (removes variables). The backward method with the criteria of α equals to 0.1 was chosen to obtain the predictors.

Three stepwise analyses were performed to find the most significant predictors. The proposed predictors were used to start the regression analysis. The regression analyses were performed until the best results showed. The final selected variables (parameters) for the multiple regression analysis are presented in Table 6.2. Results show that the moisture content had the most significant influence on the resilient modulus, while the dry unit weight had the least significant influence on the resilient modulus. The detailed analysis may be found in Appendix E.

6.5 RESILIENT MODULUS PREDICTION MODEL

In the multiple regression model, if the model coefficient of determination is closer to 1, the form of the response and predictors can be changed to reciprocal value, logarithm value, or others. The selection of multiple regression equation form basically followed the model proposed by Zhang (2004). The variables were selected according to the importance of the influence factors which were indicated by the stepwise analysis results and the analysis findings in Section 5.5.

From the laboratory resilient modulus test results, different resilient modulus values were obtained for each soil according to different conditions. The logarithm value of the full-length resilient modulus under the stress state of 2 psi confining stress and 6 psi deviator stress was chosen as the model responses. After the regression model was developed, the usability of the model was then checked through the analysis of variance F-test. A detailed theory of the F-test can be seen in Appendix E.

The development processes of the regression models are discussed in the following sections.

6.5.1 Development of Prediction Model for A-3 Soils

From the stepwise analysis (see Appendix E, Table E.1), the moisture content and permeability were found to be the most important factors for the A-3 soils. The first trial of the regression analysis (see Appendix E, Table E.2) used those two parameters as the predictors. The regression analysis showed an R-square value of 24.4%, which is relatively low and considered to be failed.

By incorporating more predictors, the R-square value may be increased. The second trial added four more predictors, i.e., the percent of fines, coefficient of curvature (C_c), uniformity coefficient (C_u), and dry unit weight, which are relatively easy to obtain in the laboratory. The results showed an R-square value of 50.0% and an F-value of 2.67 (see Appendix E, Table E.3). The required F value to reject the null hypothesis based on the alpha value of 0.05 is 2.7413. The F-value of 2.67 of the model was too low to reject the null hypothesis. Thus, this model was considered to be failed again.

By further adding and removing predictors from the initially selected eight parameters, the final regression model (see Appendix E, Table E.4) was based on the properties of coefficient of curvature (C_c), moisture content, and permeability. The regression equation is shown as follows:

$$\ln(M_r) = 9.5 + 0.161C_c - 0.0123\omega + 71.4k \qquad (6.2)$$

Where,

M_r = Resilient modulus in psi, at 2 psi confining pressure

C_c = Coefficient of curvature

ω = Optimum gravimetric moisture content in percentage (0~100) as determined by AASHTO T-99

k = Coefficient of permeability in cm/sec

This model had an R-square value of 47.3% and an F value of 5.68, which is greater than the required F value with the alpha of 0.05 [F(0.05,3,19)=3.1274], and is considered to be a statistically useful model.

6.5.2 Development of Prediction Model for A-2-4 Soils

From the stepwise analysis (see Appendix E, Table E.5), the moisture content, coefficient of curvature (C_c), uniformity coefficient (C_u), and percent of clay were found to be the most important factors for the A-2-4 soils. The first trial (see Appendix E, Table E.6) used those four parameters as the predictors. The regression analysis showed an R-square value of 51.4% and the F value of 8.47, which is greater than the required F value with the alpha of 0.05 [F(0.05,4,30)=2.6896]. This model is considered to be a statistically useful one.

By incorporating more predictors, the R-square value can be further increased. Since the properties of the percent of fines and dry unit weight are usually available, these two parameters were added in the second trial (see Appendix E, Table E.7) to check the R-square value. The results showed an R-square value of 51.7% and an F value of 5.35. It resulted in a slight improvement (0.3%) on the R-square, but with a much more significant decrease of the F value. Therefore, it appeared that the first trial should be considered to be a suitable model for the A-2-4 Soils. The regression equation is shown as follows:

$$\ln(M_r) = 9.87 - 0.0593C_c + 0.0118C_u - 0.0414\omega + 0.0337Clay \quad (6.3)$$

Where,

M_r	= Resilient modulus in psi, at 2 psi confining pressure
C_c	= Coefficient of curvature
C_u	= Uniformity coefficient
ω	= Optimum gravimetric moisture content in percentage (0~100) as determined by AASHTO T-99
Clay	= Percent of clay content (0~100)

6.5.3 Development of Prediction Model for A-3 and A-2-4 Soils

From the stepwise analysis (see Appendix E, Table E.8), the moisture content, coefficient of curvature (C_c), uniformity coefficient (C_u), and LBR were found to be the most important factors for the A-3 and A-2-4 soils. The first trial (see Appendix E, Table E.9) used those four parameters as the predictors. The regression analysis showed an R-square value of 36.0%, which is relatively low and is considered to be failed.

By incorporating more predictors, the R-square value can be further increased. The second trial (see Appendix E, Table E.10) involved all eight parameters. The results showed an R-square value of 52.5% and an F value of 5.25. Since the F value was not high enough, another trial was taken. The third trial (see Appendix E, Table E.11) adopted the predictors used in both the A-3 and A-2-4 prediction models. The results showed an R-square value of 51.4% and an F value of 8.67. The required F value for rejecting the null hypothesis based on the 0.05 alpha value is 2.4495, i.e., F(0.05,5,40)=2.4495. This model gave a much higher F value with about 1% decrease on the R-square value, and should be considered to be a suitable model for the A-3 and A-2-4 granular soils. The regression equation is shown as follows:

$$\ln(M_r) = 9.76 - 0.0602C_c + 0.121C_u - 0.0297\omega + 0.0303Clay + 6.7k \tag{6.4}$$

Where,

M_r = Resilient modulus in psi, at 2 psi confining pressure

C_c = Coefficient of curvature

C_u = Uniformity coefficient

ω = Optimum gravimetric moisture content in percentage (0~100) as determined by AASHTO T-99

$Clay$ = Percent of clay content (0~100)

k = Coefficient of permeability in cm/sec

A summary of the developed resilient modulus prediction models is presented in Table 6.3.

6.6 PERFORMANCE OF PREDICTION MODELS

The proposed prediction models were examined to evaluate the performance. Figure 6.1, Figure 6.2, and Figure 6.3 are shown to illustrate the comparisons between the measured laboratory resilient modulus and predicted resilient modulus values for the three proposed models. Figure 6.4, Figure 6.5, and Figure 6.6 are shown to demonstrate the ratios of the predicted resilient modulus over the measured laboratory resilient modulus value versus the measured laboratory resilient modulus for the three proposed models. The resilient modulus ratios versus the moisture content are shown in Figure 6.7, Figure 6.8, and Figure 6.9 for the three proposed models. From the data shown in these figures, most of the ratios of the predicted resilient modulus over the laboratory measured resilient modulus were within the ranges from 0.8 to 1.2, which meant that the usability of the proposed regression models would obtain a reasonably predicted resilient modulus value within $\pm$20% error. To achieve a 90% confidence level, the predicted resilient modulus should have a 20% reduction to compensate for the regression errors.

Table 6.1 Summary of Data Points for Evaluating Resilient Modulus Regression Model

Variable	Description	Data Points for A-3	Data Points for A-2-4
Fines. %	Percentage passing No. 200 sieve	67	69
Clay, %	Percentage of clay	21	53
MC, %	Moisture content of the test specimen	111	105
DUW, pcf	Dry unit weight of the test specimen	111	105
LBR	Lime Rock Bearing Ratio	107	91
Cc	Coefficient of Curvature	44	43
Cu	Uniformity Coefficient	44	43
Perm, cm/sec	Permeability in 7 psi confining pressure	30	67

Table 6.2 Predictors for Regression Models

	A-3 Soils		A-2-4 Soils		A-3 and A-2-4 Soils	
Variable	Initial Proposed	Final Selected	Initial Proposed	Final Selected	Initial Proposed	Final Selected
Fines, %						
Clay, %			x	x		x
MC, %	x	x	x	x	x	x
DUW, pcf						
LBR					x	
Cc		x	x	x	x	x
Cu			x	x	x	x
Perm, cm/sec	x	x				x

Table 6.3 Summary of Developed Resilient Modulus Prediction Models

Soil Type	Multiple Regression Model
A-3	$\ln(M_r) = 9.5 + 0.161 C_c - 0.0123\,\omega + 71.4k$
A-2-4	$\ln(M_r) = 9.87 - 0.0593\,C_c + 0.0118\,C_u - 0.0414\,\omega + 0.0337\,Clay$
A-3, A-2-4	$\ln(M_r) = 9.76 - 0.0602\,C_c + 0.121 C_u - 0.0297\,\omega + 0.0303\,Clay + 6.7k$

M_r= Resilient modulus in psi, at 2 psi confining pressure
C_c = Coefficient of Curvature
C_u = Uniformity Coefficient
ω = Gravimetric moisture content in percentage (0~100)
Clay = Percent of Clay (0~100)
k = Coefficient of Permeability in cm/sec

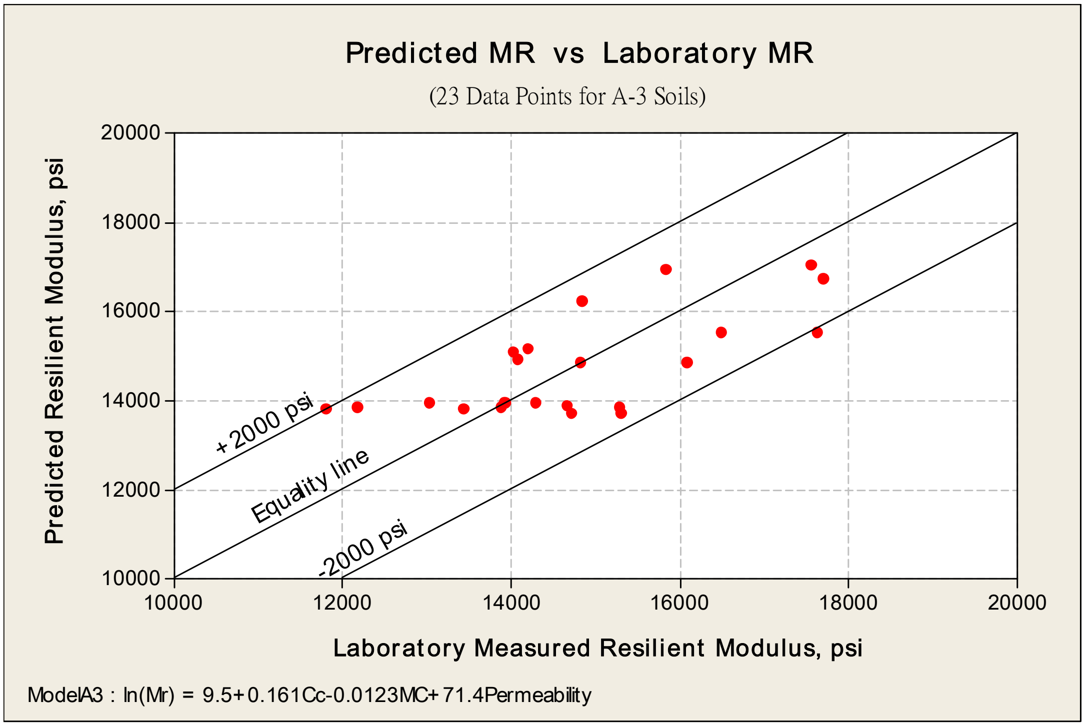


Figure 6.1 Predicted Resilient Modulus versus Lab Measured Resilient Modulus for A-3 Soils

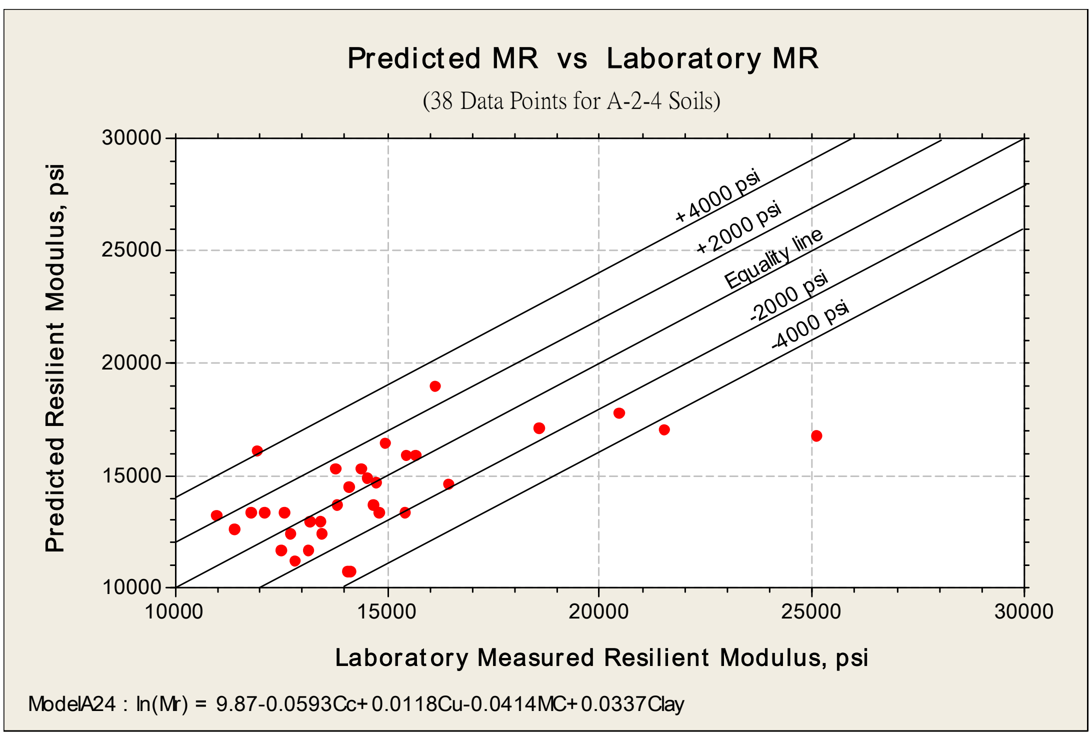


Figure 6.2 Predicted Resilient Modulus versus Lab Measured Resilient Modulus for A-2-4 Soils

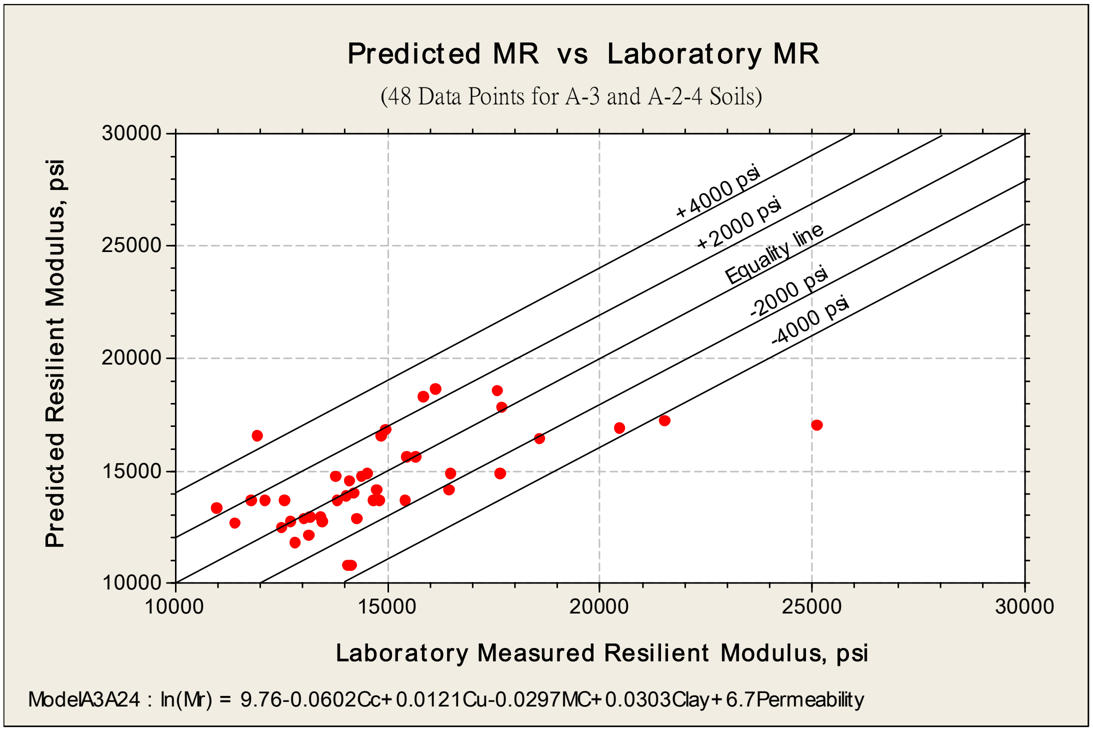


Figure 6.3 Predicted Resilient Modulus versus Lab Measured Resilient Modulus for A-3 and A-2-4 Soils

