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HARMONIZED TEST METHODS FOR LABORATORY DETERMINATION OF RESILIENT MODULUS FOR FLEXIBLE PAVEMENT DESIGN

FINAL REPORT

Volume I
Unbound Granular Material

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FOREWORD

This report deals with the test procedure for measuring the non- linear Resilient Modulus parameters for unbound base, subbase and subgrade soils for use in advanced pavement response models. This is the first volume (Volume I) of the NCHRP 1-28A project dealing with the development of harmonized test protocol approaches to measure the resilient response of both unbound (soil subgrades, granular subbases and bases) as well as asphalt mixtures.

All of the testing for the Volume I report was completed while the Principal Investigator was on the faculty at the University of Maryland. All of the data analysis and report preparation was accomplished under the auspices of the Principal Investigator while he was at the University of Maryland.

The comprehensive testing program, contained in this report, as well as the analysis of the data was conducted by Mr. Dragos Andrei, in his role of a Graduate Research Assistant at the University of Maryland. He performed his work under the direct overview of the Principal Investigator. His work was also heavily guided by Dr. Jacob Uzan of the Technion University, in Israel, and Dr. Charles Schwartz of the University of Maryland. The technical assistance from both of these individuals is gratefully acknowledged by the Principal Investigator.

Finally, special acknowledgement is given to the staff at Arizona State for preparation of the draft and final report of this study.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

NCHRP Note:

Report contains blank, numbered pages for tables & figures after Annex C-2

Introduction

Background

The determination of the elastic moduli of pavement materials is of vital importance for any mechanistically based design/analysis procedure for flexible pavements. The resilient modulus (M_R) of unbound materials has been extensively researched in the U.S. for well over 30 years and was universally introduced in the American Association of State Highway and Transportation Officials (AASHTO) Pavement Design Guide in the 1986 Edition. The selection of an appropriate design M_R value for base, subbase and/or subgrade materials has always been significantly complicated by many test and analysis problems. Because of numerous inherent problems in accurately measuring M_R, the National Cooperative Highway Research Program (NCHRP) initiated NCHRP Project 1-28, "Laboratory Determination of Resilient Modulus for Flexible Pavement Design". This NCHRP study produced an excellent set of findings regarding M_R characterization using triaxial testing for unbound base/subbase/subgrade soils. However, the NCHRP Project 1-28 recommendation for yet another set of test protocols for determining M_R for unbound materials complicates the standardization of a unified or harmonized test protocol that has universally accepted implementability in the pavement community. As a consequence of this limitation the NCHRP Project 1-28A "Harmonized Test Methods for Laboratory Determination of Resilient Modulus for Flexible Pavement Design" was initiated.

Objectives

The major objective of the NCHRP 1-28A Project (Task II – Unbound Materials) is to develop a single test method for measurement of the resilient modulus of unbound granular base/subbase materials and subgrade soils that harmonizes all existing testing protocols (i.e. AASHTO T 292-91, AASHTO T 294-92, AASHTO T P46-94 and NCHRP 1-28 Draft-96).

The specific objectives of the research are as follows:

- Review of the state-of-the-art procedures and equipment for laboratory resilient modulus testing;
- Preparation of the "Harmonized Method" from all existing methods;
- Conduct of necessary laboratory testing and analysis to verify that the harmonized method provides consistent, reliable results to the existing methods.
- Preparation of the verified method in AASHTO style format for submission to AASHTO.

Chapter 1. Basic Principles

Resilient Modulus and Its Application to Pavement Design

"It is well known that most pavement materials are not elastic but experience some permanent deformation after each load application. However, if the load is small compared to the strength of the material and is repeated for a large number of times, the deformation under each load repetition is nearly completely recoverable and proportional to the load and can be considered as elastic" (Huang 1993). The resilient behavior of unbound materials is illustrated in Figure 1-1. During loading – unloading cycles the material describes a closed loop in the σ-ε space, i.e. the elastic (tangent) modulus varies with time and state of stress. The resilient modulus is defined as a secant modulus and is also a function of the state of stress:

$$M_R = \frac{\sigma_{cyc}}{\varepsilon_r} \tag{1-1}$$

Where:

σ_{cyc} = Peak Axial Cyclic Stress

ε_r = Peak Axial Resilient Strain

After a sufficient number of repetitions, the material behaves elastically and the measured resilient modulus can be used to predict the stresses and strains within the pavement. Since the value of the modulus is not constant (as for linearly elastic materials) but depends on the state of stress, the resilient modulus test reproduces states of stress in the range of those actually occurring in the field. The resilient modulus is measured for all these stress combinations and then, using regression techniques, a predictive equation is calibrated and used to compute the value of the modulus for any state of stress.

Test Parameters

The parameters that describe the resilient modulus test vary from one protocol to another and are listed below:

- The load pulse: refers to the shape of the dynamic loading applied to the specimen when plotted versus time; it may be square, triangular, sinusoidal or haversine. It should simulate the dynamic load actually occurring in the pavement due to traffic loads (moving vehicles).
- The load/rest times: refers to the time between two cycles of load.
- The number of repetitions: "Nrep" represents the number of load-unload cycles to which the specimen is subjected for a given stress state. The number of repetitions should be large enough to assure the material has reached an equilibrium resilient state at which all resilient strains are relatively constant.
- Conditioning: precedes the actual testing of the material and has the following functions:
    - To reproduce the stress history (construction);
    - To minimize bedding effects (i.e. irregularities between the specimen and the top and bottom platens).

- The stress sequence: represents the set of stress combinations the specimen will be subjected to and the order they will be performed during the test. The stress sequences are usually expressed in terms of σ_1&σ_3 or τ_{oct}&θ, where:

σ_1 = Major Principal Stress

σ_2 = Intermidiate Principal Stress

σ_3 = Minor Principal Stress

θ = Bulk Stress:

$$\theta = \sigma_1 + \sigma_2 + \sigma_3 \tag{1-2}$$

τ_{oct} = Octahedral Shear Stress:

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

Predictive Equation

In order to evaluate the reliability of a pavement design, one needs to know the state of stress and deformation (strain) at any location within the pavement structure caused by the imposed traffic loads. The state of stress and deformation will be a function of the resilient moduli of the various pavement layers, and these moduli are in turn a function of the stress state. Resilient modulus predictive equations permit one to predict the modulus of the material as a function of the state of stress.

The resilient modulus predictive equation must satisfy two criteria:

1) Accuracy: i.e. the model should accurately predict measured lab data;

2) Numerical Use (Stability of Approach): the model should be implementable in a finite element code that will allow one to perform 2D or 3D stress/strain analyses.

Chapter 2. Review of Existing Methods

The review of the state-of-the-art procedures and equipment for laboratory resilient modulus testing focused on four existing protocols:

- AASHTO T 292-91;
- AASHTO T 294-92;
- AASHTO T P46-94 (predecessor of AASHTO T307);
- NCHRP 1-28 Draft-96 (Appendix E).

A summary of the specific recommendations of each of the four protocols is presented in Table 2-1.

AASHTO T 292-91

The first protocol reviewed (AASHTO T 292-91) was developed in 1991 and is in many respects outdated (e.g. the data acquisition process could be done using strip chart). In addition, the recommendations of the protocol are too general, forcing the lab technician to decide several important test details such as:

- proper loading shape (square, triangular, haversine);
- loading and rest times;
- sample size;
- compaction technique;
- stress ranges.

It is very likely that different lab technicians will run different tests for the same material, which may lead to significantly different resilient modulus results.

For testing purposes, materials are first identified using the AASHTO classification of soils and then divided in two groups: "granular" and "cohesive". While dividing materials into granular and cohesive is beneficial because it makes a distinction between materials with different mechanical behavior, using the AASHTO classification to identify the materials for testing purposes is not recommended since an eventual change of the classification would require a corresponding change of the resilient modulus protocol.

The axial strain is measured internally, on-sample, using clamps in the ¼ position. However, for very soft specimens, the LVDT's are mounted externally on the loading piston. External measurements of the load and/or axial displacement are not desired since friction between the piston and the cell and eventual deformations of the piston or triaxial cell may induce important errors in the measurements.

Three stress sequences are recommended: two for granular materials (base/subbase and subgrade) and one for cohesive materials (subgrades). This is rational, because it accounts for both the different mechanical behaviors of the materials and their functions within the flexible pavement structure (i.e. the stress range specific to a certain layer: base/subbase or subgrade). For granular materials, the stress sequence starts with stress combinations that induce the highest damage to the sample and ends with those causing little or no damage. This is not rational since we are interested in characterizing the material with the least amount of damage. For cohesive materials, there are only five stress combinations (i.e. only five data points), which may adversely affect the accuracy of the predictive models. The classical log-log k_1-k_2 equation is used for prediction:

For granular materials:

$$M_R = k_1 \cdot (\theta)^{k_2} \tag{2-1}$$

For cohesive materials:

$$M_R = k_1 \cdot \left(\sigma_d\right)^{k_2} \tag{2-2}$$

Where $\sigma_d = \sigma_1 - \sigma_3$ is the deviatoric stress and k_i are regression constants.

The model is limited, taking into account the effect of the deviatoric or bulk stress only, depending on the type of material: cohesive or granular. It is known that for most materials the resilient modulus is a function of both the deviatoric and the volumetric stress components. The improvement achieved by having both stress components in the equation is discussed in more detail in Chapter 6.

AASHTO T 294-92 (SHRP P46)

The AASHTO T 294-92 (SHRP P46) protocol is more specific in its recommendations. Materials are classified using both the AASHTO classification and their grain size distribution. The specimen size and the compaction technique are clearly stated for each type of material. Also, the loading shape and loading and rest times are fixed. The axial deformation is measured off-sample, which may induce errors. Only two stress sequences are recommended: one for base/subbase materials and one for all subgrades, regardless of the behavior of the material (i.e. coarse-grained or fine-grained). This is not rational, since the mechanical behavior of the material dictates the probability of failure of the sample (or amount of damage) specific to each stress sequence. This is discussed in more detail in Chapter 4. Some restrictions regarding the allowable plastic deformation allowed are introduced. The same log-log k_1-k_2 predictive equation is used.

AASHTO T P46-94 (Predecessor of AASHTO T307)

In the third protocol, AASHTO T P46-94, the materials are no longer identified using the AASHTO classification of soils. Instead, the grain size distribution and the plasticity index of the material are used. This makes the protocol independent of the AASHTO classification. All measurements (axial load and axial deformation) are done outside the triaxial cell, which is not desirable. Two stress sequences are provided, with the same disadvantages as discussed previously. No predictive equation is recommended. In order to reduce variability of test results a minimum ratio of the diameter of the sample to the maximum particle size of the material is to be maintained. This is done scalping off (removing) all material greater than a certain size. Also, an acceptable displacement ratio (i.e. ratio of measured displacements on opposite sides of the specimen) is defined in order to detect and eventually correct alignment problems.

NCHRP 1-28 (1996)

The fourth and the last of the reviewed protocols, NCHRP 1-28 Appendix E (1996), is a draft protocol that was not released for publication. The resilient modulus procedure proposed by NCHRP 1-28 also makes use of the grain size distribution and the plasticity index to classify the materials for test purposes. Axial deformation is measured on-sample and the load cell is located inside the triaxial cell. For very soft specimens that may be damaged by clamps, the measurements are made between the top and bottom platens. Besides clamp-mounted LVDT's, more accurate sensors such as optical extensometers and non-contact sensors may be used to measure the axial deformations. Three test procedures that take into account both the behavior of the material (granular or fine-grained) and its function within the flexible pavement structure are provided. However, an unconfined test consisting of only five stress combinations is recommended for fine-grained (cohesive) subgrade soils. The low number of data points may affect the accuracy of the predictive model and a zero confining pressure does not reflect real pavement condition. Scalping and replacing techniques are used to reduce variability in test results. The predictive equation takes into account the effects of both the deviatoric and the volumetric component of the loading in the form of a three-parameter, log-log model based on the cyclic stress (σ_{cyc}) and the confining pressure (σ_3):

$$M_R = \frac{\sigma_{cyc}}{\varepsilon_r}$$

$$\varepsilon_r = k_1 \cdot \sigma_{cyc}^{\ k_2} \cdot \sigma_3^{\ k_3} \qquad (2\text{-}3)$$

Conclusions

Some recommendations based on the critique of all four considered protocols are summarized here:

- The classification of the materials for test purposes should be independent of other classifications (e.g. AASHTO classification of soils).
- The load cell should be located inside the triaxial chamber to eliminate the effect of friction between the loading piston and the cell.
- A minimum ratio between the diameter of the sample and the maximum or nominal particle size of the material must be maintained in order to reduce the variability of results.
- Axial deformation measurements should be done on-sample, or between the top and bottom platens in order to reduce the amount of error introduced by deformations of the testing equipment. The height of the specimen should be at least two times its diameter and the axial measurements should be made over the middle half of the sample where the end-friction effects are negligible.
- Three stress sequences are needed in order to account for both the mechanical behavior of the material and its function within the pavement. The stress sequence should be designed to minimize the probability of failure of the sample in the early stages of the test. However, in all the reviewed protocols, the stress path followed by the specimen during the test is oscillating between states of stress that induce high damage and possible failure of the sample and states of stress of little or no damage. This aspect is discussed in more detail in Chapter 4.

- The larger the number of data points, the higher the accuracy of the predictive equation. The use of a three or four parameter predictive equation requires a larger number of data points to assure accurate predictions.
- The predictive equation should take into account both the deviatoric and the volumetric components of loading.

Chapter 3. Recommended Harmonized Protocol

The purpose of this chapter is to summarize the harmonized protocol developed in this work. The complete harmonized protocol is presented in AASHTO format in Appendix A. The protocol closely follows the recommendations of the NCHRP 1-28 Draft Final Report - Appendix E, with some exceptions that are detailed in Chapter 4.

The same testing system is recommended, i.e. closed loop electro-hydraulic testing machine with a function generator capable of applying repeated cycles of a haversine shaped load-pulse having a 0.1 sec. loading time / 0.9 sec rest time for base/subbase materials and a 0.2 sec. loading time / 0.8 sec rest time for subgrade soils. Pertinent details of the testing machine include:

- A triaxial chamber made of a transparent material and using air as the confining fluid is recommended.
- Confinement is used for all tests.
- The axial load is measured with a load cell located inside the chamber.
- The axial deformation is measured on-sample, using clamps in the ¼ position. For very soft specimens, the displacement is measured between the top and bottom platens.

An analog to digital data acquisition system is required. The system should meet or exceed the following requirements:

- Automatic data reduction;
- 25 msec. A/D conversion time;
- 12 bit resolution;
- Single or multiple channel throughput (gain = 1), 30 kHz;

- Software selectable gains;
- Measurement accuracy of full scale (gain = 1) of +/- 0.02%;
- Nonlinearity (LSBS) OF +/- 0.5;
- A minimum of 200 data points from each LVDT shall be recorded.

For testing purposes, four types of materials are defined. The grain size distribution of the material is used as the selection criteria:

- Material Type 1 - Includes all unbound granular base and subbase materials and all untreated subgrade soils with maximum particle sizes greater than 9.5 mm (0.375 in).
- Material Type 2 - Includes all unbound granular base and subbase materials and all untreated subgrade soils which have a maximum particle size less than 9.5 mm (0.375 in) and which have less than 10% passing the 75μm (No. 200) sieve.
- Material Type 3 - Includes all untreated subgrade soils, which have a maximum particle size less than 9.5 mm (0.375 in) and which have more than 10% passing the 75μm (No. 200) sieve.
- Material Type 4 - Includes thin-walled tube samples of untreated subgrade soils. Material Type 4 is intended for undisturbed samples of fine-grained subgrade soils, tested as 71 mm (2.8 in) diameter specimens.

The specimen size is selected according to the maximum particle size of the material:

- A 152 mm (6.0 in) diameter by 305 mm (12 in) high specimen is used for all materials having maximum particle sizes greater than 19 mm (0.75 in). For these specimens, all material greater than 25.4 mm (1.0 in) shall be scalped off prior to testing.

- For all materials having maximum particle sizes less than 19 mm (0.75 in), a 102 mm (4.0 in) diameter by 204 mm (8.0 in) high specimens is used.

The load pulse has a haversine shape. A loading time of 0.2 seconds followed by a 0.8 seconds rest time is recommended for subgrade soils while a load time of 0.1 seconds and a rest period of 0.9 seconds is recommended for the base/subbase materials. Three test sequences are recommended:

- Granular base/subbase materials (Procedure Ia)
- Coarse-grained subgrades (Procedure Ib)
- Fine-grained subgrades (Procedure II)

The three procedures consider the state of stress specific to a certain layer in the pavement structure (i.e. base/subbase and subgrade) and the mechanical behavior of the material (i.e. coarse-grained and fine-grained). Different from all previous protocols, the three procedures are designed to assure the lowest probability of failure of the sample early in the test. They also provide the largest possible number of data points, regardless of the values of the strength parameters (c, ϕ) of the material (explained in Chapter 4).

A five-parameter log-log model is used for prediction:

$$\begin{cases} M_R = k_1 \cdot p_a \cdot \left(\dfrac{\theta - 3k_6}{p_a} \right)^{k_2} \cdot \left(\dfrac{\tau_{oct}}{p_a} + k_7 \right)^{k_3} \\ k_1, k_2 \geq 0 \\ k_3, k_6 \leq 0 \\ k_7 \geq 1 \end{cases} \qquad (3\text{-}1)$$

In which p_a is the atmospheric pressure and k_i are regression constants.

In Table 3-1, the protocol is compared to NCHRP 1-28 Appendix E. At the beginning of Chapter 4, the flowcharts of the two protocols are presented in Figures 4-1 and 4-2.

Chapter 4. Detailed Explanation and Presentation of the Changes

As previously mentioned, the harmonized protocol in this research closely follows the recommendations of the NCHRP 1-28 Draft Final Report - Appendix E, with some exceptions. In this chapter all the alterations and/or modifications are discussed and explained. In order to illustrate the differences between two protocols, a flowchart has been drawn for each (Figures 4-1, 4-2). Also, Table 3-1 from the previous chapter can be used for comparison.

Types of Materials, Specimen Size and Compaction Method

The definition of a certain type of material is related to both the process of preparing the material for compaction and the method of compaction. The NCHRP protocol uses sieve analysis and Atterberg limits to classify materials as Type1 or Type 2. The intention is to make a distinction between granular, low plasticity materials (Type 1), and cohesive, plastic materials (PI>10) having a large percent of fines (Type 2). These two types of materials require different compaction techniques in order to simulate the structure of the material as compacted on site.

Once the material is identified, the next question to be addressed in the protocol is the size of the sample. The NCHRP protocol recommends the use of 71mm (2.8in), 102mm (4in) and 152mm (6in) diameter samples, depending on the maximum particle size (d_{max}) of the material. Also, for both types of materials (Type 1 and Type 2), the method of scalping and replacing the coarser fractions is used, in certain conditions, as illustrated in the flow chart (Figure 4-1). The method of scalping and replacing coarser fractions of material is directly related to the dimensions of the specimen and has the

purpose of maintaining an acceptable ratio d_{max}/D, where D is the diameter of the sample (mold). In the case of a Type 2 material, it is used in order to make possible the use of the 71mm (2.8in) mold for materials with less than 10% retained on the 12.5mm (0.5in) sieve.

In the proposed harmonized protocol (Figure 4-2), the use of the 71mm (2.8in) diameter mold (specimen) is not recommended for laboratory prepared specimens as the use of 71mm (2.8in) compaction equipment is not standardized and will generally not be available. Instead, the use of the 102mm (4in) mold is recommended for all materials having a maximum particle size (d_{max}) less than 19mm (¾ in). The 102mm (4in) diameter sample can be prepared and handled as easily as the 71mm (2.8in) diameter sample, but retaining the original gradation of the material (i.e. no scalping) and a larger sample size leads to more accurate results. No scalping and replacing is to be done on the 102mm (4in) samples. Materials with maximum particle sizes greater than 19mm (¾in) should be compacted in a 152mm (6in) diameter mold. All material greater than 25.4mm (1.0in) should be scalped off prior to testing. While the 71mm (2.8in) diameter specimen is not recommended for laboratory prepared specimens, undisturbed field samples (i.e. from standard thin-wall Shelby tubes) with this small diameter can be evaluated for M_R testing.

The methods of compaction in the NCHRP protocol are a function of the type, mechanical behavior of the material, and field conditions. In the harmonized protocol, the methods of compaction depend on the maximum particle size of the material and on its mechanical properties. For laboratory compacted specimens, three types of materials corresponding to the three methods of compaction are defined:

- Type 1 (Impact or vibratory compaction) – includes materials with coarse particles, having a maximum particle size greater than 9.5mm (3/8in); these may be base/subbase materials or fine-grained materials containing coarser particles.
- Type 2 (Vibratory compaction) – includes granular sandy type materials, with a d_{max} < 9.5mm (3/8in) and less than 10% passing the 75μm (No.200) sieve.
- Type 3 (Impact or kneading compaction) – includes fine-grained cohesive materials with a d_{max} < 9.5mm (3/8in) and more than 10% passing the 75μm (No.200) sieve. While kneading compaction in general better reproduces the in situ structure of the compacted material for most cohesive fine-grained soils, there is not a significant difference in soil structure for fine-grained materials compacted by either impact (dynamic) or kneading compaction. However, in the case of fat clays, kneading compaction is considered more appropriate.
- While materials Type 1, 2 and 3 refer to laboratory prepared specimens, undisturbed samples of fine-grained subgrade soils are identified as Type 4.

The provisions of the harmonized protocol are stricter with respect to the minimum ratio D/d_{max}, requiring a ratio of 6 for the 152mm (6in) diameter mold ($D/d_{max} = 6/1$) and 5.33 for the 102mm (4in) diameter mold ($D/d_{max} = 4/0.75$). This compares to the ratio of 4 required by the NCHRP procedure. The use of the 71mm (2.8in) mold is not required and the method of kneading compaction is recommended instead of static compaction. The material types, specimen size and compaction method recommendations are clearly defined and easier to follow.

Increased Loading Time for Subgrade Soils

As one goes deeper into a pavement structure, the stresses caused by a wheel load are distributed over a larger area. For a moving wheel load, the loading time at the top of the base layer will be shorter than the loading time at the top of the subgrade. Therefore, due to the distribution of the stresses caused by wheel loads, the loading time will increase with depth. As a consequence, the harmonized protocol recommends increasing the loading time to 0.2 sec. for all subgrade materials and decreasing the rest time to 0.8 sec. since this more realistically simulates field conditions.

Revised Stress Sequences

Theoretical Approach

It has been common practice in the resilient modulus test to maintain a constant confining pressure (σ_3) while increasing the deviatoric stress (σ_d). As a result, the state of stress increments applied to the sample will follow a stress path towards a failure state of stress, as illustrated in Figure 4-3. In order to avoid failure, a maximum value of the ratio of the principal stresses (σ_1/σ_3) considered low enough for the group of materials being tested is specified in the protocol as a limiting value. Once this value is reached, the deviatoric stress is decreased and a similar sequence is performed at a higher confining pressure (i.e. the stress path proceeds from 1 to 2 to 3 etc.).

Following this stress procedure, the material is constantly oscillating throughout the test between states of stress that are close to failure and states of stress of minimum damage. A weak material might fail early in the test, even at the first confining stress, when it first approaches failure. In this case, the test must be repeated at lower levels of

stresses. On the other hand, there will be no information about the behavior of a very strong material at stress ratios higher than the safe limit.

A more logical approach to minimize the probability of test failure is to apply first the stress combinations with the lowest probability of failing the sample. This probability can be estimated for any (σ_1, σ_3) combination of stresses and depends on the mechanical behavior of the material.

Granular Base/Subbase Materials

For pure granular materials (c=0), there is indeed a direct relationship between the friction angle of the material (ϕ) and the ratio of the principal stresses (σ_1/σ_3) for which the sample will fail:

$$\left(\frac{\sigma_1}{\sigma_3}\right)_f = N_\phi = \frac{1+\sin\phi}{1-\sin\phi} \tag{4-1}$$

The higher the friction angle of the material, the higher the stress ratio needed to fail the sample. Hence, for a lower stress ratio, the probability of failure is lower.

The recommended new stress sequence for base/subbase materials is a more rational approach that maintains a constant stress ratio by increasing both principal stresses simultaneously. Since the sequence starts with the minimum stress ratio, the probability of failing the sample is minimized. Then, a similar sequence is performed at a higher stress ratio, i.e. a higher probability of failure. The method is illustrated in Figure 4-4, in comparison to the classical method adopted by all previous protocols. The actual stress combinations for both the NCHRP and the proposed harmonized procedures are plotted for comparison in σ-τ space in Figure 4-5. The points are connected with lines in the order that they are applied in the test.

Two failure lines corresponding to a weak and a strong material are also illustrated. Following the NCHRP procedure, the weak material would fail at the third stress combination of the sequence. This would require the test to be repeated at lower stress levels. In the case of a very strong material, the NCHRP procedure does not cover stress ratios higher than the safe limit (stress combinations that still plot below the failure line of the material). The predictions of the model developed over the limited domain will therefore be less accurate for higher stress ratios.

Following the harmonized procedure, the material fails only after it passes through all the stress combinations that plot below its failure line. Premature failure of the sample is avoided and a maximum number of data points is obtained over the domain in which the model will be used to predict. Note that this procedure is also valid for a granular material with some cohesion.

A complete description of the two stress sequences is given for comparison in Table 4-1. Note the larger number of data points specific to the harmonized procedure.

Coarse Grained Subgrades

For coarse-grained subgrades, the same approach is adopted and a more rational stress sequence is designed. The difference between the sequences for base/subbase materials and coarse-grained subgrades is only in the magnitude of the stresses. For subgrade materials, these stress levels are lower and reflect the probable lower quality of this material group and the lower induced stresses from traffic. The NCHRP and harmonized procedures are presented in Figure 4-6, for comparison. A complete description of the two stress sequences is given in Table 4-2.

Fine Grained Subgrades

For pure cohesive materials (ϕ=0), the strength of the material is controlled by cohesion, which is related to the deviatoric stress as:

$$c = \frac{\sigma_d}{2} \tag{4-2}$$

The higher the cohesion (strength) of the material the higher the deviatoric stress needed to fail the sample. Thus, for this category of materials, the stress sequence starts with a minimum deviatoric stress. This will lead to a low probability of sample failure. Decreasing both principal stresses at a constant deviatoric stress causes the stress ratio to increase. For a pure cohesive material the stress ratio is not important. However, for a cohesive material with some friction, the probability of failure increases with both deviatoric stress and stress ratio. It is therefore more rational to decrease both principal stresses while maintaining a constant deviatoric stress. The method is illustrated in Figure 4-7, in comparison with existing stress sequence protocols.

The actual stress combinations for both NCHRP and "harmonized" procedures are plotted for comparison in σ-τ space in Figure 4-8. The points are connected with lines in the order they occur in the test.

Again, the failure lines of a weak and a strong material are plotted. In both cases, the harmonized procedure avoids premature failure and assures a maximum number of data points. Note that the procedure is valid also for a cohesive material with some friction. The two stress sequences are presented for comparison in Table 4-3.

In Appendix B, Table B-3, the complete description of the harmonized and NCHRP stress sequences is given, for base/subbase materials, coarse-grained subgrades and fine-grained subgrades. An experimental resilient modulus study was done to

investigate the effect of using the harmonized test sequences upon test results and is presented Chapter 5.

Selected Model

A five-parameter log-log model is selected from 14 candidate models that were used to predict resilient modulus lab data from 35 tests on 6 different materials (including fine-grained subgrade, coarse-grained subgrade and base/subbase materials) compacted to near optimum dry density and moisture content:

$$\begin{cases} M_R = k_1 \cdot p_a \cdot \left(\dfrac{\theta - 3k_6}{p_a} \right)^{k_2} \cdot \left(\dfrac{\tau_{oct}}{p_a} + k_7 \right)^{k_3} \\ k_1, k_2 \geq 0 \\ k_3, k_6 \leq 0 \\ k_7 \geq 1 \end{cases} \tag{4-3}$$

All model forms, goodness of fit statistics, and measured versus predicted Mr plots are presented in Chapter 6 and Appendix C. Different from the model recommended by NCHRP 1-28 Appendix E, the selected model uses θ and τ_{oct} as predictor variables in order to facilitate implementation in a finite element program. Due to normalization by atmospheric pressure (p_a), the regression constants are dimensionless and therefore independent of the system of units used. The model exhibits the best goodness of fit statistics by introduction of the terms k_6 and k_7. The selection of the model is described in Chapter 6.

Chapter 5. Experimental Study

Introduction

The objective of the study was to investigate the influence of changing the stress sequence on resilient modulus test results. Three materials representative of base/subbase, coarse-grained subgrade and fine-grained subgrade were tested with both the NCHRP Appendix E and the harmonized procedures. As a minimum, three complete replicates (soil specimens) were used for each of the six tests. The target dry densities and moisture contents as well as the actual values achieved for each replicate are shown in Appendix B, Table B-1.The complete stress sequences are given in Table B-3. Also, a description of the materials is given in Table B-4 and the grain size distribution in Table B-5. Actual test data is presented in Table B-6.

Testing Equipment and Set Up

An MTS closed loop, top-loading, electro-hydraulic system was used in this study. The triaxial cell uses air as the confining fluid and the measurements were done on the sample, with two vertical and four radial LVDT's. The set-up of the test is shown in Figure 5-1. The software used for control and data acquisition is MTS TestStar V4.0.

Findings

Base/Subbase Materials

The material used in the test was a class 6 base from the MnRoad project (S12, see Table B-4). The material is classified as A-1-a according to the AASHTO classification (SW-SM in the Unified Soil Classification System) and was compacted by dynamic (impact) compaction with a Modified Proctor compactive effort in a 152mm (6in) diameter by 305mm (12in) height mold.

Test results for all replicates are plotted in a 3D chart in θ, τ_{oct} and M_R coordinates. Projections of the points on the three orthogonal planes are also provided. Results are presented separately for each procedure in Figures 5-2 and 5-3 and then overlapped for comparison in Figure 5-4.

In the same range of stress combinations, the harmonized procedure tends to give lower results. This may be due to the increased number of repetitions characteristic to the harmonized procedure. It should be observed that the smaller stress range in the NCHRP procedure is contained within the broader range of the harmonized procedure. The dependency of M_R on both θ and τ_{oct} is evident in the projection planes.

Coarse Grained Subgrades

The material used in this part of the study was a silty sand from the Moulton Pit (S1, see Table B-4). This soil is classified as an A-4(1) according to the AASHTO classification (SM in the Unified Soil Classification System) and was compacted by dynamic (impact) compaction with a Modified Proctor compactive effort in a 102mm (4in) diameter by 204mm (8in) height mold.

The results for all replicates are plotted in a 3D chart in θ, τ_{oct} and M_R coordinates. The projections of the points on the three orthogonal planes are also provided. The results are presented separately for each procedure in Figures 5-5 and 5-6 and then overlapped for comparison in Figure 5-7.

In the same range of stress combinations, the two procedures give similar results. The smaller stress range of the NCHRP 1-28 Appendix E procedure is included in the broader range of the harmonized procedure.

Fine Grained Subgrades

The material used in the test was a clay from St. Albans (S3, see Table B-4). It is classified according to the AASHTO classification as an A-6 (CL in the Unified Soil Classification System). The material was compacted by dynamic (impact) compaction with a Standard Proctor compactive effort in a 102mm (4in) diameter by 204mm (8in) height mold.

The resilient modulus results for all replicates are plotted in a 3D chart in θ, τ_{oct} and M_R coordinates. The projections of the points on the three orthogonal planes are also provided. The results are presented separately for each procedure in Figures 5-8 and 5-9 and then overlapped for comparison in Figure 5-10.

The range of stress combinations is different from one procedure to the other. However the measured values of the resilient modulus are of the same order of magnitude.

Conclusions

The resilient modulus values measured with the two procedures are similar for the similar ranges of stress combinations. However, the harmonized protocol includes stress combinations beyond the range of the NCHRP 1-28 Appendix E protocols and therefore can be expected to produce more robust predictive equations for M_R.

Chapter 6. Model Selection

Introduction

Fourteen resilient modulus predictive equations were considered for selection. Each of the models was used to predict measured resilient modulus values from 35 tests. The first 20 tests were performed on the three materials described in Chapter 5: a base material from MnRoad, a silty sand from Moulton Pit and a clay from St. Albans. Each material was tested using two different procedures (NCHRP 1-28 Appendix E and harmonized) and a minimum of 3 replicates per test. In all of these tests, the materials were compacted to moisture and density conditions near the Modified Proctor optimum value. The remaining 15 tests were performed on three additional materials: a subbase and a subgrade from MnRoad and a subgrade from the FHWA-ALF (Accelerated Load Facility). Each of these materials were tested at five moisture/density combinations. All materials are described in Appendix B, Tables B-4 and B-5. The specimen size, method of compaction and moisture/density values for each test are given in Tables B-1 and B-2. The actual test data is given in Table B-6 for the first 20 tests and in Table B-7 for the other 15. In this chapter, the model forms are presented, the advantages and disadvantages of each are addressed, and the model with the best overall performance is selected. Regression constants, Se/Sy ratios and R^2 values are compiled in Appendix C, Table C-1. In Annex C-2, graphs of the predicted vs. measured M_R are drawn for all models and all tests (14x35).

The Models

Models with different mathematical structures (log-log, semi-log and more complicated), different number of parameters (regression constants) and different predictor variables were investigated. The range of options considered were:

- General model form:
    - Power law (log-log transformation)
    - Semi-logarithmic
- Number of regression parameters: from 2 to 6
- Predictor variables:
    - σ_3 and σ_{cyc} (physically and statistically independent variables)
    - θ and τ_{oct} (stress invariants, see Equations 1-2, 1-3)

All models are similar to, or extensions of, models that have been proposed in past literature.

The rationality of each model can be evaluated in terms of the following expected physical trends in M_R:

- M_R can never be negative
- Increasing volumetric stress terms (σ_3 or θ) should produce a stiffening of the material, i.e. a higher M_R. The only exception to this might be fine-grained subgrade soils, particularly at high saturation levels, where excess pore water pressure generated during the test may negate, or even reverse, the expected trend.
- Increasing deviatoric stress terms (σ_{cyc} or τ_{oct}) should produce a softening of the material, i.e. a lower M_R, in all cases.

With these physical considerations in mind, the various model forms studied in this research can be presented and discussed. All of the models share the following notations:

- M_R = Resilient Modulus
- σ_3 = Minor Principal Stress (Confining Pressure)
- σ_{cyc} = Cyclic Stress (See Figure 1-1)
- θ = Bulk Stress:

$$\theta = \sigma_1 + \sigma_2 + \sigma_3 \tag{1-2}$$

- τ_{oct} = Octahedral Shear Stress:

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

- k_i = regression constants
- p_a = atmospheric pressure (14.7 psi)

In all models, the stress terms (σ_3, σ_{cyc}, θ, τ_{oct}) are normalized with respect to atmospheric pressure (p_a). Consequently, all of the regression constants are dimensionless (except k_6) and may be used with any system of units. Below each model, the physical limits for the regression constants are specified. However, when performing the analysis, no restraints were imposed on the constants.

1) Log-log k_1, k_2 (□ or □$_{oct}$)

Granular materials:

$$M_R = k_1 \cdot p_a \cdot \left(\frac{\theta}{p_a}\right)^{k_2}$$
$$k_1, k_2 \geq 0 \qquad (6\text{-}1\text{-}a)$$

Cohesive materials:

$$M_R = k_1 \cdot p_a \cdot \left(\frac{\tau_{oct}}{p_a}\right)^{k_2}$$
$$k_1 \geq 0$$
$$k_2 \leq 0 \qquad (6\text{-}1\text{-}b)$$

The classical log-log k_1-k_2 (θ or τ_{oct}) model has long been and still is used in the pavement community. However, as shown in the test results, M_R is correlated with both θ and τ_{oct}, for most materials (whether coarse-grained or fine-grained). The model is therefore limited because it uses only one of these variables. In the form in which the model is generally used, the stress terms are not normalized by p_a. In this analysis, for purpose of comparison, normalization is applied to all models.

2) Log-log k_1, k_2, k_3 (□, □$_{oct}$)

$$M_R = k_1 \cdot p_a \cdot \left(\frac{\theta}{p_a}\right)^{k_2} \cdot \left(\frac{\tau_{oct}}{p_a}\right)^{k_3}$$
$$k_1, k_2 \geq 0$$
$$k_3 \leq 0 \qquad (6\text{-}2)$$

A generalization of the log-log k_1-k_2 model, this model takes into account the influence of both θ and τ_{oct}. The use of the stress invariants θ and τ_{oct} as predictor variables facilitates for the implementation of the model into a finite element code. The model is physically irrational for values of $\theta < 0$ (M_R becomes negative) and $\tau_{oct} = 0$ (M_R becomes very large/infinite).

3) Log-log k_1, k_2, k_3 (□$_3$, □$_{cyc}$)

$$M_R = k_1 \cdot p_a \cdot \left(\frac{\sigma_3}{p_a}\right)^{k_2} \cdot \left(\frac{\sigma_{cyc}}{p_a}\right)^{k_3}$$
$$k_1, k_2 \geq 0$$
$$k_3 \leq 0 \tag{6-3}$$

The model is similar to Equation 6-2. In Equation 6-2, σ_3 is present in both predictor variables (θ and τ_{oct}), unlike in Equation 6-3, where the predictor variables (σ_{cyc} and σ_3) are independent. Theoretically, independent predictor variables should increase the accuracy of the model. However, the variables are not suited for implementation into a finite element code, particularly for 3D analyses, where σ_2 may play a significant role. The model is physically irrational for $\sigma_3 < 0$ (M_R negative) or $\sigma_{cyc} = 0$ (M_R infinite).

4) Log-log k_1, k_2, k_3, k_6 (□, □$_{oct}$)

$$M_R = k_1 \cdot p_a \cdot \left(\frac{\theta - 3k_6}{p_a}\right)^{k_2} \cdot \left(\frac{\tau_{oct}}{p_a}\right)^{k_3}$$
$$k_1, k_2 \geq 0$$
$$k_3, k_6 \leq 0 \tag{6-4}$$

The k_6 regression constant is intended to account for pore water pressure or cohesion. This is in fact the formulation of the resilient modulus model from the SHRP-Superpave model for M_R and ν_r (resilient Poisson's Ratio). This model form allows the modulus to be predicted in terms of effective stresses. Also, k_6 is a measure of the ability of the material to resist tension. The model is no longer irrational for values of $\theta < 0$, as long as $\theta > 3k_6$ (M_R is positive). When $\theta = 3k_6$ the material is failed in tension. However, for $\tau_{oct} = 0$ the model is still irrational (M_R infinite).