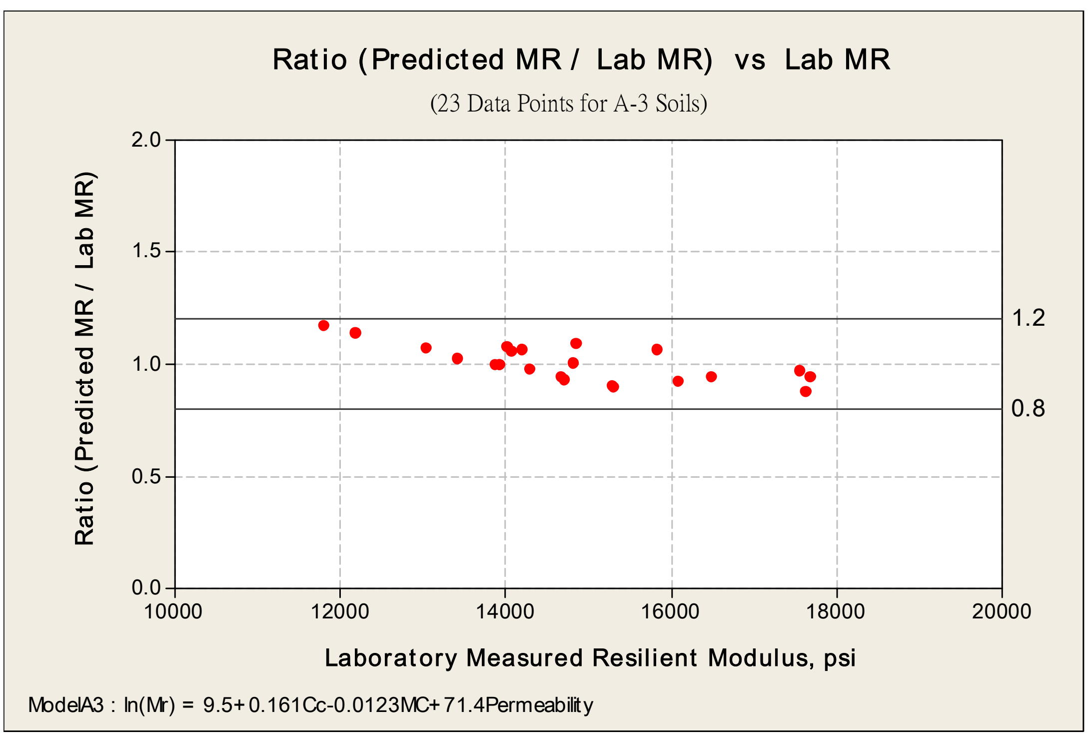


Figure 6.4 Ratio of Predicted MR over Lab MR versus Lab MR for the A-3 Soils

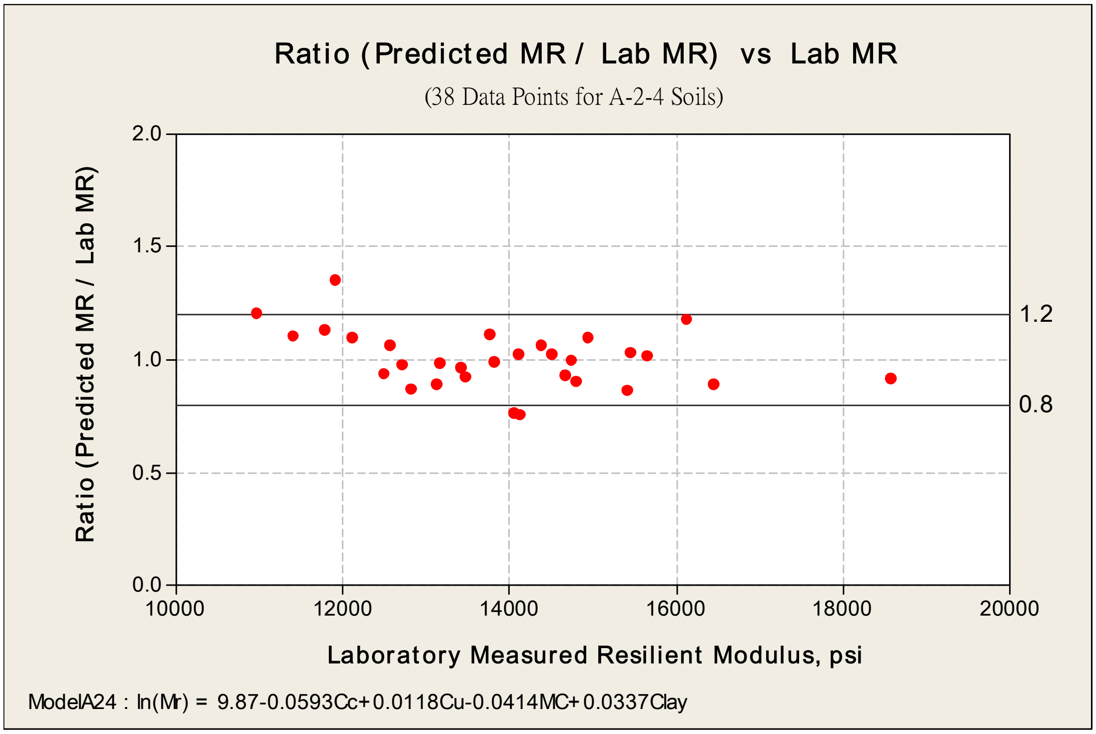


Figure 6.5 Ratio of Predicted MR over Lab MR versus Lab MR for the A-2-4 Soils

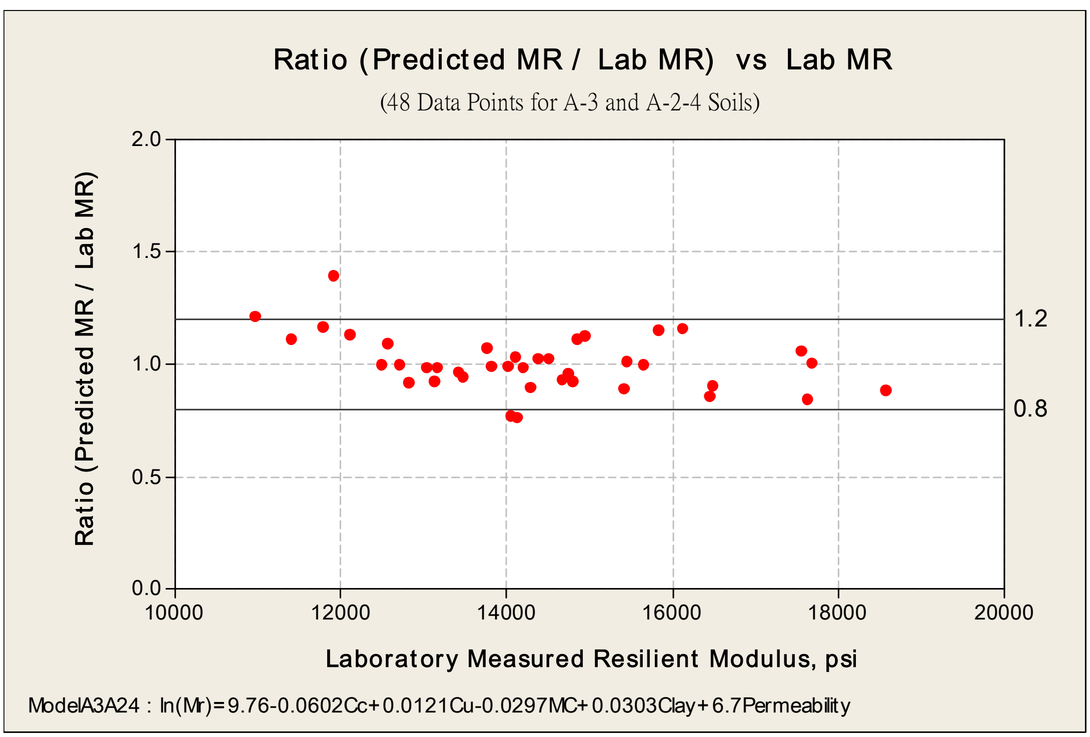


Figure 6.6 Ratio of Predicted MR over Lab MR versus Lab MR for the A-3 and A-2-4 Soils

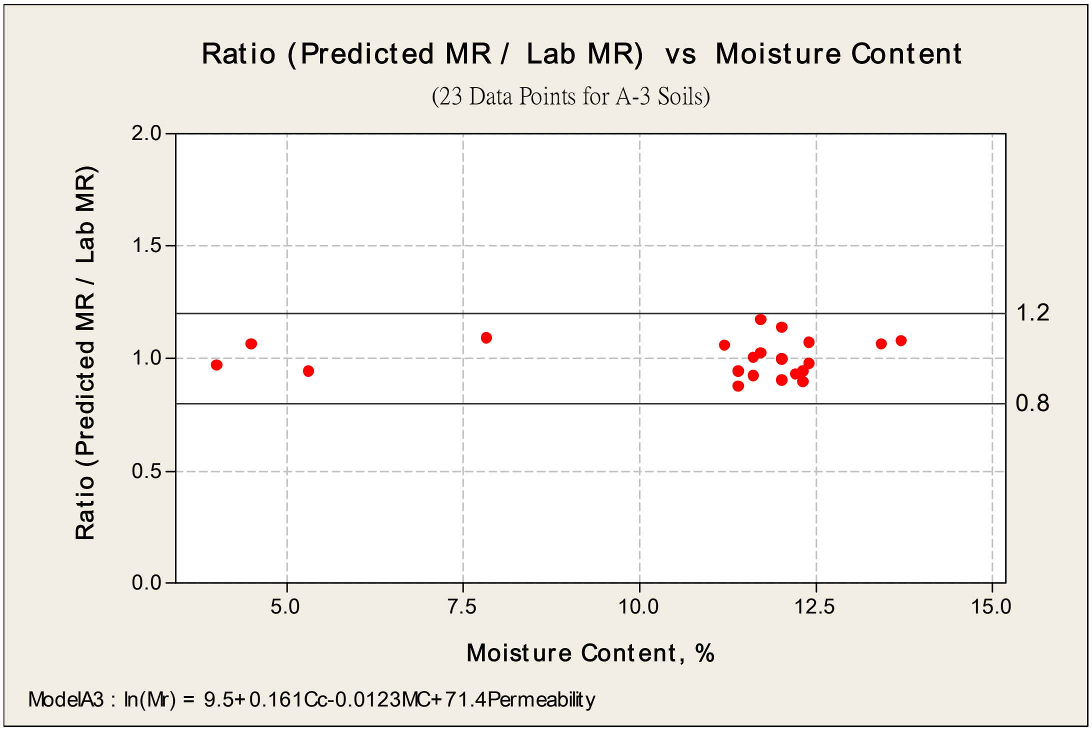


Figure 6.7 Ratio of Predicted MR over Lab MR versus Moisture Content for the A-3 Soils

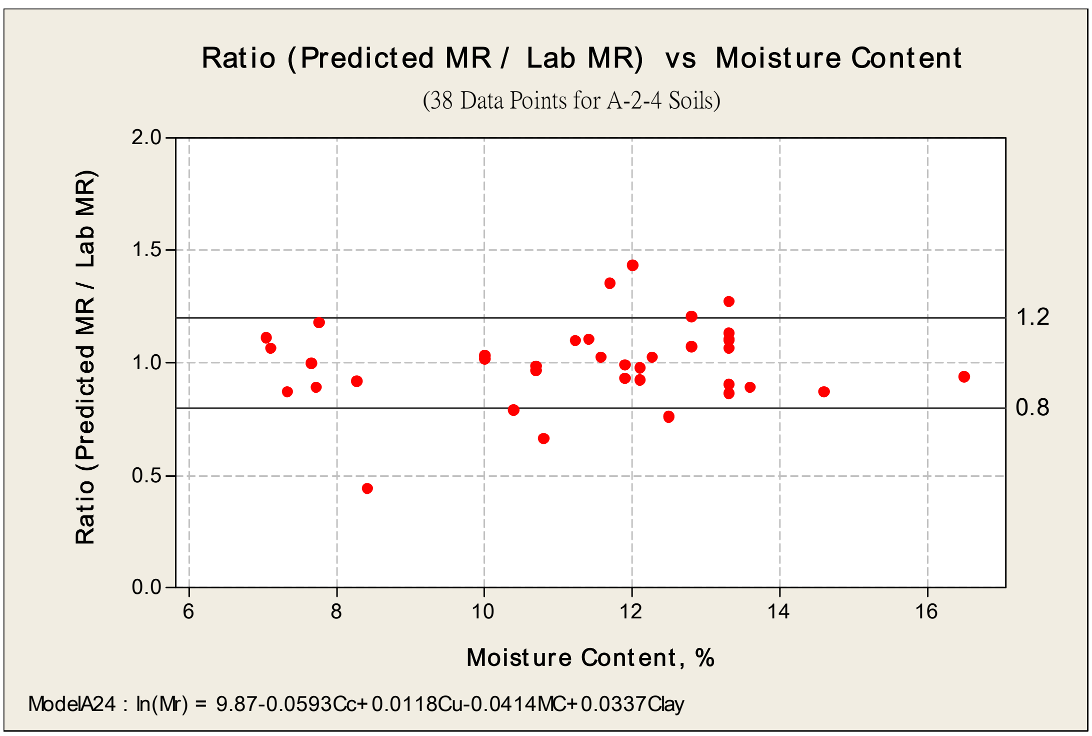


Figure 6.8 Ratio of Predicted MR over Lab MR versus Moisture Content for the A-2-4 Soils

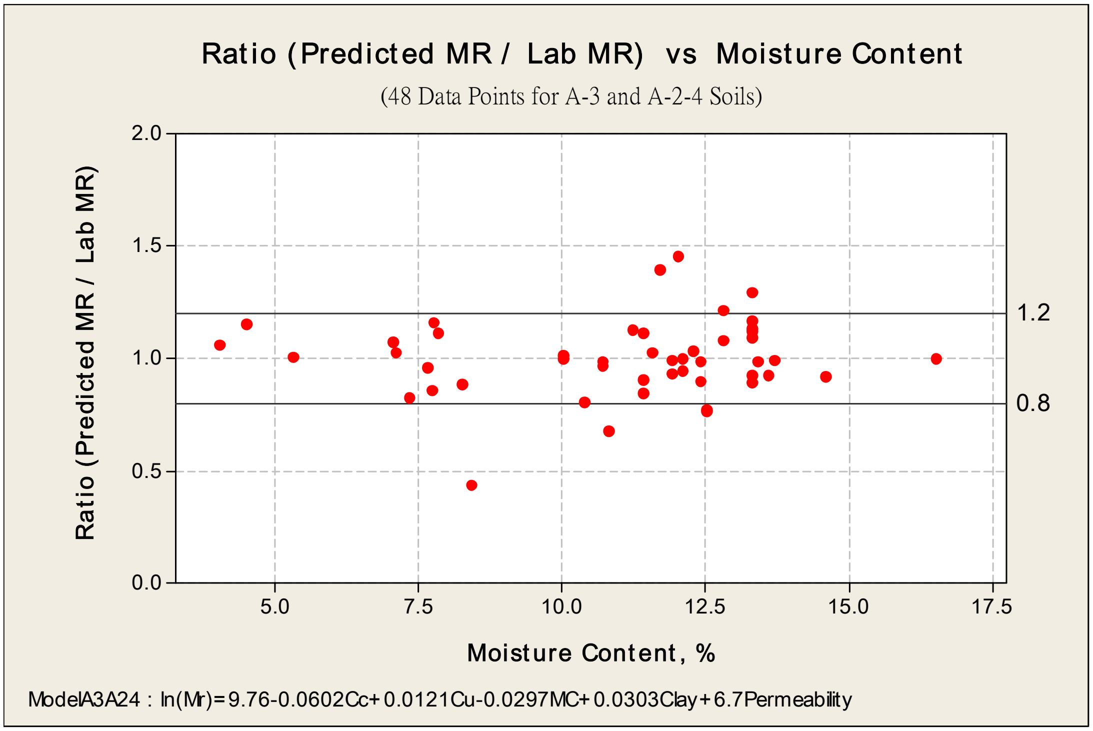


Figure 6.9 Ratio of Predicted MR over Lab MR versus Moisture Content for the A-3 and A-2-4 Soils

CHAPTER 7
SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

7.1 SUMMARY

The primary objective of this research study was to populate and enhance the previously developed resilient modulus database with additional resilient test data for the purpose of establishing resilient modulus models based on basic material physical properties in Florida. To achieve the objective, 25 subgrade materials were collected for testing from the FDOT district offices around the state. The basic physical properties of the soil materials were tested and characterized by the State Materials Office. The subgrade materials were transported to the laboratory in Tallahassee where 168 resilient modulus tests were performed using the AASHTO T307-99 test procedure. All of the test data concerning the basic engineering properties and the resilient modulus test results were stored in an enhanced database using Microsoft Access.

Two databases were presented for this study. One was the existing database “Soillab.mdb” with two additional resilient modulus tables. The other one was an enhanced database “MRAnalyzer.mdb” that included integration and analysis functions embedded in the database to give the users an easier way to keep track of the data. More tables were also developed in the database for analysis. In addition to populating and developing the database, a comprehensive literature review was conducted to evaluate the resilient modulus of granular subgrade materials.

The resilient modulus test results were analyzed using a statistical approach (Minitab statistical software) to evaluate the effect of soil physical properties on the resilient modulus. The multiple regression analyses were performed to find the optimum resilient modulus prediction models based on the various soil types, test methods, and other test conditions. The resilient modulus values obtained from the prediction models were generally within a range of +/- 20% of the laboratory measured resilient modulus values. The research findings from this study could be adopted for future implementation of the mechanistic-empirical pavement design in Florida.

7.2 CONCLUSIONS

Based upon the analyses and findings of this research study, the conclusions are drawn and summarized as follows:

1. Twenty five soil materials were collected for resilient modulus testing. A total of 168 resilient modulus tests were performed in the laboratory for this study.
2. Two databases were presented in this study. One was “soillab.mdb” that included existing database tables updated with newly performed test data. The other one was “MRAnalyzer.mdb” that contained additional tables to incorporate the integration and analysis functions. Both databases were saved in a CD-R and submitted to the FDOT for future implementation of the mechanistic-empirical pavement design.
3. The resilient modulus test data for the A-3, A-2-4, and A-2-6 soils using the T292-91I and T307-99 test procedures were selected for further analysis, which included a total of 276 data points with 152 sets from the T307-99 test and 124 sets from the T292-91I test.
4. The overall resilient modulus values varied within a range from 7,368 psi to 26,110 psi with an average resilient modulus value of 14,241 psi.
5. The resilient modulus test results showed that the physical properties of a soil material such as water content, dry unit weight, and LBR have more significant effects on the resilient modulus of the A-2-4 soils than on the A-3 soils.

6. The resilient modulus for the A-2-4 soils increased with an increase in the percent of fines and clay content. The effect of the percent fines and clay content on the resilient modulus of the A-3 soils was not significant.
7. No significant correlations were found between resilient modulus and the coefficient of curvature (C_c), uniformity coefficient (C_u), and permeability due to the limited data points.
8. The permeability data showed a strong correlation between the permeability value and the percent of fines and clay content. The permeability value decreased with an increase in the percent of fines, the percent of clay content and the dry unit weight.
9. The Poisson’s ratio values were recorded in the raw output data file as well as in the MS Access database. The Poisson’s ratio was found to be unstable for the same sample in a test.
10. An evaluation of the resilient modulus data was performed using the prediction model developed by Zhang (2004). The results showed that 80% of the laboratory measured resilient modulus values were within +/- 3,000 psi of the predicted resilient modulus values from Zhang’s model.
11. Three prediction models were proposed based on the resilient modulus test results. The prediction models

had an average R-square value of 50% and F value of 7.2. An average of 20% reduction should be applied to the predicted resilient modulus values for practical applications.

7.3 RECOMMENDATIONS

1. The missing properties of the tested materials using the T292-91I test method should be recovered for a better interpretation of the prediction model analysis.
2. For sandy soils, the static compaction or gyratory compaction should be used to achieve the optimum compacted condition.
3. More resilient modulus test data should be collected and integrated into the database. A thorough examination of the test data qualification and reliability should be performed to ensure the data quality. This should include all the soil material properties information and the test conditions.
4. The resilient modulus test procedures should be standardized to obtain more reliable and repeatable resilient modulus test results. This includes unified resilient modulus test equipment, software configuration, sample preparation method, and the laboratory test environment.

5. The prediction models developed in this study would only be practical in estimating resilient modulus values for the soils similar to those being used to develop the prediction regression equations.

APPENDIX A
SUMMARY OF RESILIENT MODULUS TEST DATA FILES

Table A.1 MR Test File Name Index

Test File Name Index (1)

FDOT District	FDOT Lab. #	Location	FSU Sample ID	FSU Test #	File Name
1	21981-S	Earth Source	ES001	A1	MR-01-ES001A1.xls
1	21981-S	Earth Source	ES001	B1	MR-01-ES001B1.xls
1	21981-S	Earth Source	ES001	D1	MR-01-ES001D1.xls
1	21981-S	Earth Source	ES001	E1	MR-01-ES001E1.xls
1	21906-S	Polk Masaic Mine	MM001	A1	MR-01-MM001A1.xls
1	21906-S	Polk Masaic Mine	MM001	B1	MR-01-MM001B1.xls
1	21906-S	Polk Masaic Mine	MM001	D1	MR-01-MM001D1.xls
1	21906-S	Polk Masaic Mine	MM001	E1	MR-01-MM001E1.xls
1	21980-S	SMR Pit	SMR001	A1	MR-01-SMR001A1.xls
1	21980-S	SMR Pit	SMR001	B1	MR-01-SMR001B1.xls
1	21980-S	SMR Pit	SMR001	C1	MR-01-SMR001C1.xls
1	21980-S	SMR Pit	SMR001	D1	MR-01-SMR001D1.xls
2	21982-S	Blue Rock Pit	BR001	A1	MR-02-BR001A1.xls
2	21982-S	Blue Rock Pit	BR001	B2	MR-02-BR001B2.xls
2	21982-S	Blue Rock Pit	BR001	D1	MR-02-BR001D1.xls
2	21982-S	Blue Rock Pit	BR001	E1	MR-02-BR001E1.xls
2	21982-S	Blue Rock Pit	BR001	F1	MR-02-BR001F1.xls
2	21982-S	Blue Rock Pit	BR001	G1	MR-02-BR001G1.xls
2	21671~3	Branch	BH001	C1	MR-02-BH001C1.xls
2	21671~3	Branch	BH001	D2	MR-02-BH001D2.xls
2	21671~3	Branch	BH001	E1	MR-02-BH001E1.xls
2	21671~3	Branch	BH001	F1	MR-02-BH001F1.xls
2	21671~3	Branch	BH001	G1	MR-02-BH001G1.xls
2	21671~3	Branch	BH001	H1	MR-02-BH001H1.xls
2	21668~70	Iron Bridge	IB001	C1	MR-02-IB001C1.xls
2	21668~70	Iron Bridge	IB001	D1	MR-02-IB001D1.xls
2	21668~70	Iron Bridge	IB001	E1	MR-02-IB001E1.xls
2	21668~70	Iron Bridge	IB001	F1	MR-02-IB001F1.xls
2	21984-S	Osteen	OS001	A1	MR-02-OS001A1.xls
2	21984-S	Osteen	OS001	B1	MR-02-OS001B1.xls
2	21984-S	Osteen	OS001	C1	MR-02-OS001C1.xls
2	21984-S	Osteen	OS001	D1	MR-02-OS001D1.xls
2	21665~7	Spring Cemetery	SC001	C1	MR-02-SC001C1.xls
2	21665~7	Spring Cemetery	SC001	D2	MR-02-SC001D2.xls
2	21665~7	Spring Cemetery	SC001	E1	MR-02-SC001E2.xls
2	21665~7	Spring Cemetery	SC001	F1	MR-02-SC001F2.xls
2	21157	US 90	21157	A1	21157s1.xls
2	21159	US 90	21159	B1	21159s2a.xls
2	21157	US 90	21157	B1	21157s2.xls
2	21158	US 90	21158	A1	21158s1.xls
2	21158	US 90	21158	B1	21158s2.xls
2	21159	US 90	21159	A1	21159s1.xls
2	21983-S	Watson Pit	WT001	A1	MR-02-WT001A1.xls
2	21983-S	Watson Pit	WT001	B1	MR-02-WT001B1.xls
2	21983-S	Watson Pit	WT001	D1	MR-02-WT001D1.xls
2	21983-S	Watson Pit	WT001	E1	MR-02-WT001E1.xls
3	21851-S	Airport	AP001	C1	MR-03-AP001C1.xls
3	21851-S	Airport	AP001	D1	MR-03-AP001D1.xls
3	21851-S	Airport	AP001	E3	MR-03-AP001E3.xls
3	21851-S	Airport	AP001	F1	MR-03-AP001F1.xls
3	21851-S	Airport	AP001	G1	MR-03-AP001G1.xls
3	21851-S	Airport	AP001	H1	MR-03-AP001H1.xls
3	21851-S	Airport	AP001	I1	MR-03-AP001I1.xls
3	21851-S	Airport	AP001	J1	MR-03-AP001J1.xls
3	21851-S	Airport	AP001	K3	MR-03-AP001K3.xls
3	21851-S	Airport	AP001	L1	MR-03-AP001L1.xls

Table A.1 MR Test File Name Index (Continued)

Test File Name Index (2)

FDOT District	FDOT Lab. #	Location	FSU Sample ID	FSU Test #	File Name
3	21897-S	BallFarm 15-20 Comb.	BF002	A5	MR-03-BF002A5.xls
3	21897-S	BallFarm 15-20 Comb.	BF002	B3	MR-03-BF002B3.xls
3	21897-S	BallFarm 15-20 Comb.	BF002	C1	MR-03-BF002C1.xls
3	21897-S	BallFarm 15-20 Comb.	BF002	D1	MR-03-BF002D1.xls
3	21897-S	BallFarm 15-20 Comb.	BF002	E1	MR-03-BF002E1.xls
3	21897-S	BallFarm 15-20 Comb.	BF002	F1	MR-03-BF002F1.xls
3	21897-S	BallFarm 15-20 Comb.	BF002	G1	MR-03-BF002G1.xls
3	21897-S	BallFarm 15-20 Comb.	BF002	H1	MR-03-BF002H1.xls
3	21881-S	BallFarm 1-6 Comb.	BF001	A1	MR-03-BF001A1.xls
3	21881-S	BallFarm 1-6 Comb.	BF001	B5	MR-03-BF001B5.xls
3	21881-S	BallFarm 1-6 Comb.	BF001	C1	MR-03-BF001C1.xls
3	21881-S	BallFarm 1-6 Comb.	BF001	D1	MR-03-BF001D1.xls
3	21881-S	BallFarm 1-6 Comb.	BF001	F1	MR-03-BF001F1.xls
3	21881-S	BallFarm 1-6 Comb.	BF001	G1	MR-03-BF001G1.xls
3	21881-S	BallFarm 1-6 Comb.	BF001	H1	MR-03-BF001H1.xls
3	21881-S	BallFarm 1-6 Comb.	BF001	I1	MR-03-BF001I1.xls
3	21852-S	Fairfield	FF001	A1	MR-03-FF001A1.xls
3	21852-S	Fairfield	FF001	B1	MR-03-FF001B1.xls
3	21852-S	Fairfield	FF001	C1	MR-03-FF001C1.xls
3	21852-S	Fairfield	FF001	D2	MR-03-FF001D2.xls
3	21852-S	Fairfield	FF001	D3	MR-03-FF001D3.xls
3	21852-S	Fairfield	FF001	E1	MR-03-FF001E1.xls
3	21852-S	Fairfield	FF001	F1	MR-03-FF001F1.xls
3	21852-S	Fairfield	FF001	G1	MR-03-FF001G1.xls
3	21852-S	Fairfield	FF001	H1	MR-03-FF001H1.xls
3	Shelfer Rd.	Shelfer Rd. Pit	LS001	A1	MR-03-LS001A1.xls
3	Shelfer Rd.	Shelfer Rd. Pit	LS001	A2	MR-03-LS001A2.xls
3	Shelfer Rd.	Shelfer Rd. Pit	LS001	B1	MR-03-LS001B1.xls
3	Shelfer Rd.	Shelfer Rd. Pit	LS001	B2	MR-03-LS001B2.xls
3	Shelfer Rd.	Shelfer Rd. Pit	LS001	B3	MR-03-LS001B3.xls
3	Shelfer Rd.	Shelfer Rd. Pit	LS001	B4	MR-03-LS001B4.xls
3	21383	SR 83 Watson	21383	A1	21383s1.xls
3	21387	SR 83 Watson	21387	A1	21387s1.xls
3	21383	SR 83 Watson	21383	B1	21383s2.xls
3	21384	SR 83 Watson	21384	A1	21384s1.xls
3	21384	SR 83 Watson	21384	B1	21384s2.xls
3	21385	SR 83 Watson	21385	A1	21385s1.xls
3	21385	SR 83 Watson	21385	B1	21385s2.xls
3	21386	SR 83 Watson	21386	A1	21386s1.xls
3	21386	SR 83 Watson	21386	B1	21386s2b.xls
3	21387	SR 83 Watson	21387	B1	21387s2.xls
3	21388	SR 83 Watson	21388	A1	21388s1.xls
3	21388	SR 83 Watson	21388	B1	21388s2.xls
3	21389	SR 83 Watson	21389	A1	21389s1d.xls
3	21389	SR 83 Watson	21389	B1	21389s2.xls
3	21390	SR 83 Watson	21390	A1	21390s1.xls
3	21390	SR 83 Watson	21390	B1	21390s2a.xls
3	21391	SR 83 Watson	21391	A1	21391s1.xls
3	21391	SR 83 Watson	21391	B1	21391s2.xls
4	21989-S	SR 15	SR1501	A1	MR-04-SR1501A1.xls
4	21989-S	SR 15	SR1501	B1	MR-04-SR1501C1.xls
4	21989-S	SR 15	SR1501	C1	MR-04-SR1501D1.xls
4	21989-S	SR 15	SR1501	D1	MR-04-SR1501B1.xls
4	21990-S	SR 60	SR6001	A1	MR-04-SR6001A1.xls
4	21990-S	SR 60	SR6001	B1	MR-04-SR6001B1.xls
4	21990-S	SR 60	SR6001	D1	MR-04-SR6001D1.xls