5) Log-log k_1, k_2, k_3, k_6 (□$_3$, □$_{cyc}$)

$$
\begin{aligned}
&M_R = k_1 \cdot p_a \cdot \left(\frac{\sigma_3 - k_6}{p_a}\right)^{k_2} \cdot \left(\frac{\sigma_{cyc}}{p_a}\right)^{k_3} \\
&k_1, k_2 \geq 0 \\
&k_3, k_6 \leq 0
\end{aligned}
\qquad (6\text{-}5)
$$

This model is similar to the previous one, but uses σ_{cyc} and σ_3 as predictor variables.

6) Semi-log k_1, k_2 (□ or □$_{oct}$)

Granular materials:

$$
\begin{aligned}
&\log\left(\frac{M_R}{p_a}\right) = k_1 + k_2 \cdot \left(\frac{\theta}{p_a}\right) \\
&k_1, k_2 \geq 0
\end{aligned}
\qquad (6\text{-}6\text{-}a)
$$

Cohesive materials:

$$
\begin{aligned}
&\log\left(\frac{M_R}{p_a}\right) = k_1 + k_2 \cdot \left(\frac{\tau_{oct}}{p_a}\right) \\
&k_1 \geq 0 \\
&k_2 \leq 0
\end{aligned}
\qquad (6\text{-}6\text{-}b)
$$

This model is the equivalent of the log-log k_1-k_2 model in the semi-log form. It has the same limitations related to the use of only one component of loading for prediction. A great advantage of all semi-log models is that they are still rational for values of $\theta < 0$ and $\tau_{oct} - 0$.

7) Semi-log k_1, k_2, k_3 ($\square$, $\square_{oct}$)

$$\log\left(\frac{M_R}{p_a}\right) = k_1 + k_2 \cdot \left(\frac{\theta}{p_a}\right) + k_3 \cdot \left(\frac{\tau_{oct}}{p_a}\right)$$
$$k_1, k_2 \geq 0$$
$$k_3 \leq 0 \qquad (6\text{-}7)$$

The model is similar to the log-log k_1-k_2-k_3 and takes into account both components of loading.

8) Semi-log k_1, k_2, k_3 ($\square_3$, $\square_{cyc}$)

$$\log\left(\frac{M_R}{p_a}\right) = k_1 + k_2 \cdot \left(\frac{\sigma_3}{p_a}\right) + k_3 \cdot \left(\frac{\sigma_{cyc}}{p_a}\right)$$
$$k_1, k_2 \geq 0$$
$$k_3 \leq 0 \qquad (6\text{-}8)$$

This model is similar in form to the previous one but uses σ_3 and σ_{cyc} instead of τ_{oct} and θ.

9) Semi-log k_1, k_2, k_3, k_6 ($\square$, $\square_{oct}$)

$$\log\left(\frac{M_R}{p_a}\right) = k_1 + k_2 \cdot \left(\frac{\theta - 3k_6}{p_a}\right) + k_3 \cdot \left(\frac{\tau_{oct}}{p_a}\right)$$
$$k_1, k_2 \geq 0$$
$$k_3, k_6 \leq 0 \qquad (6\text{-}9)$$

The semi-log form of the log-log k_1, k_2, k_3, k_6 also takes into account the pore water pressure or cohesion and predicts in terms of effective stresses.

10) Semi-log k_1, k_2, k_3, k_6 ($\square_3$, $\square_{cyc}$)

$$\log\left(\frac{M_R}{p_a}\right) = k_1 + k_2 \cdot \left(\frac{\sigma_3 - k_6}{p_a}\right) + k_3 \cdot \left(\frac{\sigma_{cyc}}{p_a}\right)$$
$$k_1, k_2 \geq 0$$
$$k_3, k_6 \leq 0 \qquad (6\text{-}10)$$

Using σ_3 and σ_{cyc} instead of τ_{oct} and θ as predictor variables, the accuracy of the model should increase.

11) SHRP-SUPERPAVE k_1, k_2, k_3, k_4, k_5, k_6 ($\square$, $\square_{oct}$)

The SHRP-Superpave model consists in fact of two models: one for resilient modulus and one for resilient Poisson's ratio, as illustrated in Figure 6-1. The two models are not independent, they have common regression constants: k_2, k_3 and k_6. In order to achieve similar accuracy on both models (i.e. to optimize the model as a whole), the values of k_2, k_3 and k_6 are chosen such that the Se/Sy ratios of the two component models are maximum. The more complicated process of optimization of the SHRP-Superpave model is described for all tests in Appendix C, Table C-2.

12) Modified Log-log k_1, k_2, k_3 (□, □$_{oct}$)

$$M_R = k_1 \cdot p_a \cdot \left(\frac{\theta}{p_a}\right)^{k_2} \cdot \left(\frac{\tau_{oct}}{p_a}+1\right)^{k_3}$$
$$k_1, k_2 \geq 0$$
$$k_3 \leq 0 \tag{6-12}$$

In an attempt to eliminate the irrationality of the log-log models at $\tau_{oct} = 0$, this alternative model is considered. By adding +1 to the τ_{oct} term, for $\tau_{oct} = 0$ the term in the parentheses = 1. Also, this modification assures a negative value for k_3 (the log of the parenthesis will always be positive). The model is still irrational for values of $\theta < 0$ (M_R negative).

13) Modified Log-log k_1, k_2, k_3, k_6 (□, □$_{oct}$)

$$M_R = k_1 \cdot p_a \cdot \left(\frac{\theta - 3k_6}{p_a}\right)^{k_2} \cdot \left(\frac{\tau_{oct}}{p_a}+1\right)^{k_3}$$
$$k_1, k_2 \geq 0$$
$$k_3, k_6 \leq 0 \tag{6-13}$$

Using k_6 in the θ term and +1 in the τ_{oct} term, the model is no longer irrational for $\theta < 0$ (as long as $\theta < 3k_6$) or $\tau_{oct} = 0$.

14) Log-log k_1, k_2, k_3, k_6, k_7 (□, □$_{oct}$)

$$M_R = k_1 \cdot p_a \cdot \left(\frac{\theta - 3k_6}{p_a}\right)^{k_2} \cdot \left(\frac{\tau_{oct}}{p_a}+k_7\right)^{k_3}$$
$$k_1, k_2 \geq 0$$
$$k_3, k_6 \leq 0$$
$$k_7 \geq 1 \tag{6-14}$$

The last model considered for selection uses k_6 and k_7 as additional constants. For $k_7 = 0$ the model takes the form of the model discussed at point (4). For $k_7 = 1$, it takes the form discussed at point (13). Theoretically, due to its flexibility, the model will always be at least as good as the models: (2), (4), (11), (12) and (13) which are only particular cases of model (14).

Method of Analysis

With the exception of the SHRP-Superpave model, all other models were analyzed following similar steps. First, a linear regression in the log-log or semi-log space was performed, for all two and three-parameter models. The k_i values obtained by linear regression are then used as start or guess values for a nonlinear optimization (Solver, MS Excel). While the linear regression is performed in the log-log or semi-log space, the nonlinear optimization is performed in the arithmetic space. As expected, goodness of fit statistics in the arithmetic space are always better when using the constants obtained through nonlinear optimization. For the four and five-parameter models, linear regression cannot be used. However, setting $k_6 = 0$ and $k_7 = 0$, the models take the form of the three-parameter models already analyzed. Given that, a nonlinear optimization is performed on all four and five-parameter models using as guess values the regression constants obtained for the three-parameter models and setting the start values for the additional constants (k_6 and k_7) equal to 0. For the SHRP-Superpave model, the two predictive models are optimized first independently and then values for the common regression constants (k_2, k_3 and k_6) are chosen subjectively until the Se/Sy ratios of the two models are maximum. However, when it was impossible to find a solution (to keep both Se/Sy ratios less than 1), no data was included in the table (see Table 6-1). The process is illustrated in Table C-2.

All regression coefficients presented in Table C-1 are obtained by nonlinear optimization in the arithmetic space, as described above. Se/Sy and R^2 values are also computed in the arithmetic space and take into account the degrees of freedom for all models. Although the physical limits of the regression constants are presented with each model, no constraints were imposed in this analysis. A series of charts showing the performance of the models on all tests done on one specific material is presented in Annex B-1. The charts show Se/Sy values and R^2 values for all models.

Interpretation of results

Decision Criteria

The models were evaluated using these criteria:

- Se/Sy ratio: represents the ratio of the standard deviation of the errors to the standard deviation of the sample; this ratio is a measure of the improvement in prediction achieved by using the model instead of the mean.
- R^2: the square of the correlation coefficient is probably the most used indicator of the accuracy of prediction. However, according to its statistical definition, the correlation coefficient applies only to linear, unbiased models. Since all M_R models considered in the analysis are non-linear, the ratio Se/Sy is given more weight.
- Visual examination of the predicted vs. measured M_R: in order to identify local bias (i.e. incorrect model form).

Effect of Stress Sequence on Model Accuracy

In Table 6-1, Se/Sy values are given for all models, for the three materials tested with both the harmonized and NCHRP 1-28 Appendix E procedures. For each procedure, the models are ranked by the average Se/Sy ratio. As expected, a higher number of data points (stress states) and a larger range of variation of the predictor variables results in the higher accuracy (lower Se/Sy ratios) obtained using the harmonized stress sequence.

Evaluation of All Models Using Harmonized Protocol Data

Using only the tests performed with the harmonized procedure, the average Se/Sy ratio is computed for each model and the results are presented in Table 6-2 in the order in which the models were presented at the beginning of this chapter. In Table 6-3, the models are rearranged in the order of their rank (increasing Se/Sy). The variation of the Se/Sy ratio by model rank is illustrated in Figure 6-2. It is observed that log-log models are relatively more accurate than semi-log models. The least accurate models are the two-parameter models (log-log and semi-log). The most accurate model is the five-parameter log-log model (Equation 6-14).

Compared to the other log-log models, the log-log k_1, k_2 (θ or τ_{oct}) (Equation 6-1) has the lowest accuracy of prediction and the lowest goodness of fit statistics. This is expected because the model takes into account only one component of loading. Test results clearly show that for all materials, M_R depends on both volumetric and deviatoric components of loading. A similar argument holds for the semi-log k_1, k_2 (θ or τ_{oct}) (Equation 6-6) which of all models shows the lowest accuracy of prediction.

The three-parameter models (log-log or semi-log k_1, k_2, k_3) are clearly superior to the limited k_1, k_2 models. According to Table 6-3 or Figure 6-2, the use of σ_3 and σ_{cyc} instead of τ_{oct} and θ does not increase the accuracy of the models.

The four-parameter models use a fourth regression constant (k_6) in the volumetric (θ or σ_3) term. The use of k_6 results in increased accuracy for the log-log form of models (4, 5 vs. 2, 3). This is not true for the semi-log formulation where the models do not show any improvement over the version without k_6.

The six-parameter SHRP-Superpave model shows relatively low accuracy compared to the other models, when a solution is possible. This is because the values of k_2, k_3 and k_6 that optimize the M_R model are usually different from those necessary to optimize the ν_r model. When the two models are optimized independently, k_3 results negative for M_R but positive (irrational, τ_{oct} is a softening term) for ν_R. This is an indication that the model is irrational. The optimization results in an increased accuracy of the ν_r model at the expense of the M_R model. The M_R model considered independently as log-log k_1, k_2, k_3, k_6 (θ, τ_{oct}) (Equation 6-4) had excellent goodness of fit statistics (rank 2).

For some tests and some materials, the log-log k_1, k_2, k_3 (θ, $\tau_{oct}/p_{a+1}1$) model shows a clear improvement while for others it actually looses accuracy. Adding k_6 to the "+1" model increases the accuracy but the model remains inconsistent: for some materials it shows improvement and for some it looses accuracy. Since the "+1" models (were not consistent in showing improvement on all tests or for all materials, it was obvious that "1" was not always the right value. Hence, in the last model (14), a regression constant k_7 was introduced. As expected, the analysis showed that the model exhibits the best overall goodness of fit statistics.

Conclusions

One Predictor Variable Vs. Two Predictor Variables

It is obvious that models that use only one of the components of loading (volumetric or deviatoric) will always be less accurate. For all materials, regardless of their mechanical behavior (i.e., granular or cohesive), the resilient modulus is a function of both the volumetric (θ) and the deviatoric (τ_{oct}) components of loading. Therefore, the use of a k_1-k_2 type model is inappropriate. In Figure 6-3, the effect of adding the second predictor variable in the model is illustrated. On the average, there is a 30% increase in explained variance when both components of loading are considered.

Log-Log Vs. Semi-Log

Overall, the log-log models are better (see Figure 6-2) while the semi-log models, in all their forms exhibit local bias, as shown in Figure 6-4. Only for one material (S3), the log-log models exhibit local bias and the semi-log models look better. Since S3 is the only cohesive subgrade involved in the study, we cannot generalize that the semi-log models predict better for this type of materials. However, the more flexible four and five-parameter log-log models (4, 14) are able to predict with the same accuracy as the semi-log models, even for this material (i.e. no local bias).

Stress Invariants Vs. Statistically Independent Variables

Since σ_3 is present in both θ and τ_{oct}, it is recommended, from a statistical point of view, to use independent predictor variables, as σ_{cyc} and σ_3. However, a model that uses σ_{cyc} and σ_3 cannot be used in a 3D analysis where σ_2 may play an important role. Generally, for the log-log models, there is only a slight increase in accuracy due to the use of independent variables. In some cases though, the model looses accuracy. It is therefore preferred to use θ and τ_{oct} as predictor variables. The semi-log models exhibit the same accuracy, regardless of the pair of variables used.

Effect of k_6 and k_7

Adding k_6 to the model generally leads to increased accuracy, but only for the log-log models (see Figure 6-5). The optimization of the semi-log models usually returns a value of zero for k_6. The k_7 constant is only a location parameter that enables the log-log model to use that part of the exponential function that will better fit the measured data. No semi-log model using k_7 was considered. Since the use of k_6 or the use of different variables does not affect the accuracy of the semi-log models, it is very likely that the model is also not sensible to k_7. The effect of adding k_7 to a log-log model is illustrated in Figure 6-6.

Recommended Model

The model with the best overall goodness of fit statistics is the five-parameter model (14). This was expected, since depending on the values of k_6 and k_7 the model collapses in the form of model 4 or 3 that are the second best and the third best respectively (for log-log models). It also can take the form of models 11 and 12. However, for some materials, k_7 is negative which is irrational (M_R infinite for $\tau_{oct} = |k_7|p_a$). In order to correct this, a restrain is imposed on k_7, namely $k_7 > 1$. The comparison charts presented in Annex C-1 show that in some cases the model will be less accurate than model 4 (i.e. $k_7 = 0$) but this eliminates the irrationality related to $\tau_{oct} = 0$.

$$\begin{cases} M_R = k_1 \cdot p_a \cdot \left(\dfrac{\theta - 3k_6}{p_a}\right)^{k_2} \cdot \left(\dfrac{\tau_{oct}}{p_a} + k_7\right)^{k_3} \\ k_1, k_2 \geq 0 \\ k_3, k_6 \leq 0 \\ k_7 \geq 1 \end{cases} \tag{6-15}$$

Note that for the recommended model (Equation 6-15), the regression constants are restrained.

Chapter 7. Summary of Key Findings and Recommendations for Future Research

Summary of Key Findings

The harmonized method developed in this research closely follows the recommendations of the latest resilient modulus protocol NCHRP 1-28 Appendix E with some exceptions. The main modifications are a revised, more rational stress sequence and a more accurate predictive equation.

The revised stress sequences minimize the probability of failing the sample early in the test, cover a broader range of stress states and provide a larger number of data points for analysis. The experimental study presented in Chapter 5 shows that in the M_R values measured with the two procedures (harmonized and NCHRP 1-28 Appendix E) are similar for similar ranges of stress combinations.

The new predictive equation is selected out of 14 candidates. Models with different mathematical forms, predictor variables and regression constants are considered. The most accurate model is found to be a five-parameter log-log model (Equation 6-15).

Computational Stability Study

The predictive equation has to satisfy two criteria: accuracy of prediction (i.e. how well the model can predict lab measured data) and numerical use (i.e. how well the model performs in a finite element analysis and how stable the solution is). The analysis presented in Chapter 6 evaluates only the accuracy of the models. Therefore, for all the models that may be implemented into a finite element code, it is necessary to conduct a computational stability study. The model to be selected for final recommendation should be accurate as well as provide a stable solution when implemented into a finite element code.

Repeatability/Reproducibility Studies

In order to establish the practical implementability of the harmonized protocol, repeatability / reproducibility studies should be initiated at DOT's and other laboratories throughout US. These studies will assure that the revised test procedures (stress sequences) give reproducible and repeatable results in a real world production laboratory environment.

Establish Material Database

It is desired to develop a database of "default" k_i values for all unbound pavement materials, ideally at different combinations of moisture and density. The database can serve several purposes:

- Predict M_R for materials similar to those included in the database, just by using the appropriate model and regression constants; or verify test results with predicted M_R according to the database.
- Develop material relationship of modulus vs. moisture content for use in advanced mechanistic design to permit inclusion of seasonal moisture change effects.
- Develop relations between the k_i regression constants and measurable physical properties of the material (moisture, density, grain size distribution, Atterberg limits, etc). Knowledge of these relations would reduce the necessity of the M_R test.

Software development "Mr Lab Test Assistant"

By their nature, test protocols may be a difficult reading for the lab technician. Usually it takes some time for the technician to familiarize with the text, to be aware of and to respect all the recommendations of the protocol. Confusion or eventual misunderstandings may cause delays in this learning process. Besides running the test, the technician needs to spend some time designing spreadsheets, entering data, consulting complementary protocols and eventually performing the statistical analysis and printing final reports. The amount of time and effort spent by the laboratory technician could be significantly shortened by using specialized software, designed to help the user through the protocol step by step, from identification of materials and preparation of the sample to printing the results of the statistical analysis. It would also provide the technician with easy access to all necessary documentation. Ideally, the lab technician would not have to use any other computer programs from the beginning of the test until obtaining the final product.

List of References

AASHTO, 1991. Standard Method of Test for Resilient Modulus of Subgrade Soils and Untreated Base/Subbase Materials, AASHTO Designation T 292-91, Standard Specifications for Transportation Materials and Methods of Sampling and Testing, Part II, Methods of Sampling and Testing, American Association of State Highway and Transportation Officials.

AASHTO, 1992. Standard Method of Test for Resilient Modulus of Unbound Granular Base/Subbase Materials and Subgrade Soils – SHRP Protocol P46, AASHTO Designation T 294-92, Standard Specifications for Transportation Materials and Methods of Sampling and Testing, Part II, Methods of Sampling and Testing, American Association of State Highway and Transportation Officials.

AASHTO, 1994. Standard Test Method for Determining the Resilient Modulus of Soils and Aggregate Materials, AASHTO Designation T P46-94, Standard Specifications for Transportation Materials and Methods of Sampling and Testing, Part II, Methods of Sampling and Testing, American Association of State Highway and Transportation

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Uzan, J. 1992. Resilient Characterization of Pavement Materials. International Journal for Numerical and Analytical Methods in Geomechanics, vol. 16, 453-459 (1992).

APPENDIX A

NCHRP 1-28 A Project

Procedure for Resilient Modulus of Unstabilized Aggregate Base and Subgrade Materials

RECOMMENDED STANDARD METHOD FOR ROUTINE RESILIENT MODULUS TESTING OF UNBOUND GRANULAR BASE/SUBBASE MATERIALS AND SUBGRADE SOILS

1. Scope

1.1 This test method describes the laboratory preparation and testing procedures for the routine determination of the resilient modulus (M_r) of unbound granular base/subbase materials and subgrade soils for pavement design. The stress conditions used in the test represent the ranges of stress states likely to be developed beneath flexible pavements subjected to moving wheel loads. The test procedure has been adapted from the standard test methods given by NCHRP 1-28 Draft Final Report Appendix E and AASHTO DESIGNATION: T 294-92, TP 46 and T 292-91.

1.2 The methods described herein are applicable to: (1) undisturbed samples of natural and compacted subgrade soils, and (2) disturbed samples of unbound base, subbase and subgrade soils prepared for testing by compaction in the laboratory.

1.3 In this test procedure, stress states used for resilient modulus testing are based upon whether the specimen is located in the base/subbase or the subgrade. Specimen size for testing depends upon the maximum particle size of the material.

1.4 The value of the resilient modulus determined from this procedure is a measure of the elastic modulus of unbound base and subbase materials and subgrade soils recognizing its nonlinear variation with deviatoric stress and confining pressure.

1.5 Resilient modulus values can be used with structural response analysis models to calculate the pavement structural response to wheel loads, and with pavement design procedures to design pavement structures.

1.6 The values stated in SI units are to be regarded as the standard.

1.7 *This standard may involve hazardous materials, operations, and equipment. This standard does not purport to address all of the safety problems associated with its use. It is the responsibility of whoever uses this standard to consult and establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

Note 1 – Test specimens and equipment described in this method may be used to obtain other useful and related information such as the Poisson's ration and rutting characteristics of subgrade soils and base/subbase materials. Procedures for obtaining these are not covered in this standard.

2. Referenced Documents

2.1 AASHTO Standards:

T88 Particle Size Analysis of Soils
T89 Determining the Liquid Limit of Soils
T90 Determining the Plastic Limit and the Plasticity Index of Soils
T99 Moisture-Density Relations of Soils Using a 2.5 kg (5.5 lb) Rammer and a 305 mm (12 in) Drop
T100 Specific Gravity of Soils
T180 Moisture-Density Relations of Soils Using a 4.54 kg (10 lbs) Rammer and a 457 mm (18 in) Drop
T233 Density of Soil In-Place by Block, Chunk or Core Sampling
T265 Laboratory Determination of Moisture Content of Soils
T296 Unconsolidated, Undrained Compressive Strength of Cohesive Soils in Triaxial Compression
T310 In Place Density and Moisture Content of Soil and Soil-Aggregate by Nuclear Methods (Shallow Depth)

2.2 ASTM Standards:

D1586-99 Standard Test Method for Penetration Test and Split-Barrel Sampling of Soils
D3441-98 Standard Test Method for Mechanical Cone Penetration Tests of Soil

3. Terminology

3.1 Unbound Granular Base and Subbase Materials - These include soil-aggregate mixtures and naturally occurring materials. No binding or stabilizing agent is used to prepare unbound granular base or subbase layers. These materials are classified as Type 1 and Type 2, as subsequently defined in 3.3 and 3.4.

3.2 Subgrade - Subgrade soils may be naturally occurring or prepared and compacted before the placement of subbase and/or base layers. These materials are classified as Type 1, Type 2, Type 3 and Type 4, as subsequently defined in 3.3, 3.4, 3.5 and 3.6.

3.3 Material Type 1 - Includes all unbound granular base and subbase materials and all untreated subgrade soils with maximum particle sizes greater than 9.5 mm (0.375 in). All material greater than 25.4 mm (1.0 in) shall be scalped off prior to testing. Materials classified as Type 1 shall be molded in either a 152 mm (6 in) diameter mold or a 102 mm (4 in) diameter mold as described in section 7.1. Materials classified as Type 1 shall be compacted by impact or vibratory compaction.

3.4 Material Type 2 - Includes all unbound granular base and subbase materials and all untreated subgrade soils which have a maximum particle size less than 9.5 mm (0.375 in) and which meet the criteria of less than 10% passing the 75mm (No. 200) sieve. Materials classified as Type 2 shall be molded in a 102 mm (4 in) diameter mold and compacted by vibratory compaction.

3.5 Material Type 3 - Includes all untreated subgrade soils which have a maximum particle size less than 9.5 mm (0.375 in) and which meet the criteria of more than 10% passing the 75mm (No. 200) sieve. Materials classified as Type 3 shall be molded in a 102 mm (4 in) diameter mold and compacted by impact or kneading compaction.

3.6 Material Type 4 - Includes thin-walled tube samples of untreated subgrade soils. Materials Type 4 represent undisturbed samples of subgrade soils, tested as 71 mm (2.8 in) diameter specimens.

3.7 Resilient Modulus - The resilient modulus is determined by repeated load compression tests on test specimens of the unbound material. Resilient modulus (M_r) is the ratio of the peak axial repeated deviator stress to the peak recoverable axial strain of the specimen.

3.8 Loading Wave Form - Test specimens are loaded using a haversine load pulse as shown in Figure A-1.

3.9 Maximum Applied Axial Load (P_{max}) - The load applied to the sample consisting of the contact load and cyclic load (confining pressure is not included):

$P_{max} = P_{contact} + P_{cyclic}$

3.10 Contact Load ($P_{contact}$) - Vertical load placed on the specimen to maintain a positive contact between the loading ram and the specimen top cap. The contact load includes the weight of the top cap and the static load applied by the ram of the loading system.

3.11 Cyclic Axial Load - Repetitive load applied to a test specimen:

$P_{cyclic} = P_{max} - P_{contact}$

3.12 Maximum Applied Axial Stress (S_{max}) - The axial stress applied to the sample consisting of the contact stress and the cyclic stress (the confining stress is not included):

$S_{max} = P_{max} / A$

Where: A = initial cross sectional area of the sample.

3.13 Cyclic Axial Stress - Cyclic (resilient) applied axial stress:

$S_{cyclic} = P_{cyclic} / A$

3.14 Contact Stress ($S_{contact}$) - Axial stress applied to a test specimen to maintain a positive contact between the specimen cap and the specimen:

$S_{contact} = P_{contact} / A$

The contact stress shall be maintained so as to apply a constant anisotropic confining stress ratio:

$(S_{contact} + S_3)/S_3 = 1.2$

Where: S_3 is the confining pressure.

3.15 S_3 is the applied confining pressure in the triaxial chamber (i.e. the minor principal stress σ_3).

3.16 e_r is the resilient (recoverable) axial deformation due to S_{cyclic}.

3.17 ε_r is the resilient (recoverable) axial strain due to S_{cyclic}:

$\varepsilon_r = e_r / L$

Where: L = distance between measurement points for resilient axial deformation, e_r.

3.18 Resilient Modulus (M_r) is defined as:

$S_{cyclic} / \varepsilon_r$

3.19 Load duration is the time interval the specimen is subjected to a cyclic stress pulse.

3.20 Cycle duration is the time interval between the successive applications of a cyclic stress (usually 1.0 sec.).

4. Summary of Method

4.1 A repeated axial stress of fixed magnitude, load duration and cycle duration is applied to a cylindrical test specimen. The test is performed in a triaxial cell and the specimen is subjected to a repeated (cyclic) stress and a constant confining stress provided by means of cell air pressure. The total resilient (recoverable) axial deformation response of the specimen is measured and used to calculate the resilient modulus. A flowchart of the method is presented in Figure A-2.

5. Significance and Use

5.1 The resilient modulus test results provides a basic constitutive relationship between stiffness and stress state of pavement materials for use in pavement design procedures and the structural analysis of layered pavement systems. The resilient modulus test simulates the conditions in a pavement due to application of moving wheel loadings. As a result, the test provides an excellent means for comparing the behavior of pavement construction materials under a variety of conditions (i.e. moisture, density, gradation, etc.) and stress states.

6. Resilient Modulus Test Apparatus

6.1 Triaxial Pressure Chamber - The pressure chamber is used to contain the test specimen and the confining fluid during the test. A typical triaxial chamber suitable for use in resilient modulus testing of soils is shown in Figure A-3(a). The axial deformation is measured internally, directly on the specimen using an optical extensometer, non-contact sensors or clamps (Figure A-3). For soft and very soft subgrade specimens (i.e., S_u <36 kPa or 750 psf, where S_u is the undrained shear strength of the soil), clamps should not be used since they may damage the specimen. However, a pair of LVDTs extending between the top and bottom platens can be used to measure axial deformation of these weak soils.

6.1.1 Air shall be used in the triaxial chamber as the confining fluid for all testing,

6.1.2 The chamber shall be made of polycarbonate, acrylic or other suitable see-through material. If an optical extensometer is used the line of sight must pass through a flat face of the chamber. Hence, a standard cylindrical chamber cannot be used with an optical extensometer.

6.2 Loading device - The loading device shall be a top loading, closed loop electro-hydraulic testing machine with a function generator which is capable of applying repeated cycles of a haversine-shaped load pulse. Each pulse shall have a 0.1 sec. duration followed by a rest period of 0.9 sec. duration for base/subbase materials and a 0.2 sec. duration followed by a rest period of 0.8 sec. duration for subgrade materials. For non-plastic granular materials, it is permissible, if desired, to reduce the rest period to 0.4 sec. to shorten testing time: the loading time may be increased to 0.15 sec. if required.

6.2.1 The haversine-shaped load pulse shall conform to section 3.8 except as noted above. All conditioning and testing shall be conducted using a haversine-shaped load pulse. The electro-hydraulic system generated haversine waveform and the response waveform shall be displayed to allow the operator to adjust the gains to ensure they coincide during conditioning and testing.

6.3 Load and Specimen Response Measuring Equipment:

6.3.1 The axial load measuring device should be an electronic load cell located inside the triaxial cell as shown in Figure A-3 (a). The following load cell capacities are required:

Sample Diameter mm (in)	Max. Load Capacity kN (lbs)	Required Accuracy N (lbs)
71 (2.8)	2.2 (500)	+/- 4.5 (+/- 1)
102 (4.0)	8.9 (2000)	+/- 17.8 (+/- 4)
152 (6.0)	22.24 (5000)	+/- 22.24 (+/- 5)

Note 3 – During periods of resilient modulus testing, the load cell shall be monitored and checked once every two weeks or after every fifty resilient modulus tests with a calibrated proving ring to assure that the load cell is operating properly. An alternative to using a proving ring is to inset an additional calibrated load cell and independently measure the load applied by the original cell. Additionally, the load cell shall be checked at any time there is a suspicion of a load cell problem. Resilient modulus testing shall not be conducted if the testing system is found to be out of calibration.

6.3.2 The test chamber pressures shall be monitored with conventional pressure gages, manometers or pressure transducers accurate to 0.7 kPa (0.1 psi).

6.3.3 Axial Deformation: Axial deformation is to be measured on the specimen using one of the following devices: (1) optical extensometer, (2) non-contact sensors or (3) clamps attached to the specimen. Table A-1 summarizes the specifications for non-contact and clamp measurement devices. Deformation shall be measured over approximately the middle ½ of the specimen. For methods (2) or (3) of the above, deformation shall be measured independently on each side of the specimen using gages having the maximum practical sensitivity.

6.3.3.1 Optical Extensometer: the optical extensometer should have at least the following minimum requirements: (1) resolution: 0.0002 in; (2) frequency response: 200 Hz bandwidth; (3) linearity: 0.1%; (4) displacement range: 0.5 in; (5) gage length range: 2.5 in to 5.0 in; (6)

analog to digital output signal. If displacement is measured on a single side of the specimen, two external or internally mounted LVDTs or dial indicators should be used to determine specimen eccentricity under loading.

6.3.3.2 Non-contact Proximity Sensors: Proximity gages shall have the minimum voltage output given in Table A-1.

6.3.3.3 Clamp Mounted LVDTs: LVDTs shall have the minimum voltage output indicated in Table A-1. A pair of spring loaded LVDTs are placed on the specimen at ¼ point (Figure A-3 (b)). Each clamp shall be rigid with the clamp weight not exceeding the following values: 6 in clamp: 2.4 N (0.55 lbs); 4 in clamp: 1.8 N (0.40 lbs); 2.8 in clamp: 1.0 N (0.22 lbs). Minimize clamp weight by drilling small holes in the clamp. Clamp spring force should be as follows: 6 in clamp: 44.5 N (10.0 lbs); 4 in clamp: 33.4 N (7.5 lbs); 2.8 in clamp: 18.2 N (4.1 lbs). Use two pairs of 12 mm (0.5 in) diameter rods, cut to the correct length to position the clamps in a horizontal plane at the correct location on the specimen.

6.3.3.4 Spring loaded LVDT's shall be used to maintain a positive contact between the LVDTs and the surface on which the tips of the transducers rest. If the specimen is soft enough to be damaged by clamps or slippage of clamps is suspected, use one of the other alternative axial displacement measurement techniques. Slippage of clamps may be a problem for soft and very soft subgrade soils which undergo large deformations. Specimen damage due to clamps and clamp slippage should not be a problem for reasonable quality base and subbase specimens. The two LVDTs, or proximity gages, shall be wired so that each transducer is read, and the results reviewed, independently. The measured displacements shall be averaged for calculating the resilient modulus.

Note 4 – Misalignment or dirt on the shaft of the transducer can cause the shafts of the LVDTs to stick. The laboratory technician shall depress and release each LVDT back and forth a number of times prior to each test to assure that they move freely and are not sticking. A cleaner/lubricant specified by the manufacturer shall be applied to the transducer shafts on a regular basis.

6.3.4 Data Acquisition: An analog to digital data acquisition system is required. The overall system should include automatic data reduction to minimize the chance for errors and maximize production. Suitable signal excitation, conditioning, and recording equipment are required for simultaneous recording of axial load and deformations. The system should meet or exceed the following additional requirements: (1) 25 μs A/D conversion time; (2) 12 bit resolution; (3) single or multiple channel throughput (gain = 1), 30 kHz; (4) software selectable gains; (5) measurement accuracy of full scale (gain = 1) of +/- 0.02%; and (6) non-linearity (LSBS) of +/- 0.5%. The signal shall be clean and free of noise (use shielded cables properly grounded. Filtering the output signal during or after data acquisition is discouraged. If a filter is used, it should have a frequency higher than 10 to 20 Hz. A supplemental study should be made to insure correct peak readings are obtained from filtered data compared to unfiltered data. A minimum of 200 data points from each LVDT shall be recorded per load cycle.

6.4 Specimen Preparation Equipment: A variety of equipment is required to prepare undisturbed samples for testing and to prepare compacted specimens that are representative of field conditions. Use of different materials and different methods of compaction in the field requires the use of varying compaction techniques in the laboratory. Specimen preparation is given in Annex A1 and specimen compaction equipment and compaction procedures in Annexes A2 (vibratory), A3 (impact) and A4 (kneading).

6.5 Equipment for trimming test specimens from undisturbed thin-wall tube samples of subgrade soils shall be as described in AASHTO T 296.

6.6 Miscellaneous Apparatus: This includes calipers, micrometer gauge, steel rule (calibrated to 0.5 mm (0.02 in)), rubber membranes from 0.25 to 0.79 mm (0.02 to 0.031 in) thickness, rubber O-rings, vacuum source with bubble chamber and regulator, membrane expander, porous stones (subgrade), 6.4 mm (0.25 in) thick porous stones or bronze discs (base/subbase), scales, moisture content cans and data sheets.

6.7 Periodic System Calibration: The entire system (transducers, signal conditioning and recording devices) shall be calibrated every two weeks or after every fifty resilient modulus tests. Daily and other periodic checks of the system may also be performed as necessary. No resilient modulus testing will be conducted unless the entire system meets the established calibration requirements.

6.7.1 The response of the deformation measurement system shall be checked daily during use. Additionally, the deformation measurement system shall be calibrated every two weeks, or after every 50 resilient modulus tests, whichever comes first. Calibration shall be accomplished using a micrometer with compatible resolution or a set of specifically machined, close tolerance gauge blocks. Resilient modulus testing shall not be conducted if the measurement system does not meet the manufacturer's requirements for accuracy.

7. Preparation of Test Specimens

7.1 The following guidelines, based on the sieve analysis test results, shall be used to determine the test specimen size:

7.1.1 Use 152 mm (6.0 in) diameter and 305 mm (12 in) high specimens for all materials with maximum particle sizes greater than 19 mm (0.75 in). All material greater than 25.4 mm (1.0 in) shall be scalped off prior to testing.

7.1.2 Use 102 mm (4.0 in) diameter and 204 mm (8.0 in) high specimens for all materials with maximum particle sizes less than 19 mm (0.75 in).

7.2 Undisturbed Subgrade Soil Specimens - Trim and prepare thin-walled tube samples of undisturbed subgrade soil specimens as described in T 234. The natural moisture content (w) of a tube sample shall be determined after triaxial M_r testing following the procedure T 265.

The following procedure shall be followed for the thin-walled tube samples:

7.2.1 Standard penetration tests (ASTM D 1586) or cone penetration tests (ASTM D 3441) performed adjacent to thin-walled tube sample locations and elsewhere along the route are encouraged. The results obtained from penetration testing are used to aid in establishing representative subgrade conditions and selecting a representative sample for testing. The sample selected should be of acceptable quality, representative of the subgrade conditions near the surface, and preferably taken from the uppermost tube pushed into the subgrade.

7.2.2 To be suitable for testing, a specimen cut from the tube sample must have a length equal to at least twice its diameter after preparation. The sample must be free from defects that would result in unacceptable or biased test results. Such defects include sampling/trimming induced cracks in the specimen, corners broken off that cannot be repaired during preparation, presence of particles much larger than typical for the material (for example + 19.0 mm (+ 0.75 in) stones in a fine grained soil), the presence of foreign objects not representative of the subgrade such as large roots, wood particles, organic material and gouges due to gravel hanging on the edge of the tube.

7.3 Laboratory Compacted Specimens: Reconstituted test specimens of all types shall be prepared to the specified or in-situ dry density (γ_d) and moisture content (w). Laboratory compacted specimens shall be prepared for all unbound granular base and subbase material and for all subgrade soils for which undisturbed tube specimens could not be obtained.

7.3.1 Moisture Content: For in-situ materials, the moisture content of the laboratory compacted specimen shall be the in-situ moisture content for that layer obtained in the field using T 310. If data is not available on in-situ moisture content, refer to Section 7.3.3.

7.3.1.1 The moisture content of the laboratory compacted specimen should not vary from the required value by more than +/- 0.5% for all materials.

7.3.2 Compacted Density: The density of a compacted specimen shall be the in-place dry density obtained in the field for that layer using T 310 or other suitable methods. If this data is not available on in-situ density, then refer to Section 7.3.3.

7.3.2.1 The dry density of a laboratory compacted specimen should not vary more than +/- 1% from the target dry density for that layer.

7.3.3. If either the in-situ moisture content or the in-place dry density is not available, then use the optimum moisture content and 95% of the maximum dry density by using T 180 for the base/subbase and 95% of T99 for the subgrade.

7.3.3.1 The moisture content of the laboratory compacted specimen should not vary from the required value by more than +/- 0.5% for all materials. The dry density of a laboratory compacted specimen should not vary more than +/- 1% from the target dry density for that layer.