Table A.1 MR Test File Name Index (Continued)

Test File Name Index (3)

FDOT District	FDOT Lab. #	Location	FSU Sample ID	FSU Test #	File Name
4	21990-S	SR 60	SR6001	E1	MR-04-SR6001E1.xls
4	21991-S	SR 80	SR8001	A1	MR-04-SR8001A1.xls
4	21991-S	SR 80	SR8001	B1	MR-04-SR8001B1.xls
4	21991-S	SR 80	SR8001	C2	MR-04-SR8001C1.xls
4	21991-S	SR 80	SR8001	D1	MR-04-SR8001D1.xls
5	21887-S	UFRES # 1	UF001	A1	MR-05-UF001A1.xls
5	21887-S	UFRES # 1	UF001	A2	MR-05-UF001A2.xls
5	21887-S	UFRES # 1	UF001	A3	MR-05-UF001A3.xls
5	21887-S	UFRES # 1	UF001	B1	MR-05-UF001B1.xls
5	21887-S	UFRES # 1	UF001	E1	MR-05-UF001E1.xls
5	21887-S	UFRES # 1	UF001	F1	MR-05-UF001F1.xls
5	21887-S	UFRES # 1	UF001	G1	MR-05-UF001G1.xls
5	21887-S	UFRES # 1	UF001	H1	MR-05-UF001H1.xls
5	21887-S	UFRES # 1	UF001	I1	MR-05-UF001I1.xls
5	21887-S	UFRES # 1	UF001	J1	MR-05-UF001J1.xls
5	21888-S	UFRES # 2	UF002	A1	MR-05-UF002A1.xls
5	21888-S	UFRES # 2	UF002	B1	MR-05-UF002B1.xls
5	21888-S	UFRES # 2	UF002	E1	MR-05-UF002E1.xls
5	21888-S	UFRES # 2	UF002	F1	MR-05-UF002F1.xls
5	21888-S	UFRES # 2	UF002	G1	MR-05-UF002G1.xls
5	21888-S	UFRES # 2	UF002	H1	MR-05-UF002H1.xls
5	21888-S	UFRES # 2	UF002	I1	MR-05-UF002I1.xls
5	21888-S	UFRES # 2	UF002	J1	MR-05-UF002J1.xls
5	21889-S	UFRES # 3	UF003	A1	MR-05-UF003A1.xls
5	21889-S	UFRES # 3	UF003	B1	MR-05-UF003B1.xls
5	21889-S	UFRES # 3	UF003	C1	MR-05-UF003C1.xls
5	21889-S	UFRES # 3	UF003	E1	MR-05-UF003E1.xls
5	21889-S	UFRES # 3	UF003	F1	MR-05-UF003F1.xls
5	21889-S	UFRES # 3	UF003	G1	MR-05-UF003G1.xls
5	21889-S	UFRES # 3	UF003	H1	MR-05-UF0H03H1.xls
5	21889-S	UFRES # 3	UF003	I1	MR-05-UF003I1.xls
5	21889-S	UFRES # 3	UF003	J1	MR-05-UF003J1.xls
6	21994-S	MIC Project	MIC001	A1	MR-06-MIC001A1.xls
6	21994-S	MIC Project	MIC001	B2	MR-06-MIC001B2.xls
6	21994-S	MIC Project	MIC001	D1	MR-06-MIC001D1.xls
6	21994-S	MIC Project	MIC001	E1	MR-06-MIC001E1.xls
6	21992-S	SR 826/NW 36	SR82601	A1	MR-06-SR82601A1.xls
6	21992-S	SR 826/NW 36	SR82601	B1	MR-06-SR82601B1.xls
6	21992-S	SR 826/NW 36	SR82601	C1	MR-06-SR82601C1.xls
6	21992-S	SR 826/NW 36	SR82601	D1	MR-06-SR82601D1.xls
6	21993-S	SR 826/NW 8	SR82602	A1	MR-06-SR82602A1.xls
6	21993-S	SR 826/NW 8	SR82602	B1	MR-06-SR82602B1.xls
6	21993-S	SR 826/NW 8	SR82602	D1	MR-06-SR82602D1.xls
6	21993-S	SR 826/NW 8	SR82602	E1	MR-06-SR82602E1.xls
7	21905-S	Hills. CR39	CR3901	A1	MR-07-CR3901A1.xls
7	21905-S	Hills. CR39	CR3901	B1	MR-07-CR3901B1.xls
7	21905-S	Hills. CR39	CR3901	C1	MR-07-CR3901C1.xls
7	21905-S	Hills. CR39	CR3901	D1	MR-07-CR3901D1.xls
7	21910-S	Shelly Lake	SL001	A1	MR-07-SL001A1.xls
7	21910-S	Shelly Lake	SL001	B1	MR-07-SL001B1.xls
7	21910-S	Shelly Lake	SL001	C1	MR-07-SL001C1.xls
7	21910-S	Shelly Lake	SL001	D1	MR-07-SL001D1.xls
7	21909-S	US 19	US1901	A1	MR-07-US1901A1.xls
7	21909-S	US 19	US1901	B1	MR-07-US1901B1.xls
7	21909-S	US 19	US1901	C1	MR-07-US1901C1.xls
7	21909-S	US 19	US1901	D1	MR-07-US1901D1.xls

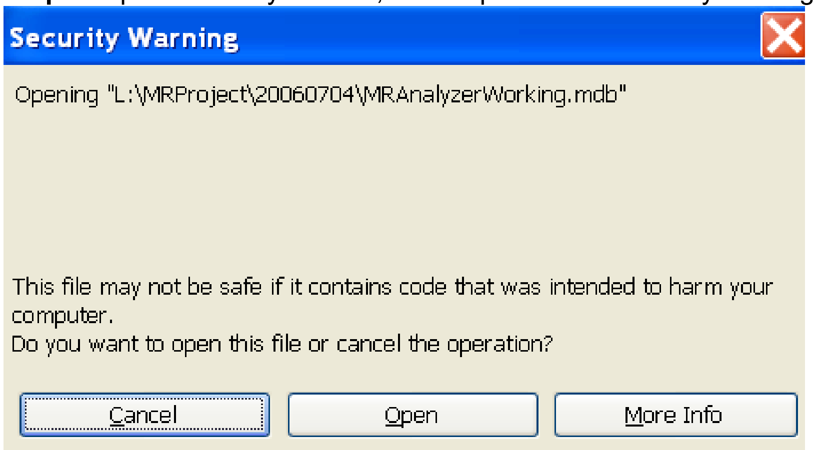
APPENDIX B
SUMMARY OF PERMEABILITY TEST DATA FILES

Table B.1 Permeability Test File Name Index

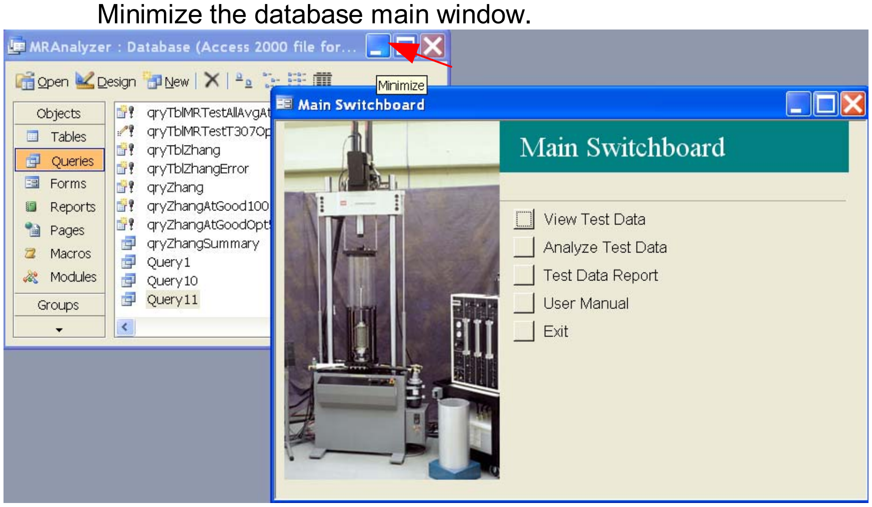
SampleID	Test No	Project	TestApproach	CompactedDUW	Initial S	Final S	Permeability(cm/sec)	ConfiningPressure	ExcelFileName
A24-12%		DesignHighWater	Panel	NA	NA	NA	0.000305	7	NA
A24-20%		DesignHighWater	Panel	NA	NA	NA	0.000104	7	NA
A24-24%		DesignHighWater	Panel	NA	NA	NA	0.000065	7	NA
A24-30%		DesignHighWater	Panel	NA	NA	NA	0.0000201	7	NA
AP001		MRDB2	Panel	124.2	75	96	0.00000645	7	PM-03-AP001A.XLS
BF001	E	MRDB2	Panel	112.5	87	99	0.000000207	7	PM-03-BF002E.XLS
BF002	G	MRDB2	Panel	118.9	78	98	0.00000361	7	PM-03-BF002E.XLS
BH001		MRDB2	Panel	131.2	83	96	0.000000742	7	PM-03-BH001A.XLS
BR001	C	MRDB2	Panel	106.5		98	0.000164	7	PM-02-BR001C.XLS
ES001	C	MRDB2	Panel	109.3		97	0.000547	7	PM-01-ES001C.XLS
FF001		MRDB2	Panel	123.3	90	96	0.00000165	7	PM-03-FF001-1.XLS
IB001		MRDB2	Panel	133.8	86	96	0.00000056	7	PM-03-IB001A.XLS
Levy		DesignHighWater	Constant Head	107.7	57	98	0.00552		NA
LS001		MRDB2	Panel	121.2	70	85	0.000188	6	PM-03-LS001-1.XLS
MIC001	C	MRDB2	Panel	114.2		100	0.000472	7	PM-06-MIC001C.XLS
SC001	B	MRDB2	Panel	118.8	64	98	0.000276	6	PM-02-SC001B.XLS
SR6001	C	MRDB2	Panel	114.7		98	0.000245	7	PM-04-SR6001C.XLS
SR70-A24		DesignHighWater	Panel	117.6	65		0.00025		NA
SR70-A3		DesignHighWater	Constant Head	109.7	61	98	0.00206		NA
SR82602	C	MRDB2	Panel	116.9		100	0.000185	7	PM-06-SR82602C.XLS
UF001	D	MRDB2	Panel	110.9	72	99	0.0000521	7	PM-05-UF001D.XLS
UF002	D	MRDB2	Panel	113.4	78	99	0.0000221	7	PM-05-UF002D.XLS
UF003	D	MRDB2	Panel	115.6	75	98	0.0000133	7	PM-05-UF003D.XLS
US1901	E	MRDB2	Panel	108.6	65	99	0.000305		PM-01-US1901C.XLS
WT001	C	MRDB2	Panel	105.1		98	0.000654	7	PM-02-WT001C.XLS

APPENDIX C
DATABASE “MRANALYZER.MDB” USER MANUAL

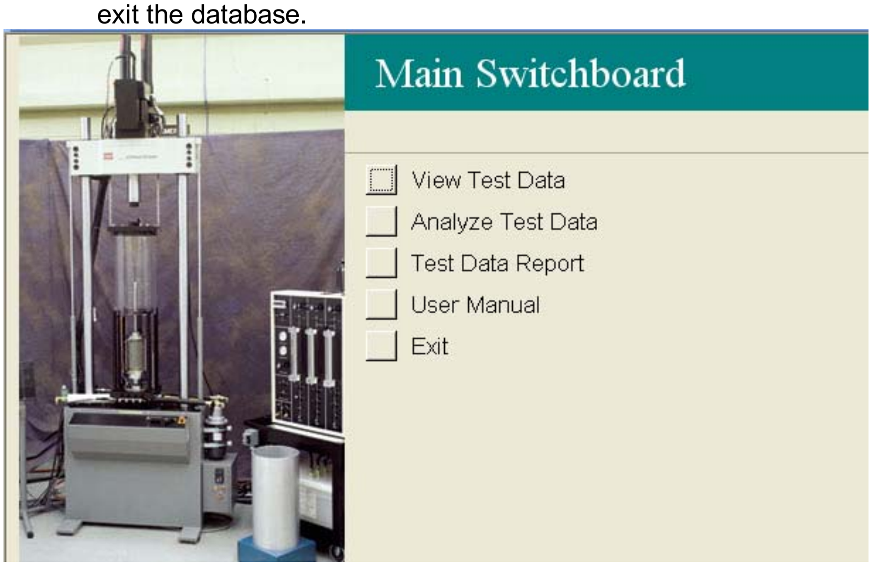
Step 1: Open MRAnalyzer.mdb, click “Open” on the security warning dialog.



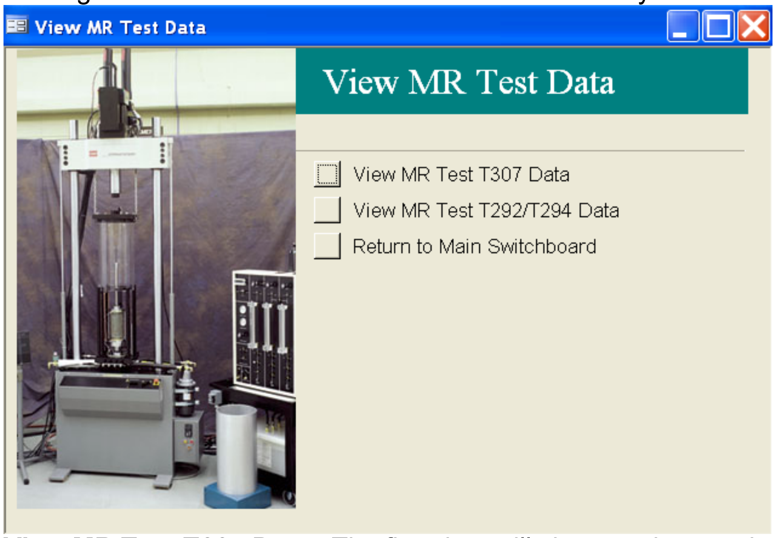
Step 2: After the opening, both the database main window and the Main Switchboard are displayed. Minimize the database main window.



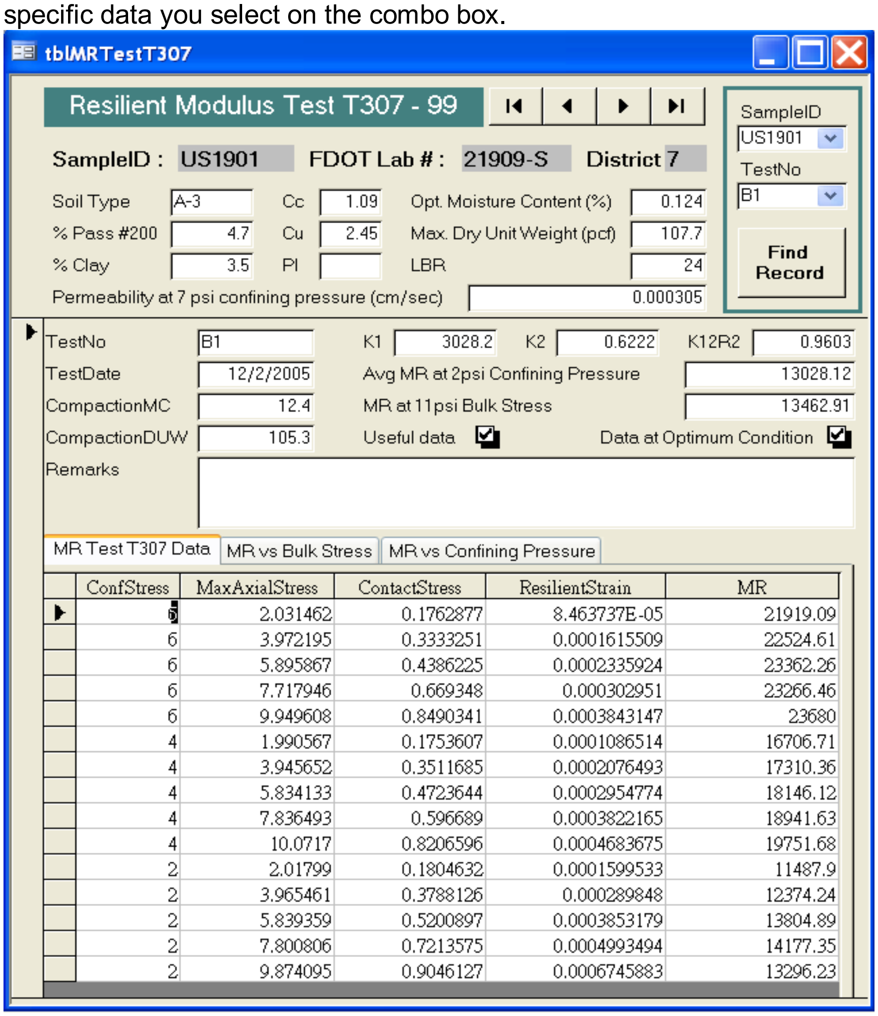
Step 3: Click on the main switchboard functions to go to the desired sub-forms. Click on “Exit” will exit the database.



View MR Test Data : You can view the resilient modulus test data by clicking on the "View Test Data" on the main switchboard. Then you can either go to the T307 or T292/T294 test data. By clicking on the "Return to Main Switchboard" will lead you to the Main Switchboard.

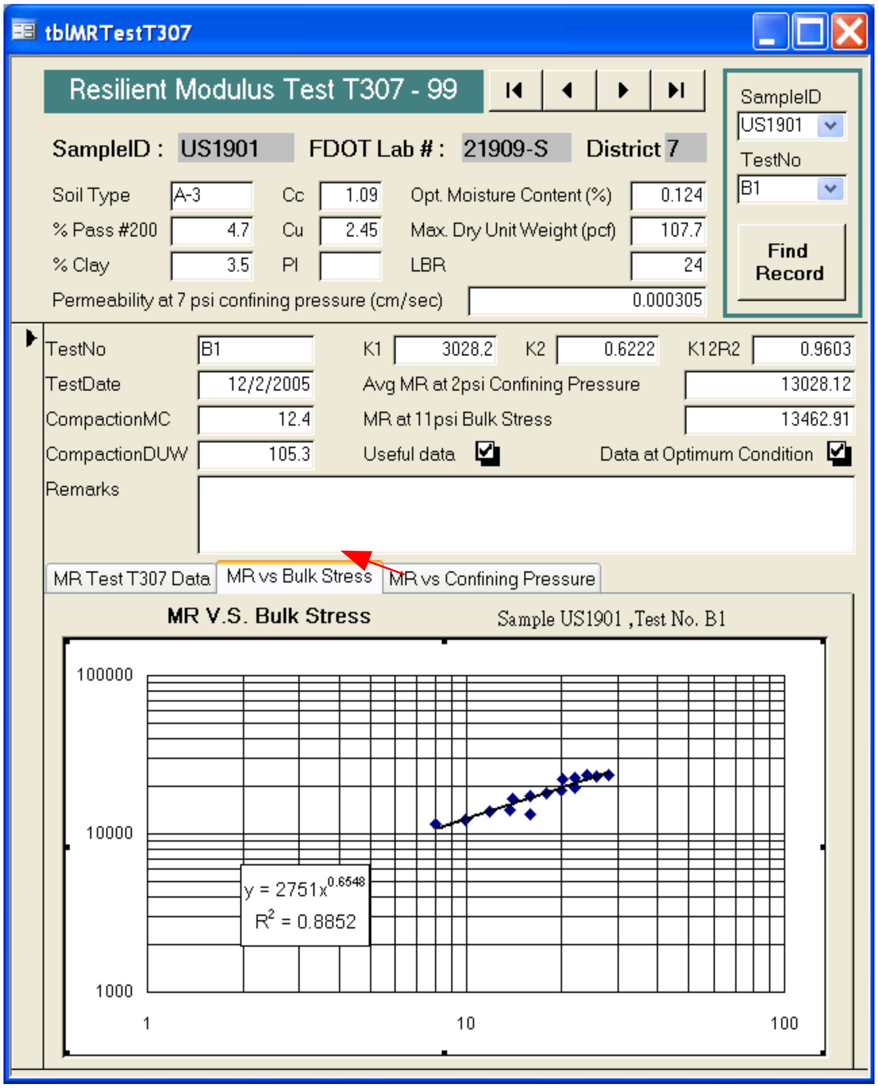


View MR Test T307 Data : The first data will show on the opening. You can click the "first", ""next", "previous", and the "last" button to access the data. You can also click the "find record" to find the specific data you select on the combo box.

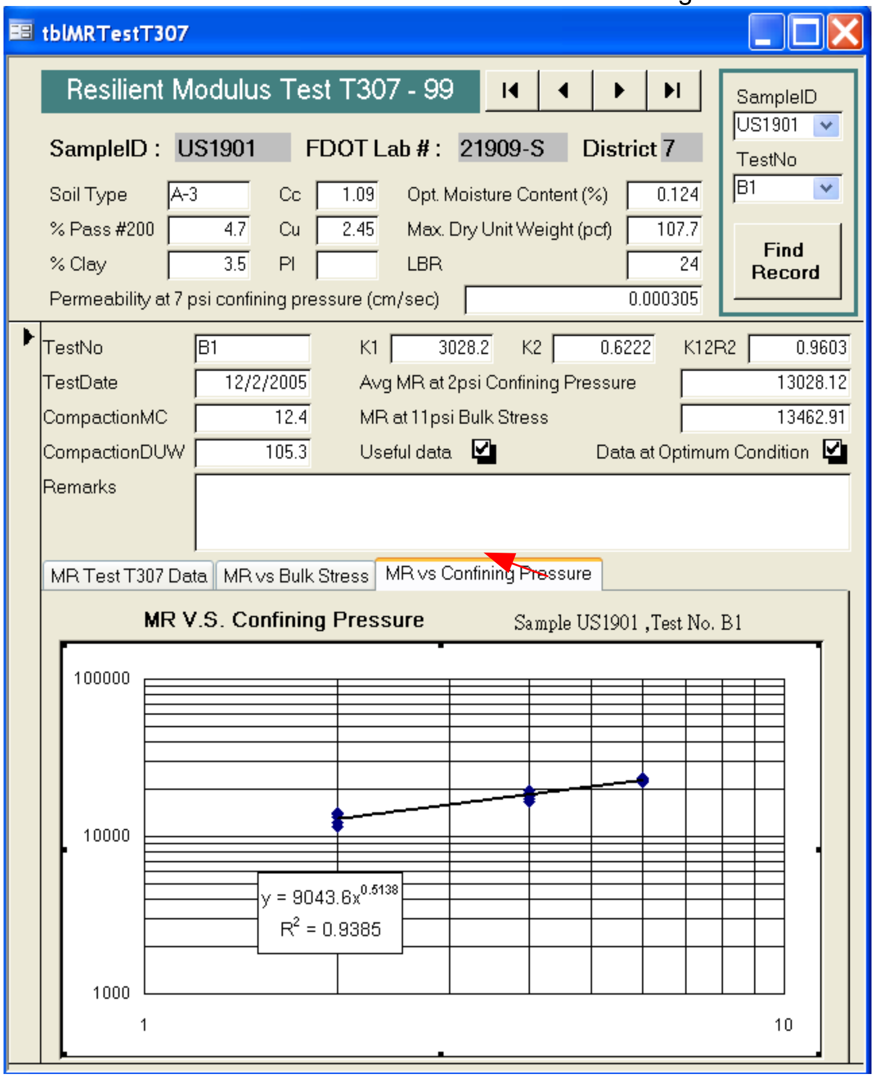


ConfStress	MaxAxialStress	ContactStress	ResilientStrain	MR
6	2.031462	0.1762877	8.463737E-05	21919.09
6	3.972195	0.3333251	0.0001615509	22524.61
6	5.895867	0.4386225	0.0002335924	23362.26
6	7.717946	0.669348	0.000302951	23266.46
6	9.949608	0.8490341	0.0003843147	23680
4	1.990567	0.1753607	0.0001086514	16706.71
4	3.945652	0.3511685	0.0002076493	17310.36
4	5.834133	0.4723644	0.0002954774	18146.12
4	7.836493	0.596689	0.0003822165	18941.63
4	10.0717	0.8206596	0.0004683675	19751.68
2	2.01799	0.1804632	0.0001599533	11487.9
2	3.965461	0.3788126	0.000289848	12374.24
2	5.839359	0.5200897	0.0003853179	13804.89
2	7.800806	0.7213575	0.0004993494	14177.35
2	9.874095	0.9046127	0.0006745883	13296.23

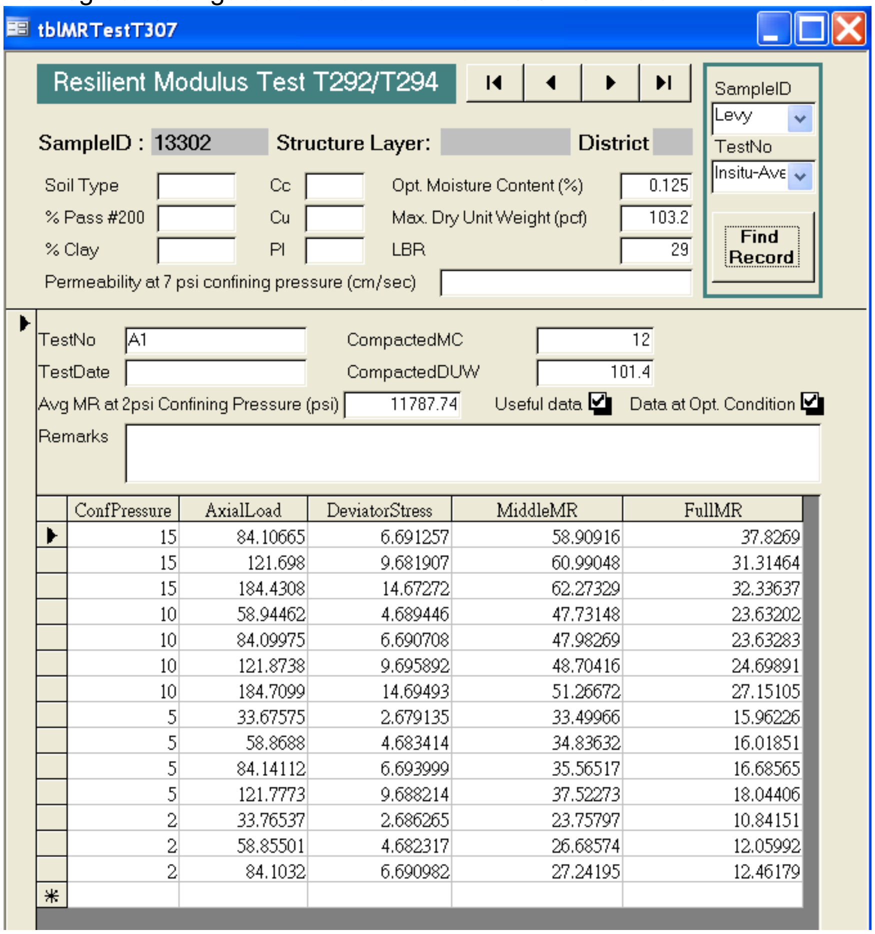
View MR Test T307 Data : The “MR vs Bulk Stress” can be found in the Tabbed Pane.



View MR Test T307 Data : Same as the "MR vs Confining Pressure".

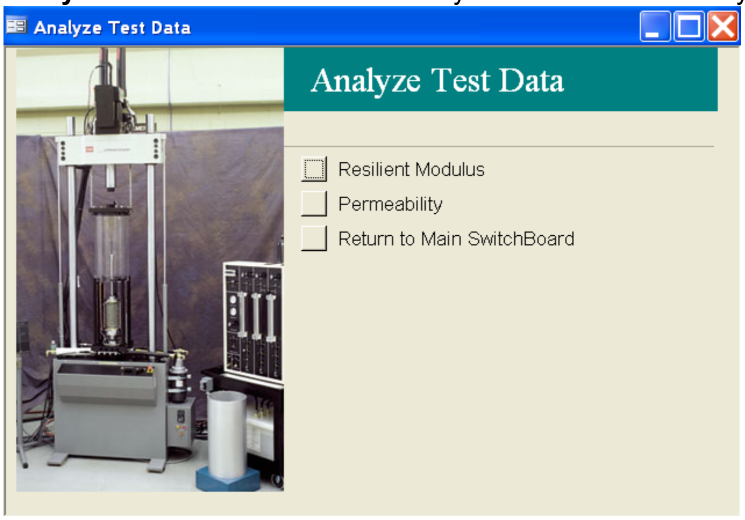


View MR Test T292/T294 Data : Follow the same procedure to get to the T292/T294 MR Test data. No Regression Figures available for the T292/T294 Data

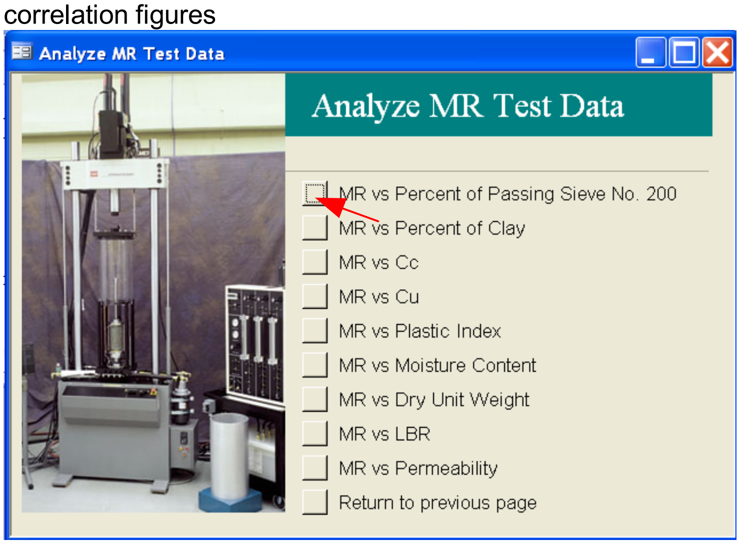


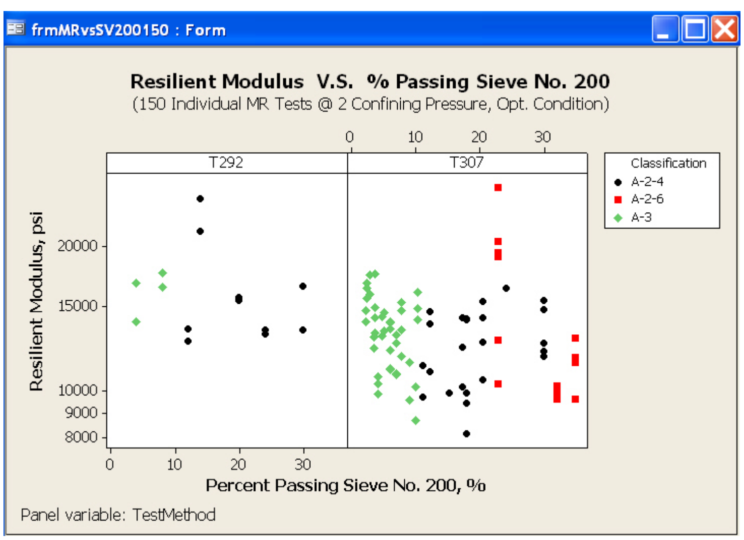
ConfPressure	AxialLoad	DeviatorStress	MiddleMR	FullMR
15	84.10665	6.691257	58.90916	37.8269
15	121.698	9.681907	60.99048	31.31464
15	184.4308	14.67272	62.27329	32.33637
10	58.94462	4.689446	47.73148	23.63202
10	84.09975	6.690708	47.98269	23.63283
10	121.8738	9.695892	48.70416	24.69891
10	184.7099	14.69493	51.26672	27.15105
5	33.67575	2.679135	33.49966	15.96226
5	58.8688	4.683414	34.83632	16.01851
5	84.14112	6.693999	35.56517	16.68565
5	121.7773	9.688214	37.52273	18.04406
2	33.76537	2.686265	23.75797	10.84151
2	58.85501	4.682317	26.68574	12.05992
2	84.1032	6.690982	27.24195	12.46179