7.3.4 Sample Reconstitution - Reconstitute the specimen for all materials in accordance with the provisions given in Annex A1. The target moisture content and density to be used in determining needed material qualities are given in Section 7.3. Annex A1 provides guidelines to obtain a sufficient amount of material to prepare the appropriate specimen type at the designated moisture content and density. After this step is completed, specimen compaction can begin.

7.4. Compaction Methods and Equipment for reconstituting specimens:

7.4.1 Specimens of Type 1 materials shall be compacted by vibratory or impact compaction. The general method of vibratory compaction is given in Annex A2. The general method of impact compaction is given in Annex A3.

7.4.3 Specimens of Type 2 materials shall be compacted by vibratory compaction. The general method of vibratory compaction is given in Annex A2.

7.4.4 Specimens of Type 3 materials shall be compacted by kneading or impact compaction. The general method of kneading compaction is given in Annex A4. The general method of impact compaction is given in Annex A3.

8. Test Procedure

8.1 Initial System Calibration: The testing system including loading apparatus and triaxial cell, must be calibrated before each major test series including minimizing system compliance, insuring accurate specimen and system alignment and by using synthetic specimens to establish overall test accuracy.

8.2 Test Methods: Following this test procedure, the resilient modulus test is performed on all materials using a triaxial cell (confined).

8.3. Coarse Grained Subgrade Soils (Procedure Ib): This procedure is used for all laboratory compacted specimens of subgrade soils for which the percent passing 75 μm (No. 200) sieve is less than 35%. Reconstructed specimens will usually be compacted directly on the pedestal of the triaxial cell.

8.3.1 Assembly of the Triaxial Chamber – If not already in place, place the specimen with end platens into position on the pedestal of the triaxial cell. If a fixed triaxial cell is used, place the specimen under the axial repeated loading device. Proper positioning of the specimen is extremely critical in applying a concentric load to the specimen. Couple the loading device to the specimen using a smooth steel ball. To center the specimen, slowly rotate the ball as the clearance between the load piston ball decreases and a small amount of load is applied to the specimen. Be sure the ball is concentric with the piston which applies the load (watch the gap around the ball). Shift the specimen laterally to achieve a concentric loading.

8.3.2 Set up the axial displacement measurement system (refer to section 6.3.3.) and verify it is working properly.

8.3.3. If a mobile triaxial cell is used, slide the triaxial cell into position under the axial repeated loading device. Positioning of the chamber is extremely critical in applying concentric load to the specimen and minimizing friction forces on the piston rod. Tighten the chamber tie rods firmly to a uniform tension using a torque wrench.

8.3.4 Open all valves on drainage lines leading to the inside of the specimen. This is necessary to develop confining pressure on the specimen.

8.3.5 If not already connected, connect the confining air pressure supply line to the triaxial chamber.

8.3.6 Apply the specified conditioning confining pressure of 27.6 kPa (4.0 psi) to the test specimen. A contact stress equal to 20% of the confining pressure shall be applied to the specimen so that the load piston stays in contact with the top platen at all times.

8.3.7 Conditioning - Begin the test by applying a minimum of 1000 repetitions of a load equivalent to a maximum axial stress of 60.72 kPa (8.8 psi) and a corresponding cyclic stress of 55.2 kPa (8 psi) using a haversine shaped, 0.2 second load pulse followed by a 0.8 second rest period.

8.3.8 If the vertical permanent strain reaches 5% during conditioning, the conditioning process shall be terminated. A review shall be conducted of the compaction process to identify any reason(s) why the sample did not attain adequate compaction. If this review does not provide an explanation, the material shall be recompacted and tested a second time. If the sample again reaches 5% total vertical permanent strain during preconditioning, then the test shall be terminated and the appropriate item on the data sheet shall be completed. No further testing of this material is necessary.

8.3.8.1 Conduct appropriate comparative checks of the individual displacement output from the two vertical displacement transducers during the conditioning phase of each M_r test to identify and minimize specimen misalignment. The two measured resilient vertical displacements should have an acceptable vertical displacement ratio. An acceptable displacement ratio (R_v) is defined as $R = Y_{max} / Y_{min}$ less than or equal to 1.10 where Y_{max} equals the largest of the two measured displacements and Y_{min} the smaller value. If unacceptable vertical deformation ratios are obtained, then the test should be discontinued and the specimen alignment difficulties corrected. Very slightly tapping the triaxial cell base in the correct direction or tightening the tension rod nuts on one side of the cell may reduce the eccentricity ratio. Proper equipment alignment is essential. The top of the specimen (and top cap) must be at right angles to the axis of the specimen. Once acceptable vertical deformation values are obtained, then the test should be continued to completion. Specimen alignment is critical for good M_r results.

8.3.9 Specimen Testing: Perform the resilient modulus test following the load sequence showed in Table A-2 (Procedure Ib – Granular and Low Cohesion Subgrades). Begin by decreasing the maximum axial stress to 9.66 kPa (1.4 psi) (Sequence No. 1 Table A-2) and set the confining pressure to 13.8 kPa (2 psi).

8.3.10 Apply 100 repetitions of the corresponding cyclic axial stress using a haversine-shaped load pulse consisting of a 0.2 second load followed by a 0.8 second rest period. Record the average recovered deformations for each LVDT separately for the last five cycles on the Report Form 1.

8.3.11 Increase the maximum axial stress to 19.32 kPa (2.8 psi) and set the confining pressure to 27.6 kPa (4 psi) (Sequence No. 2, Table A-2 and repeat the previous step at this new stress level).

8.3.12 Continue the test for the remaining stress sequences in Table A-2 (3 to 20) recording the vertical recovered deformation. If at any time the total permanent strain of the sample exceeds 5%, stop the test and report the result on the appropriate worksheet.

8.3.13 At the completion of the test, reduce the confining pressure to zero and remove the sample from the triaxial chamber.

8.3.14 Remove the membrane from the specimen and use the entire specimen to determine moisture content in accordance with T 265.

8.4 Cohesive Subgrade Soils (Procedure II): This procedure is used for all laboratory compacted specimens of subgrade soils for which the percent passing 75 µm (No. 200) sieve is greater than 35% and for all undisturbed specimens of cohesive subgrade soils.

8.4.1 Assembly of the triaxial cell: refer to section 8.3.1

8.4.2 Stiff to Very Stiff Specimens: For stiff and very stiff cohesive specimens ($S_u > 36$ kPa (750 psf)), axial deformation should preferably be measured either directly on the specimen or else between the solid end platens using grouted specimen ends. The symbol Su denotes the undrained shear strength of the soil.

These stiff to very stiff specimens generally have a resilient modulus greater than 69,000 kPa (10,000 psi). If the specimen ends are not grouted, axial deformation measurement between end platens can still be performed. Following this less reliable approach, however, the measured resilient modulus must be empirically increased to account for the presence of irregular specimen end contacts. The empirical correction factors should be developed for each category of subgrade soil to be tested. To do this, use either specimens with grouted ends and top to bottom axial deformation measurement or specimens having axial deformation measurements made directly on them.

8.4.3 Soft Specimens: The axial deformation of soft subgrade soils (S_u < 37.9 kPa (750 psf)) should not be measured using clamps placed on the specimen. If the measured resilient modulus is less than 69,000 kPa (10,000 psi), axial deformation can be measured between top and bottom platens. An empirical correction is not required for irregular specimen end contacts for these low moduli soils. If the resilient modulus is greater than 69,000 kPa (10,000 psi), follow the procedures given in 8.4.2.1.

8.4.4 Specimen End Grouting: All grouted test specimens shall be grouted to the top and bottom end platens using a Hydrostone paste (or equivalent) having a thickness no greater than 3.0 mm (0.12 in). The hydrostone paste allows adjustment of the level of the top cap and pedestals to accommodate or eliminate any imperfections in the specimen end surfaces. The grout also helps to improve both the uniformity of the applied repeated stress and the accuracy of the deformation measurements of the specimen.

8.4.4.1 The grout paste shall be prepared using potable water and hydrostone cement mixed in a (W/C) ratio of 0.40. Once the water is mixed with the grout, the hydration begins, with consistency rapidly obtained. A minimum of 120 min. is recommended as curing time; this assures that the grout will be strong enough to withstand the applied stresses in the resilient modulus test without risking the accuracy and reliability of the measurements.

8.4.4.2 To expedite this operation, the grouting can be performed on a pedestal frame, similar to the one used in capping concrete cylinders, with additional steel caps that can be bolted to the original end platens. Refer to Annex A-5 for detailed grouting procedures for specimen ends.

8.4.5 Install Axial Displacement Devices: Carefully install the axial displacement instrumentation selected under 8.4.2 or 8.4.3. For top to bottom displacement measurement, attach the LVDTs or proximity gages on steel or aluminum bars extending between the top and bottom platens. If an optical extensometer is to be used, attach the two targets directly to the specimen using at least two small pins for each target. If clamps are used, place clamps at the ¼ points of the specimen using two height gages to insure that clamps are positioned horizontally at correct height. Each height gage can consist of two circular aluminum rods machined to the correct length. These rods are placed on each side of the clamp to insure proper location. Then insure the displacement instrumentation is working properly by displacing each device and observing the resulting voltage output as shown by the data acquisition system.

8.4.6 Refer to section 8.3.3

8.4.7 If not already connected, connect the confining air pressure supply line to the triaxial chamber.

8.4.8 Open all valves on drainage lines leading to the inside of the specimen. This is necessary to develop confining pressure on the specimen.

8.4.9 Apply the specified conditioning confining pressure of 27.6 kPa (4.0 psi) to the test specimen. A contact stress equal to 20% of the confining pressure shall be applied to the specimen so that the load piston stays in contact with the top platen at all times.

8.4.10 Conditioning: Begin the test by applying a minimum of 1000 repetitions of a load equivalent to a maximum axial stress of 53.8 kPa (7.8 psi) and a corresponding cyclic stress of 48.3 kPa (7 psi) using a haversine shaped, 0.2 second load pulse followed by a 0.8 second rest period.

8.4.10.1 If the vertical permanent strain reaches 5% during conditioning, the conditioning process shall be terminated. A review shall be conducted of the compaction process to identify any reason(s) why the sample did not attain adequate compaction. If this review does not provide an explanation, the material shall be recompacted and tested a second time. If the sample again reaches 5% total vertical permanent strain during preconditioning, then the test shall be terminated and the appropriate item on the data sheet shall be completed. No further testing of this material is necessary.

8.4.10.2 Eccentricity of Load: Minimizing eccentricity of load to an acceptable level is extremely important in resilient modulus testing. To do this observe the output from the two independent measurement gages during conditioning. Then satisfy the requirements given in 8.3.8.1. An optical extensometer may be used with axial deformation being measured on only one side of the specimen. For this condition, set up two LVDT's or proximity gages between top and bottom platens.

8.4.11 Specimen Testing: Perform the resilient modulus test following the load sequence showed in Table A-3 (Procedure II – Cohesive Subgrades). Begin by decreasing the maximum axial stress to 38.6 kPa (5.6 psi) (Sequence No. 1 Table A-3) and set the confining pressure to 55.2 kPa (8 psi).

8.4.12 Apply 100 repetitions of the corresponding cyclic axial stress using a haversine-shaped load pulse consisting of a 0.2 seconds load followed by a 0.8 seconds rest period. Record the average recovered deformations for each LVDT separately for the last five cycles on the Report Form X1.1.

8.4.13 Decrease the maximum axial stress to 35.8 kPa (5.2 psi) and set the confining pressure to 41.4 kPa (6 psi) (Sequence No. 2 Table A-3 and repeat the previous step at this new stress level).

8.4.14 Continue the test for the remaining stress sequences in Table A-3 (3 to 16) recording the vertical recovered deformation. If at any time the total permanent strain of the sample exceeds 5%, stop the test and report the result on the appropriate worksheet.

8.4.15 At the completion of the test, reduce the confining pressure to zero and remove the sample from the triaxial chamber.

8.4.16 Remove the membrane from the specimen and use the entire specimen to determine moisture content in accordance with T 265.

8.5 Base/Subbase Materials (Procedure Ia): The procedure described in this section applies to all unbound granular base and subbase materials.

8.5.1 Assembly of the triaxial cell: refer to section 8.3.1

8.5.2 Adjust as required the axial displacement measurement system (refer to section 6.3.3), load cell and data acquisition system and verify they are working properly.

8.5.3 Refer to section 8.3.3

8.5.3 If not already connected, connect the confining air pressure supply line to the triaxial chamber.

8.5.4 Open all valves on drainage lines leading to the inside of the specimen. This is necessary to develop confining pressure on the specimen.

8.5.5 Apply the specified conditioning confining pressure of 103.5 kPa (15.0 psi) to the test specimen. A contact stress equal to 20% of the confining pressure shall be applied to the specimen so that the load piston stays in contact with the top platen at all times.

8.5.6 Conditioning: Begin the test by applying a minimum of 1000 repetitions of a load equivalent to a maximum axial stress of 227.7 kPa (33 psi) and a corresponding cyclic stress of 207 kPa (30 psi) using a haversine shaped, 0.1 second load pulse followed by a 0.9 second rest period.

8.5.6.1 If the vertical permanent strain reaches 5% during conditioning, the conditioning process shall be terminated. A review shall be conducted of the compaction process to identify any reason(s) why the sample did not attain adequate compaction. If this review does not provide an explanation, the material shall be recompacted and tested a second time. If the sample again reaches 5% total vertical permanent strain during preconditioning, then the test shall be terminated and the appropriate item on the data sheet shall be completed. No further testing of this material is necessary.

8.5.6.2 Eccentricity of Load: Minimizing eccentricity of load to an acceptable level is extremely important in resilient modulus testing. To do this observe the output from the two independent measurement gages during conditioning. Then satisfy the requirements given in 8.3.8.1. An optical extensometer may be used with axial deformation being measured on only one side of the specimen. For this condition, set up two LVDT's or proximity gages between top and bottom platens.

8.5.7 Specimen Testing: Perform the resilient modulus test following the load sequence showed in Table A-4 (Procedure Ia – Base/Subbase Materials). Begin by decreasing the maximum axial stress to 14.5 kPa (2.1 psi) (Sequence No. 1 Table A-4) and set the confining pressure to 20.7 kPa (3 psi).

8.5.8 Apply 100 repetitions of the corresponding cyclic axial stress using a haversine-shaped load pulse consisting of a 0.1 second load followed by a 0.9 second rest period. Record the average recovered deformations for each LVDT separately for the last five cycles on the Report Form 1.

8.5.9 Increase the maximum axial stress to 30 kPa (4.2 psi) and the confining pressure to 41.4 kPa (6 psi) (Sequence No. 2 Table A-4 and repeat the previous step at this new stress level).

8.5.10 Continue the test for the remaining stress sequences in Table A-4 (3 to 30) recording the vertical recovered deformation. If at any time the total permanent strain of the sample exceeds 5%, stop the test and report the result on the appropriate worksheet.

8.5.11 At the completion of the test, reduce the confining pressure to zero and remove the sample from the triaxial chamber.

8.5.12 Remove the membrane from the specimen and use the entire specimen to determine moisture content in accordance with T 265.

9. Calculations

9.1 Perform the calculations to obtain resilient modulus values using the tabular arrangement similar to that shown on Report Form 1. As indicated on the work sheet, the resilient modulus computed for each of the last 5 cycles of each load sequence and then averaged. The data acquisition and data reduction processes should be fully automated to minimize the chance for human error.

9.2 Fit using nonlinear regression techniques the following resilient modulus model to the data obtained from the applied procedure (Table A-2 or Table A-3 or Table A-4)

Equation for normalized log-log k_1, k_2, k_3, k_6, k_7 model:

$$M_R = k_1 \cdot p_a \cdot \left(\frac{\theta - 3k_6}{p_a}\right)^{k_2} \cdot \left(\frac{\tau_{oct}}{p_a} + k_7\right)^{k_3}$$

$$k_1, k_2 \geq 0$$
$$k_3, k_6 \leq 0$$
$$k_7 \geq 1 \qquad \text{(E-1)}$$

where:

M_R = Resilient Modulus

θ = Bulk Stress:

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

τ_{oct} = Octahedral Shear Stress:

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

$\sigma_1, \sigma_2, \sigma_3$ = Principal Stresses
k_i = regression constants
p_a = atmospheric pressure (14.7 psi)

Assign initial values of zero for k_6 and one for k_7; Restrain all regression constants according to the model. Report the constants k_1, k_2, k_3, k_6 and k_7, the ratio of the standard error of estimate to the standard deviation and the square of the correlation coefficient on Report Form 1.

10. Report

10.1 The resilient modulus test report should contain the following:

10.1.1 Hard copy of the Report Form 1: The acquisition system data used to generate this report, as well as the report, shall be stored on a computer diskette in ASCII format.

10.1.2 Report Form 2 (re-compacted specimens) or Report Form 3 (thin-walled tube specimens).

10.2 The following general information is to be recorded on all the Report Forms:

10.2.1 The specimen identification, the material type (Type 1, 2, 3 or 4) and test date.

10.3 Report the following information on the appropriate data sheet:

10.3.1 Report Form 2 shall be used to record general information concerning the specimen being tested. This form shall be completed only for those specimens that are re-compacted from bulk samples. This form shall not be used to record information for thin-walled tube samples.

10.3.1.1 Item 4: Record a “Y” (Yes) or “N” (No) to denote whether the sample reached 5% total vertical permanent strain during the testing sequence. Record the number of test sequences completed, either partially or completely, for the given sample.

10.3.1.2 Item 5: Record the specimen dimensions and perform the area and volume calculations.

10.3.1.3 Item 6: Record the compaction masses as outlined in the compaction Annexes.

10.3.1.4 Item 7: Record the in-situ moisture content/density values used as the basis for compaction of the specimen as per sections 7.3.1. and 7.3.2. These values were obtained from nuclear methods in the field. If these values are not available, record the optimum moisture content, maximum dry density and 95% maximum dry density values used as the basis for compaction of the specimen as per section 7.3.3.

10.3.1.5 Item 8: Record the moisture content of the compacted material. Record the moisture content of the material after the resilient modulus test as per section 8.3.14 (Coarse Grained Subgarde) or section 8.4.16 (Fine Grained Subgrade) or section 8.5.12 (Base/Subbase). Also, record the target density used for specimen re-compaction.

10.3.2 Report Form 3 shall be used to record general information concerning the specimen being tested. This form shall be completed only for thin-walled tube specimens. This form shall not be used to record information for re-compacted samples.

10.3.2.1 Item 4: Record the approximate distance from the top of the subgrade to the top of the specimen (if known).

10.3.2.2 Item 5: Record a "Y" (Yes) or "N" (No) to denote whether the sample reached 5% total vertical permanent strain during the conditioning stage of the test procedure. Also note with a "Y" (Yes) or "N" (No) whether or not the sample reached 5% total vertical permanent strain during the testing sequence. Record the number of test sequences completed, either partially or completely, for the given sample.

10.3.2.3 Item 6: Record the specimen dimensions and perform the area and volume calculations. Record the mass of the specimen.

10.3.2.4 Item 7: Record the moisture content (in-situ) prior to resilient modulus testing. Record the moisture content at the completion of the resilient modulus testing as per section 8.3.14 record the wet and dry density of the thin-walled tube sample.

10.3.3 Record the test data for each specimen in a format similar to Report Form 1 and attach with Report Form 2 or Report Form 3. The following information shall be recorded on Report Form 1

10.3.3.1 Column 1: Record the chamber confining pressure for the testing sequence. Only one entry need be made for the last five load cycles. This entry should correspond exactly with the confining pressure levels shown in Tables A-2, A-3 or A-4.

10.3.3.2 Column 2: Record the nominal axial cyclic stress for the testing sequence. Only one entry need be made for the last five load cycles. This entry should correspond exactly with the nominal axial cyclic stress required in Tables A-2, A-3 or A-4.

10.3.3.3 Column 4 through 9: Record the actual applied loads and stresses for each of the last five load cycles as shown on the worksheet.

10.3.3.4 Columns 10 through 12: Record the recoverable axial deformation of the sample for each LVDT independently for each of the last five load cycles. Average the response from the two LVDT's and record this value in column 12. This value will be used to calculate the axial strain of the material.

10.3.3.5 Column 13: Compute the axial strain for each of the last five load cycles. This value is computed by dividing column 12 by the initial distance between clamps, L_0.

10.3.3.6 Column 14: Compute the resilient modulus for each of the last five load cycles. This value is computed by dividing column 8 by column 13.

10.3.3.7 Average: Compute the average of the last five load cycles for each column.

10.3.3.8 Standard Deviation: Compute the standard deviation of the values for each column for the last five load cycles using the equation:

$$s = \sqrt{\frac{\sum (x_i - \bar{x})^2}{n-1}}$$

10.3.3.9 Summary Resilient Modulus: Calculate and report on Form 1 a summary resilient modulus (MRR) using equation (E-1) described in section 9.2. For aggregate base/subbase materials calculate and report on this form the resilient modulus using the above equation for S_3 = 35 kPa (5 psi) and S_{cyclic} = 103 kPa (15 psi). For subgrade soils calculate and report the resilient modulus using the same equation for S_3 = 14 kPa (2 psi) and S_{cyclic} = 41 kPa (6 psi).

ANNEX A-1

NCHRP 1-28 A Project

Sample Preparation

Annex A-1 Sample Preparation

(Mandatory Information)

1. Scope

1.1 The following provides guidelines for reconstituting the material to be tested so as to produce a sufficient amount of material needed to prepare the appropriate sample type (Type 1, 2 or 3) at the designated moisture content and density.

2. Preparation for Compaction

2.1 Sample Conditioning – If the sample is damp when received from the field, dry it until it becomes friable. Drying may be in air or by use of a drying apparatus such that the temperature does not exceed 60°C (140°F). Then thoroughly break up the aggregations in such manner as to avoid reducing the natural size of individual particles. Moderate pressure using a rubber covered implement to push the particles through a 4.75 mm (No. 4) sieve.

2.2 Sample Preparation – Determine the moisture content (w_1) of the sample as per T265. The mass of the sample for moisture determination shall not weight less than 200 g for samples with a maximum particle size smaller than the 4.75 mm (No. 4) sieve and not less than 500 g for samples with a maximum particle size greater than 4.75 mm (No. 4) sieve.

2.2.1 Determine the appropriate total volume (V) of the compacted specimen to be prepared. The total volume must be based on height of the compacted specimen slightly greater than that required for resilient testing to allow for trimming of the specimen ends if necessary. Compacting to a height/diameter ratio of 2.1 to 2.2 will provide adequate material for this purpose.

2.2.2 Determine the mass of oven-dry soil solids (Ws) required to obtain the desired dry density (γ_d) and moisture content (w) as follows:

$$W_s = 453.59\, \gamma_d\, V$$

where:
W_s = Mass of oven-dry solids, g,
γ_d = Desired dry density, lb/ft^3
V = Total volume of compacted specimen, ft^3.

1.1.2.3 Determine the mass of the dried sample, (W_{ad}), with the moisture content (w_1) required to obtain W_s plus an additional amount W_{as} of at least 500 grams to provide material for the determination of moisture content at the time of compaction.

$$W_{ad} = (W_s + W_{as})(1 + w_1/100)$$

where:
W_{ad} = Mass of sample at water content w_1, g,
W_{as} = Mass of moisture content specimen (usually 500g), g,
w_1 = Water content of prepared material, %.

1.1.2.4 Determine the mass of water (W_{aw}) required to change the water content from the existing water content, w_1, to the desired compaction water content, w.

$$W_{aw} = (W_s + W_{as})[(w - w_1)/100]$$

where:
W_{aw} = Mass of water needed to obtain water content w, g,
w = Desired water content of compacted material, %.

2.2.5 Place a sample of mass W_{ad} into a mixing pan.

2.2.6 Add the mass of water (W_{aw}), needed to change the water content from w_1 to w, to the sample in small amounts and mix thoroughly after each addition.

2.2.7 Place the mixture into a plastic bag. Seal the bag, place it in a second bag and seal it. Cure the sample for 16 to 48 hours, determine the mass of the wet soil and container to the nearest gram and record this value on Report Form 2.

2.2.8 The material is now ready for compaction.

2.3 Compaction

2.3.1 Refer to Annexes A-2, A-3 and A-4 for vibratory, impact and kneading compaction methods.

2.3.2 When the compaction process is complete, carefully open the mold and retrieve the specimen. Record the mass and the dimensions of the specimen on Report Form 2 or 3, as appropriate.

2.3.3 Coarse-grained subgrade specimens should be protected from moisture change by immediately applying the triaxial membrane and testing within 1 day of preparation unless saturation, drying or curing of the specimen is to be carried out.

2.3.4 Store fine-grained subgrade compacted specimens wrapped in impermeable material and placed in a sealed container, for 1 day in a moisture room before testing.

3. Prepare the specimen for testing:

3.1 Place presoaked porous stones no more than 6.25 mm (0.25 in) thick on both the base and the top of the specimen. If clogging of the porous stones is found to be a problem, presoaked filter paper cut to size can be used between the porous stone and the specimen.

3.2.2 Place vacuum grease on the sides of the end platens to facilitate a good seal between the membranes and end platens.

3.2.3 Carefully place the specimen on the porous stone/base. Place the membrane on a membrane stretcher, apply vacuum to the stretcher, then carefully place the membrane on the sample and add the top platen. Remove the membrane from the stretcher, cut off the vacuum and remove the membrane stretcher. Seal the membrane to the top and bottom platens with rubber O rings. A second membrane can be added if puncturing of the membrane is a problem due to the presence of sharp aggregate.

3.2.4 Test for Leaks: Connect the specimen's bottom drainage line to the vacuum source through the medium of a bubble chamber. Apply a vacuum of 35 kPa (5 psi). If bubbles are present, check for leakage caused by poor connections, holes in the membrane, or imperfect seals at the cap and base. The existence of an airtight seal ensures that the membrane will remain firmly in contact with the specimen. Leakage through holes in the membrane can frequently be eliminated by coating the surface if the membrane with liquid rubber latex or by using a second membrane. When leakage has been eliminated, disconnect the vacuum supply line. Carefully clean the O-rings/gaskets used to seal the chamber; also clean all surfaces, which the O-rings will contact.

3.2.5 The specimen is now ready for testing.

ANNEX A-2

NCHRP 1-28 A Project

Vibratory Compaction

Annex A-2 Vibratory Compaction

1. Scope

1.1 This method covers vibratory compaction procedures for use in resilient modulus testing of materials Type 1 and Type 2.

1.2 Split molds with an inside diameter of 152.4 mm (6 in) shall be used to prepare 305 mm (12 in) high test samples for all materials Type 1 or Type 2 having the maximum particle size (d_{max}) greater than 19 mm (¾ in). All material greater than 25.4 mm (1 in) shall be scalped off prior to testing. Split molds with an inside diameter of 101.6 mm (4 in) shall be used to prepare 203.2 mm (8 in) high test samples for all materials Type 1 or Type 2 having the maximum particle size (d_{max}) less than 19 mm (¾ in).

1.3 All specimens shall be compacted in 6 lifts in a split mold mounted on the base of the triaxial cell as shown in Figure A2.1. Compaction forces are generated by a vibratory impact hammer without kneading action powered by air or electricity and of sufficient size to provide the required laboratory densities while minimizing particle breakage and damage to the sample mebrane. Use a special compaction head on the final lift to insure proper specimen alignment (Figure A2.1 (b)).

2. Apparatus

2.1 A split mold, with an inside diameter of 152 mm (6 in) having a minimum height of 381 mm (15 in) (or a sufficient height to allow guidance of the compaction head for the final lift) shall be used for all materials having the maximum particle size (d_{max}) greater than 19 mm (¾ in). For materials having the maximum particle size (d_{max}) less than 19 mm (¾ in), a split mold with an inside diameter of 101.6 mm (4 in) and a minimum height of 254 mm (10 in) may be used.

2.2 Vibratory Compaction Device – Vibratory compaction shall be provided using electric rotary or demolition hammers with a rated input of 750 to 1200 watts and capable of 1800 to 3000 blows per minute.

2.3 The compactor head shall be at least 25 mm (1 in) thick and have a diameter of not less than 146 mm (5.75 in) for the 6 in diameter sample and 97 mm (3.83 in) for the 4 in diameter sample.

3. Procedure

3.1 For removable platens, tighten the bottom platen into place on the triaxial cell base. It is essential that an airtight seal is obtained and that the bottom platen interface with the cell constitutes a rigid joint.

2.3.2 Place the two porous stones and the top platen on the bottom platen. Determine the total height of the top and bottom platens and stones to the nearest 0.25 mm (0.01 in).

2.3.3 Remove the top platen and porous disc if used. Measure the thickness of the rubber membrane with a micrometer.

2.3.4 Place the rubber membrane over the bottom platen and lower porous disc. Secure the membrane to the bottom platen using an O-ring or other means to obtain an air-tight seal.

2.3.5 Place the split mold around the bottom platen and draw the membrane up through the mold. Tighten the split mold firmly in place. Exercise care to avoid pinching the membrane. During equipment calibration, insure by indexing with a dial indicator that the top of the mold is parallel to the base of the triaxial cell.

2.3.6 Stretch the membrane tightly over the rim of the mold. Apply vacuum to the mold sufficient to draw the membrane in contact with the mold. If wrinkles are present in the membrane, release the vacuum, adjust the membrane and reapply the vacuum. The use of a porous plastic forming jacket liner helps to ensure that the membrane fits smoothly inside the mold. The vacuum is maintained throughout the compaction procedure.

2.3.7 Measure to the nearest 0.25 mm (0.01 in) the inside diameter of the membrane lined mold and the distance between the top of the lower porous stone and the top of the mold.

2.3.8 Determine the volume, V, of the specimen to be prepared using the diameter determined in step 2.3.7 and an assumed value of height between 305 and 318 mm (12 and 12.5 in) for 152 mm (6 in) diameter specimens and between 203 and 216 mm (8 to 8.5 in)for 102 mm (4 in) diameter specimens.

2.3.9 Determine the mass of material, at the prepared water content, to be compacted into the volume (V), to obtain the desired density.

2.3.10 For 152 mm (6 in) diameter specimens (specimen height of 305 mm (12 in)) 6 layers of 2 in per layer are required; for 102 mm (4 in) diameter specimens 6 layers of 33.9 mm (1.33 in) per layer shall be used. Determine the weight of the wet soil, W_L required for each layer.

$$W_L = W_t/6$$

where:

W_t = total weight of the specimen to produce appropriate density.

3.11 Place the total required weight of soil for all lifts, W_{ad} into a mixing pan. Add the required amount of water, W_{aw} and mix thoroughly.

3.12 Determine the weight of the wet soil and the mixing pan.

3.13 Place the required amount of wet soil (W_L) into the mold. Avoid spillage. Using a spatula, draw soil away from the inside edge of the mold to form a small mound at the center.

3.14 Insert the vibrator head and vibrate the soil until the distance from the surface of the compacted layer to the rim of the mold is equal to the distance measured in step 3.7 minus the thickness of the layered selected in 3.10. This may require removal and reinsertion of the vibrator several times until the experience is gained in gauging the vibration time, which is required. Use a small circular spirit level to assist in keeping each layer level.

3.15 Repeat steps 3.13 and 3.14 for each new layer after first scarifying the top surface of the previous layer to a depth of about 6.4 mm (1/4 in). The measured distance from the surface of the compacted layer to the rim of the mold is successively reduced by the layer thickness. The final surface should be a smooth plane parallel to the base of the triaxial cell. Use the special compaction head shown in Figure A2.1 (b) for the final lift. As a final step, the top plate shall be placed on the sample and seated firmly by vibrating with the compactor for about 10 seconds. If necessary, due to degradation of the first membrane, a second membrane can be applied to the sample at the conclusion of the compaction process.

3.16 When the compaction process is completed, determine the mass of the mixing pan and the excess soil. This mass subtracted from the mass determined in step 3.12 is the mass of the wet soil used (mass of the specimen). Verify the compaction water, W_c of the excess soil using care in covering the pan of wetted soil during compaction to avoid drying and loss of moisture. The moisture content of this sample shall be conducted using T 265.

NOTE 1 – As an alternative for soils lacking in cohesion, a mold with a membrane installed and held by vacuum may be used.

3.17 Store or prepare the specimen for testing according to Annex 1.

ANNEX A-3

NCHRP 1-28 A Project

Impact Compaction

Annex A-3 Impact Compaction

1. Scope

1.1 This test method covers impact compaction procedures for use in resilient modulus testing. Materials are compacted in a 4 or 6 in. (101.6 or 152.4 mm) diameter mold with a 5.5 lbf (24.4 N) rammer dropped from a height of 12 in. (305 mm) producing a compactive (standard) effort of 12,400 ft-lbf/ft^3 (600 kN-m/m^3), or, with a 10 lbf (44.5 N) rammer, dropped from a height of 18 in. (457 mm) producing a compactive effort (modified) of 56,000 ft-lbf/ft^3 (2700 kN-m/m^3)

NOTE 1 – The method is adapted from ASTM Designations D 698-91 and D 1557-91.

1.2 This test method applies only to soils of Type 1 or Type 3.

NOTE 2 – For materials Type 3 with a high PI, kneading compaction is preferred.

1.3 Two alternative procedures are provided depending on the maximum particle diameter (d_{max}) of the material.

1.3.1 *Procedure A*:

1.3.1.1 *Mold* – 4 in. (101.6 mm) diameter, 8 in. (203.2 mm) height.

1.3.1.2 *Material* – Passing ¾ in. (19.0 mm) sieve.

1.3.1.3 *Layers* – Eight

1.3.1.4 *Blows per layer* – Estimate using Equation 1. Increase or decrease the number of blows/layer until the desired density is achieved.

1.3.2 *Procedure B*:

1.3.2.1 *Mold* – 6 in. (152.4 mm) diameter, 12 in (304.8 mm) height.

1.3.2.2 *Material* – Having a maximum particle diameter (d_{max}) greater than ¾ in. (19.0 mm) sieve.

1.3.2.3 *Layers* – Six

1.3.2.4 *Blows per layer* – Estimate using Equation 1. Increase or decrease the number of blows/layer until the desired density is achieved.

1.4 All material greater than 1 in. (25.4 mm) shall be scalped off prior to compacting. If more than 5% by weight oversize fraction (coarse fraction) will not be included in the test, corrections must be made to the unit weight and water content of the specimen or to the appropriate field in place density test specimen using Practice D 4718.

1.5 The values in inch-pound units are to be regarded as the standard. The values stated in SI units are provided for information only.

1.5.1 In the engineering profession it is customary practice to use, interchangeably, units representing both mass and force, unless dynamic calculations ($F = Ma$) are involved. This implicitly combines two separate systems of units, that is, the absolute system and the gravimetric system. It is scientifically undesirable to combine the use of two separate systems of units within a single standard. This test method has been written using inch-pound units (gravimetric system) where the pound (lbf) represents a unit of force. The use of mass (lbm) is for convenience of units and is not intended to convey the use is scientifically correct. Conversions are given in the SI system in accordance with Practice E 380. The use of balances or scales recording pounds of mass (lbm), or the recording of density in lbm/ft^3 should not be regarded as nonconformance with this standard.

1.6 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 ASTM Standards:

D 698 Standard Test Method for Laboratory Compaction Characteristics of Soils Using Standard Effort (12,400 ft-lbf/ft^3 (600 kN-m/m^3))

D 1557 Test Method for Laboratory Compaction Characteristics of Soil Using Modified Effort (56,000 ft-lbf/ft^3 (2700 kN-m/m^3))

C 127 Test Method for Specific Gravity and Absorption of Coarse Aggregate[2]

C 136 Method for Sieve Analysis of Fine and Coarse Aggregate[2]

D 422 Test Method for Particle Size Analysis of Soils[3]

D 653 Terminology Relating to oil, Rock and Contained Fluids[3]

D 854 Test Method for Specific Gravity of Soils[3]

D1557 Test Methods for Moisture-Density Relations of Soils and Soil Aggregate Mixtures using 10 lb (4.54 kg) Rammer and 18 in. (457 mm) Drop[3]

D 2168 Test Methods for Calibration of Laboratory Mechanical-Rammer Soil Compactors[3]

D 2216 Test Method for Laboratory Determination of Water (Moisture) Content of Soil, Rock and Soil-Aggregate Mixtures[3]

D 2487 Test Method for Classification of Soil for Engineering Purposes[3]

D 2488 Practice for Description of soils (Visual-Manual Procedure)[3]

D 4220 Practices for Preserving and Transporting Soil Samples[3]

D 4253 Test Methods for Maximum Index Density of Soils Using a Vibratory Table[3]

D 4718 Practice for Correction of Unit Weight and Water Content for Soils Containing Oversize Particles[3]

D 4753 Specification for Evaluating, Selecting and Specifying Balances and Scales for Use in Soil and Rock Testing.

E 1 Specification for ASTM Thermometers[4]

E 11 Specification for Wire-Cloth Sieves for Testing Purposes[5]

E 319 Practice for Evaluation of Single-Pan Mechanical Balances[5]

E 380 Practice for Use of the International System of Units (SI) (the Modernized Metric System)[5]

3. Terminology

3.1 *Definitions:* See Terminology D 653 for general definitions.

3.2 *Description of Terms Specific to This Standard:*

3.2.1 *oversize fraction (coarse fraction), P_c* in % - the portion of total sample not used in performing the compaction test; it is the portion of total sample retained on the 1.5 in. (38.1 mm) sieve.

3.2.2 *standard effort* – the term for the 12,400 ft-lbf/ft^3 (600 kN-m/m^3) compactive effort applied by the equipment and procedures of this test.

3.2.3 *modified effort* – the term for the 56,000 ft-lbf/ft^3 (2700 kN-m/m^3) compactive effort applied by the equipment and procedures of this test.

3.2.4 *test fraction (finer fraction) P_F* in % - the portion of the total sample used in performing the compaction test; it is the fraction passing the 1 in. (25.4 mm) sieve.

4. Summary of the Test Method

4.1 A soil at a selected water content is placed in eight (Procedure A) or six (Procedure B) layers into a mold of given dimensions with each layer compacted by the same number of blows of a 5.5 lbf (24.4 N) rammer dropped from a distance of 12 in. (305 mm) (standard effort), or of a 10 lbf (44.5 N) rammer dropped from a height of 18 in. (457 mm) (modified effort).

5. Significance and Use

5.1 Soil placed as engineering fill (embankments, foundation pads, road bases) is compacted to a dense state to obtain satisfactory engineering properties such as, shear strength, compressibility or permeability. Also, foundation soils are often compacted to improve their engineering properties. Laboratory compaction tests provide the means to create specimens with properties similar to those specific to the field compacted materials.