Analyze Test data: Click on the "Analyze Test Data" will lead you to the following sub form

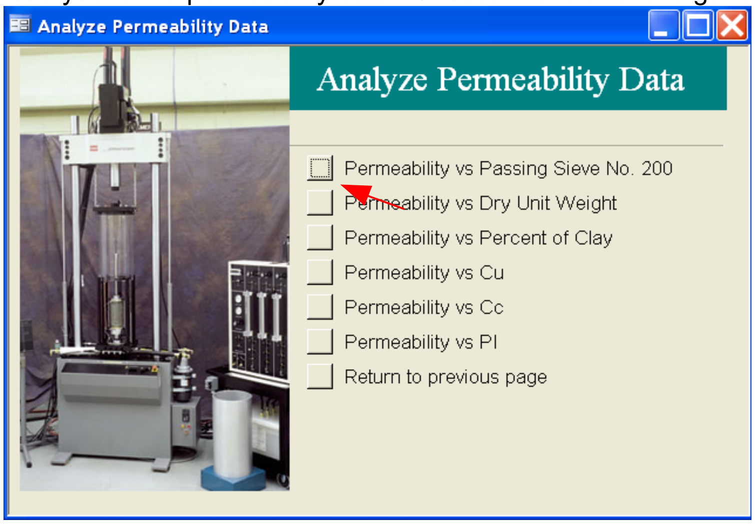


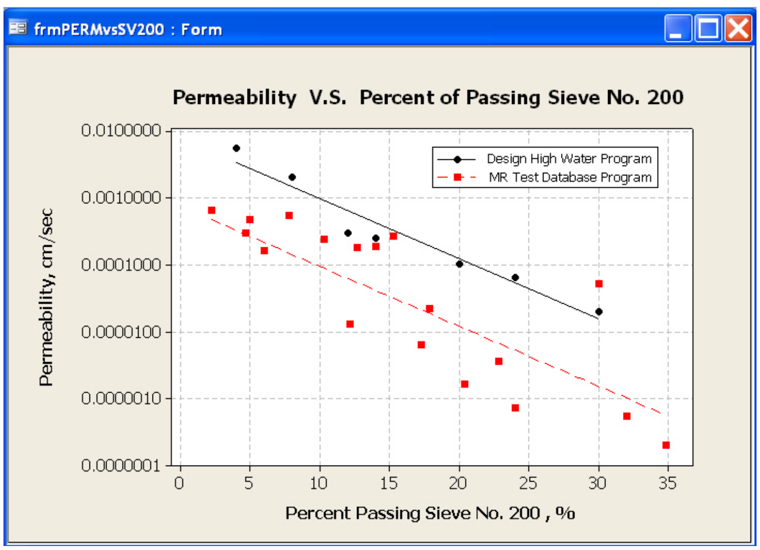
Analyze MR Test Data: Clicking on the correlation you would like to see will lead you to the correlation figures



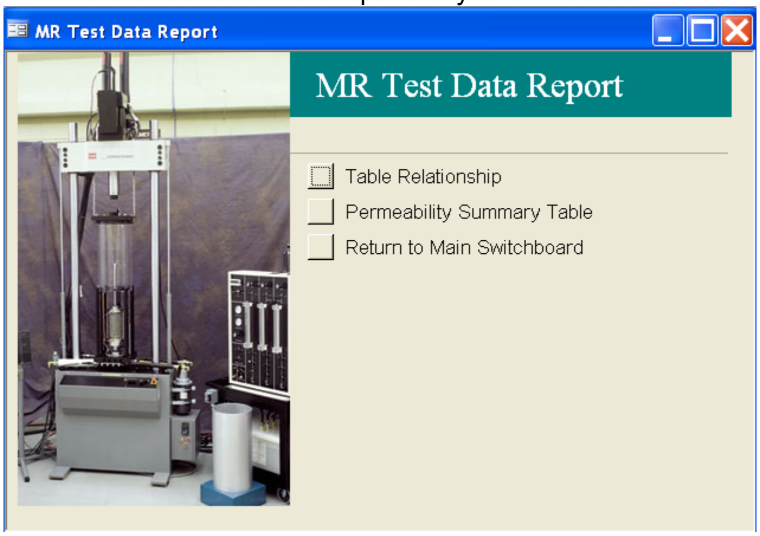


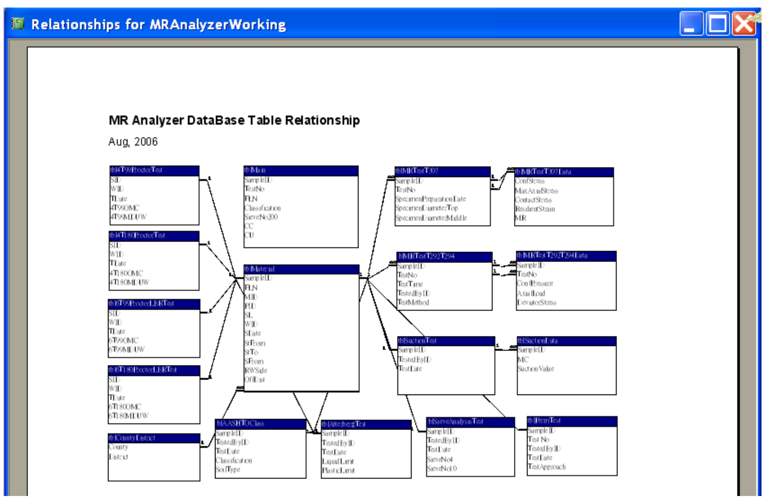
Analyze Permeability Data :Click on the "Permeability" button on the "Analyze Test Data" form will lead you to the permeability data. Choose the relations to go to the figures.

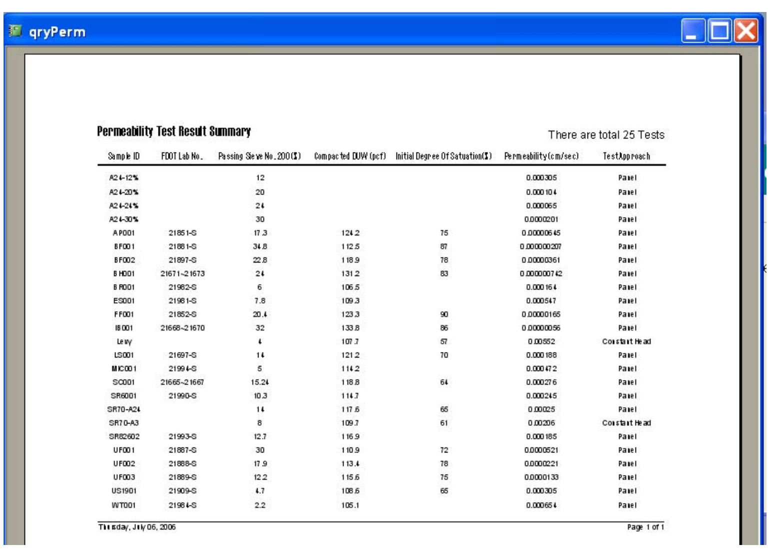




Test Data Report: There are two default reports in the database. However, the database administrator can add more reports anytime if needed.







Permeability Test Result Summary

There are total 25 Tests

Sample ID	FDOT Lab No.	Passing Sieve No.200(%)	Compacted DUW (pcf)	Initial Degree Of Satuation(%)	Permeability(cm/sec)	TestApproach
A24-12%		12			0.000305	Panel
A24-20%		20			0.000104	Panel
A24-24%		24			0.000065	Panel
A24-30%		30			0.0000201	Panel
AP001	21851-S	17.3	124.2	75	0.00000645	Panel
BF001	21881-S	34.8	112.5	87	0.000000207	Panel
BF002	21897-S	22.8	118.9	78	0.00000361	Panel
BH001	21671~21673	24	131.2	83	0.000000742	Panel
BR001	21982-S	6	106.5		0.000164	Panel
ES001	21981-S	7.8	109.3		0.000547	Panel
FF001	21852-S	20.4	123.3	90	0.00000165	Panel
IB001	21668~21670	32	133.8	86	0.0000056	Panel
Levy		4	107.7	57	0.00552	Constant Head
LS001	21697-S	14	121.2	70	0.000188	Panel
MIC001	21994-S	5	114.2		0.000472	Panel
SC001	21665~21667	15.24	118.8	64	0.000276	Panel
SR6001	21990-S	10.3	114.7		0.000245	Panel
SR70-A24		14	117.6	65	0.00025	Panel
SR70-A3		8	109.7	61	0.00206	Constant Head
SR82602	21993-S	12.7	116.9		0.000185	Panel
UF001	21887-S	30	110.9	72	0.0000521	Panel
UF002	21888-S	17.9	113.4	78	0.0000221	Panel
UF003	21889-S	12.2	115.6	75	0.0000133	Panel
US1901	21909-S	4.7	108.6	65	0.000305	Panel
WT001	21984-S	2.2	105.1		0.000654	Panel

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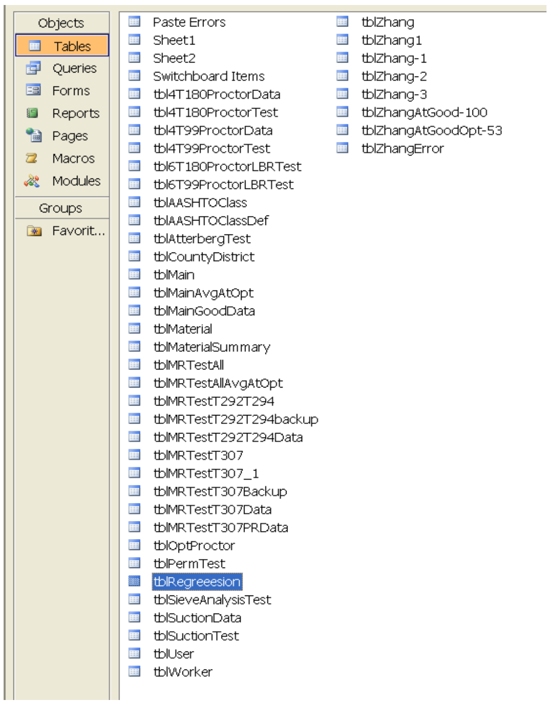
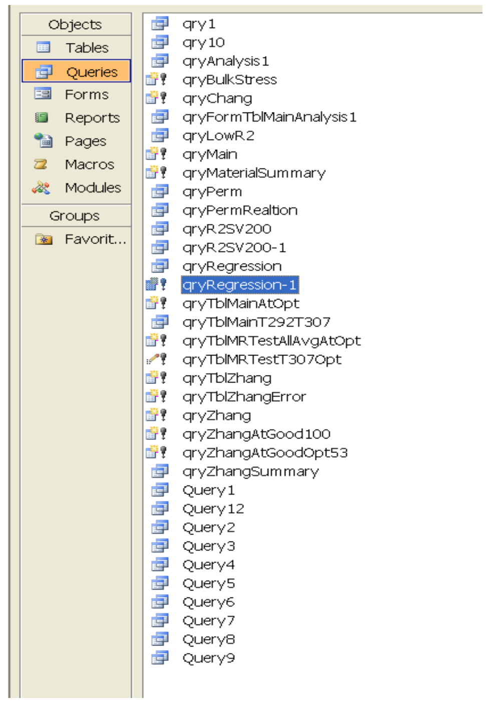
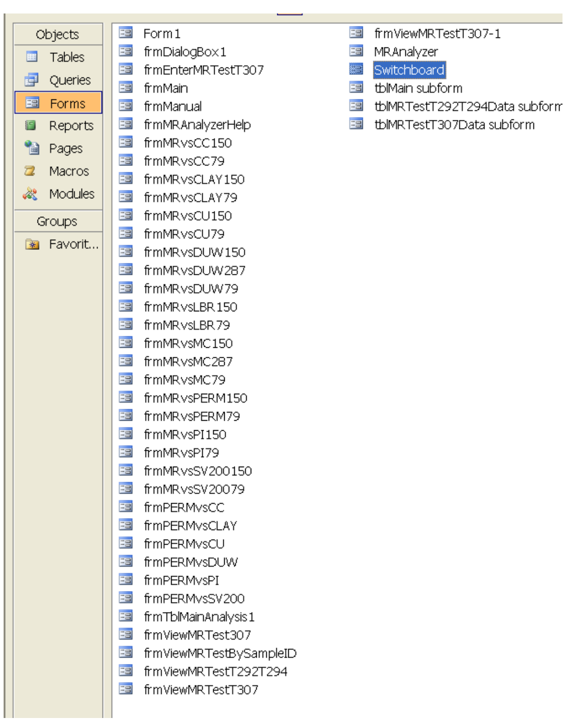
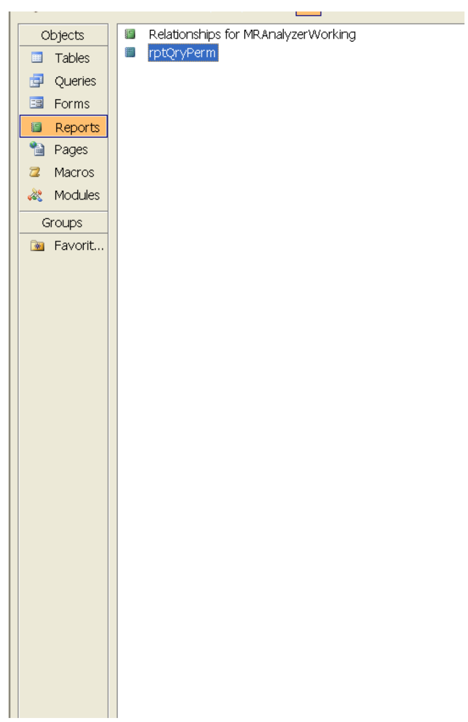
Database User Manual : Database user manual can be found in the application by clicking on the “UserManual” button on the Main Switchborad.

The following windows are the Table list, Quary list, Form list, and the Report list in the database.









MRAnalyzer.mdb Database Table List

Table name	Description
Switchboard Items	Main switchboard data
tbl4T180ProctorData	4 inch modified proctor test data
tbl4T180ProctorTest	4 inch modified proctor test
tbl4T99ProctorData	4 inch standard proctor test data
tbl4T99ProctorTest	4 inch standard proctor test
tbl6T180ProctorLBRTest	6 inch modified proctor test
tbl6T99ProctorLBRTest	6 inch standard proctor test
tblAASHTOClass	AASHTO soil type class
tblAASHTOClassDef	AASHTO soil type class definition
tblAtterbergTest	Atterberg test data
tblCountyDistrict	County and district table
tblMain	349 MR test data with material properties summary table
tblMainAvgAtOpt	Average MR test data with material properties summary table at optimum condition
tblMainGoodData	Valid MR test data with material properties summary table
tblMaterial	Basic material information
tblMaterialSummary	Material engineering properties summary table
tblMRTestAll	MR test data including T307, T292, and t294
tblMRTestAllAvgAtOpt	Average MR test data including T307, T292, and t294 at optimum condition
tblMRTestT292T294	T292 and T294 MR test summary
tblMRTestT292T294Data	T292 and T294 MR test data
tblMRTestT307	T307 MR test summary
tblMRTestT307_1	T307 MR test summary with additional information
tblMRTestT307Data	T307 MR test data
tblMRTestT307PRData	T307 Poisson's Ration test data
tblOptProctor	Proctor data at optimum condition
tblPermTest	Permeability test summary
tblSieveAnalysisTest	Sieve analysis test data
tblSuctionData	Suction test data
tblSuctionTest	Suction test summary
tblUser	User information
tblWorker	Worker information

APPENDIX D
ANOMALY TYPES

Anomaly Type 1

A regression analysis was conducted on the data from each of the 349 selected tests to determine the statistical parameters for the relationship between stress states and resilient modulus. The k_1 and k_2 coefficients were obtained from Equation 2.2 and the corresponding R-square value was also determined. The k_3, k_4 coefficients and the corresponding R-square value could also be found from Equation 2.3. It was noted that some tests had lower R-square values. The specimens with a lower R-square value between the bulk stress and resilient modulus usually had a higher stiffness than the other specimens. The R-square values of the bulk stress versus resilient modulus for the BF001, BF002, and BH001 soils are less than 0.5, and the three soils were all very stiff when compacted at the optimum condition. Those data were removed from further analysis.

Anomaly Type 2

In the beginning of the testing program, observation showed that the R-square values of the confining pressure versus resilient modulus were extremely low, and the resilient modulus values remained the same regardless of the change of the confining pressure. Subsequently, an air leakage from the triaxial cell was observed and then fixed. The test data using the incorrect confining pressures were flagged as the anomaly Type 2. 21 tests were excluded from further analysis due to the anomaly Type 2.

Anomaly Type 3

The measured deformations from tests on the OS001, SL001, and WT001 sandy soils were observed to exceed the designed limits during the last one or two test sequences due to a low stiffness. The sandy soils all contain very low percentage of fines passing the No. 200 sieve (less than 4%). The data from those tests were flagged as the anomaly Type 3, but were still considered as qualified data for further analysis.

Anomaly Type 4

A couple of specimens were tested more than once in the laboratory. The specimens that were not tested at the first time were flagged as the anomaly Type 4. The specimens were subject to further consolidation and became harder than they were at the first time. Those data were excluded from further analysis.

In addition, a few specimens were disturbed when subject to high stress states and ended up with unexpected higher resilient modulus values. The unusual high resilient moduli were eliminated from the regression analysis.

Anomaly Type 5

There were at least four tests performed on each type of soil. Additional tests were conducted to ensure the repeatability if any anomaly was found within those tests. The test data that were not repeatable were flagged as the anomaly Type 5 and were not included for the calculation of the average resilient modulus.

Anomaly Type 6

During the resilient modulus test, the contact loads were varied for some soils at the beginning of the test procedure. Some contact loads were apparently much higher than the normal ones, which should be about 70 to 80 lbs. This could happen due to different conditions of the specimen contact surface, specimen stiffness, and machine noises. This could definitely affect the resilient modulus results and should be noted for the test. The anomaly was noted as Type 6.

Anomaly Type 7

The moisture content and the dry density of some specimens were found to be outside the range specified in the T307-99 test procedure after the test. The resilient modulus data obtained in the condition outside of the optimum range using the AASHTO T-99 were marked as anomaly Type 7 and should be noted for the test.

Anomaly Type 8

There were other factors contributing to the anomalies of the test results. Any other anomalies that were not categorized in the above designated types were marked as the anomaly Type 8, such as leaks occurring in the membrane during the test, different stress states used in the test program than required by the test protocol, test specimens that began to fail or exhibit disturbance at the higher stress states, LVDT clamps that began to move or move suddenly because of vibrations during the loading sequences, and LVDTs that began to drift during the testing sequences or became restricted due to friction in the measurement system.

APPENDIX E
MULTIPLE REGRESSION ANALYSIS

E.1 Multiple Regression Models in Applications

Most practical applications of regression analysis utilize models that are more complex than the simple straight-line model. Probabilistic models that include more than one independent variable are called multiple regression models. The general form of these models is

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_k x_k + \varepsilon \tag{E.1}$$

The dependent variable y is now written as a function of k independent variables, $x_1, x_2, \ldots, x_k$. The random error term is added to make the model probabilistic rather than deterministic. The value of the coefficient β_i determines the contribution of the independent variable x_i, and β_0 is the y-intercept. The coefficients $\beta_0, \beta_1, ..., \beta_k$ are usually unknown because they represent population parameters(McClave et al, 2000)(StatSoft, 1984-2003).

The symbols $x_1, x_2, \ldots, x_k$ may represent higher-order terms for quantitative predictors or terms that represent qualitative predictors.

The steps used to develop the multiple regression model are similar to those used for the simple regression model.

Step 1. Hypothesize the deterministic component of the model. This component relates the mean, E(y), to the independent variables $x_1, x_2, \ldots, x_k$. This involves the choice of the independent variables to be included in the model.

Step 2. Use the sample data to estimate the unknown model parameters $\beta_0, \beta_1, \ldots, \beta_k$ in the model.

Step 3. Specify the probability distribution of the random error term, ε, and estimate the standard deviation of this distribution, σ.

Step 4. Check that the assumptions on ε are satisfied, and make model modifications if necessary.

Step 5. Statistically evaluate the usefulness of the model.

Step 6. When satisfied that the model is useful, use it for prediction, estimation, and other purposes.

E.2 The first-order model

A model that includes only terms for quantitative independent variables, called a first-order model, is described in the following section. Note that the first-order model does not include any higher-order terms.

$$E(y) = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + ... + \beta_k x_k \tag{E.2}$$

where $x_1, x_2, ..., x_k$ are all quantitative variables that are not functions of other independent variables.

The method of fitting first-order models and multiple regression models, in general, is identical to that of fitting the simple straight-line models : the method of least squares. That is, we choose the estimated model

$$\hat{y} = \hat{\beta}_0 + \hat{\beta}_1 x_1 + ... + \hat{\beta}_k x_k \tag{E.3}$$

that minimizes

$$SSE = \sum (y - \hat{y})^2 \tag{E.4}$$

As in the case of the simple linear model, the sample estimates $\hat{\beta}_0, \hat{\beta}_1, ..., \hat{\beta}_k$ are obtained as a solution to a set of simultaneous linear equations.

First of all, as is evident in the name, multiple linear regression, it is assumed that the relationship between variables is linear. In practice this assumption can virtually never be confirmed; fortunately, multiple regression procedures are not greatly affected by minor deviations from this assumption. However, as a rule it is prudent to always look at a bivariate scatterplot of the variables of interest. If curvature in the relationships is evident, one may consider either transforming the variables, or explicitly allowing for nonlinear components(McClave et al, 2000)(StatSoft, 1984-2003).

The primary difference between fitting the simple and multiple regression models is computational difficulty. The (k+1) simultaneous linear equations that must be solved to find the (k+1) estimated coefficients $\hat{\beta}_0, \hat{\beta}_1, \ldots, \hat{\beta}_k$ are difficult (sometimes nearly impossible) to solve with a calculator. Consequently, we resort to the use of computer software such as Minitab, SAS, SPSS, etc.

E.3 Assumptions for Random Error ε

For any given set of values of $x_1, x_2, \ldots, x_k$, the random error ε has a normal probability distribution with a mean equal to 0 and a variance equal to σ^2.

The random errors are independent (in a probabilistic sense).

We will use the estimator of σ^2 both to check the utility of the model and to provide a measure of reliability of predictions and estimates when the model is used for those purposes. Thus, we can see that the estimation of σ^2 plays an important part in the development of a regression model(McClave et al, 2000)(StatSoft, 1984-2003).

Estimator of σ^2 for a multiple regression model with k independent variables is

$$s^2 = \frac{SSE}{n - Number\ of\ estimated\ \beta\ parameters} = \frac{SSE}{n-(k+1)} \tag{E.5}$$

E.4 Inferences about the β parameters

Inferences about the individual β parameters in a model are obtained using either a confidence interval or a test of hypothesis.

Test of an Individual Parameter Coefficient in the Multiple Regression Model	
One-Tailed Test	Two-Tailed Test
$H_0: \beta_i = 0$ $H_a: \beta_i < 0 [or\ H_a: \beta_i > 0]$	$H_0: \beta_i = 0$ $H_a: \beta_i \neq 0$
Test Statistic: $t = \hat{\beta}_i / s_{\hat{\beta}_i}$	
Rejection region: $t < -t_\alpha$ $[or\ t > t_\alpha\ when\ H_a: \beta_i > 0]$	Rejection region: $\lvert t \rvert > t_{\alpha/2}$
Where t_α and $t_{\alpha/2}$ are based on $n-(k+1)$ degrees of freedom and n = Number of observations $k+1$ = Number of β parameters in the model	

A $100(1-\alpha)\%$ confidence interval for a β parameter is $\hat{\beta}_i \pm t_{\alpha/2} s_{\hat{\beta}_i}$ (McClave et al, 2000).

E.5 Checking the Overall Utility of a Model

Conducting a t-test on each β parameter in a model is not the best way to determine whether the overall model is contributing information for the prediction of y. If we were to conduct a series of t-tests to determine whether the independent variables are contributing to the predictive relationship, we would be very likely to make one or more errors in deciding which terms to retain in the model and which to exclude. In multiple regression models for which a large number of independent variables are being considered, conducting a series of t-tests may include a large number of insignificant variables and exclude some useful ones. If we want to test the utility of a multiple regression model, we will need a global test (one that encompasses all the β parameters). We would also like to find some statistical quantity that measures how well the model fits the data.

We use the multiple regression equivalent of r^2 , the coefficient of determination for the straight-line model. The multiple coefficient of determination, R^2, is defined as

$$R^2 = 1 - \frac{SSE}{SS_{yy}} = \frac{SS_{yy} - SSE}{SS_{yy}} = \frac{Explained\ \text{var}iability}{Total\ \text{var}iability} \tag{E.6}$$

Just as for the simple linear model, R^2 represents the fraction of the sample variation of the y values (measured by

SS_{yy}) that is explained by the least squares prediction equation. Thus, $R^2 = 0$ implies a complete lack of fit of the model to the data and $R^2 = 1$ implies a perfect fit with the model passing through every data point. In general, the larger the value of R^2, the better the model fits the data.

A large value of R^2 computed from the sample data does not necessarily mean that the model provides a good fit to all of the data points in the population. We will always obtain a perfect fit ($R^2 = 1$) to a set of n data points if the model contains exactly n parameters. Consequently, if we want to use the value of R^2 as a measure of how useful the model will be for the prediction of y, it should be based on a sample that contains substantially more data points than the number of parameters in the model. Most authors recommend that one should have at least 10 to 20 times as many observations (cases, respondents) as one has variables, otherwise the estimates of the regression line are probably very unstable and unlikely to be replicated if one were to do the study over.

Despite its utility, R^2 is only a sample statistic. Therefore, it is dangerous to judge the global usefulness of the model based solely on these values. A better method is to conduct a test of hypothesis involving all the β parameters (except β_0) in a model.

Testing Global Usefulness of the Model: The Analysis of Variance F-Test
$H_0 : \beta_1 = \beta_2 = \cdots = \beta_k = 0$ $H_a : At\ least\ one\ \beta_i \neq 0$
Test Statistic: $F = \frac{(SS_{yy} - SSE)/k}{SSE/[n-(k+1)]} = \frac{R^2/k}{(1-R^2)/[n-(k+1)]} = \frac{Mean\ Square\ (Model)}{Mean\ Square\ (Error)}$
Where n is the sample size and k is the number of terms in the model.
Rejection region: $F > F_\alpha$, with k numerator degrees of freedom and $[n-(k+1)]$ denominator degrees of freedom.

A rejection of the null hypothesis $H_0 : \beta_1 = \beta_2 = \cdots = \beta_k = 0$ in the global F-test leads to the conclusion [with $100(1-\alpha)\%$ confidence] that the model is statistically useful. However, statistically “useful” does not necessarily mean “best”. Another model may prove even more useful in terms of providing more reliable estimates and predictions. This global F-test is usually regarded as a test that the model must pass to merit further consideration (McClave et al, 2000).

E.6 Multiple Regression Analysis Results

Table E. 1 Stepwise Regression Analysis for A-3 soils

Stepwise Regression: ln(Mr) versus Matreial Properties

(On 109 A-3 Soils)

```
Backward elimination.  Alpha-to-Remove: 0.1
Response is ln(Mr) on 7 predictors, with N = 23
N(cases with missing observations) = 86 N(all cases) = 109
```

Step	1	2	3	4	5	6
Constant	7.730	7.730	7.546	7.638	8.777	9.699
SieveNo200	-0.017	-0.017	-0.017	-0.017		
T-Value	-0.51	-0.93	-0.97	-1.03		
P-Value	0.617	0.365	0.345	0.319		
CC	-0.00					
T-Value	-0.00					
P-Value	1.000					
CU	-0.007	-0.007	-0.005			
T-Value	-0.07	-0.12	-0.10			
P-Value	0.949	0.909	0.923			
6T180LBR	0.0003	0.0003				
T-Value	0.06	0.10				
P-Value	0.950	0.922				
Permeability	47	47	44	42	43	49
T-Value	0.44	1.07	1.39	1.63	1.66	1.88
P-Value	0.667	0.301	0.184	0.121	0.113	0.075
CompactionMC	-0.0128	-0.0128	-0.0129	-0.0128	-0.0125	-0.0140
T-Value	-1.49	-1.54	-1.60	-1.64	-1.60	-1.77
P-Value	0.156	0.143	0.129	0.118	0.125	0.092
CompactionDUW	0.0191	0.0191	0.0209	0.0200	0.0084	
T-Value	0.74	0.77	1.27	1.57	1.43	
P-Value	0.469	0.453	0.220	0.134	0.168	
S	0.0915	0.0885	0.0859	0.0835	0.0836	0.0858
R-Sq	50.01	50.01	49.97	49.95	47.02	41.31
R-Sq(adj)	26.68	31.26	35.26	38.82	38.66	35.44
Mallows C-p	8.0	6.0	4.0	2.0	0.9	0.6
PRESS	0.317508	0.270844	0.242351	0.190786	0.183901	0.191161
R-Sq(pred)	0.00	0.00	3.42	23.97	26.72	23.82

Table E. 2 Multiple Regression Analysis for A-3 soils (1st trial)

Regression Analysis: ln(Mr) versus Material Properties

(On 109 A-3 Soils)

```
The regression equation is
ln(Mr) = 9.69 - 0.0115 CompactionMC + 22.7 Permeability

30 cases used, 79 cases contain missing values

Predictor            Coef   SE Coef       T      P
Constant          9.69374   0.08622  112.43  0.000
CompactionMC    -0.011549  0.007139   -1.62  0.117
Permeability        22.69     10.36    2.19  0.037

S = 0.114807   R-Sq = 24.4%   R-Sq(adj) = 18.8%

PRESS = 0.497329   R-Sq(pred) = 0.00%

Analysis of Variance

Source          DF        SS        MS     F      P
Regression       2   0.11482   0.05741  4.36  0.023
Residual Error  27   0.35588   0.01318
Total           29   0.47069

Source        DF   Seq SS
CompactionMC   1  0.05166
Permeability   1  0.06316

Unusual Observations

Obs  CompactionMC  ln(Mr)     Fit  SE Fit  Residual  St Resid
 72          15.0  9.3753  9.6457  0.0541   -0.2704    -2.67R

R denotes an observation with a large standardized residual.
```

Table E. 3 Multiple Regression Analysis for A-3 soils (2nd trial)