6. Apparatus

6.1 *A split mold*, with an inside diameter of 152 mm (6 in) having a minimum height of 381 mm (15 in) (or a sufficient height to allow guidance of the compaction rammer for the final lift) shall be used for all materials having the maximum particle size (d_{max}) greater than 19 mm (¾ in). For materials having the maximum particle size (d_{max}) less than 19 mm (¾ in), a split mold with an inside diameter of 101.6 mm (4 in) and a minimum height of 254 mm (10 in) may be used.

6.2 *Rammer* – A rammer, either manually operated as described further in 6.2.1, 6.2.2, or mechanically operated as described in 6.2.4.

6.2.1 *Standard Effort* – The rammer shall fall freely through a distance of 12 +/- 0.05 in. (304.8 +/- 1.3 mm) from the surface of the specimen. The mass of the rammer shall be 5.5 +/- 0.02 lbm (2.5 +/- 0.01 kg), except as noted in 6.2.4.1, with a diameter when new of 2.000 +/- 0.005 in. (50.80 +/- 0.13 mm). The rammer shall be replaced if the striking face becomes worn or bellied to the extent that the diameter exceeds 2.000 +/- 0.01 in. (50.80 +/- 0.25 mm).

6.2.2 *Modified Effort* – The rammer shall fall freely through a distance of 18 +/- 0.05 in. (457.2 +/- 1.6 mm) from the surface of the specimen. The mass of the rammer shall be 10 +/- 0.02 lbm (4.54 +/- 0.01 kg), except as noted in 6.2.4.1, with a diameter when new of 2.000 +/- 0.005 in. (50.80 +/- 0.13 mm). The rammer shall be replaced if the striking face becomes worn or bellied to the extent that the diameter exceeds 2.000 +/- 0.01 in. (50.80 +/- 0.25 mm).

NOTE 3 – It is a common and acceptable practice in the inch-pound system to assume that the mass of the rammer is equal to its mass determined using either a kilogram or pound balance and 1 lbf is equal to 1lbm or 0.4536 kg. or 1N is equal to 0.2248 lbm or 0.1020 kg.

6.2.3 *Manual Rammer* – The rammer shall be equipped with a guide sleeve that has sufficient clearance that the free fall of the rammer shaft and head is not restricted. The guide sleeve shall have at least four vent holes at each end (eight holes total) located with centers ¾ +/- 1/16 in. (19.0 +/- 1.6 mm) from each end and spaced 90 degrees apart. The minimum diameter of the vent holes shall be 3/8 in. (9.5 mm). Additional holes or slots may be incorporated in the guide sleeve.

6.2.4 *Mechanical Rammer-Circular Face* – The rammer shall operate mechanically in such a manner as to provide uniform and complete coverage of the specimen surface. There shall be 0.10 +/- 0.03 in. (2.5 +/- 0.8 mm) clearance between the rammer and the inside surface of the mold at its smallest diameter. The mechanical rammer shall meet the calibration requirements of Test Methods D 2168. The mechanical rammer shall be equipped with a positive mechanical means to support the rammer when not in operation.

6.2.4.1 *Mechanical Rammer-Sector Face* – When used with the 6 in. (152.4 mm) mold, a sector face rammer may be used in place of the circular face rammer. The specimen contact face shall have the shape of a sector of a circle of radius equal to 2.90 +/- 0.02 in. (73.7 +/- 0.5 mm). The rammer shall operate in such a manner that the vertex of the sector is positioned at the center of the specimen.

6.5 *Sample Extruder (optional)* – A jack, frame or other device adapted for the purpose of extruding compacted specimens from the mold.

6.6 *Balance* – A class GP5 balance meeting the requirements of Specification D 4753 for a balance of 1-g readability.

6.7 *Drying Oven* – Thermostatically controlled, preferably of a forced-draft type and capable of maintaining a uniform temperature of 230 +/- 9 °F (110 +/- 5 °C) throughout the drying chamber.

6.8 *Straightedge* – A stiff metal straightedge of any convenient length but not less than 10 in. (254 mm). The total length of the straightedge shall be machined straight to a tolerance of +/- 0.0005 in. (+/- 0.1 mm). The scraping edge shall be beveled if it is thicker than 1/8 in. (3 mm).

6.7 *Sieves* – ¾ in. (19.0 mm), conforming to the requirements of Specification E 11.

6.8 *Mixing Tools* – Miscellaneous tools such as mixing pan, spoon, trowel, spatula, etc., or a suitable mechanical device for thoroughly mixing the sample of soil with increments of water.

7. Calibration

7.1 Perform calibrations before initial use, after repairs or other occurrences that might affect the test results, at intervals not exceeding 1000 test specimens, or annually, whichever occurs first, for the following apparatus:

7.1.1 *Balance* – Evaluate in accordance with Specification D 4753.

7.1.2 *Molds* – Determine the volume as described in Annex A1.

7.1.3 *Manual Rammer* – Verify the free fall distance, rammer mass, and rammer face in accordance with Section 6.2. Verify the guide sleeve requirements in accordance with Section 6.2.3.

7.1.4 *Mechanical Rammer* – Calibrate and adjust the mechanical rammer in accordance with Test Methods D 2168. In addition, the clearance between the rammer and the inside surface of the mold shall be verified in accordance with 6.2.4.

8. Test Sample

8.1 The required sample mass for Procedure A is approximately 35 lbm (16 kg), and for Procedure B is approximately 65 lbm (29 kg) of dry soil. Therefore, the field sample should have a moist mass of at least 50 lbm (23 kg) and 100 lbm (45 kg), respectively.

8.2 Determine the percentage of material retained on the ¾ in. (19 mm) as appropriate for choosing Procedure A or B. Make this determination by separating out a representative portion from the total sample and determining the percentages passing the sieves of interest by Test Methods D 422 or Method C 136. It is only necessary to calculate percentages for the sieve for which information is desired.

9. Preparation of Apparatus

9.1 Select the proper compaction mold in accordance with the procedure (A or B) being used. Determine and record its mass to the nearest gram. Assemble the mold.

9.2 Check that the rammer assembly is in good working condition and that parts are not loose or worn. Make any adjustments or repairs. If adjustments or repairs are made, the rammer must be recalibrated.

10. Procedure

10.1 *Soils*:

10.1.1 Do not reuse soil that has been previously laboratory compacted.

10.1.2 Specimen material shall be prepared in accordance with Annex A1

10.2 *Compaction* – After curing, if required, each specimen shall be compacted as follows:

10.2.1 Determine and record the mass of the mold or mold and base plate.

10.2.2 Assemble and secure the mold to the base plate. The mold shall rest on a uniform rigid foundation, such as provided by a cylinder or cube of concrete with a mass of not less than 200 lbm (91 kg). Secure the base plate to the rigid foundation. The method of attachment to the rigid foundation shall allow easy removal of the assembled mold and base plate after compaction is completed.

NOTE 4 – When compacting specimens wetter than optimum water content, uneven compacted surfaces can occur and operator judgement is required as to the average height of the specimen.

10.2.3 Compute the necessary number of blows/layer using Equation 1:

$$n = \frac{CE \cdot V}{N \cdot W \cdot h} \tag{1}$$

where:
n = number of blows per layer
CE = compactive effort (standard or modified as defined in 3.2.2, 3.2.3), ft-lbf/ft^3 or kN-m/m^3
V = volume of the sample, ft^3 or m^3
N = number of layers (8 for procedure A, 6 for procedure B)
W = weight of the rammer, lbf or N
h = drop height, ft or m.

10.2.4 Specimen material shall be prepared in accordance with Annex A1

10.2.5 Specimens shall be compacted in (N) lifts of equal mass. Determine the mass of soil, W_L, required for each lift according to:

$$W_L = W_T/N$$

Where:
W_T = total mass of test specimen to produce the target density.
N = number of layers

NOTE 5 – In most cases the target density will be determined by field conditions. Where this is not the case, an appropriate target density can be determined by performing a laboratory moisture-density test according to the procedure of AASHTO T99 or T180.

10.2.6 Place the mass of wet soil, W_L, for one lift in the mold. In operating the manual rammer, take care to avoid lifting the guide sleeve during the rammer upstroke. Hold the guide sleeve steady and within 5° of vertical. Apply the blows at a uniform rate of approximately 25 blows/min and in such a manner as to provide complete, uniform coverage of the specimen surface.

10.2.7 Light scarify the top surface of the compacted lift to a depth of 3 mm prior to placing soil in the mold for the next lift.

10.2.8 Repeat 10.2.6 and 10.2.7 until (N) lifts have been compacted.

10.2.9 Calculate and record the average bulk (wet) density of the entire specimen γ_S. If the average density differs from the target density by less than the tolerance allowed in Section 7.3.2 or 7.3.3, then proceed with section 2 of Annex A-1.

10.2.10 If the average density differs from the target density by more than the tolerance allowed in Section 7.3.2 or 7.3.3, then increase or decrease the number of blows/layer and repeat compaction.

ANNEX A-4

NCHRP 1-28 A Project

Kneading Compaction

Annex A-4 Kneading Compaction

1. Scope

1.1 This method covers kneading compaction of Type 3 soils for use in resilient modulus testing,

1.2 Specimens shall be compacted in five lifts (layers) in a split mold. Either a pneumatic manual compactor or a hydraulic mechanical compactor provides the compactive effort. The number of tamps per lift and the compaction pressure are constant for all lifts. The compaction pressure is adjusted to achieve the required laboratory density.

2. Significance and Use

2.1 Kneading compaction will yield a structure in Type 3 soils that is characteristically obtained by field compaction methods. Thus, when compacted dry of optimum moisture content the soil structure is mostly flocculated, and when compacted wet of optimum is mostly dispersed.

2.2 This procedure may result in a gradient of soil density within the specimen, which may affect the resilient modulus, M_R. Where it is important achieve a uniform density in all specimen layers, the procedure described in Annex A-4.1 should be used.

3. Apparatus

3.1 Test Specimen Mold – A split mold with a removable collar, as shown in Figure A4.1, shall be used. The minimum mold inside diameter should be 71 mm. The mold shall have a minimum inside diameter not less than 5 times the maximum particle size. The trimmed length of all specimens should be at least two times the diameter.

NOTE 1 – As an alternative for soils lacking in cohesion, a mold with the membrane installed and held by vacuum, as described in Annex A-2, may be used.

3.2 Manual Compactor – A pneumatic manual compactor, as shown in Figure A4.2, may be used. The volume of the air reservoir shall be a minimum of 200 times the volume of the compactor at full piston extension. The compactor rod shall be threaded to receive tamping feet of various diameters from 13 to 19 mm. The reservoir pressure regulator and gage shall be capable of adjusting and reading air pressure from zero to 400 kPa. Calibration shall be checked annually using a calibrated proving ring or load cell.

NOTE 2 – This device is modeled after the Harvard miniature compactor. A pneumatically operated compactor is referred to a spring loaded compactor due to the more consistent compactive effort and reduced operator variability.

3.3 Mechanical Compactor – A hydraulic mechanical compactor capable of applying a foot pressure from 250 to 2000 kPa and meeting the requirements of AASHTO T 190 may be used. When a mechanical compactor is used, the split mold inside diameter shall be chosen as required to work with the compactor, provided that the requirements of Section 3.1 are met.

4. Manual Compaction Procedure

4.1 Specimen material shall be prepared in accordance with Annex A1. The specimen will be fabricated 6 to 8 mm overheight to allow trimming to a square end. Increase the quantity of material preparated to allow for the trimming.

4.2 Specimens shall be compacted in five lifts of equal mass. Determine the mass of soil, W_L, required for each lift according to:

$$W_L = W_T/5$$

Where:

W_T = total mass of test specimen to produce the target density including the allowance for trimming.

NOTE 3 – In most cases the target density will be determined by field conditions. Where this is not the case, an appropriate target density can be determined by performing a laboratory moisture-density test according to the procedure of AASHTO T99 or T180.

4.3 Adjust the air reservoir pressure to the level to be used in the first trial. Thread the desired diameter tamper foot onto the compactor piston. Determine the required number of tamps for one coverage of each lift according to Table A4.1.

NOTE 4 – Maintaining a database of compaction variables, soil types and moisture density conditions will assist with selection of starting air pressure to achieve the desired specimen density.

4.4 Place the mass of wet soil, W_L, for one lift in the mold. Using a spatula, draw the soil away from the edge of the mold to form a slight mound in the center.

4.5 holding the compactor vertically, apply the required number of tamps to the soil. Tamps should be distributed evenly over the specimen cross-section. Each tamp should be applied slowly with just enough force to move the piston approximately 5 – 10 mm in the compactor.

NOTE 5 – *Caution.* The piston should not be moved all the way to the end of the compactor, as this will cause an unregulated force o be applied.

4.6 Light scarify the top surface of the compacted lift to a depth of 3 mm prior to placing soil in the mold for the next lift.

4.7 Repeat 4.5 and 4.6 until 5 lifts have been compacted. Continue with Section 6.1.

5. Mechanical Compaction Procedure

5.1 Specimen material shall be prepared and weighed in accordance with Section 4.1 and 4.2

5.2 Adjust the foot pressure to the level to be used in the first trial.

5.3 Place the mass of wet soil, W_L, for one lift in the mold. Using a spatula, draw the soil away from the edge of the mold to form a slight mound in the center.

5.4 Apply one revolution of tamps to the first lift (normally 5 to 7 tamps per revolution, according to AASHTO T 190) to achieve one coverage over the specimen cross section.

Table 4.1 Number of Tamps for One Coverage of a Lift – Manual Procedure

Specimen Diameter	Tamper Foot Diameter			
	13 mm	15 mm	17 mm	19 mm
71 mm	30	22	17	14
86 mm	44	33	26	20
102 mm	62	46	36	29
152 mm	137	103	80	64

5.5 Lightly scarify the top surface of the compacted lift to a depth of 3 mm prior to placing coil in the mold for the next lift.

5.6 Repeat 5.3 through 5.5 until 5 lifts have been compacted.

6. Specimen Trimming and Calculations

6.1 Remove the collar and carefully screed off the specimen to the top of the mold. Small depressions in the screeded surface caused by removal of larger particles shall be filled with fines. Remove the split mold from the base halves from the specimen.

6.2 Determine and record the mass of the entire specimen to the nearest gram. Use a tabular form as in Figure A4.3 to record the data.

6.3 Determine and record the moisture content of the remaining soil according to AASHTO T 265.

6.4 Calculate and record the average bulk (wet) density of the entire specimen γ_S. If the average density differs from the target density by less than the tolerance allowed in Section 7.3.2 or 7.3.3, then proceed with section 2 of Annex A-1.

6.5 If the average density differs from the target density by more than the tolerance allowed in Section 7.3.2 or 7.3.3, then the compaction pressure shall be adjusted to increase or decrease the average density toward the target density. Repeat 4.4 or 4.5.

NOTE 6 – If a sufficient quantity of material is available it is preferable to use new material for each subsequent specimen. If the old material is reused this will have an effect on the structure of subsequently compacted specimens.

ANNEX A-5

NCHRP 1-28 A Project

Grouting

Annex A-5 Specimen End Preparation

To give better contact between the top and bottom plates and the specimen, the ends of specimens can be grouted with hydrostone. The clamps used to grout the specimen ends are shown in Figure A5.1. The grouting procedure is shown in Figure A5.2 and described as follows:

1. Mix 28 ml of water with 70 gm of hydrostone cement until it becomes a liquid. The water-hydrostone cement (W/C) ratio is 0.4 by weight.
2. Let the mixture hydrate for about 15 min. as to become a paste.
3. Pour the paste into the aluminum split clamps around the pedestal shown in Figure A5.2 (a). Place the sample on top of the hydrostone grout.
4. Center the sample vertically by using an acrylic plate with 5.0 in diameter hole in the middle and supported horizontally on three steel rods fixed to the base of the triaxial cell as shown in Figure A5.2 (b).
5. Remove the clamps from around the bottom of the sample 10 min. after pouring the grout into the mold.
6. Repeat steps 1 and 2.
7. Place the clamps around the top end of the sample using the acrylic plate as a support as shown in Figure A5.2 (b).
8. Repeat step 3.
9. Place the top cap on the top of the hydrostone paste and center it in the direction to fit the LVDT clamps.
10. Place a rubber membrane around the specimen and form a seal using two rubber O-rings. Leave it for about two hours to allow the hydrostone paste to reach its required strength.
11. Fix the LVDT rod carriers to the bottom of the triaxial cell and attach the LVDT's to them.

The specimen is now ready for testing.

ANNEX A-6

NCHRP 1-28 A Project

Obtaining a Uniform Density in Type 3 Soils

Annex A-6 Obtaining a Uniform Density in Type 3 Soils

1. SCOPE

1.1 This method provides procedures for measuring and minimizing or eliminating density gradients in a specimen of Type 3 soil for use in resilient modulus testing.
1.2 Specimens should be compacted in five lifts (layers) in a density gradient mold. Kneading compaction (Annex A-4) shall be used. The number of tamps per lift shall be adjusted for each lift to avoid imparting a density gradient to the specimen.

2. Significance and Use

2.1 A specimen fabricated in layers, with each lift receiving equal compactive effort, will typically exhibit a density gradient with the first lift compacted being more dense than the last. To measure this effect, the density gradient mold is used to determine the density of each lift. A trial and error process is used to adjust the compactive effort for each lift until the desired specimen density is obtained with minimum gradient.
2.2 Density gradients can occur with vibratory (Annex A-2), impact (Annex A-3) or kneading (Annex A-4) compaction methods. The density gradient mold can be used in conjuctioon with any of the three compaction methods to measure density gradients from top to bottom within the specimen.
2.3 For the most accurate characterization of resilient modulus, the density gradient within the test specimen should be minimized. The test specimen should have a structure that closely approximates the one that will be obtained in field compaction. The use of kneading compaction can help to achieve the proper structure.

3. Apparatus

3.1 Density Gradient Mold – The density gradient mold is shown in Figure A-6-1. This is a split mold with the inside milled to receive 5 interchangeable solid rings that have been permanently numbered from 1 to 5. The ring I.D. shall be equal to the mold I.D. The mold height and diameter shall be the same as is used in preparing specimens for the resilient modulus testing (Annex a-4).
3.2 Compactor – To measure the density gradient (using section 5.4), the same type of compactor shall be used as is used in preparing specimens for resilient modulus testing, as described in Annex A-2, A-3 or A-4. To minimize the density gradient (using section 5.5), either a manual or mechanical kneading compactor, as described in Annex A4, shall be used.

4. Procedure for Compacting Specimens to Measure Density Gradients

4.1 Specimen material shall be prepared in accordance with Annex A-1. If the maximum particle size exceeds 25 percent of the mold inside diameter, the oversize particles shall be scalped. The specimen will be fabricated 6 to 8 mm over height to allow trimming to a square end. Increase the quantity of material prepared to allow for the trimming.
4.2 Specimens shall be compacted to the same diameter, and using the same apparatus and procedure as is used in preparing specimens for resilient modulus testing, as described in Annex A-2, A-3 or A-4.
4.3 Remove the collar and carefully screed off the specimen to the top of the mold. Small depressions in the screeded surface, caused by removal of larger particles, shall be filled with fines. Remove the split mold from the base and the mold halves from the specimen. Leave the five rings on the specimen.
4.4 Determine and record the net mass of the entire specimen to the nearest gram. To do this subtract the mass of the specimen with rings attached.
4.5 Determine and record the moisture content of the remaining soil according to AASHTO T 265.
4.6 Using a hacksaw or other abrasive device, carefully cut the specimen into 5 pieces. Each cut should be made midway between the rings. Screed off each piece to form square ends at the top and bottom of each ring. Small depressions in the screeded surface, caused by removal of larger particles, shall be filled with fines.
4.7 Determine and record the net mass of each numbered piece to the nearest gram. Use a tabular form, as in figure A-5-2, to record the data.
4.8 Determine and record the moisture content of each numbered piece.
4.9 Calculate and record the average bulk (wet) density of the entire specimen, γ_s, and densities of each 5 pieces, γ_s to γ_5.
4.10 If the maximum difference between the density of each individual piece and the average

density is 1.0 percent or less, report the density gradient as being uniform. If the maximum difference between the density of each individual piece and the average density is more than 1.0 percent, report the density gradient as being non-uniform.

5. Procedure for Compacting Test Specimens to Achieve a Uniform Density

5.1 Follow the procedure in Sections 4.1 through 4.9, using either the manual or mechanical kneading compaction procedure (Annex A-4).

NOTE 1 – The requirements in Annex A-4 that the number of tamps per lift be constant is waived. However, it is recommended that the number of tamps per lift be constant for each lift in the first trial specimen in order to establish that a density gradient does exist.

5.2 If the average bulk density differs from the target density by more than the tolerance allowed in Section 7.3.2 or 7.3.3, then the compaction pressure shall be adjusted, holding the number of tamps per lift constant, to increase or decrease the average density toward the target density. Repeat 5.1

5.3 After the target average density is achieved, check the density uniformity according to Section 4. If the density is non-uniform, hold the compaction pressure constant and adjust the number of tamps per lift until a uniform density gradient is achieved.

NOTE 2 – If a sufficient quantity of material is available, it is preferable to use new material for each subsequent specimen. If the old material is reused it will have an effect on the structure of subsequently compacted specimens.

Use the compaction pressure and number of tamps per lift thus determined to prepare specimens for resilient modulus testing using the procedure in Annex A-4.

APPENDIX B

NCHRP 1-28 A Project

Test Data

APPENDIX C

NCHRP 1-28 A Project

Statistics, Charts and Plots

NCHRP 1-28A

Standard Test Method for Determining the Resilient Modulus of Bituminous Mixtures by Indirect Tension

1. SCOPE

1.1 General

This proposed protocol describes procedures for the determination of the resilient modulus of hot mix asphalt concrete (HMA), using repeated load indirect tensile test techniques. The procedure involves resilient modulus testing at 77°F.

1.2 Testing Prerequisites

Resilient modulus testing shall be conducted after system response has been verified by testing synthetic specimens, as outlined in section 8.1 of this protocol.

1.3 Sample Size

Resilient modulus testing shall be conducted on 6-inch diameter specimens that are 1.5 inches to 2.5 inches in thickness. The test specimens can be obtained from field coring or from a Gyratory compacted specimen. Depending upon the height of the Gyratory compacted specimen and the thickness of the test specimen, two or three specimens can be sawed from the Gyratory plug.

1.4 Pretest Tensile Strength

Prior to performing the resilient modulus test the indirect tensile strength shall be determined for one test specimen taken from the same layer and as close as possible to the location of the core specimen(s) to be tested for resilient modulus. For lab specimens, a sample having the same mix properties will be selected for indirect tensile strength testing. The indirect tensile strength test is performed as a basis for selecting the loading levels for the resilient modulus testing. Test shall be performed in accordance with attachment A of SHRP P07 protocol (November 1, 1992).

1.5 Definitions

The following definitions are used throughout this protocol:

(a) Layer – that part of the pavement produced with similar material and placed with similar equipment and techniques. The layer thickness can be equal to or less than the core thickness or length.

(b) Core – an intact cylindrical specimen of pavement materials which is removed from the pavement by drilling and sampling at the designated core location. A core may consist of, or include, one, two or more different layers.

(c) Test Specimen – that part of the layer which is used for, or in, the specified test. The thickness of the test specimen can be equal to or less than the layer thickness.

(d) Haversine Shaped Load Form - the required load pulse from the resilient modulus test. The load pulse is in the form $(1-\cos\theta)/2$ and the cyclic load is varied from the contact load ($P_{contact}$) to the maximum load (P_{max}), as shown in Figure C-1 (from SHRP P07 protocol).

(e) Maximum Applied Load (P_{max}) – the maximum total load applied to the sample, including the contact and cyclic (resilient) loads.

$$P_{max} = P_{contact} + P_{cyclic}$$

Contact Load ($P_{contact}$) – the vertical load placed on specimen to maintain a positive contact between the loading trip and the specimen. The contact load is four percent of the maximum load (0.04 P_{max}) and is not less than 5 lbs, but not more than 20 lbs.

(f) Cyclic Load (Resilient Vertical Load, P_{cyclic}) – load applied to a specimen, respectively, which is directly used to calculate resilient modulus.

$$P_{cyclic} = P_{max} + P_{contact}$$

(g) Instantaneous Resilient Modulus – determined from the deformation-time plots (both horizontal and vertical) as described herein.

To determine the instantaneous deformation values, it is recommended to perform regression in three portions of the deformation curve:

1. Linear regression in the straight portion of the unloading path.

2. Regression in the curved portion that connects the unloading path and the recovery portion to yield the following hyperbolic equation:

$$Y = a + b/X$$

Where

Y = deformation value,
X = time, and
a, b = regression constants

3. Regression in the recovery portion between 40% and 90% (recommended range) of the rest period to yield a hyperbolic

equation. A tangent should be drawn to this hyperbola at the point correspondence to 55% (recommended point) of the rest period.

Two linear equations, one from the unloading path and other from the tangent of the hyperbola in the recovery period, shall be solved to determine the intersection. Then the point on the hyperbolic curve corresponding to the time coordinate of the intersection (for convenience, say point A) is selected to determine the instantaneous deformation by subtracting the deformation at the point A from the peak deformation.

(h) Total Resilient Modulus – determine from the deformation-time plots (both horizontal and vertical) by subtracting deformation obtained at the end of one load-unload cycle, as determined by taking the average of deformation values obtained for the time period between 85% completion to 95% completion of the rest period from the peak deformation values. This value includes both the instantaneous recoverable deformation and the time-dependent continuing recoverable deformation during the rest period portion of one cycle.

2. APPLICABLE DOCUMENTS

SHRP Protocol P07	Resilient Modulus for Asphalt Concrete (November 1, 1992)

3. SUMMARY OF METHOD

3.1 The repeated-load indirect tension resilient modulus test of asphalt concrete is conducted through repetitive applications of compressive loads in a haversine waveform. The compressive load is applied along a diametral plane of a cylindrical Asphalt Concrete specimen. The resulting horizontal and vertical deformations are measured. Values of resilient Poisson's ratio shall be calculated using recoverable vertical and horizontal deformations. The resilient modulus values are subsequently calculated using the calculated Poisson's ratio.

3.2 Two separate resilient modulus values are obtained. One, termed instantaneous resilient modulus, is calculated using the recoverable horizontal deformation that occurs during the unloading portion of one load-unload cycle. The other, termed total resilient modulus, is calculated using recoverable deformation which includes both the instantaneous recoverable and time-dependent continuing recoverable deformation during the unload or rest-period portion of one cycle.

3.3 For each resilient modulus test, the following general procedures must be followed:

(a) The tensile strength is determined on the test specimen at 77 ± 2°F using the procedure described in attachment A to SHRP P07 protocol. The value of tensile strength obtained from this procedure is used to determine the indirect tensile stress and corresponding compressive load to be respectively applied to the test specimens during the resilient modulus determination.

(b) The test specimen(s) are to be tested along two perpendicular diametral axes at test temperatures of 77 ± 2°F. A repetitive haversine load pulses of 0.1 second duration followed by a rest period of 0.9 seconds between load pulses are applied to the individual test specimens. The magnitude of the load pulse will be selected to produce a predefined indirect tensile stress on the specimen based on a percentage of the indirect tensile strength (see section 3.3(a) above).

(c) After completion of resilient modulus testing along the two perpendicular diametral planes, indirect tensile strength shall be performed in accordance with attachment A of the SHRP P07 protocol. This test is performed to determine the tensile strength of the specific specimen actually used in resilient modulus testing. For this specimen the loading axis shall be 90° to the second diametral axis used for modulus determination.

4. SIGNIFICANCE AND USE

Resilient modulus can be used in evaluation of materials quality and as input for pavement design, evaluation and analysis. With this method, the effects of temperature and load on resilient modulus can also be investigated.

5. APPARATUS

5.1 Testing Machine

The testing machine shall be a top loading, closed loop, electro-hydraulic testing machine with a function generator which is capable of applying a haversine shaped load pulse over a range of load durations, load levels, and rest periods.

5.2 Loading Device

The loading device should be capable of testing 6 inch diametral specimen with thickness up to 2.5 inches. The device should be compact enough to be used within the environmental chamber. It should have a fixed bottom loading plate and a moving upper loading plate. The movement of the upper plate should be guided by two columns, one on each side of the specimen and equidistance from the loading axis and the loading strips, to ensure it has minimal translational or rotational motion during loading of the specimen. The guide columns shall have a frictionless bearing surface that shall be kept well lubricated. The surface of the guide columns shall be frequently inspected for any grooves caused due to friction. Alignment of the device, within the loading system, shall be achieved so that such friction is limited to the minimum possible extent. The upper plate shall be rigid enough to prevent any deflections during loading. If heavyweight plates are used to achieve rigidity, the testing should be able to counteract all the weight, such that no more than 2 lbs. of load is transferred to the specimen when the load is not being applied. It is recommended that high strength material be used to achieve rigidity and keep the weight small. The loading strips shall preferably be perpendicular to the line connecting the two guide columns, so that visual alignment of the sample in the device is easier.

5.3 Temperature Control System

The temperature-control system should be capable of maintaining temperature control within 2°F (1.1°C), at a setting value of 77°F (25°C). The system shall include a temperature-controlled cabinet large enough to house the loading device, and a cabinet adequate to pre-condition at least three test specimens at a time prior to testing.

5.4 Measurement and Recording System

The measuring and recording system shall include sensors for measuring and simultaneously recording horizontal and vertical deformations and loads. The system shall be capable of recording horizontal and vertical deformations in the range of 0.000015 inch (0.00038 mm) of deformation. Load cells shall be accurately calibrated with a resolution of 2 lbs. or better.

5.4.1 Data Acquisition – The measuring or recording devices must provide real time deformation and load information and should be capable of monitoring readings on tests conducted to 1 Hz. Computer monitoring systems are recommended. The data acquisition system shall be capable of collecting 200 scans per second (a scan includes all deformation and load values at a given point of time). Capability to have real-time plots (simultaneous to the data collection by the computer monitoring system) shall also be provided to check the progress of the test. If strip chart recorders are used without computer monitoring systems, the plotting scale shall be adjusted such that there is a balance between the scale reduction required as a result of the pen reaction time and the scale amplification needed for purposes of accurate measurement of values from a plot.

Actual load values, and not the intended load values, shall be used for calculation purposes and so the data acquisition system shall also be capable of monitoring the load values continuously during testing.

5.4.2 Deformation Measurement – Both horizontal and vertical deformation shall be measured on the surface of the specimen by mounting LVDTs between gage points along the horizontal and vertical diameter. The gage length shall be half the diameter of the specimen (3 inch for 6 inch diameter specimen). It is required to have the two LVDTs, on each face of the specimen, one horizontal and one vertical resulting in a total of four LVDTs for deformation measurement. Extensometers, if used, should also be calibrated from time to time. The surfaces on which the knife edges of the extensometer assembly rests should be kept smooth and free of grooves.

5.4.3 Load Measurements – The repetitive loads shall be measured with an electronic load cell with a capacity adequate for the maximum required loading, and a sensitivity of 0.5% of the intended peak load.

During periods of resilient modulus testing, the load cell shall be monitored and checked once a month with a calibrated proving ring to assure that the load cell is operating properly. Additionally, the load cell shall be checked at any time that the QA/QC testing with in-house synthetic specimen (section 8.1) indicates a change in the system response or when there is a suspicion of a load cell problem.

5.5 Loading Strips

Steel loading strips, with concave sample contact surfaces, machined to the radius of curvature of a 6.000 ± 0.006 inch diameter specimen, are required to apply load to the test specimens. The contact area of the loading strip shall be ¾ inches wide. The outer edges of the curved surface shall be filed lightly to remove sharp edges that might cut the specimen during testing. Thin lines should be drawn along the length of the strip at its center, to help alignment. Also, appropriate marking should be made so as to center the specimens within the length of the strips. This could be either done by matching the center of specimen with a mark at the center of the strip or by positioning the specimen between two marks at the ends of the specimen thickness, or both.

5.6 Marking and Alignment Devices

A marking device shall be used to mark mutually perpendicular axes on the front and back faces of the specimen through the center. The axes shall be simultaneously marked on the front and back faces of the specimen to ensure that the axes on the front and the back lie in a single plane.

An alignment device shall be used to position and place horizontal and vertical LVDTs along the horizontal and vertical diameter of the specimen and hold it there, until the glue that holds the LVDTs cures. It shall be easily removable, without disturbing the LVDT (once the glue cures), and shall not be destructively mounted on the specimen. The device shall preferably have the capability to mount the LVDT at different gage lengths but mainly at a gage length of half the diameter of the specimen. The LVDT shall be as close to (but not touching) the surface of the specimen so as to minimize the bulging effect. To ensure uniform test results, a height of 0.2 inch is recommended. The axis of LVDT shall not be at a distance greater than 0.25 inch from the surface of the specimen.

6. TEST SPECIMEN

6.1 Core specimen - cores for test specimen preparation, which may contain one or more testable layers, must have smooth and uniform vertical (curved) surfaces, and must be no less than 5.85 inch or more than 6.15 inch in diameter. Cores which are obviously deformed or have any visible cracks must be rejected. Irregular top and bottom surfaces shall be trued up as necessary, and individual layer specimens obtained by cutting with a diamond saw using water or air as a coolant.

6.2 The test specimen designated for testing shall not be more than 2.5 inches in thickness. However, for base course or large-stone mixes the thickness shall not be greater than 3.5 inches. If a core specimen has more than one layer the layers shall be separated at the layer interface by sawing. Layers containing more than one lift of the same material as placed under contract specification, may be tested as a single specimen. Traffic direction shall be marked on each layer after cutting, to maintain the correct orientation. Layers too thin to test (less than 1.5 inch for 6 inch diameter specimen), as well as any thin surface treatments, shall be removed and discarded.

A test specimen shall consist of a single pavement material or layer greater than 1.5 inches in thickness. The desired thickness for testing is approximately 2.0 inches for a 6 inch diameter specimen. If the thickness of a particular AC layer scheduled for testing is one inch or more greater than the desired testing thickness, then the specimen to be used for testing shall be obtained from the middle of the AC layer is between 1.5 and 2.5 inches for a 6 inch diameter specimen, and has relatively smooth front and back faces then no sawing is required and the specimen for this layer may be tested as is.

6.3 Diametral Axis – Marking of the diametral axis to be tested shall be done using a suitable marking device as described in section 5.6. The axis shall be parallel to the traffic direction symbol (arrow) or "T" marked during the field coring operations. This diametral axis location can be rotated slightly, if necessary, to avoid contact of the loading strips with abnormally large aggregate particles or surface voids; or to avoid the mounting of the vertical LVDT over large surface voids. The second making will be perpendicular to the first marked diametral axis. These marking are required for mounting horizontal and vertical LVDTs.

6.4 The thickness (t) of each test specimen shall be measured to the nearest 0.01 inch (0.25 mm) prior to testing. The thickness shall be determined by averaging four measurements located at ¼ points around the sample perimeter, and ½ to 1 inch in from the specimen edge.

6.5 The diameter (D) of each test specimen shall be determined prior to testing to nearest 0.01 inch (0.25 mm) by averaging diametral measurements. Measure the diameter of the specimen at mid-height along (1) the axis parallel to the direction of traffic and (2) the axis perpendicular (90 degrees) to the axis measured in (1) above. The two measurements shall be averaged to determine the diameter of the test specimen.

7. PROCEDURE

7.1 General

For deformation measurement both in the horizontal and vertical direction, mount the gage points by gluing them to the test specimen. Wait until the gage points are properly set and the glue is dry. The asphalt cores are then placed in a controlled temperature cabinet/chamber and brought to the specified test temperature. Unless the core specimen temperature is monitored in some manner and the actual temperature known, the core samples shall remain in the cabinet/chamber for a minimum of 6 hours prior to testing at 77°F (25°C).

(a) Determine the tensile strength of the test specimens at 77° ± 2°F using the procedure described in Attachment A to SHRP Protocol P07.

(b) The test specimen(s) designated for resilient modulus testing shall be brought to the test temperature (77 ± 2°F) as specified in section 7.1.

(c) Attach the LVDTs on the two faces of the specimen. This consists of two horizontal and two vertical LVDTs. The electronic measuring system shall be adjusted and gains set as necessary for the four LVDTs. Prior to testing, zero the extensometers and the surface-mounted LVDTs. An initial negative offset might be necessary if high gain is being used and/or there is a possibility of exceeding the range of voltage otherwise.

7.2 Alignment and Specimen Seating

Position the test specimen so that the mid-thickness mark (cross mark for the two diamteral axis) on the test specimen is located in the line of action of the actuator shaft or alternately, ascertain that the specimen is centered exactly between end markings on loading strips. The diametral markings are then used to ensure that the specimen is aligned from top to bottom and front to back. The alignment of the front face of the specimen can be checked by ensuing that the diametral marking is centered on the top and bottom loading strips. With the use of a mirror, the back face can be similarly aligned.

The contact surface between the specimen and each loading strip is critical for proper test results. Any projections or depressions in the specimen to strip contact surface, which leave the strip in non-contact condition over a length of more than 0.75 inches after completion of load conditioning stage, shall be reason for rotating the test axis or rejecting the specimen. If no suitable replacement specimen is available, test shall be conducted on the available sample and the situation documented.

7.3 Preconditioning

Preconditioning and testing shall be conducted while the specimen is located in a temperature-controlled cabinet meeting the requirements of section 6.3.

7.3.1 Selection of applied loads for preconditioning and testing at the test temperature is based on the indirect tensile strength, determined as specified in Attachment A to the SHRP Protocol P07. Tensile stress levels of 15 percent of the tensile strength measured at 77°F are to be used in conducting the test at temperature of 77 ± 2°F. Specimen contact loads specified in section 1.5 (e) shall be maintained during testing.

7.3.2 The sequence of resilient modulus testing shall consist of initial testing along the first diametral axis (or along the traffic direction for the field cores) followed by rotating the specimen at 90 degree. It is important that the test specimen be maintained at 77°F. The computer-generated waveform shall be as closely matched as possible by adjusting the gains. The number of load applications to be applied for each rotation for preconditioning cycles is 100. However, the minimum number of load application for a given situation must be such that the resilient modulus deformations are stable (section 7.5.1). When, using more preconditioning cycles, the number of preconditioning cycles shall be recorded and the reason documented. Also, if specimen has to be realigned, or when precondition has to be stopped for any other reason, sufficient time should be given to the specimen for relaxation before resuming the test.

7.4 Horizontal and Vertical Deformation

Both the horizontal and vertical deformations shall be monitored during preconditioning. If total cumulative vertical deformations greater than 0.03 inch occur, the applied load shall be reduced to the minimum value possible and still retain adequate deformations for measurement purposes. If use of smaller load levels are not adequate for measurement purposes, discontinue preconditioning and generate 10 load pulses for resilient modulus determination, and so indicate on the test report.