Regression Analysis: ln(Mr) versus Material Properties

(On 109 A-3 Soils)

```
The regression equation is
ln(Mr) = 7.64 - 0.0128 CompactionMC - 0.0103 CU - 0.0157 SieveNo200
         + 49.9 Permeability + 0.0198 CompactionDUW + 0.027 CC

23 cases used, 86 cases contain missing values

Predictor            Coef    SE Coef      T      P
Constant            7.638      2.082   3.67  0.002
CompactionMC    -0.012840   0.008304  -1.55  0.142
CU               -0.01029    0.08697  -0.12  0.907
SieveNo200       -0.01565    0.02601  -0.60  0.556
Permeability        49.87      89.60   0.56  0.585
CompactionDUW     0.01984    0.02255   0.88  0.392
CC                 0.0273     0.3674   0.07  0.942

S = 0.0885618   R-Sq = 50.0%   R-Sq(adj) = 31.2%
PRESS = 0.279082   R-Sq(pred) = 0.00%

Analysis of Variance

Source          DF        SS        MS     F      P
Regression       6  0.125450  0.020908  2.67  0.055
Residual Error  16  0.125491  0.007843
Total           22  0.250941

Source         DF    Seq SS
CompactionMC    1  0.077694
CU              1  0.023624
SieveNo200      1  0.003217
Permeability    1  0.008883
CompactionDUW   1  0.011989
CC              1  0.000043


Unusual Observations

Obs  CompactionMC  ln(Mr)     Fit  SE Fit  Residual  St Resid
 37          12.0  9.6338  9.4938  0.0590    0.1401     2.12R

R denotes an observation with a large standardized residual.
```

Table E. 4 Multiple Regression Analysis for A-3 soils (3rd trial)

Regression Analysis: ln(Mr) versus Material Properties

(On 109 A-3 Soils)

The regression equation is
ln(Mr) = 9.50 + 0.161 CC - 0.0123 CompactionMC + 71.4 Permeability

23 cases used, 86 cases contain missing values

Predictor	Coef	SE Coef	T	P
Constant	9.4971	0.1710	55.52	0.000
CC	0.1615	0.1103	1.46	0.159
CompactionMC	-0.012314	0.007786	-1.58	0.130
Permeability	71.36	29.62	2.41	0.026

S = 0.0834603 R-Sq = 47.3% R-Sq(adj) = 38.9%

PRESS = 0.191724 R-Sq(pred) = 23.60%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	3	0.118595	0.039532	5.68	0.006
Residual Error	19	0.132347	0.006966		
Total	22	0.250941			

Source	DF	Seq SS
CC	1	0.000560
CompactionMC	1	0.077617
Permeability	1	0.040418

Table E. 5 Stepwise Regression Analysis for A-2-4 soils

Stepwise Regression: ln(Mr) versus Material properties

(On 103 A-2-4 Soils)

```
Backward elimination.  Alpha-to-Remove: 0.1
Response is ln(Mr) on 8 predictors, with N = 37
N(cases with missing observations) = 66 N(all cases) = 103
```

Step	1	2	3	4	5
Constant	8.191	9.425	9.512	9.737	9.871
SieveNo200	0.0116	0.0073	0.0056		
T-Value	0.62	0.67	0.60		
P-Value	0.541	0.508	0.555		
CC	-0.061	-0.053	-0.048	-0.057	-0.059
T-Value	-1.52	-1.88	-2.08	-3.23	-3.46
P-Value	0.141	0.070	0.046	0.003	0.002
CU	0.0104	0.0097	0.0091	0.0110	0.0118
T-Value	1.77	1.85	1.89	3.18	3.63
P-Value	0.087	0.075	0.068	0.003	0.001
6T180LBR	-0.0047	-0.0015			
T-Value	-0.38	-0.32			
P-Value	0.704	0.750			
Permeability	1328	945	785	358	
T-Value	0.79	0.95	0.92	0.77	
P-Value	0.438	0.352	0.365	0.445	
CompactionMC	-0.043	-0.044	-0.041	-0.040	-0.041
T-Value	-2.52	-2.64	-3.10	-3.07	-3.27
P-Value	0.018	0.013	0.004	0.004	0.003
CompactionDUW	0.009				
T-Value	0.28				
P-Value	0.778				
Clay	0.161	0.091	0.057	0.046	0.034
T-Value	0.60	0.81	1.93	2.01	2.04
P-Value	0.555	0.422	0.063	0.053	0.050
S	0.177	0.174	0.171	0.169	0.168
R-Sq	53.21	53.08	52.91	52.35	51.43
R-Sq(adj)	39.85	41.75	43.49	44.67	45.36
Mallows C-p	9.0	7.1	5.2	3.5	2.1
PRESS	1.54588	1.43222	1.36285	1.31985	1.29651
R-Sq(pred)	17.16	23.25	26.97	29.27	30.52

Table E. 6 Multiple Regression Analysis for A-2-4 soils (1st trial)

Regression Analysis: ln(Mr) versusMaterial properties

(On 103 A-2-4 Soils)

```
The regression equation is
ln(Mr) = 9.87 - 0.0593 CC + 0.0118 CU - 0.0414 CompactionMC
         + 0.0337 Clay

37 cases used, 66 cases contain missing values

Predictor          Coef    SE Coef      T      P
Constant         9.8710     0.1660  59.47  0.000
CC             -0.05929    0.01712  -3.46  0.002
CU             0.011845   0.003265   3.63  0.001
CompactionMC   -0.04141    0.01268  -3.27  0.003
Clay            0.03367    0.01654   2.04  0.050

S = 0.168299   R-Sq = 51.4%   R-Sq(adj) = 45.4%
PRESS = 1.29651   R-Sq(pred) = 30.52%

Analysis of Variance

Source          DF       SS       MS     F      P
Regression       4  0.95976  0.23994  8.47  0.000
Residual Error  32  0.90638  0.02832
Total           36  1.86615

Source        DF   Seq SS
CC             1  0.19096
CU             1  0.37449
CompactionMC   1  0.27684
Clay           1  0.11747

Unusual Observations

Obs    CC    ln(Mr)     Fit  SE Fit  Residual  St Resid
 27   5.1    9.0540  9.4170  0.0393   -0.3630    -2.22R
 86  58.3   10.1306  9.7404  0.0754    0.3902     2.59R
 89  58.3    9.3854  9.7031  0.0771   -0.3177    -2.12R

R denotes an observation with a large standardized residual.
```

Table E. 7 Multiple Regression Analysis for A-2-4 soils (2nd trial)

Regression Analysis: ln(Mr) versus Material Properties

(On 103 A-2-4 Soils)

```
The regression equation is
ln(Mr) = 10.2 - 0.0429 CompactionMC + 0.0369 Clay + 0.0123 CU - 0.0616 CC
         - 0.00165 SieveNo200 - 0.0027 CompactionDUW

37 cases used, 66 cases contain missing values

Predictor           Coef    SE Coef      T      P
Constant          10.213      1.374   7.43  0.000
CompactionMC    -0.04290    0.01687  -2.54  0.016
Clay             0.03691    0.01978   1.87  0.072
CU              0.012294   0.003555   3.46  0.002
CC              -0.06164    0.01866  -3.30  0.002
SieveNo200     -0.001648   0.005170  -0.32  0.752
CompactionDUW   -0.00272    0.01147  -0.24  0.814

S = 0.173380   R-Sq = 51.7%   R-Sq(adj) = 42.0%
PRESS = 1.41542   R-Sq(pred) = 24.15%

Analysis of Variance

Source          DF        SS        MS     F      P
Regression       6   0.96433   0.16072  5.35  0.001
Residual Error  30   0.90182   0.03006
Total           36   1.86615

Source         DF   Seq SS
CompactionMC    1  0.46420
Clay            1  0.07493
CU              1  0.08087
CC              1  0.33976
SieveNo200      1  0.00287
CompactionDUW   1  0.00170

Unusual Observations

Obs  CompactionMC   ln(Mr)     Fit   SE Fit  Residual   St Resid
 27          12.0   9.0540  9.3941   0.0797   -0.3401     -2.21R
 86          10.8  10.1306  9.7403   0.0778    0.3903      2.52R
 89          11.7   9.3854  9.7028   0.0800   -0.3174     -2.06R

R denotes an observation with a large standardized residual.
```

Table E. 8 Stepwise Regression Analysis for A-3 and A-2-4 soils

Stepwise Regression: ln(Mr) versus Material Properties

(On 211 A-3 and A-2-4 Soils)

```
Backward elimination.  Alpha-to-Remove: 0.1
Response is ln(Mr) on 8 predictors, with N = 47
N(cases with missing observations) = 164 N(all cases) = 211
```

Step	1	2	3	4	5
Constant	10.007	9.820	9.817	9.881	9.865
SieveNo200	-0.0034	-0.0034	-0.0034	-0.0047	
T-Value	-0.78	-0.78	-0.79	-1.31	
P-Value	0.441	0.439	0.436	0.197	
CC	-0.051	-0.053	-0.055	-0.057	-0.055
T-Value	-1.71	-2.22	-3.66	-4.08	-3.93
P-Value	0.095	0.032	0.001	0.000	0.000
CU	0.0106	0.0108	0.0111	0.0117	0.0114
T-Value	2.08	2.53	3.84	4.25	4.12
P-Value	0.045	0.016	0.000	0.000	0.000
Clay	-0.013	-0.006			
T-Value	-0.14	-0.09			
P-Value	0.886	0.926			
6T180LBR	0.00239	0.00195	0.00168	0.00160	0.00118
T-Value	0.48	0.65	2.27	2.21	1.80
P-Value	0.634	0.523	0.029	0.033	0.079
Permeability	45	37	29		
T-Value	0.37	0.40	0.63		
P-Value	0.710	0.694	0.534		
CompactionMC	-0.0268	-0.0265	-0.0269	-0.0282	-0.0315
T-Value	-2.47	-2.57	-2.87	-3.12	-3.59
P-Value	0.018	0.014	0.006	0.003	0.001
CompactionDUW	-0.002				
T-Value	-0.11				
P-Value	0.912				
S	0.162	0.160	0.158	0.156	0.158
R-Sq	52.52	52.51	52.49	52.03	50.02
R-Sq(adj)	42.52	43.98	45.37	46.18	45.26
Mallows C-p	9.0	7.0	5.0	3.4	3.0
PRESS	1.56058	1.45737	1.42126	1.40726	1.41381
R-Sq(pred)	25.36	30.30	32.03	32.70	32.38

Table E. 9 Multiple Regression Analysis for A-3 and A-2-4 soils (1st trial)

Regression Analysis: ln(Mr) versus Material Properties

(On 211 A-3 and A-2-4 Soils)

```
The regression equation is
ln(Mr) = 9.81 - 0.0224 CompactionMC + 0.0120 CU - 0.0584 CC
         + 0.000747 6T180LBR

81 cases used, 130 cases contain missing values

Predictor           Coef     SE Coef       T      P
Constant         9.81332     0.09672  101.47  0.000
CompactionMC   -0.022400    0.007253   -3.09  0.003
CU              0.012029    0.002596    4.63  0.000
CC              -0.05841     0.01319   -4.43  0.000
6T180LBR       0.0007470   0.0005157    1.45  0.152

S = 0.155593   R-Sq = 36.0%   R-Sq(adj) = 32.6%

PRESS = 2.23137   R-Sq(pred) = 22.38%

Analysis of Variance

Source           DF        SS        MS      F      P
Regression        4   1.03486   0.25871  10.69  0.000
Residual Error   76   1.83989   0.02421
Total            80   2.87475

Source        DF   Seq SS
CompactionMC   1  0.44603
CU             1  0.10483
CC             1  0.43321
6T180LBR       1  0.05079

Unusual Observations

Obs  CompactionMC   ln(Mr)     Fit  SE Fit  Residual  St Resid
 49          12.0   9.0540  9.4778  0.0217   -0.4238    -2.75R
162          13.1   9.1964  9.5045  0.0221   -0.3081    -2.00R
164          12.4   9.1937  9.5202  0.0212   -0.3266    -2.12R
178           7.8   9.6877  9.8164  0.0719   -0.1287    -0.93 X
179          10.8  10.1306  9.7483  0.0696    0.3823     2.75RX
180          10.4   9.9770  9.7575  0.0695    0.2196     1.58 X
181          11.2   9.6114  9.7386  0.0699   -0.1273    -0.92 X
182          11.7   9.3854  9.7281  0.0703   -0.3427    -2.47RX
200          12.5   9.5558  9.2687  0.0637    0.2871     2.02R

R denotes an observation with a large standardized residual.
X denotes an observation whose X value gives it large influence.
```

Table E. 10 Multiple Regression Analysis for A-3 and A-2-4 soils (2nd trial)

Regression Analysis: ln(Mr) versus Material Properties

(On 211 A-3 and A-2-4 Soils)

The regression equation is

ln(Mr) = 9.76 - 0.0602 CC + 0.0121 CU - 0.0297 CompactionMC + 0.0303 Clay + 6.7 Permeability

47 cases used, 164 cases contain missing values

Predictor	Coef	SE Coef	T	P
Constant	9.7600	0.1359	71.79	0.000
CC	-0.06018	0.01607	-3.74	0.001
CU	0.012097	0.003074	3.94	0.000
CompactionMC	-0.029744	0.009230	-3.22	0.002
Clay	0.03035	0.01470	2.06	0.045
Permeability	6.75	36.92	0.18	0.856

S = 0.157438 R-Sq = 51.4% R-Sq(adj) = 45.5%

PRESS = 1.42330 R-Sq(pred) = 31.93%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	5	1.07469	0.21494	8.67	0.000
Residual Error	41	1.01625	0.02479		
Total	46	2.09094			

Source	DF	Seq SS
CC	1	0.11379
CU	1	0.54088
CompactionMC	1	0.31029
Clay	1	0.10891
Permeability	1	0.00083

Unusual Observations

Obs	CC	ln(Mr)	Fit	SE Fit	Residual	St Resid
49	5.1	9.0540	9.4290	0.0349	-0.3750	-2.44R
179	58.3	10.1306	9.7449	0.0705	0.3856	2.74R
182	58.3	9.3854	9.7182	0.0714	-0.3328	-2.37R

R denotes an observation with a large standardized residual.

Table E. 11 Multiple Regression Analysis for A-3 and A-2-4 soils (3rd trial)

Regression Analysis: ln(Mr) versus SieveNo200, CU, ...

```
The regression equation is
ln(Mr) = 10.0 - 0.00342 SieveNo200 + 0.0106 CU - 0.0016 CompactionDUW
         - 0.0132 Clay + 45 Permeability + 0.00239 6T180LBR
         - 0.0268 CompactionMC - 0.0509 CC
```

47 cases used, 164 cases contain missing values

Predictor	Coef	SE Coef	T	P
Constant	10.007	1.684	5.94	0.000
SieveNo200	-0.003418	0.004393	-0.78	0.441
CU	0.010552	0.005084	2.08	0.045
CompactionDUW	-0.00161	0.01441	-0.11	0.912
Clay	-0.01319	0.09131	-0.14	0.886
Permeability	45.2	120.9	0.37	0.710
6T180LBR	0.002391	0.004974	0.48	0.634
CompactionMC	-0.02681	0.01085	-2.47	0.018
CC	-0.05088	0.02972	-1.71	0.095

S = 0.161634 R-Sq = 52.5% R-Sq(adj) = 42.5%

PRESS = 1.56058 R-Sq(pred) = 25.36%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	8	1.09817	0.13727	5.25	0.000
Residual Error	38	0.99277	0.02613		
Total	46	2.09094			

Source	DF	Seq SS
SieveNo200	1	0.11361
CU	1	0.14358
CompactionDUW	1	0.10768
Clay	1	0.01515
Permeability	1	0.21072
6T180LBR	1	0.27515
CompactionMC	1	0.15575
CC	1	0.07653

Unusual Observations

Obs	SieveNo200	ln(Mr)	Fit	SE Fit	Residual	St Resid
49	24.0	9.0540	9.4156	0.0740	-0.3616	-2.52R
179	14.0	10.1306	9.7472	0.0724	0.3834	2.65R
182	14.0	9.3854	9.7237	0.0736	-0.3383	-2.35R

R denotes an observation with a large standardized residual.

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