7.5 Testing

At the end of preconditioning for each rotation, the resilient modulus shall be conducted as specified below.

7.5.1 Record measured deformation individually from the four deformation measuring devices and the load sensor as soon as preconditioning is over (the load pulses are to be applied continuously through preconditioning and data collection for resilient modulus). The response is only recorded (deformation and load) for the last 5 loading cycles of the total applied load pulses. One loading cycle consists of one load pulse and a subsequent rest period. The resilient modulus will be calculated and reported for each cycle using the equations in section 9 of this protocol.

7.5.2 After the specimen has been tested along the first diametral plane, rotate the specimen 90 degree and repeat section 7.3.2 through section 7.5.1 of this protocol.

7.5.3 After testing is completed for both the diametral axis, the specimen shall be brought to a test temperature of 77 ± 2°F and an indirect tensile strength test conducted on the test specimen as specified in Attachment A of SHRP P07.

7.6 Cumulative Deformation

The cumulative horizontal and vertical deformation shall be determined as per Attachment C of the SHRP P07 Protocol.

8. QUALITY ASSURANCE/QUALITY CONTROL

8.1 Prior to the start of resilient modulus testing each week, the laboratory testing personnel shall perform testing on one or more of in-house QA/QC synthetic specimens. The synthetic specimen should be selected for QA/QC to provide a response similar to the expected asphalt concrete specimen response at 77°F. Typically, materials such as Polyethylene may be used to verify the system response. The synthetic specimens shall be tested at a temperature of 77°F, at a load time of 0.1 second and a rest period of 0.9 second on both the axes at a load level expected for the AC samples.

However, QA/QC testing shall be done whenever alignment of the loading system may have changed.

The specimens shall be tested as follows:

8.1.1 The specimen shall be located in a temperature-controlled cabinet meeting the requirements of section 5.3 and at a temperature of 77°F. The applied loads for preconditioning and testing for the synthetic specimens are defined below.

8.1.2 The test specimen shall be preconditioned along the proper axis prior to testing by applying a minimum of 100 cycles of the specified haversine-shaped load pulse of 0.1 second duration with a rest period of 0.9 second. The computer generated wave form shall be matched as closely as possible by adjusting gains and preconditioning shall continue until both horizontal and vertical deformations are stable and appear to be uniform.

8.2 The results from the QA/QC testing shall be stored as a permanent record of the system response to obtain the system fingerprint. If all the synthetic specimens have not been tested for each set of 100 resilient modulus tests, QA/QC testing shall be performed on the remaining synthetic specimens in order to verify the system response.

9. CALCULATIONS

The following equations are intended for the calculation of either instantaneous or total values depending upon whether instantaneous or total deformation values are used. Consider horizontal deformation as positive and vertical deformation as negative. The load value is assumed to be positive.

9.1 Poisson's ratio:

Poisson's ratio shall be calculated from the vertical and horizontal deformation values by the use of the following equations:

$$\mu = \frac{-1.0695 - 0.2339\dfrac{\delta_v}{\delta_h}}{0.3074 + 0.7801\dfrac{\delta_v}{\delta_h}}$$

where:

μ = instantaneous or total Poisson's ratio,
δ_v = the recoverable vertical deformation measured over a gage length equal to three quarters of the diameter of the specimen, inches, and
δ_h = the recoverable horizontal deformation measured over the horizontal diameter of the specimen, inches.

It is expected that the Poisson's ratio is 0.25 – 0.45. When the calculated Poisson's ratio is outside the ranges defined above, the calculated values shall be reported and a visual inspection of the specimen should be made to study the deformation in shape and/or presence of cracks due to damage, and so reported.

The Poisson's ratio must be calculated for each set of LVDTs (horizontal and vertical). That is for the first diametral plane, two Poisson's ratio values are estimated. These are obtained from the two faces of the specimen. Another set of Poisson's ratio values are obtained after rotation, resulting in a total of four Poisson's ratio values for a single specimen.

9.2 Resilient modulus:

The resilient modulus can then be calculated from the Poisson's ratio, as obtained from section 9.1, and the recoverable horizontal deformation (instantaneous or total) according to the following equation.

$$M_R = \frac{P_{cyclic}}{\delta_h t}(0.2339 + 0.7801\mu)$$

where:

M_R = instantaneous or total resilient modulus, psi,
δ_h = recoverable horizontal deformation, inches,
P_{cyclic} = $P_{max} - P_{contact}$
= cyclic load applied to specimen, lbs.,
P_{max} = maximum applied load, lbs.
$P_{contact}$ = contact load, lbs., and
μ = instantaneous or total Poisson's ratio.

For each horizontal deformation, corresponding Poisson's ratio value must be used, resulting in a total of four resilient modulus values for a single specimen.

9.3 Replicates:

The test procedure is applicable both for the laboratory compacted and field cores. In laboratory the test specimen are obtained from Gyratory compaction. From the compacted Gyratory plug with a height of 6 inches, three test specimens with a thickness equal to 1.5 inch can be obtained. It is recommended that both ends of the Gyratory plug be sawed 0.25 inch to obtain a smooth surface. This will result in three replicates from a given Gyratory plug. In case of field cores, three field samples are needed from a homogeneous section.

Three test samples will result in a total of twelve Poisson's ratio and resilient modulus values (4 values for each sample). It is important to report the individual values, average and the standard deviation of Poisson's ratio and the resilient modulus.

10. REPORT

10.1 The following general information shall be recorded:

10.1.1 Sample Identification.

10.1.2 Average thickness of the test specimen (t), to the nearest 0.01 inch (as per section 6.4)

10.1.3 Average diameter of the test specimen (D), to the nearest 0.01 inch (as per section 6.5)

10.1.4 Indirect tensile strength (initial), to the nearest psi.; from a comparable test specimen used to select the stress (or load) level for the testing.

10.1.5 Indirect tensile strength (final), to the nearest psi.; for the test specimen after the resilient modulus test has been completed.

10.1.6 Comments: The following (and additional, if so required) comments should be recorded, when relevant.

(a) If sawing was required for core specimens.

(b) If the specimen was skewed (either end of the specimen departed from perpendicularity to the axis by more than 0.5 degrees or 1/8 inch in 12 inches), as observed by placing the specimen on a level surface and measuring the departure from perpendicularity.

(c) If a "dummy" specimen was used to monitor the temperature. If not, the time specimen was maintained at the test temperature in the environmental chamber.

(d) If tests could not be completed due to damage/failure of test specimen.

(e) If the projections/depressions on the test surface were higher or deeper than 1/16 inch and the specimen was tested as no replacement specimen was available. Record the projections/depressions in such a case.

(f) If for core specimens, no traffic direction was marked, or if test was not performed on the marked axis due to some reason.

10.2 The following information shall be recorded:

10.2.1 Instantaneous Resilient Modulus:

(a) The vertical load levels (P_{cyclic})

(b) The contact load ($P_{contact}$) used over the last 5 loading cycles.

(c) Instantaneous recoverable horizontal and vertical deformations measured over the last five cycles.

(d) The calculated instantaneous Poisson's ratio (μ_i) over the last 5 loading cycles for each temperature.

(e) The calculated instantaneous resilient modulus (M_{ri}) over the last 5 loading cycles for each test temperature.

(f) The average and standard deviation of calculated instantaneous Poisson's ratio and instantaneous resilient modulus for all the replicates used for a given mix type.

10.2.2 Total Resilient Modulus:

(a) The vertical load levels (P_{cyclic})

(b) The contact load ($P_{contact}$) used over the last 5 loading cycles.

(c) Total recoverable horizontal and vertical deformations measured over the last five cycles.

(d) The calculated total Poisson's ratio (μ_t) over the last 5 loading cycles for each temperature.

(e) The calculated total resilient modulus (M_{rt}) over the last 5 loading cycles for each test temperature.

(f) The average and standard deviation of calculated total Poisson's ratio and instantaneous resilient modulus for all the replicates used for a given mix type.

10.2.3 Permanent Horizontal and Vertical Deformations:

(a) The number of preconditioning cycles used for each rotation.

(b) The cumulative permanent vertical deformation measured, including the preconditioning cumulative deformation and the resilient modulus testing cumulative deformation.

(c) The cumulative permanent horizontal deformation measured, including the preconditioning cumulative deformation and the resilient modulus testing cumulative deformation.

(d) The total number of load cycles conducted during the test. This includes the number of cycles for preconditioning and those cycles conducted for the determination of resilient modulus.

(e) The cumulative vertical deformation measured after preconditioning prior to initiation of resilient modulus testing.

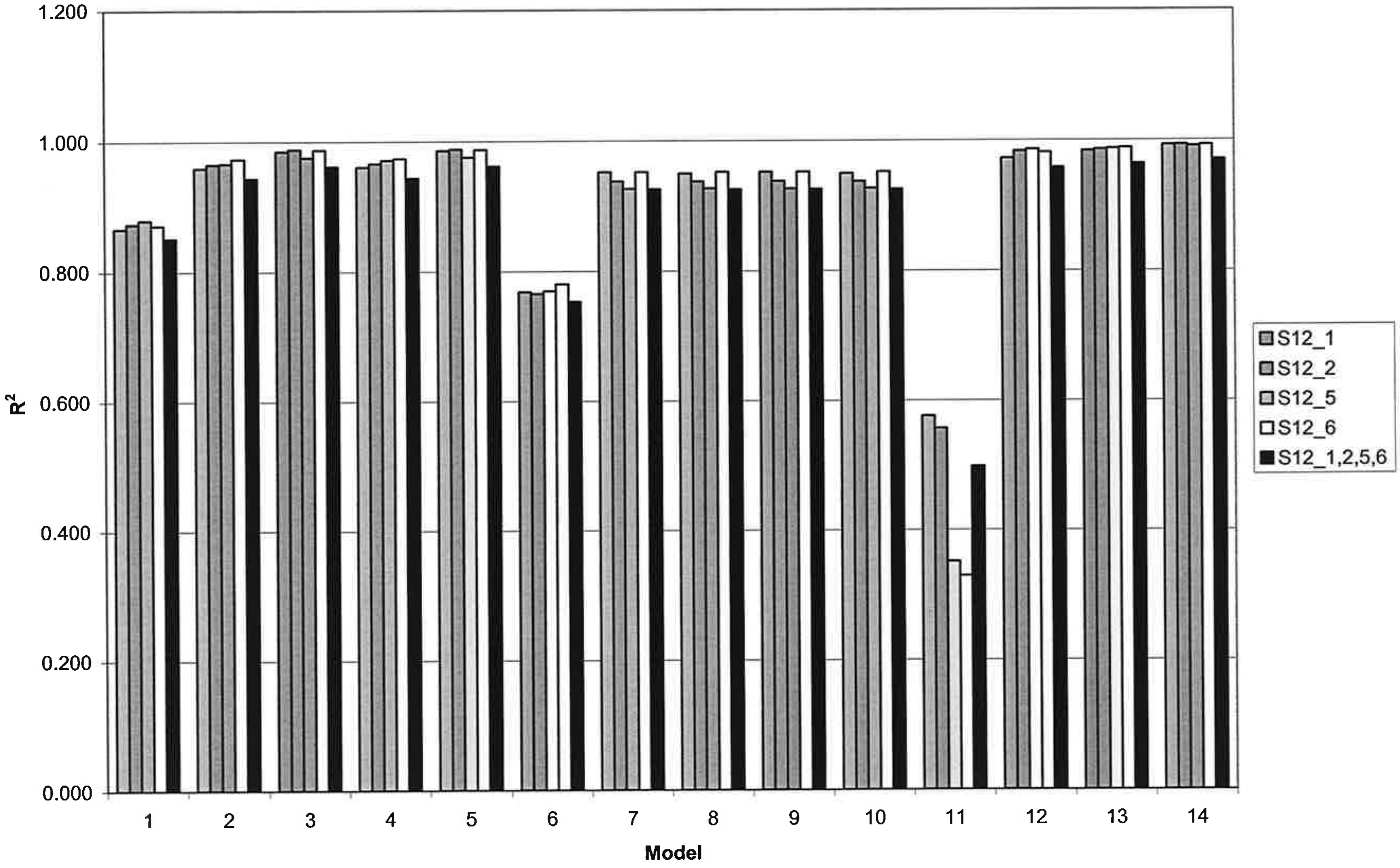
(f) The cumulative horizontal deformation measured after preconditioning prior to initiation of resilient modulus testing.

(g) The cumulative permanent vertical deformation per load cycle.

(h) The cumulative permanent horizontal deformation per load cycle.

ANNEX C-1

NCHRP 1-28 A Project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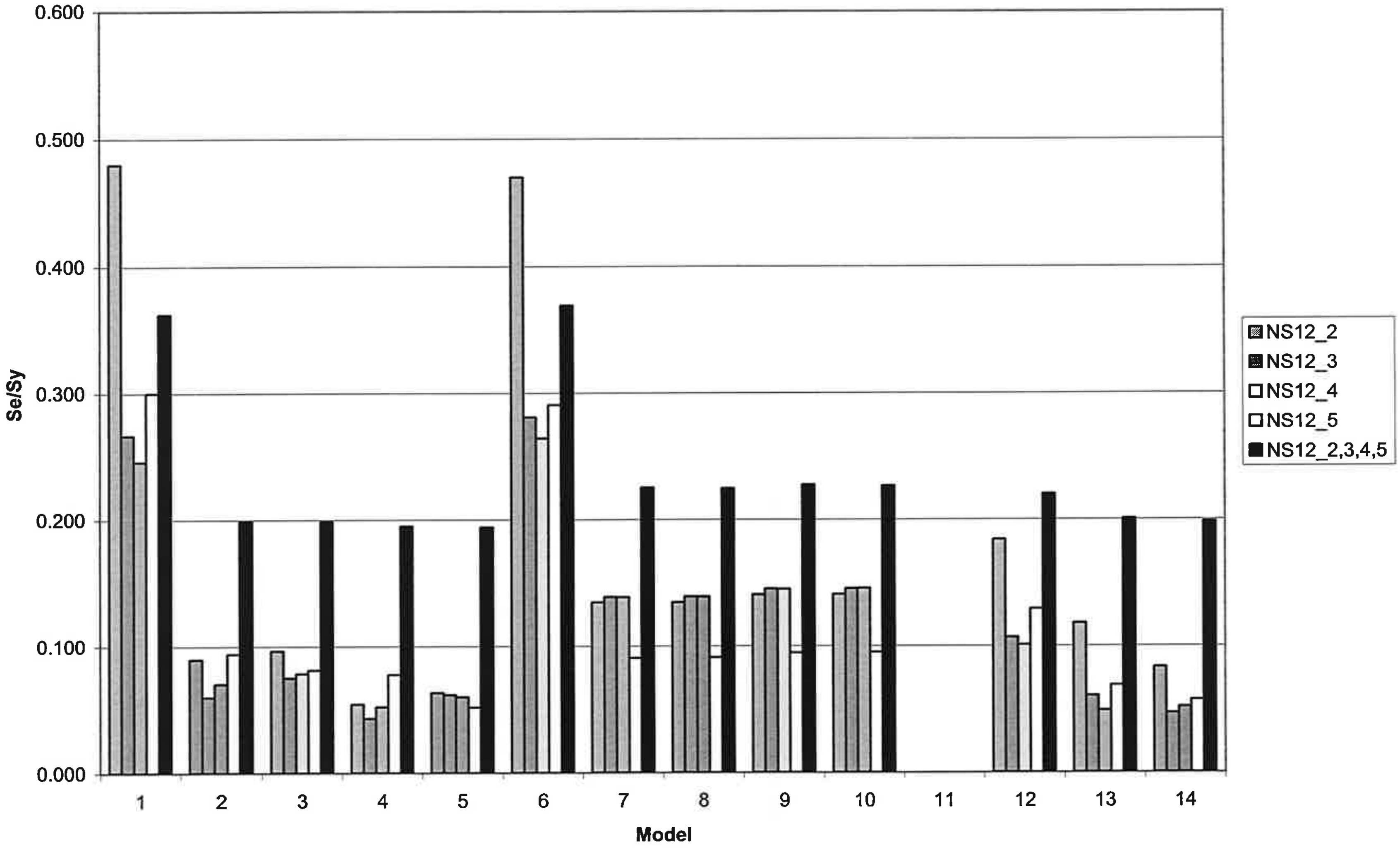
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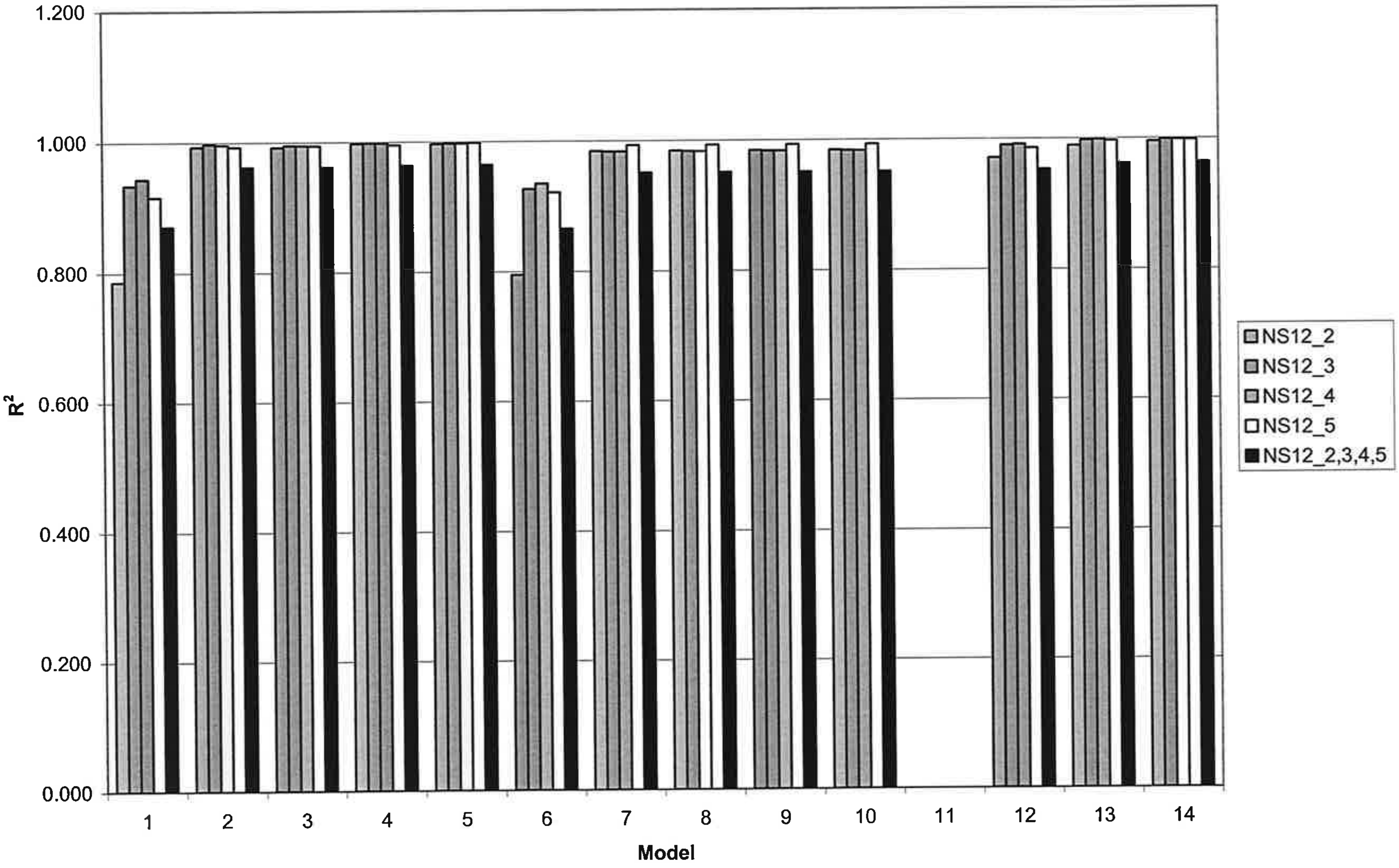
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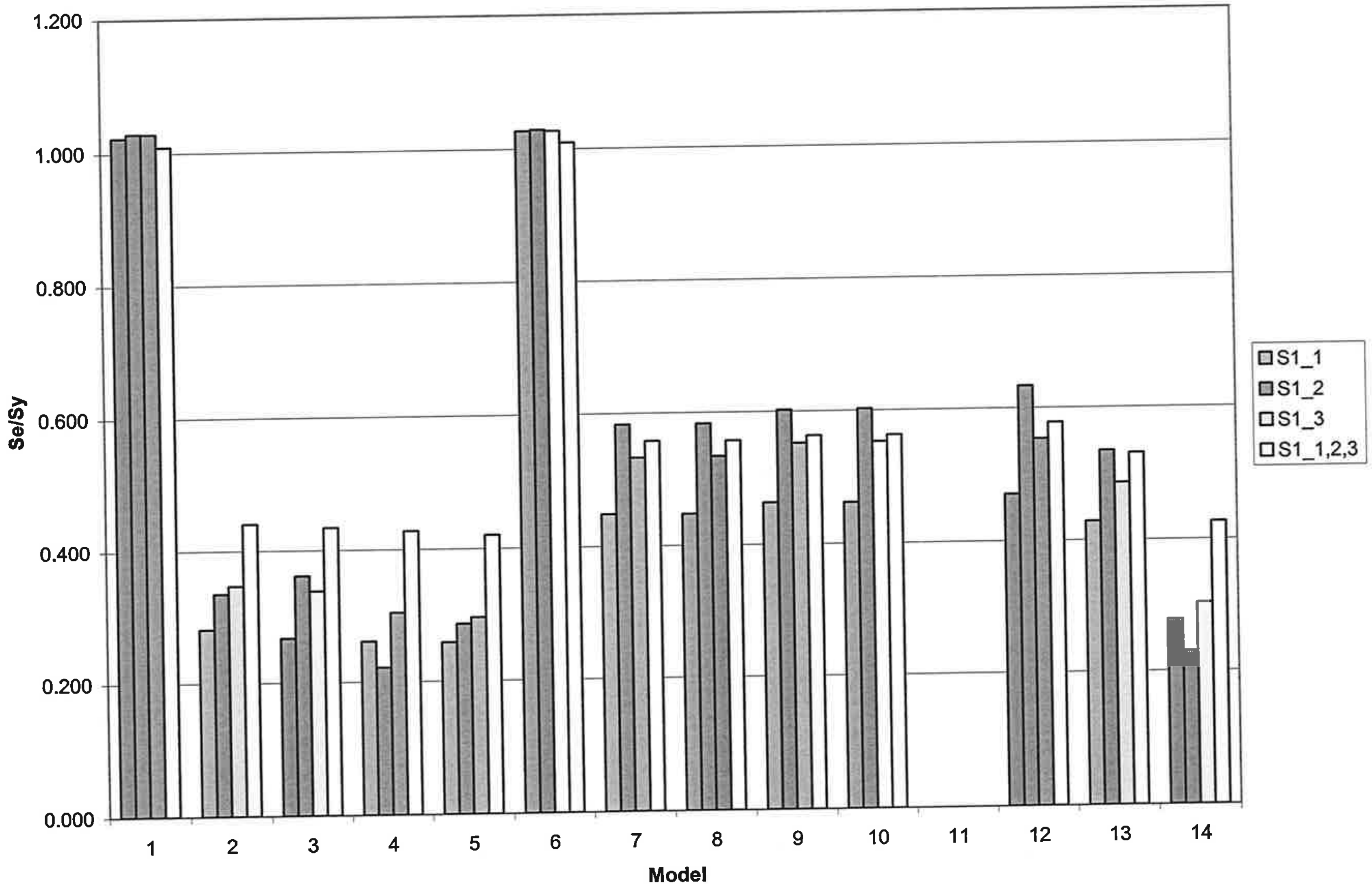
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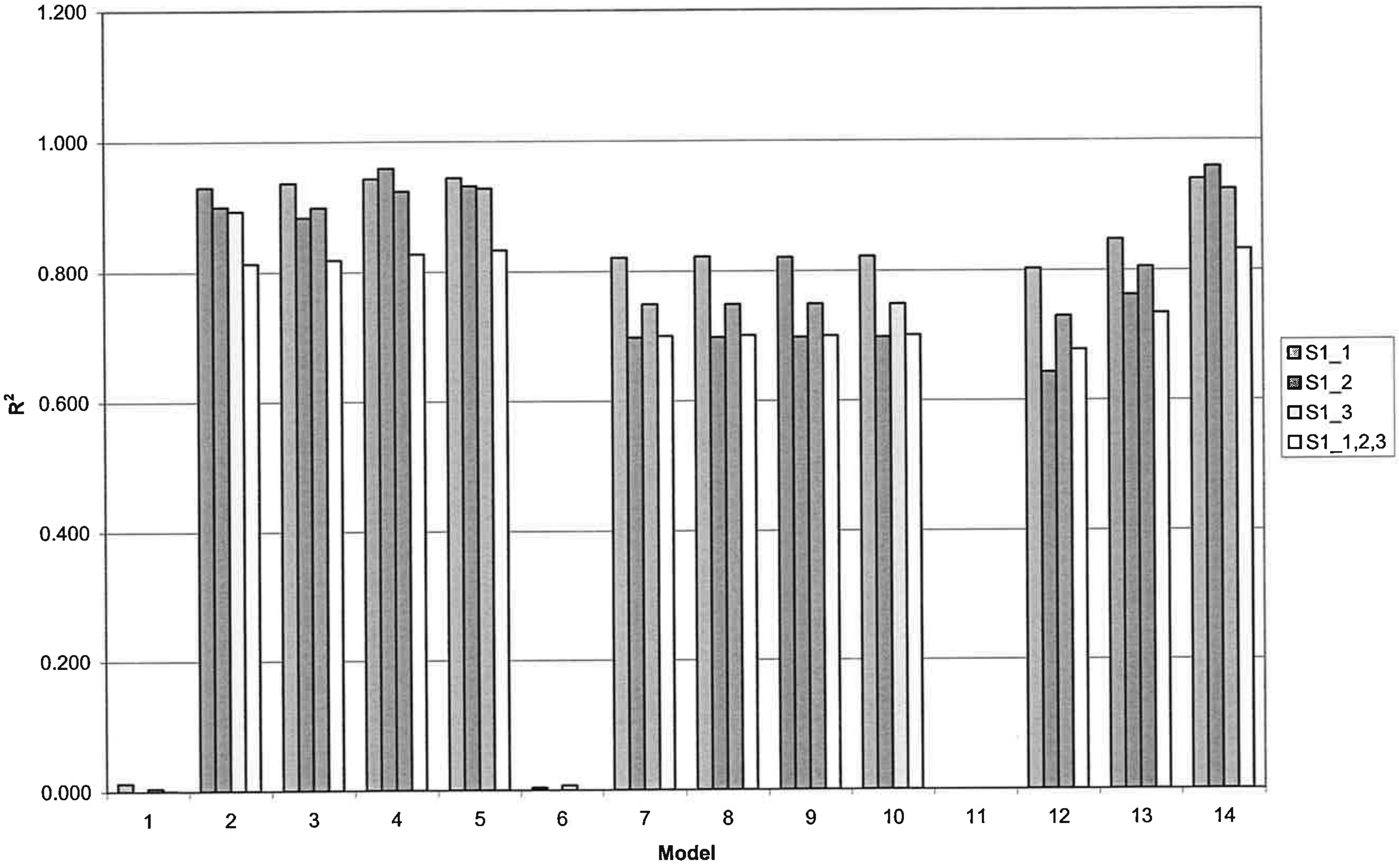
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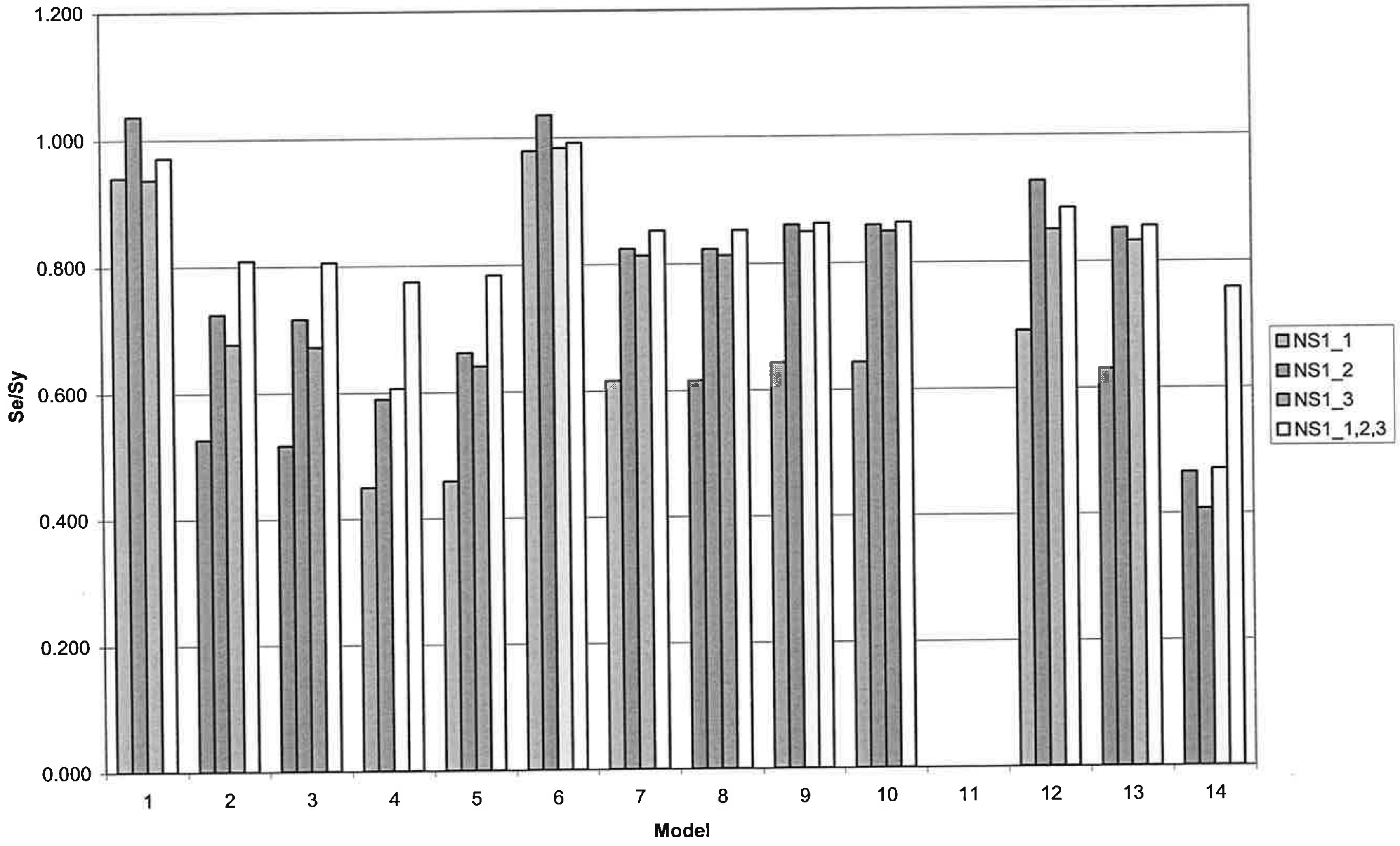
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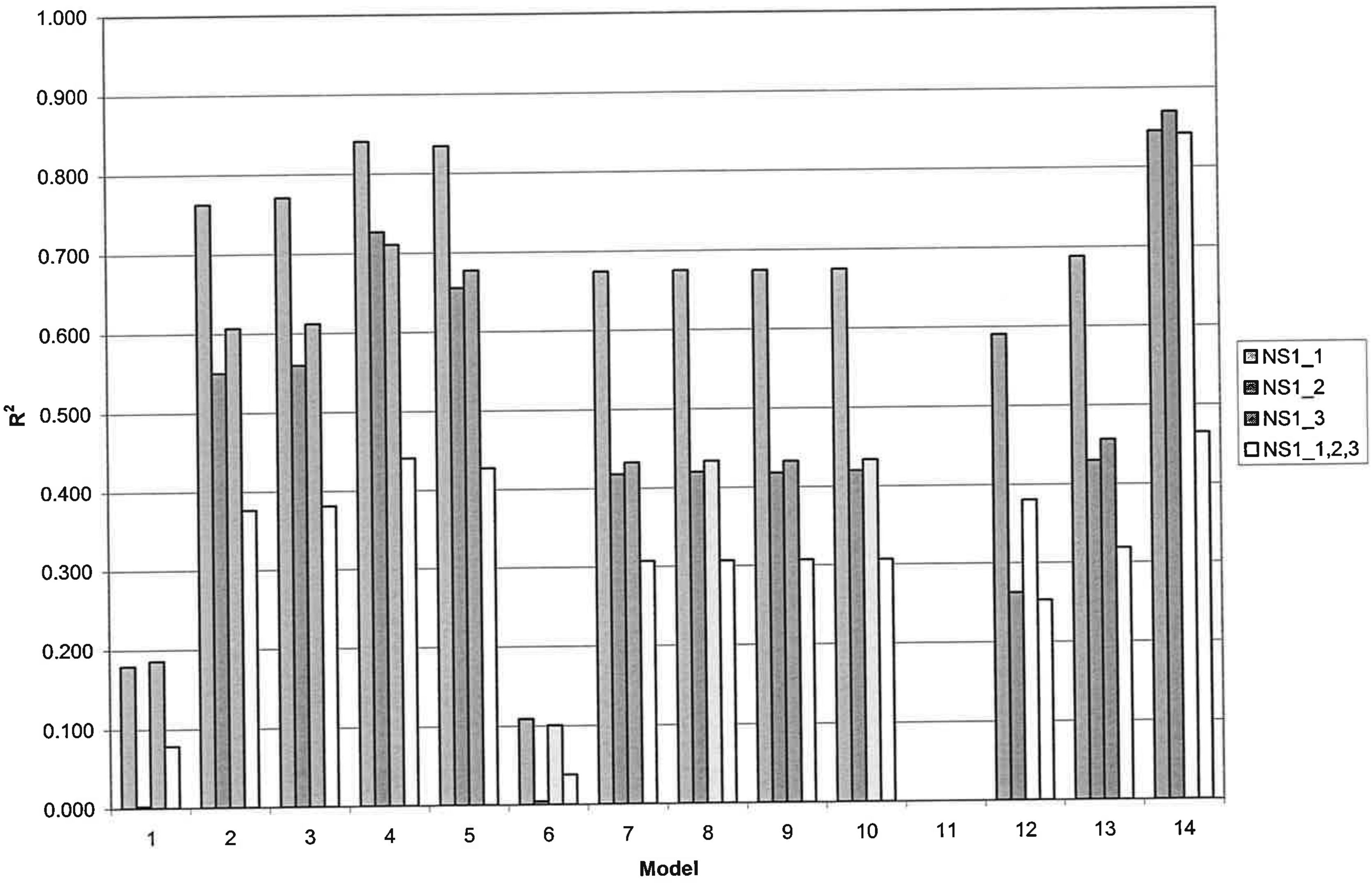
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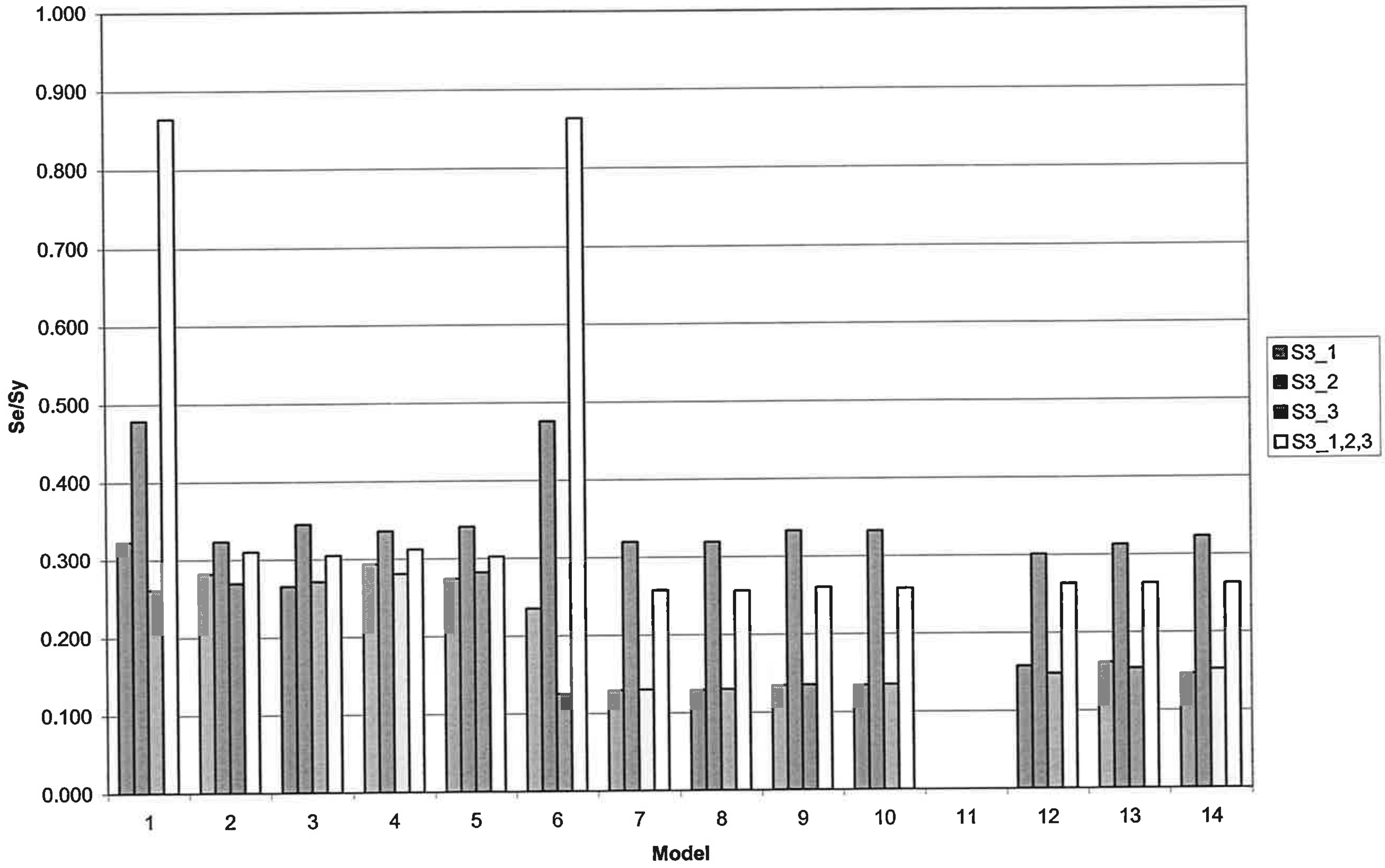
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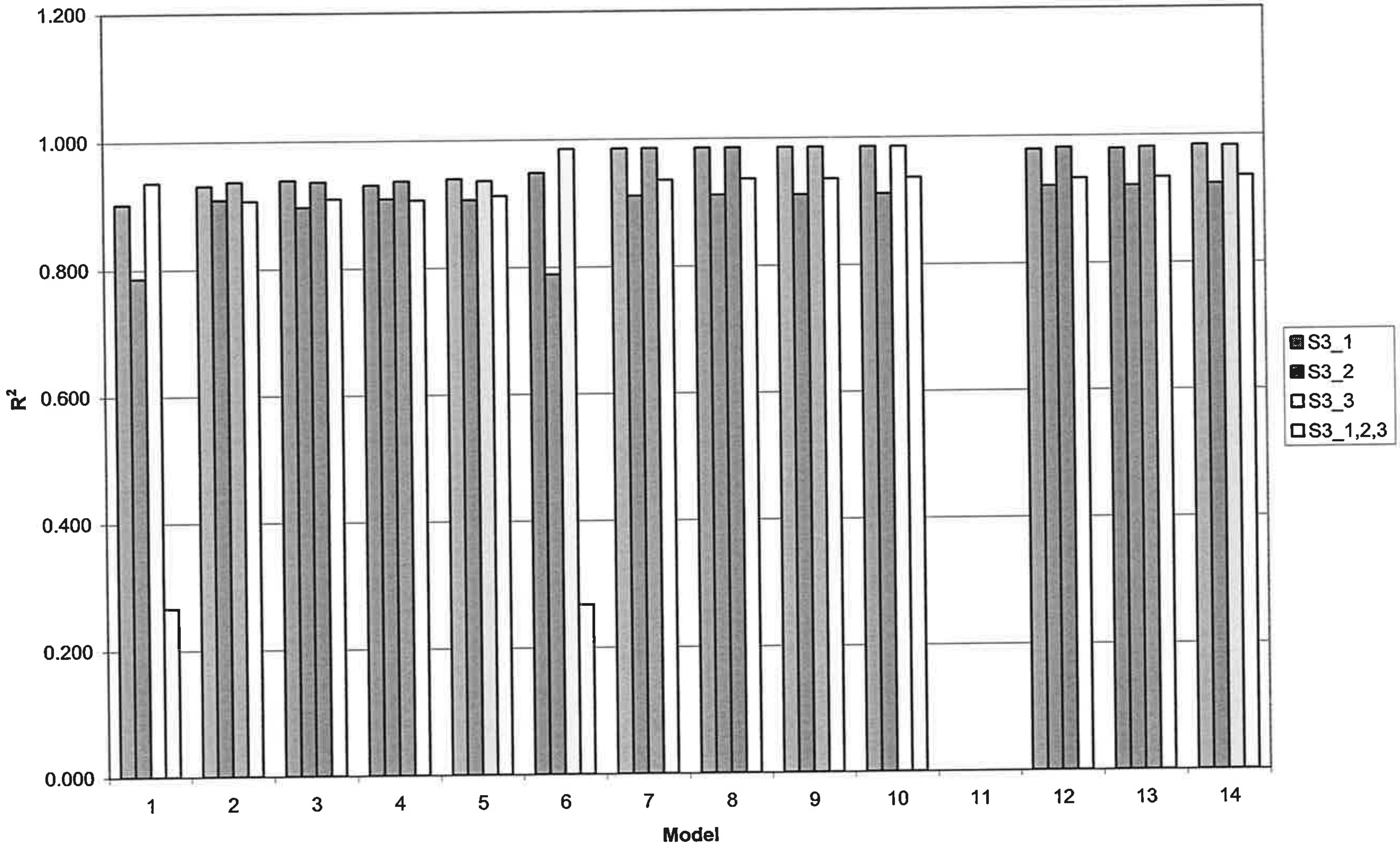
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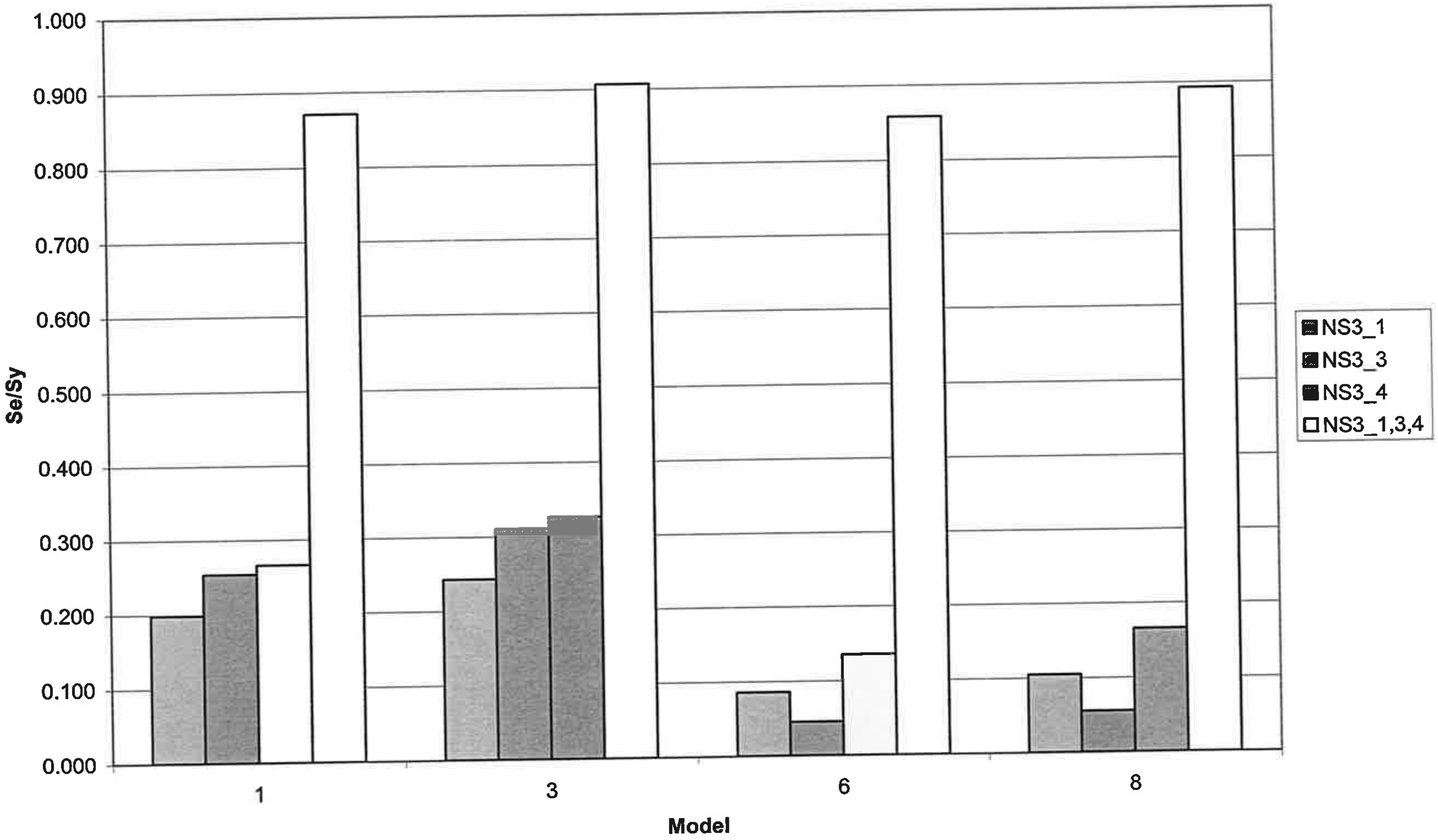
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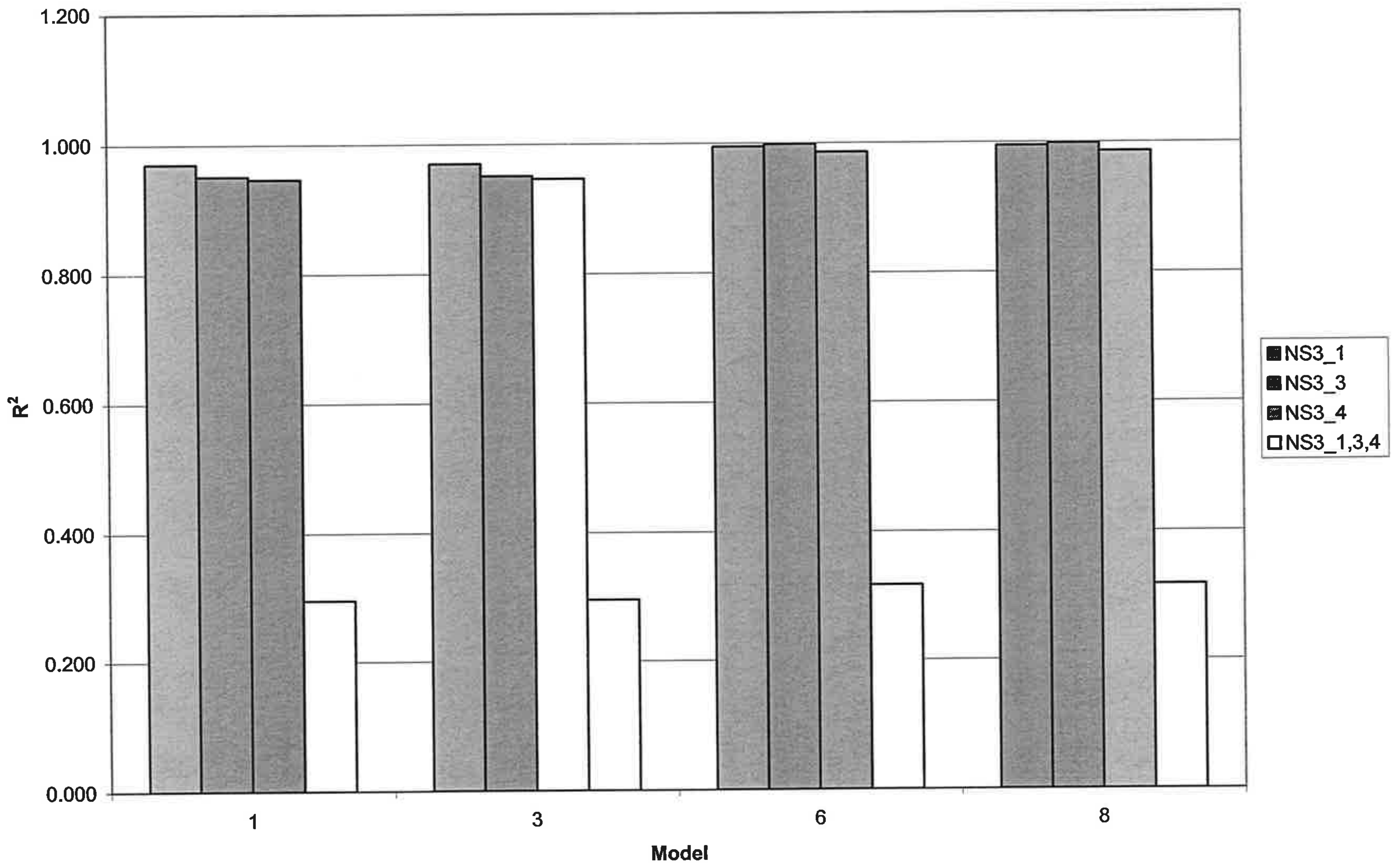
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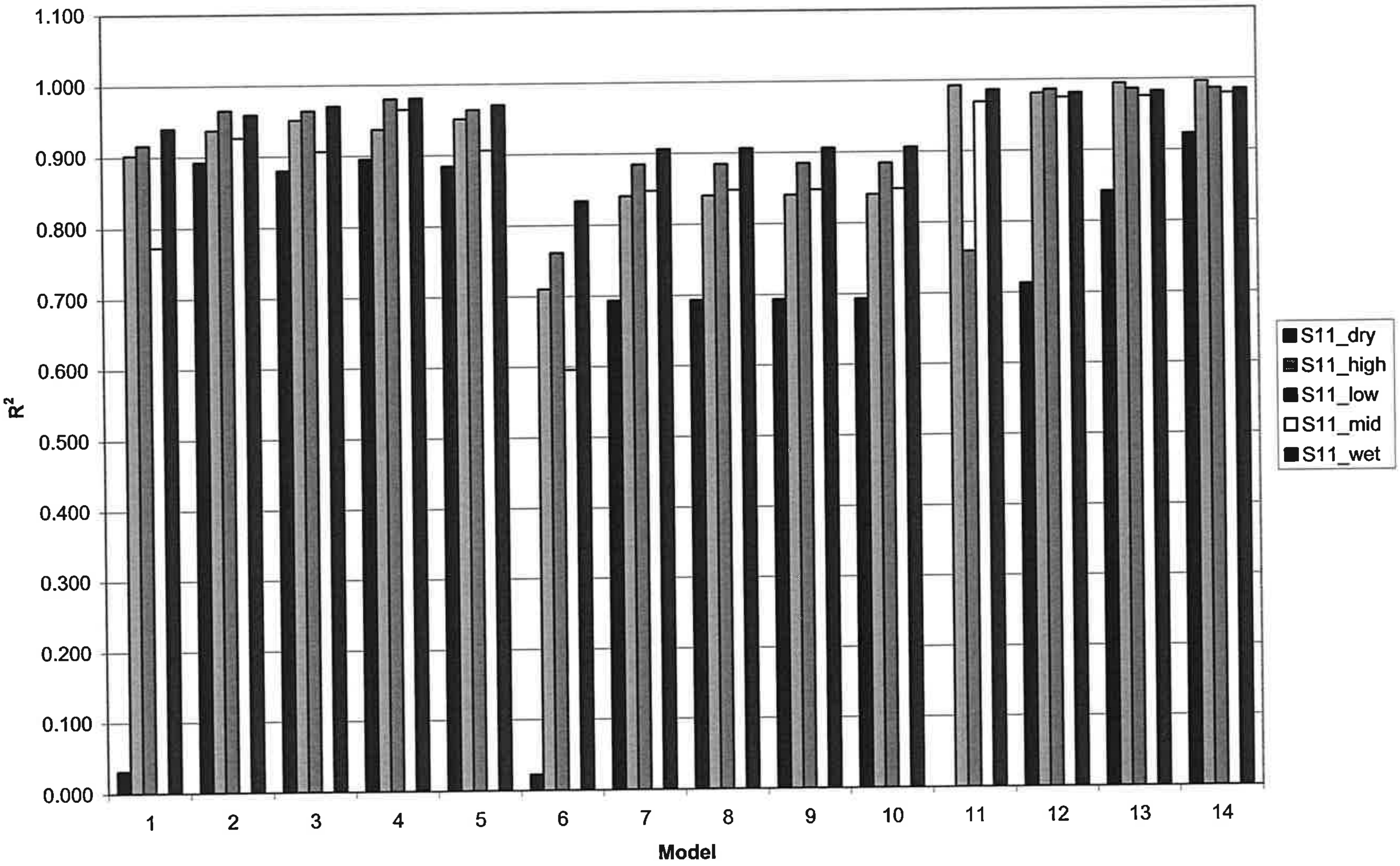
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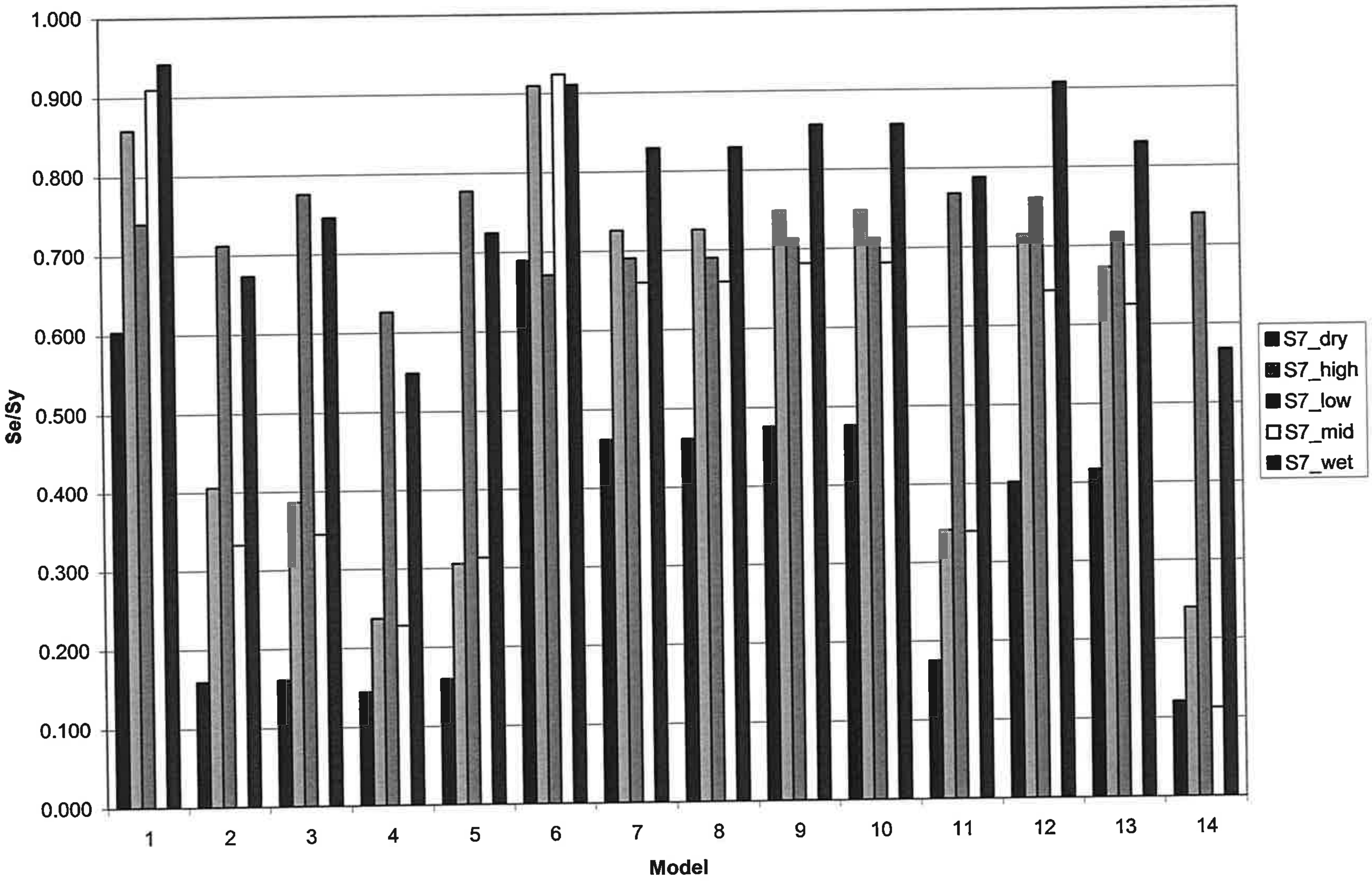
1.000
0.900
0.800
0.700
0.600
0.500
0.400
0.300
0.200
0.100
0.000
R²
1
2
3
4
5
6
7
8
9
10
11
12
13
14
Model
■ S11_dry
▨ S11_high
■ S11_low
□ S11_mid
■ S11_wet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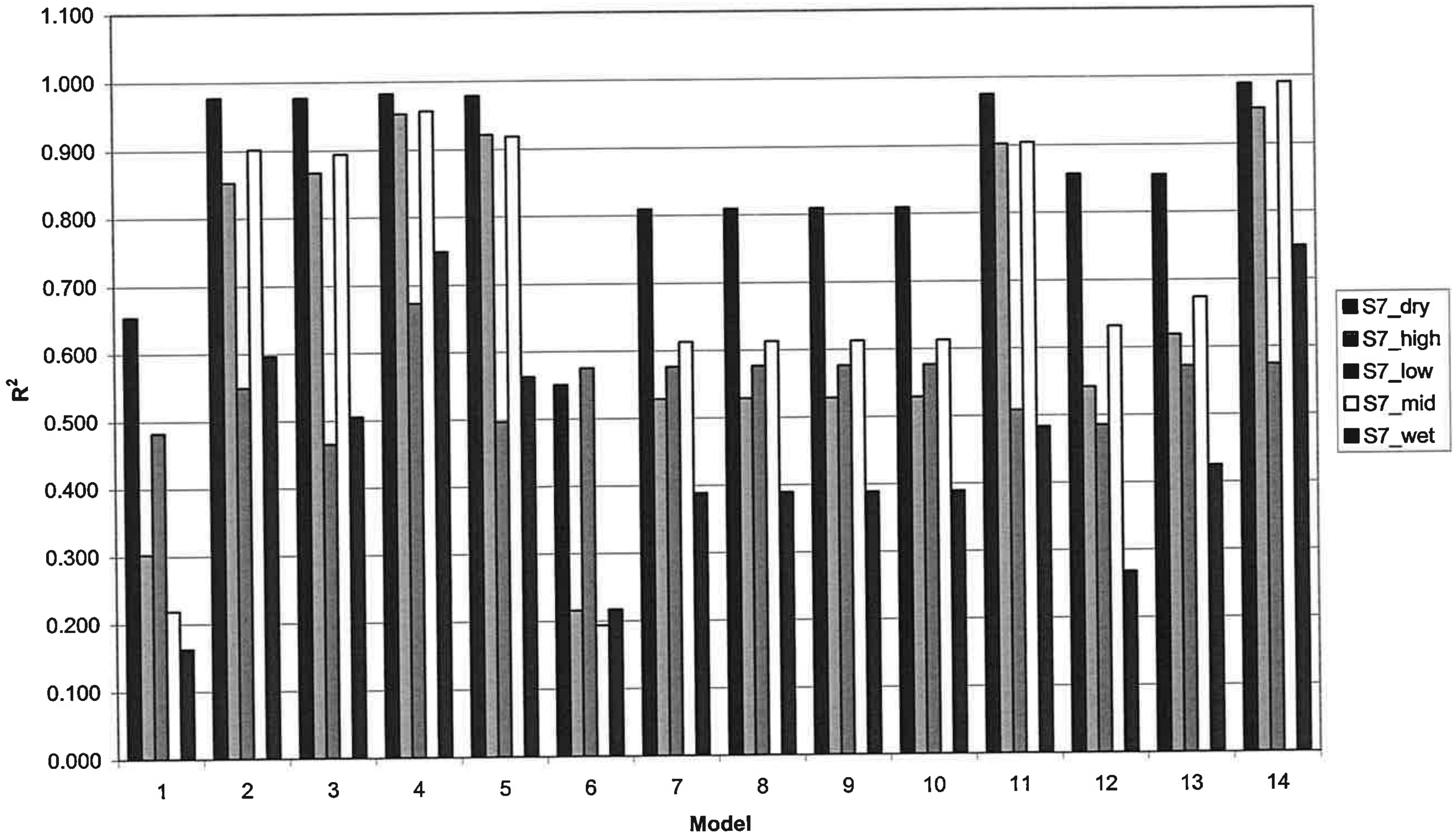
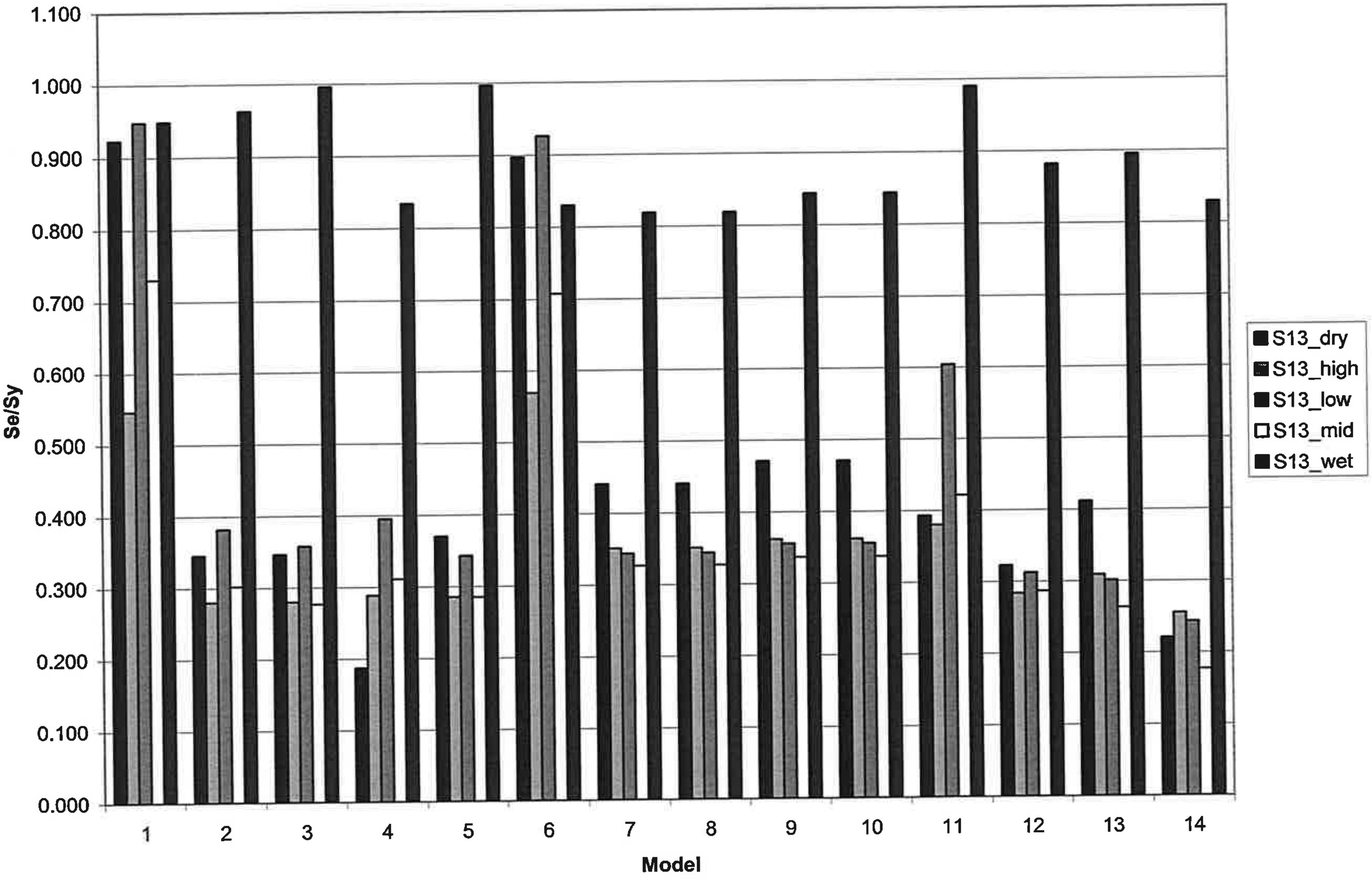
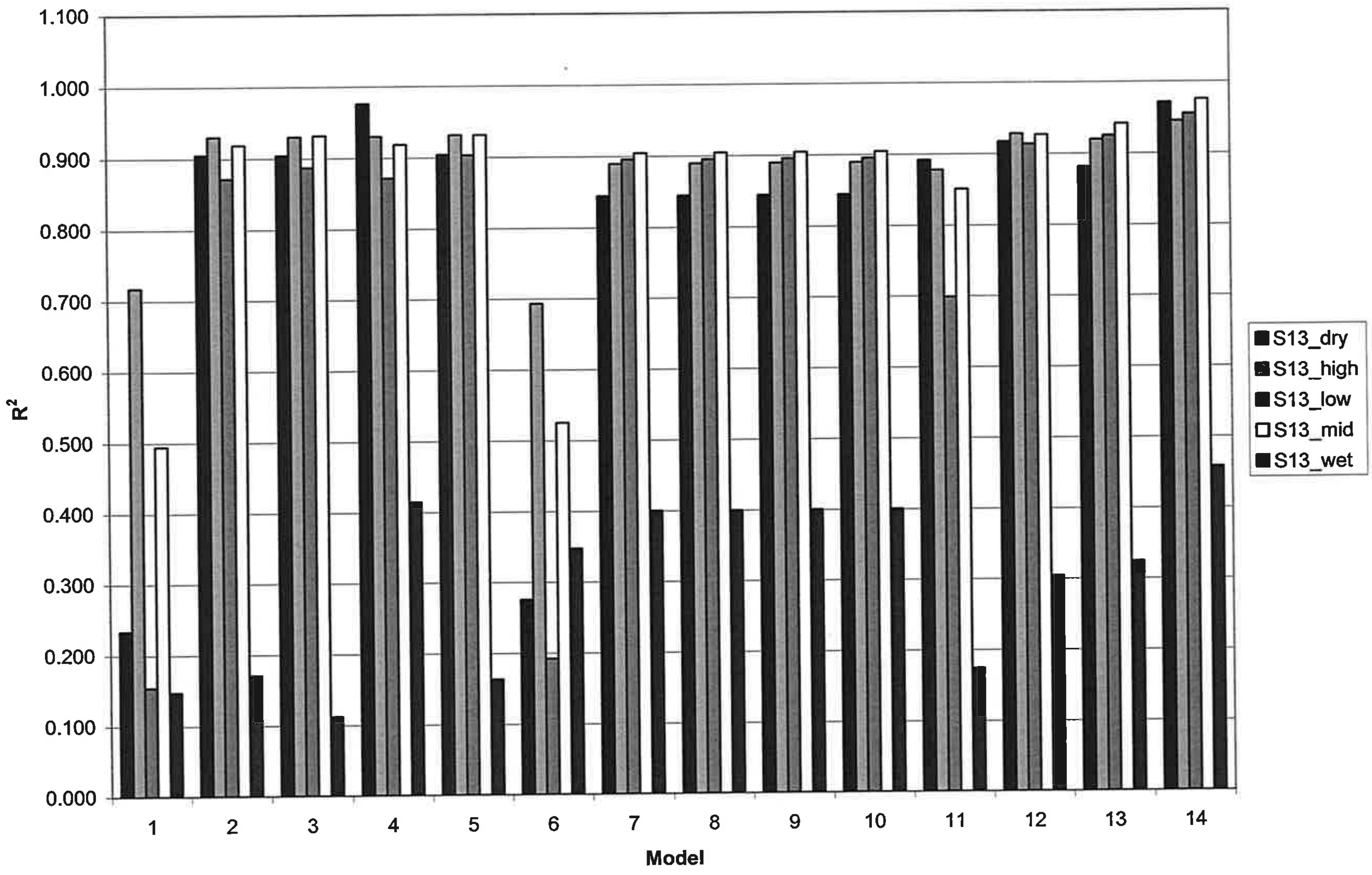
0.900
0.800
0.700
0.600
0.500
0.400
0.300
0.200
0.100
0.000
Se/Sy
1
2
3
4
5
6
7
8
9
10
11
12
13
14
Model
■ S7_dry
■ S7_high
■ S7_low
□ S7_mid
■ S7_wet

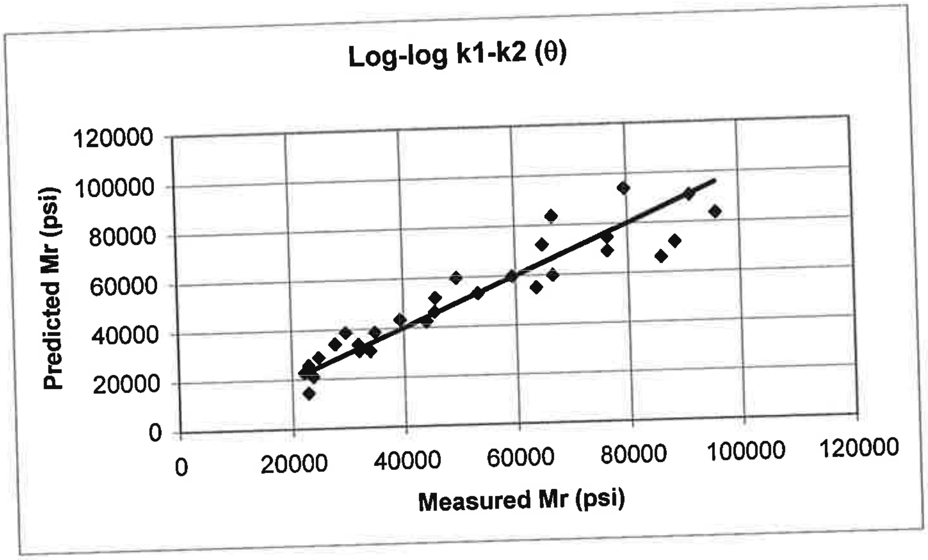

1.100
1.000
0.900
0.800
0.700
0.600
0.500
0.400
0.300
0.200
0.100
0.000
R²
1
2
3
4
5
6
7
8
9
10
11
12
13
14
Model
S7_dry
S7_high
S7_low
S7_mid
S7_wet

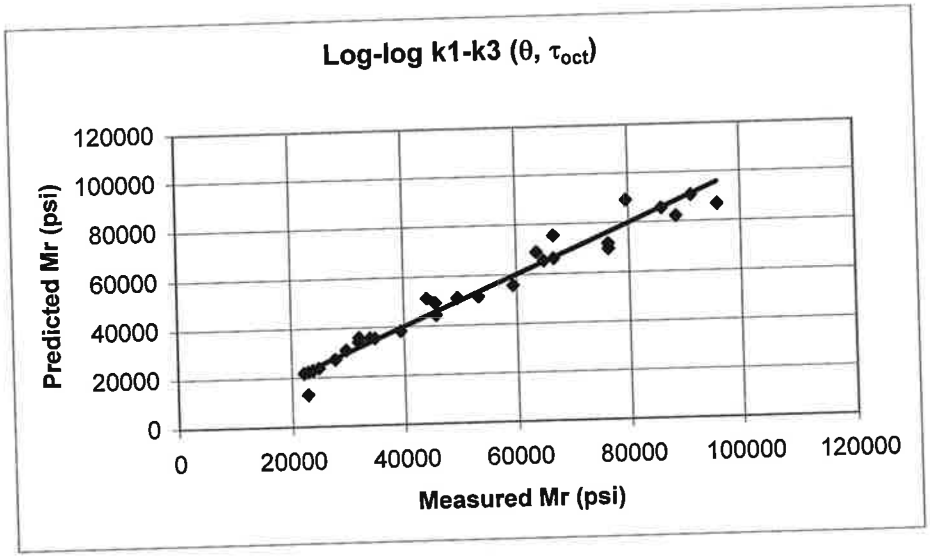

1.100
1.000
0.900
0.800
0.700
0.600
0.500
0.400
0.300
0.200
0.100
0.000
Se/Sy
1
2
3
4
5
6
7
8
9
10
11
12
13
14
Model
S13_dry
S13_high
S13_low
S13_mid
S13_wet

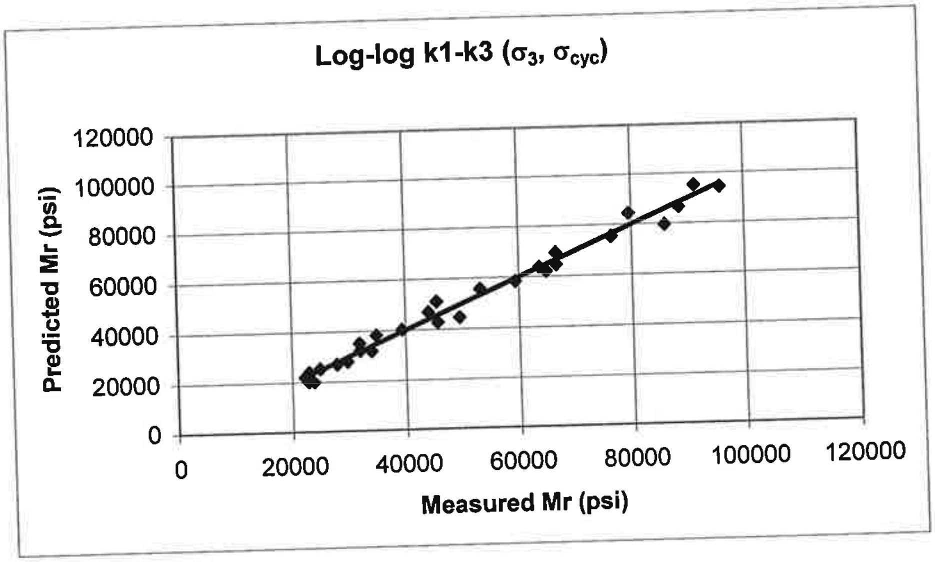

1.100
1.000
0.900
0.800
0.700
0.600
0.500
0.400
0.300
0.200
0.100
0.000
R^2
1
2
3
4
5
6
7
8
9
10
11
12
13
14
Model
■ S13_dry
■ S13_high
■ S13_low
□ S13_mid
■ S13_wet

ANNEX C-2

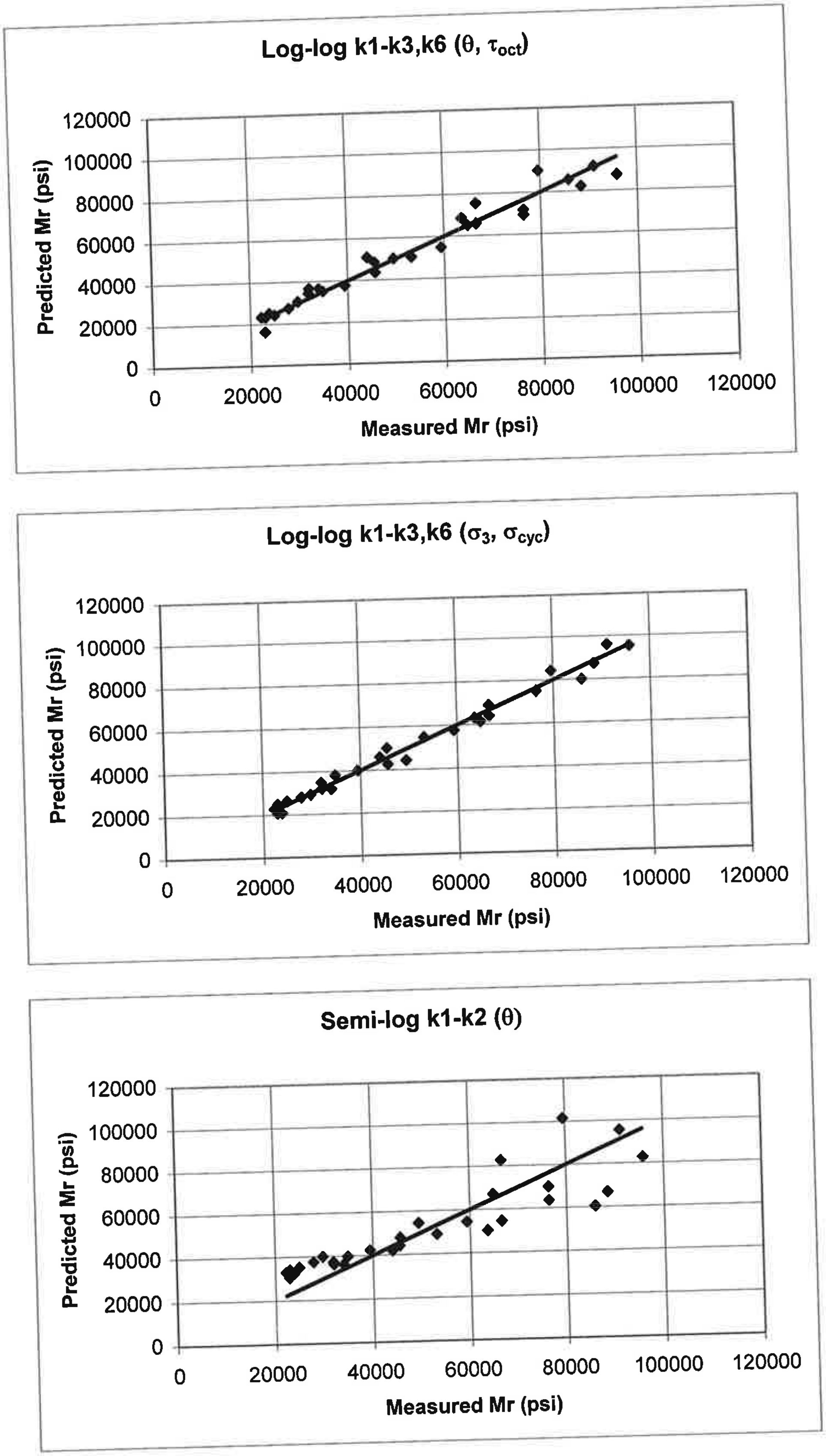
NCHRP 1-28 A Project



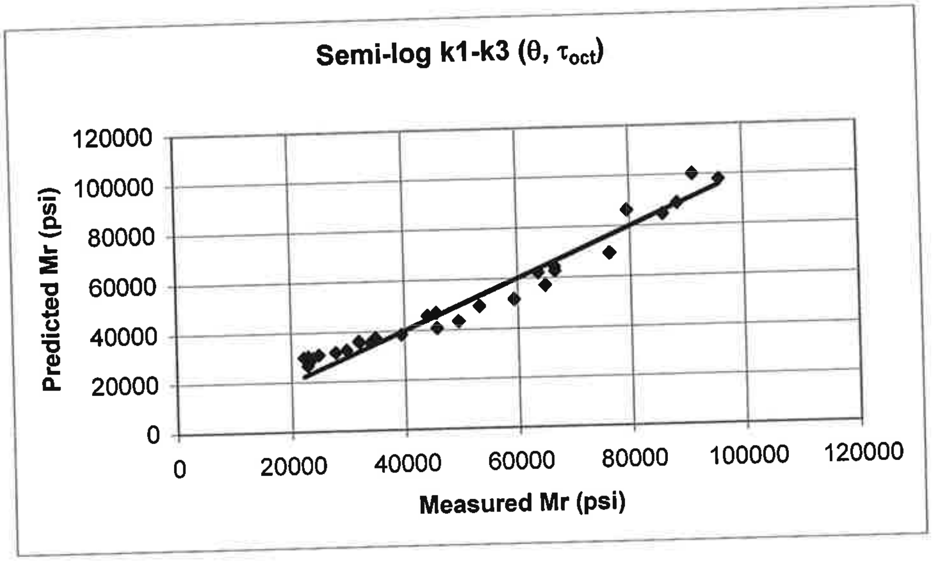


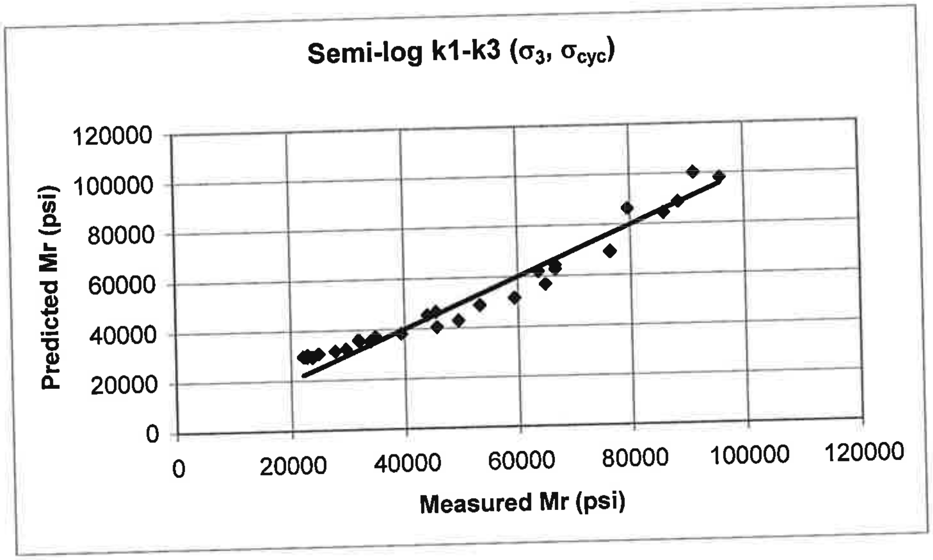


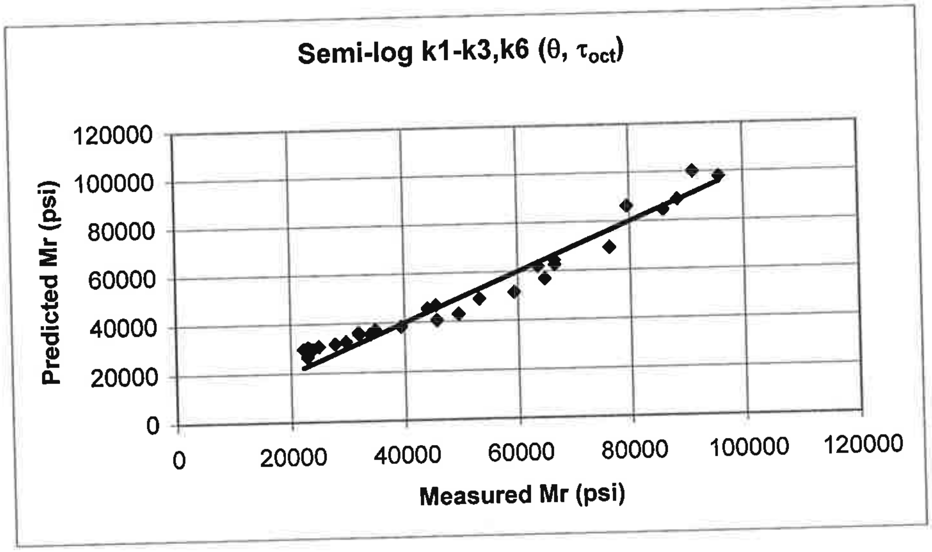
Measured Vs. Predicted M_R for Test S12_1



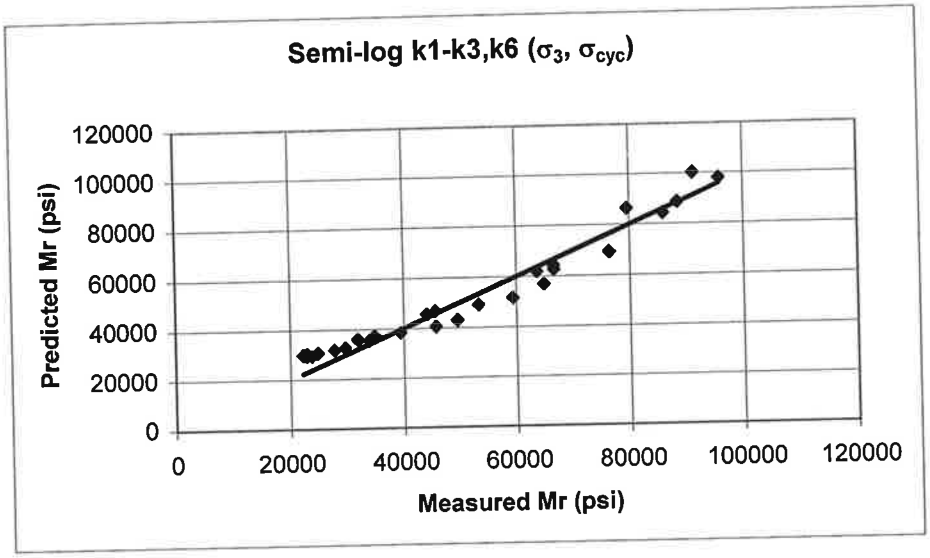
Measured Vs. Predicted M_R for Test S12_1



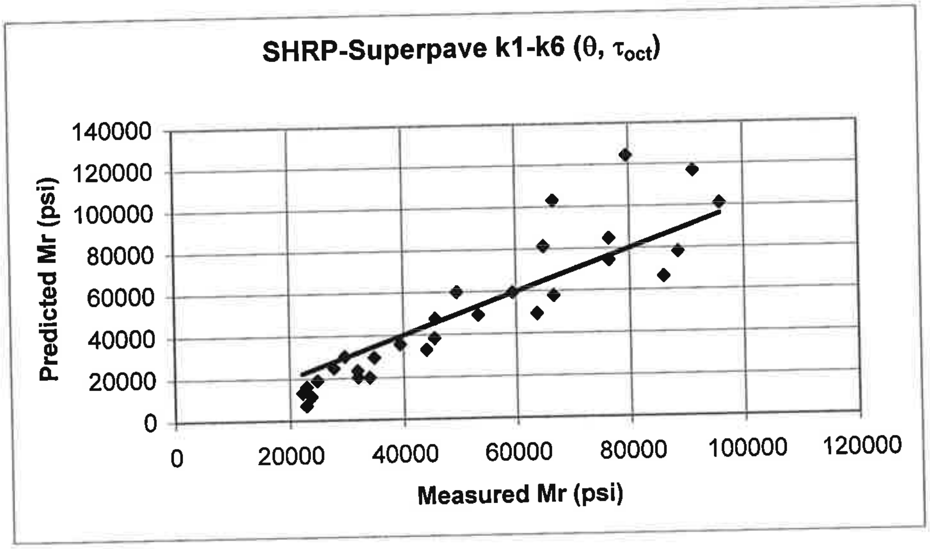




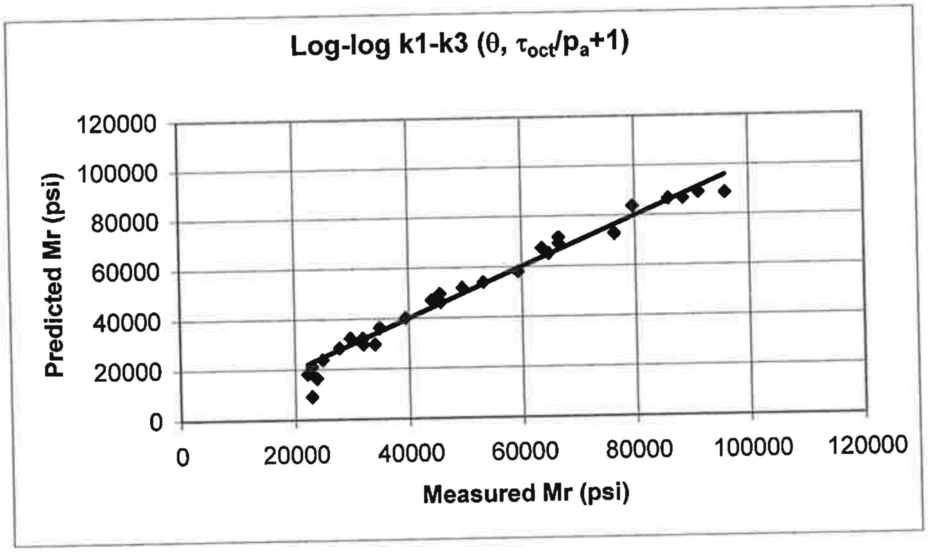
Measured Vs. Predicted M_R for Test S12_1



Semi-log k1-k3,k6 (σ_3, σ_{cyc})

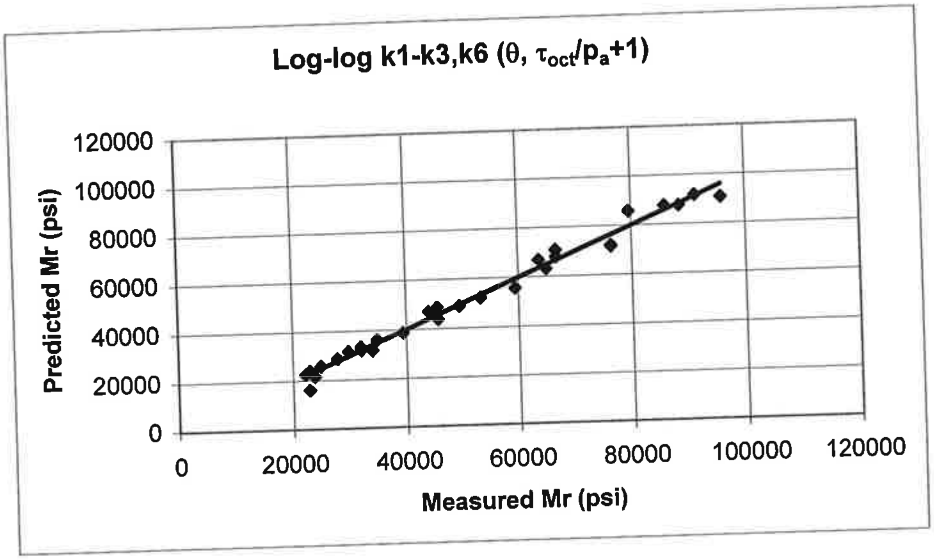


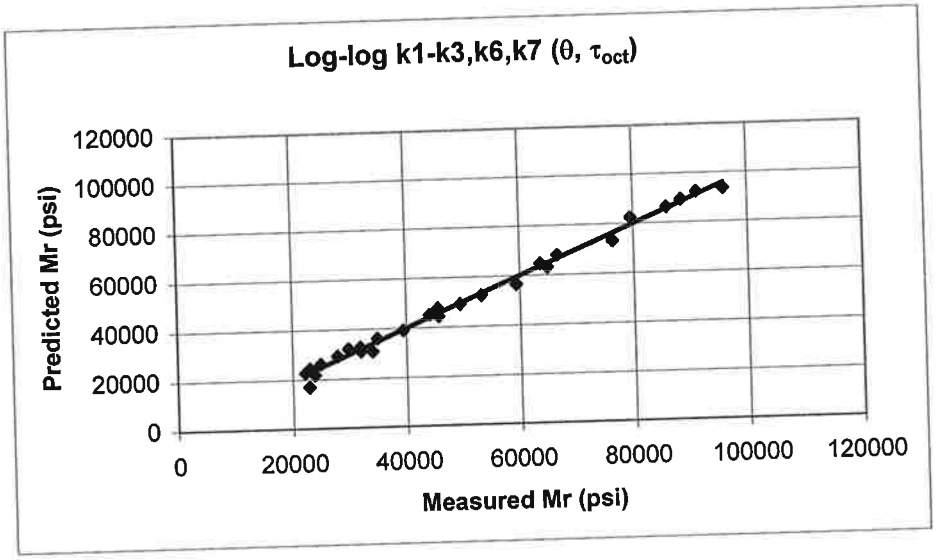
SHRP-Superpave k1-k6 (θ, τ_{oct})



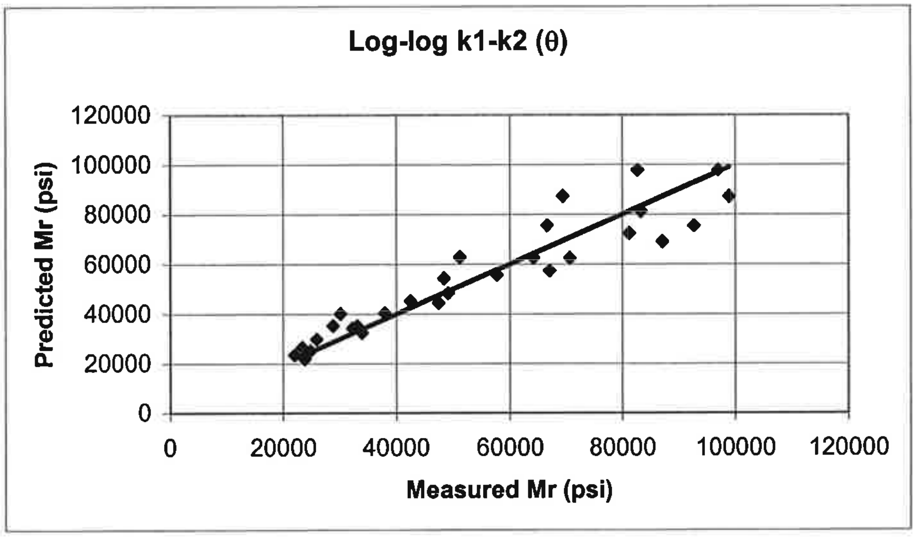
Log-log k1-k3 (θ, τ_{oct}/p_a+1)

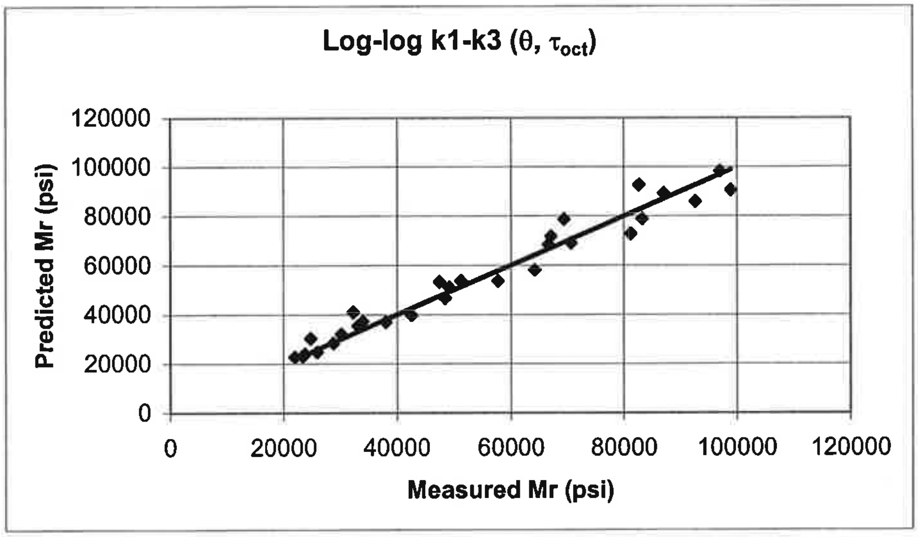
Measured Vs. Predicted M_R for Test S12_1

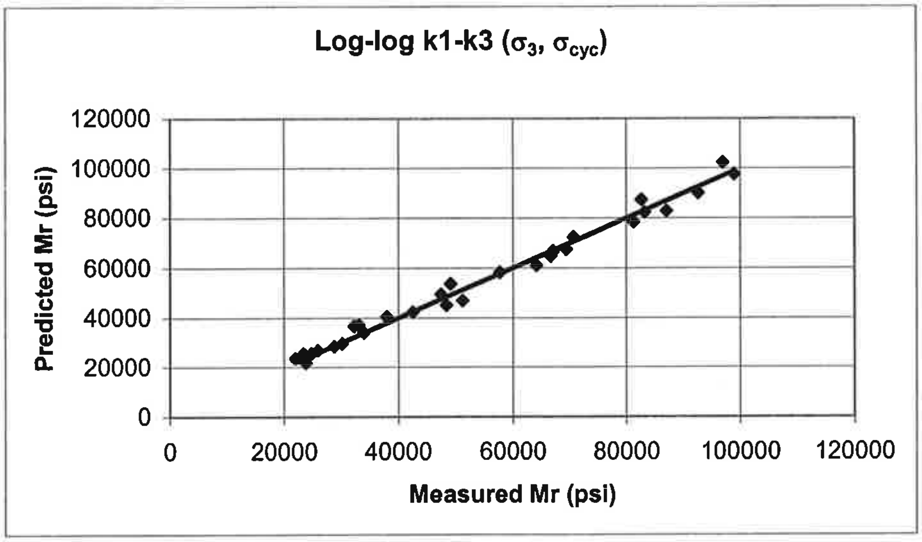




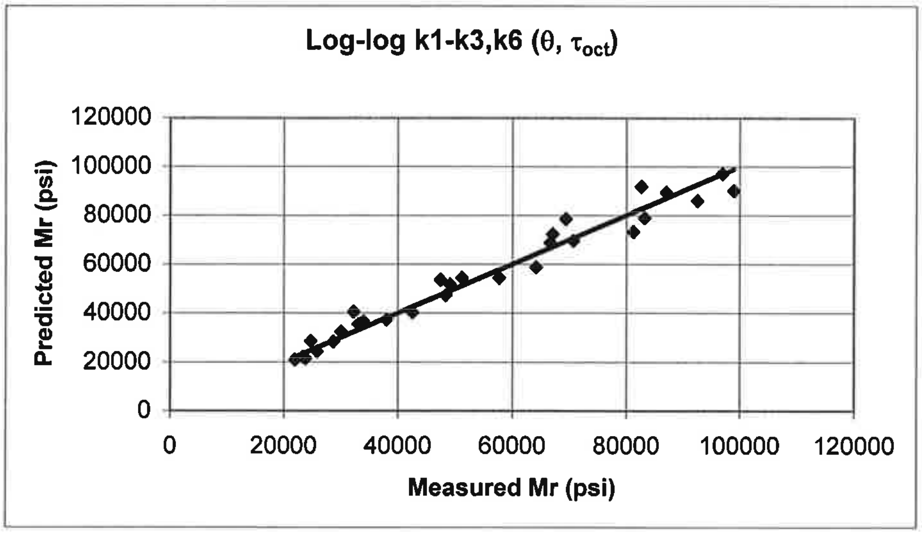
Measured Vs. Predicted M_R for Test S12_1

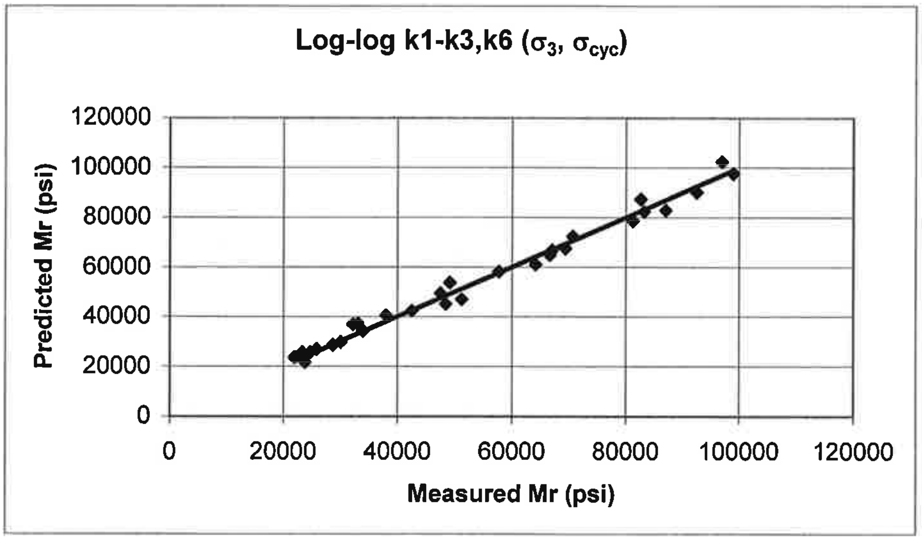

Log-log k1-k2 (θ)

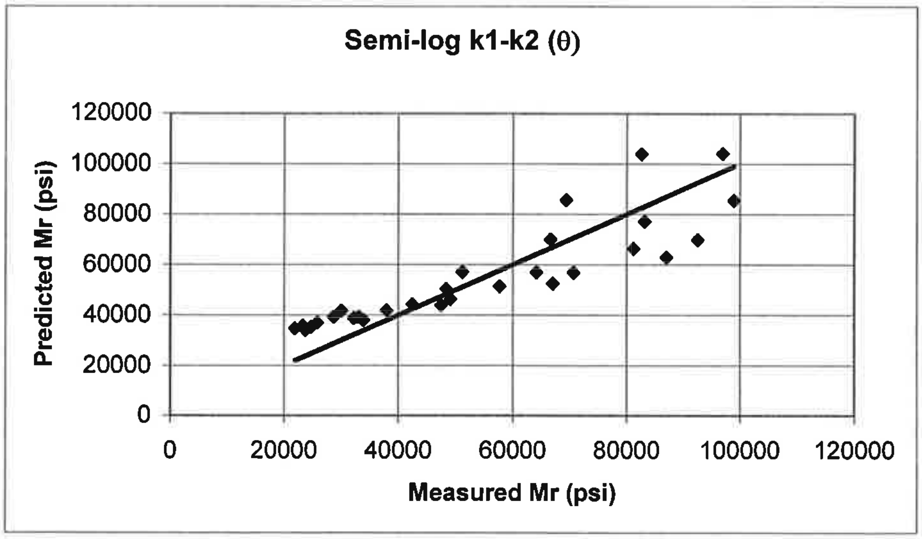

Log-log k1-k3 (θ, τ_{oct})


Log-log k1-k3 (σ_3, σ_{cyc})

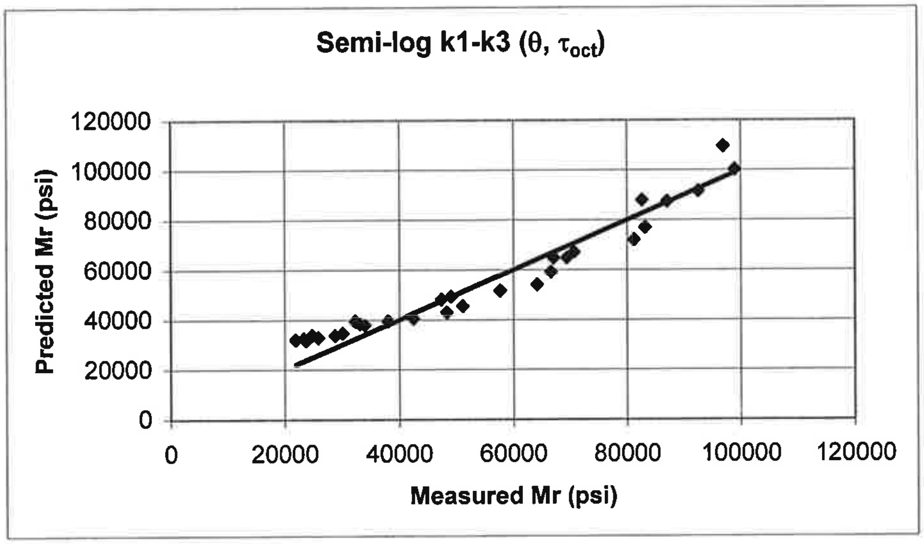
Measured Vs. Predicted M_R for Test S12_2

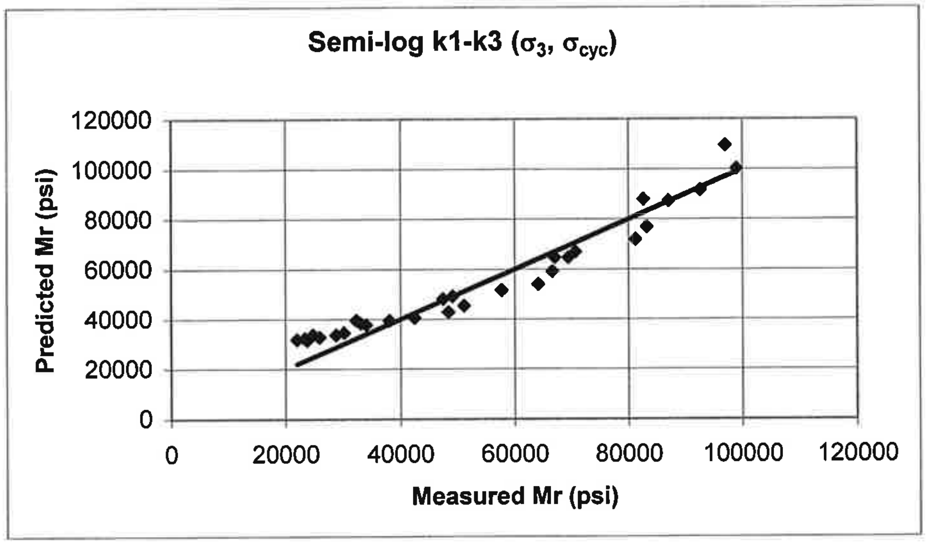


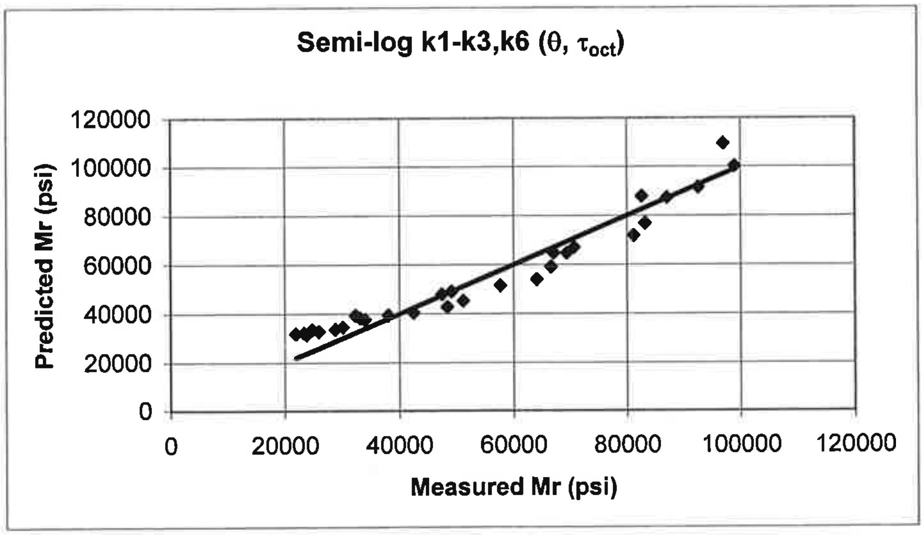




Measured Vs. Predicted M_R for Test S12_2







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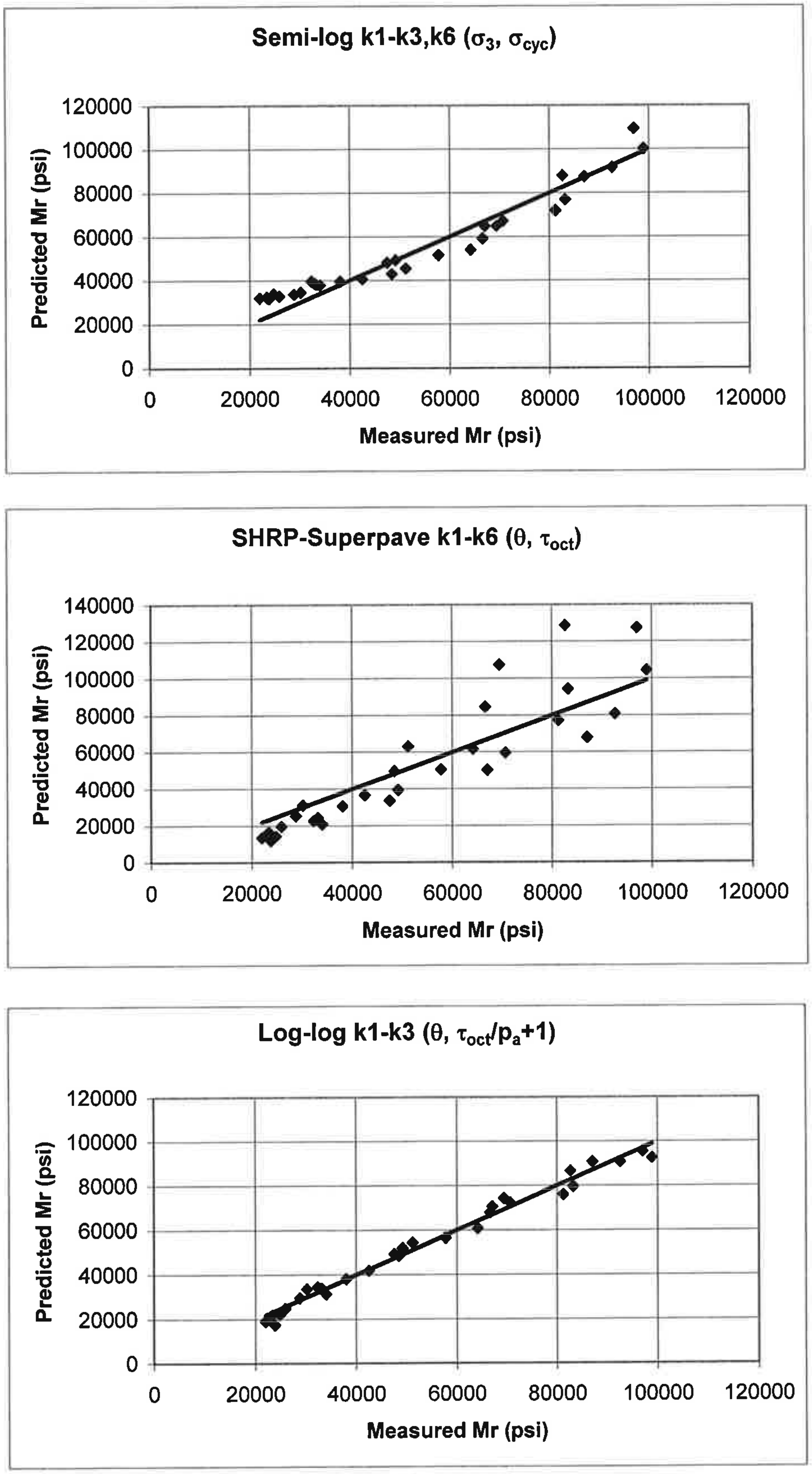

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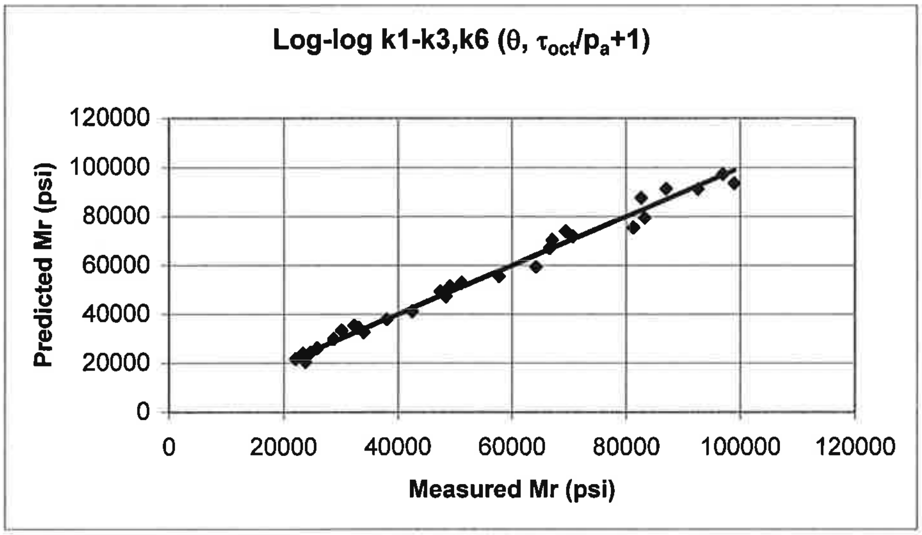

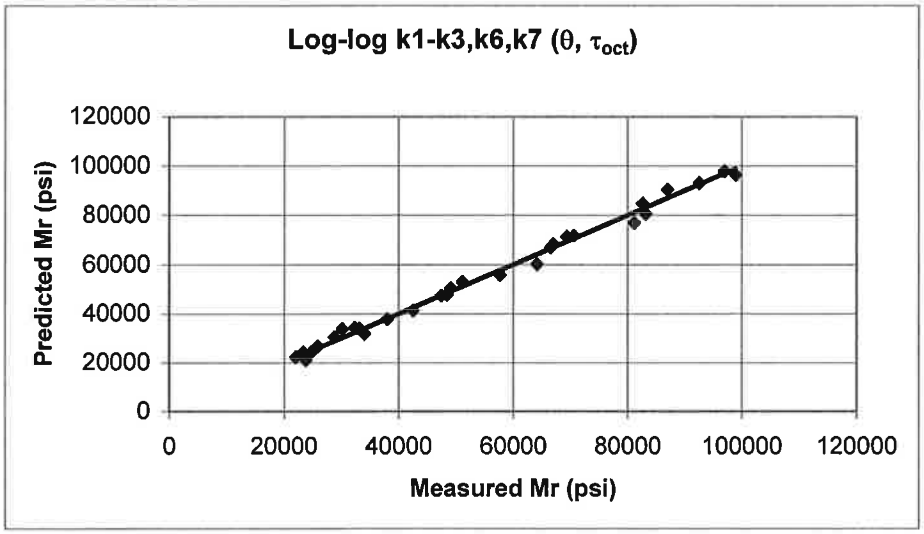

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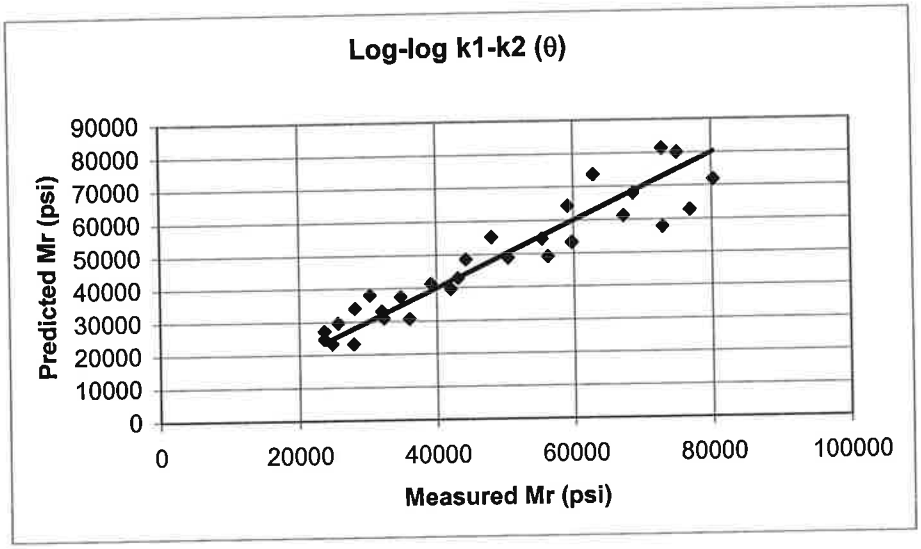
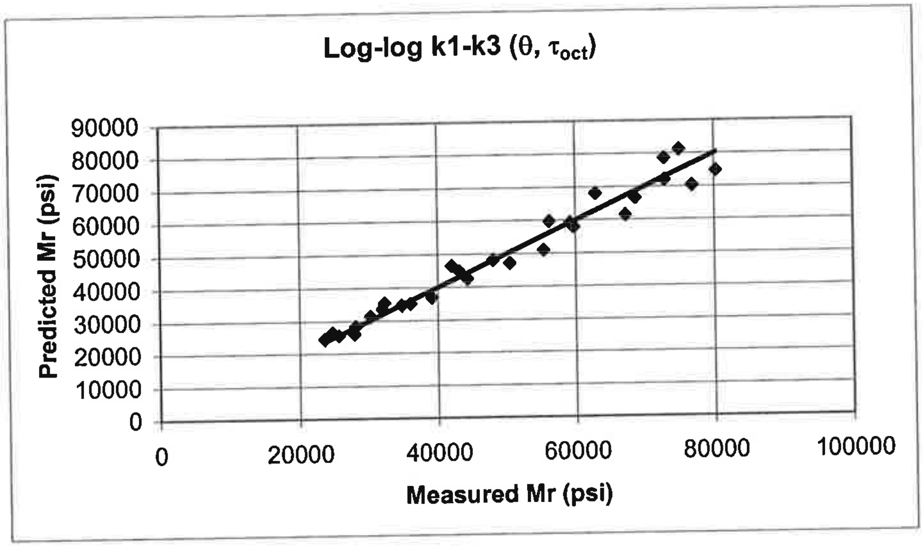
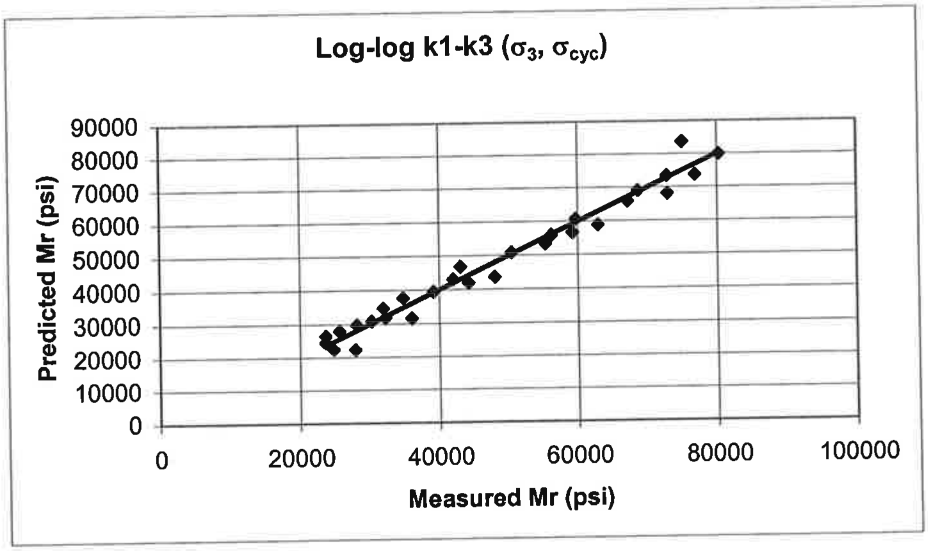
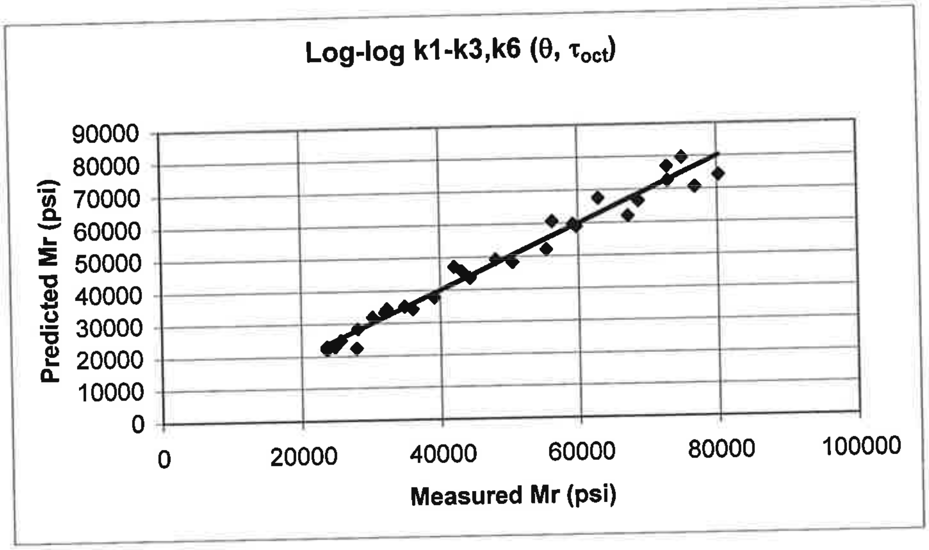
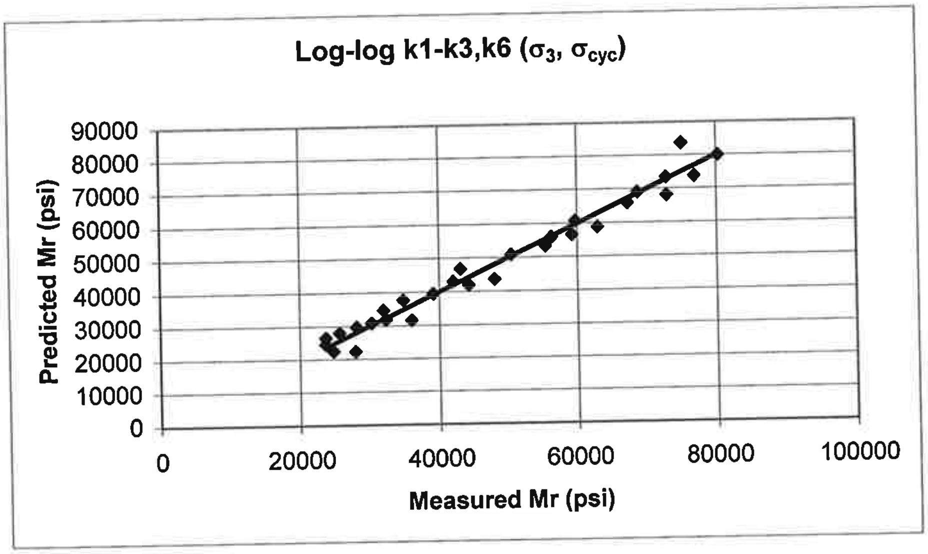


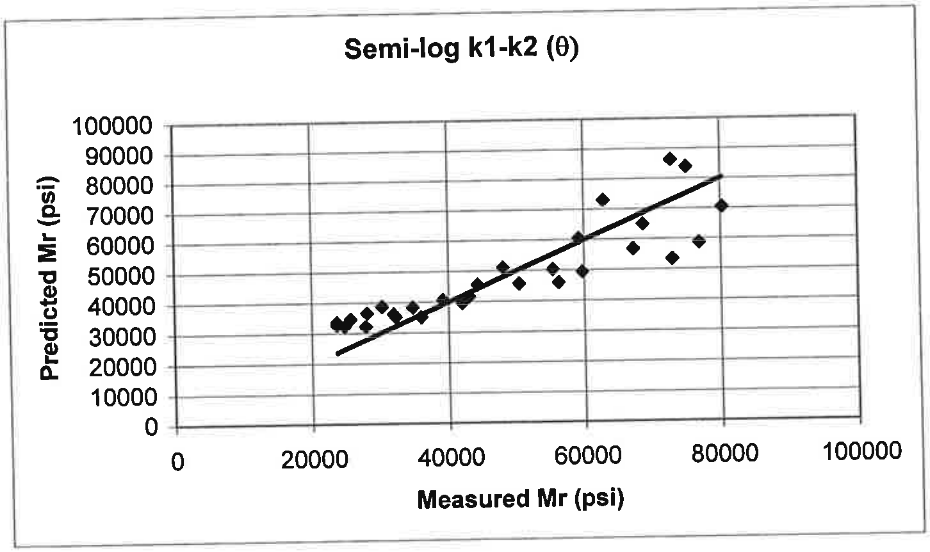




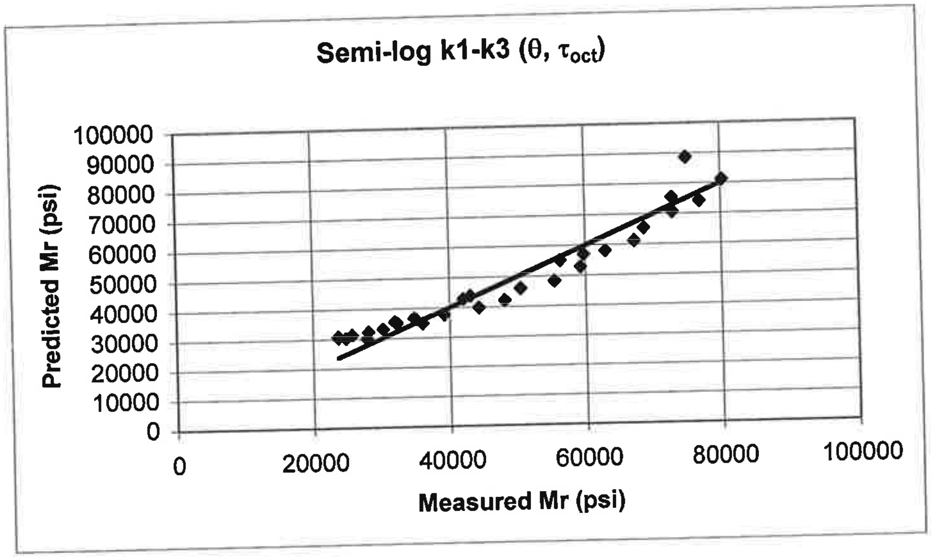
Measured Vs. Predicted M_R for Test S12_5

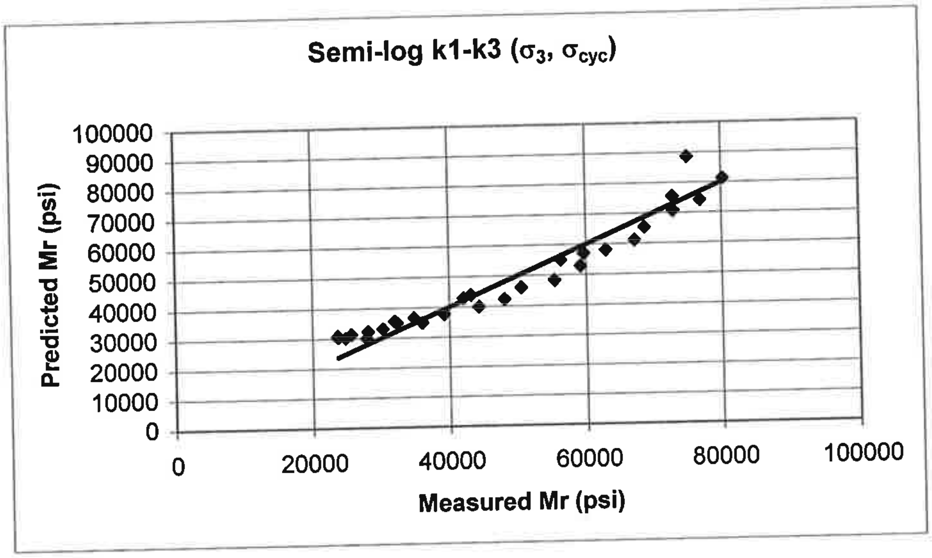


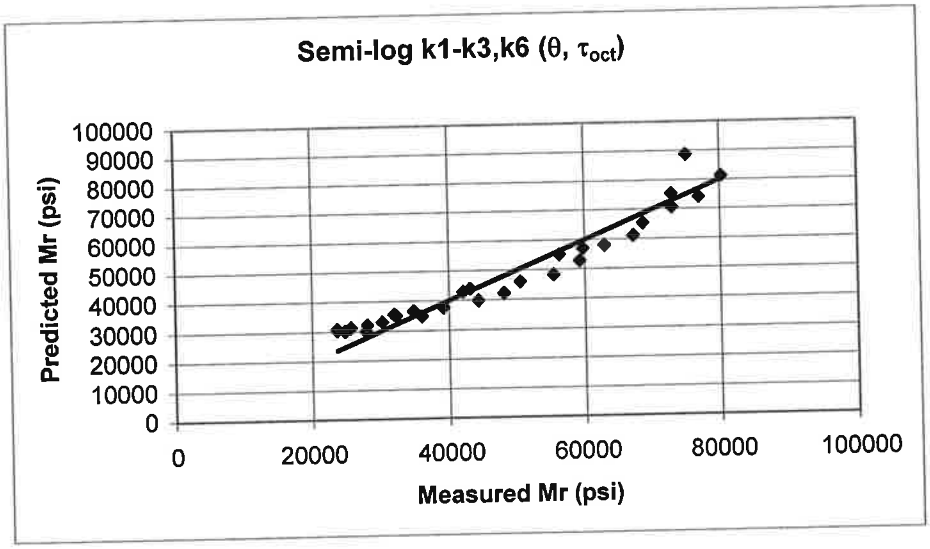




Measured Vs. Predicted M_R for Test S12_5







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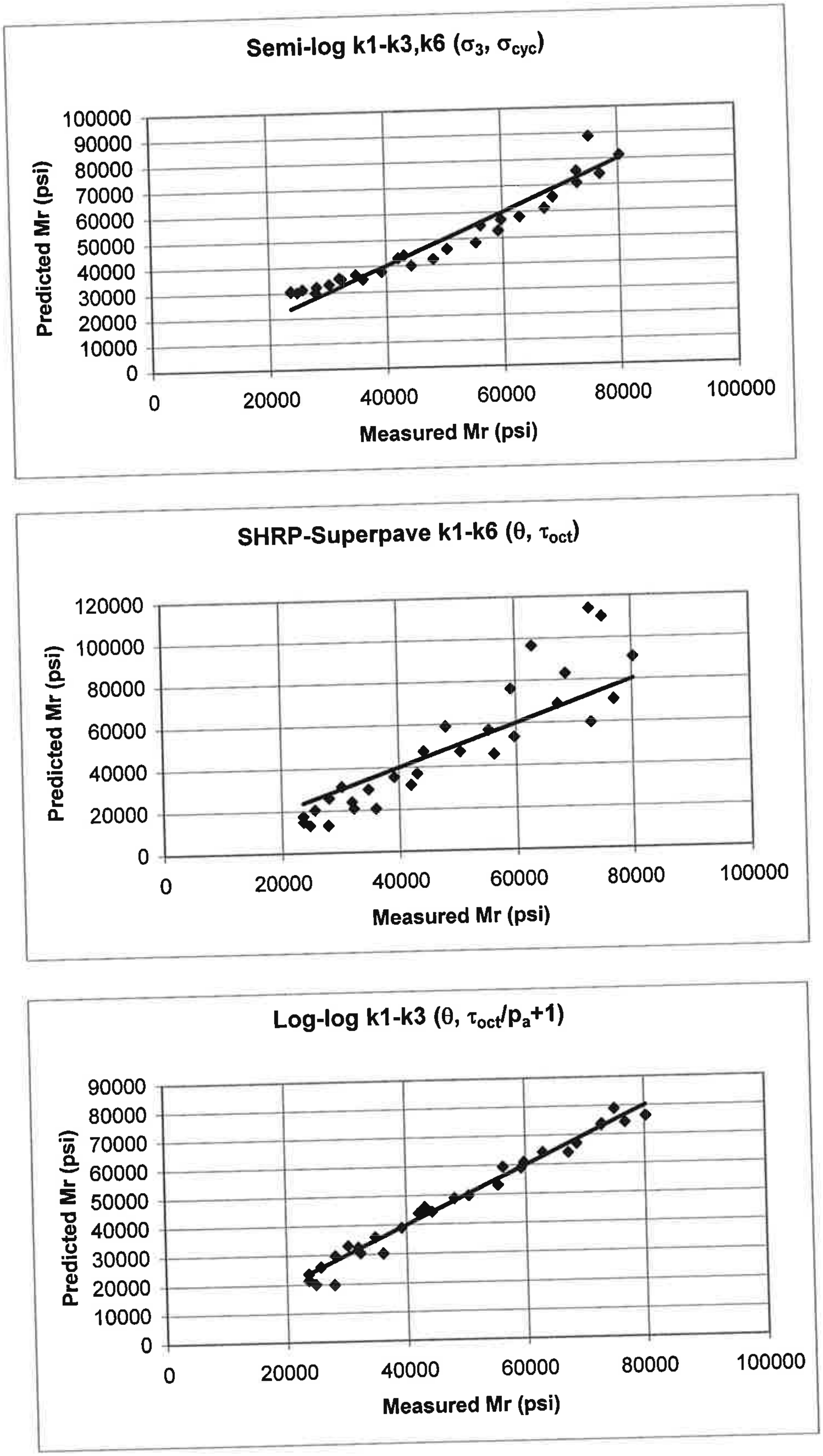

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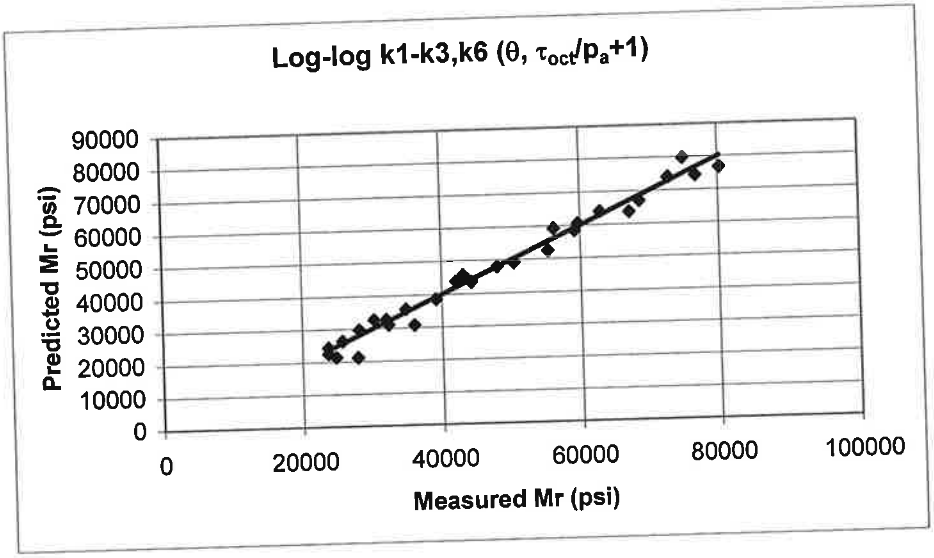

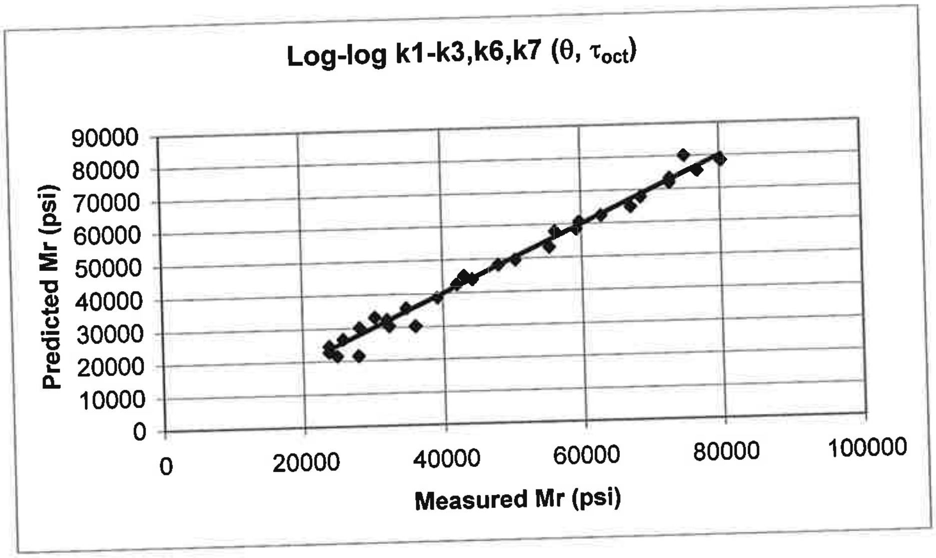

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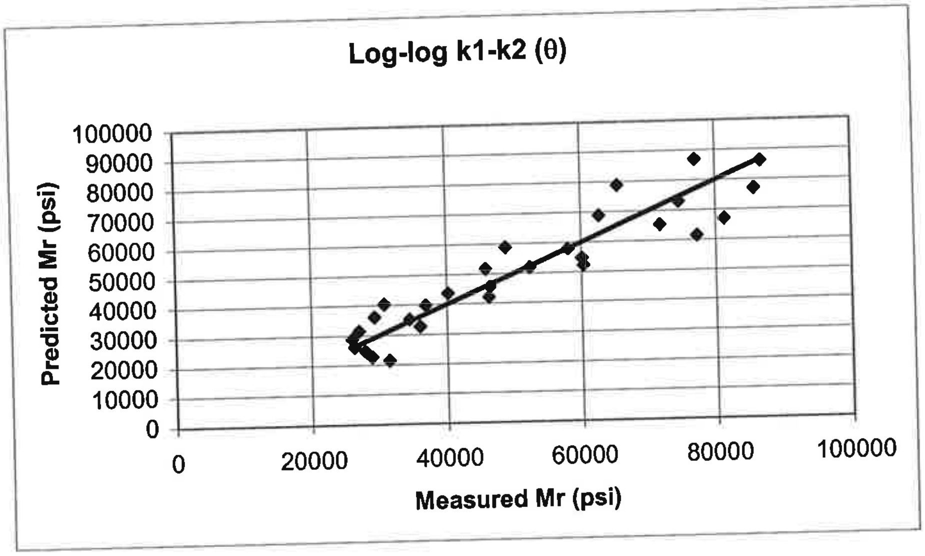
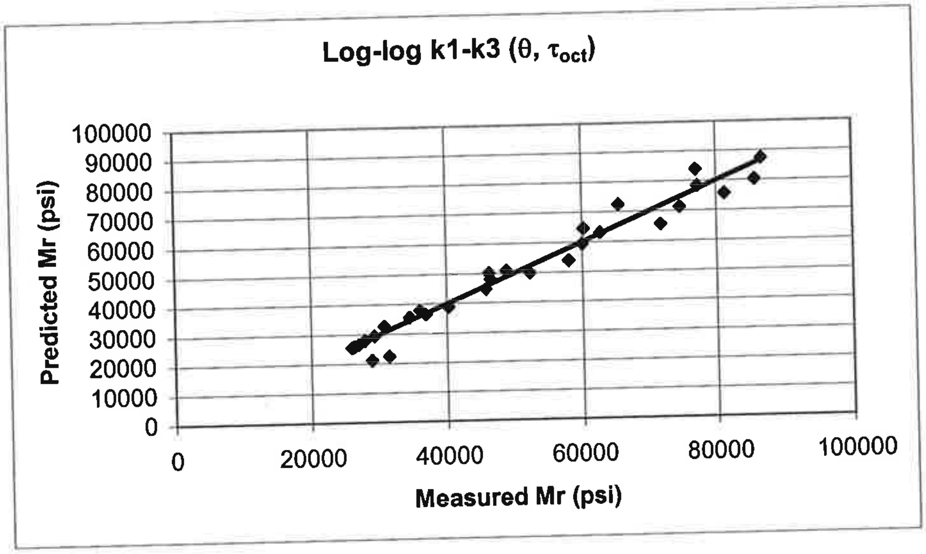
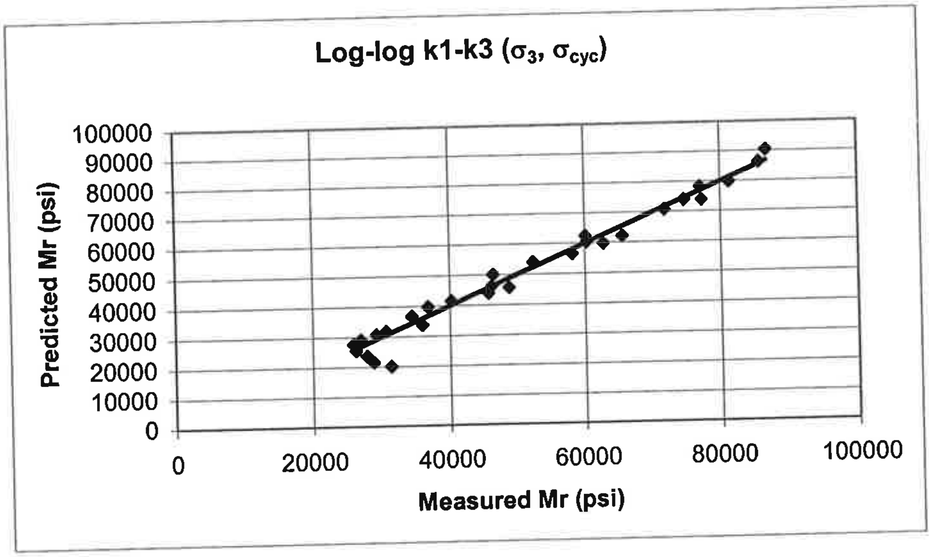
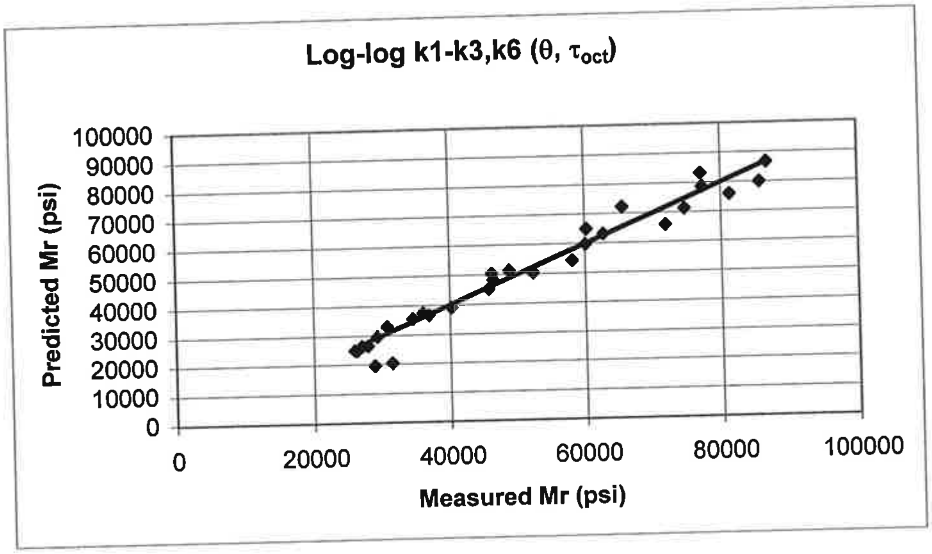
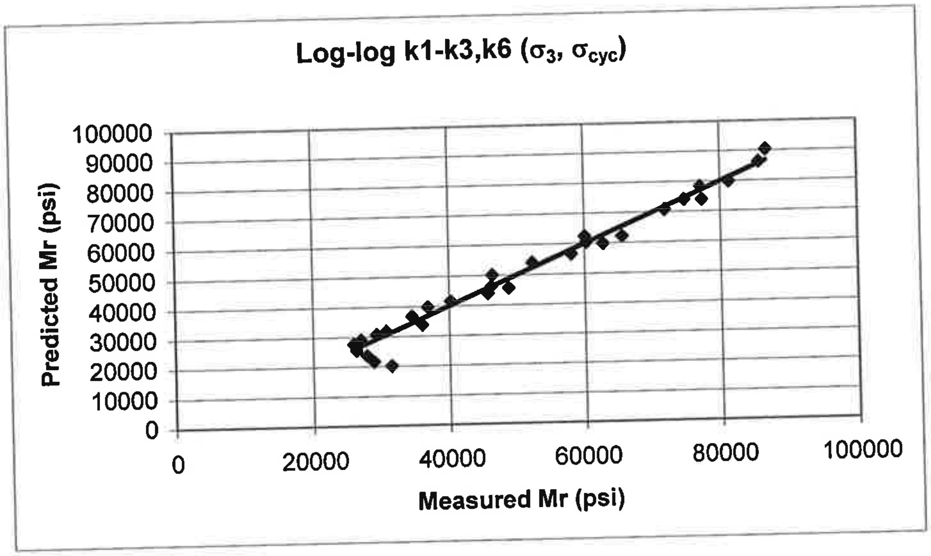


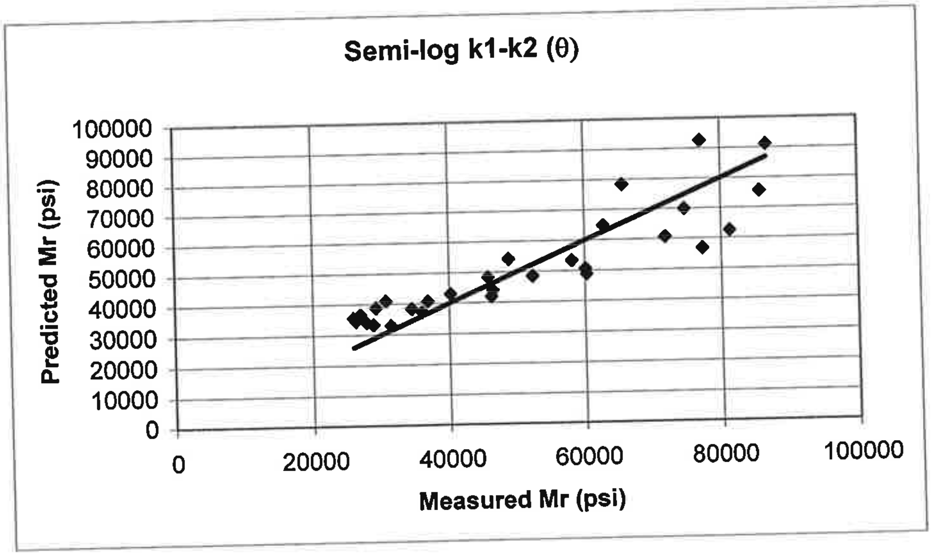




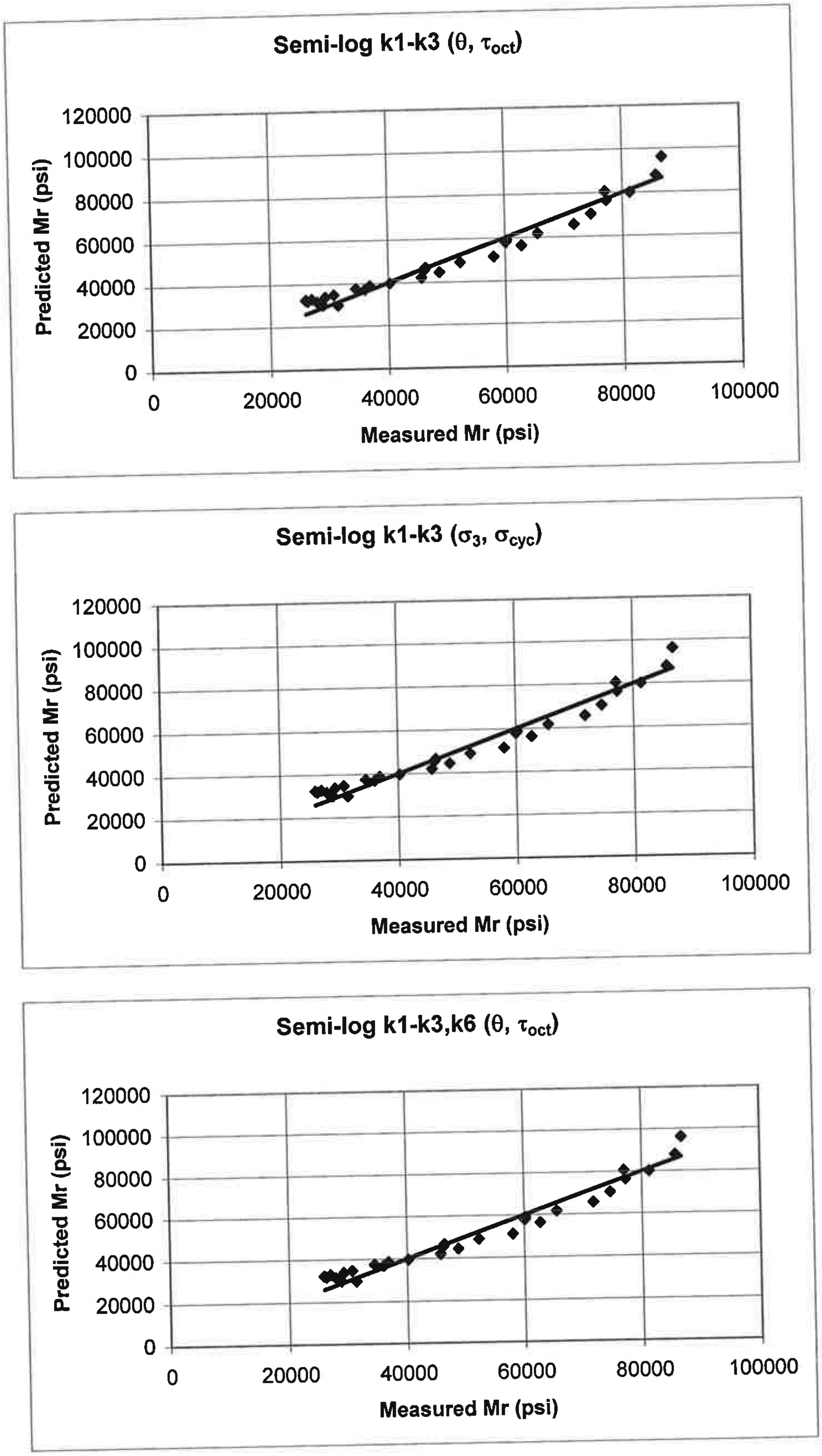
Measured Vs. Predicted M_R for Test S12_6







Measured Vs. Predicted M_R for Test S12_6

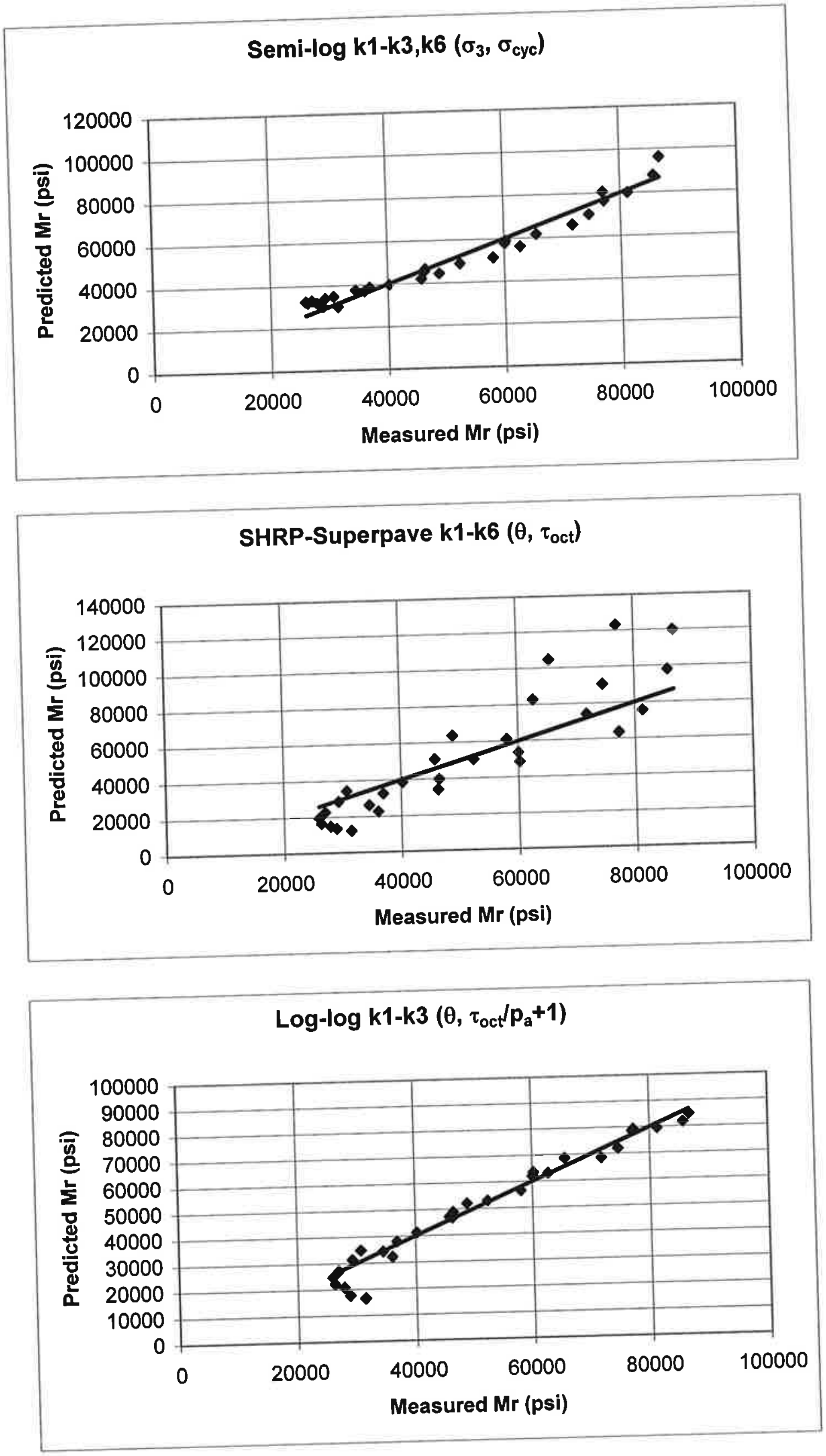


Semi-log k1-k3 (θ, τ_{oct})

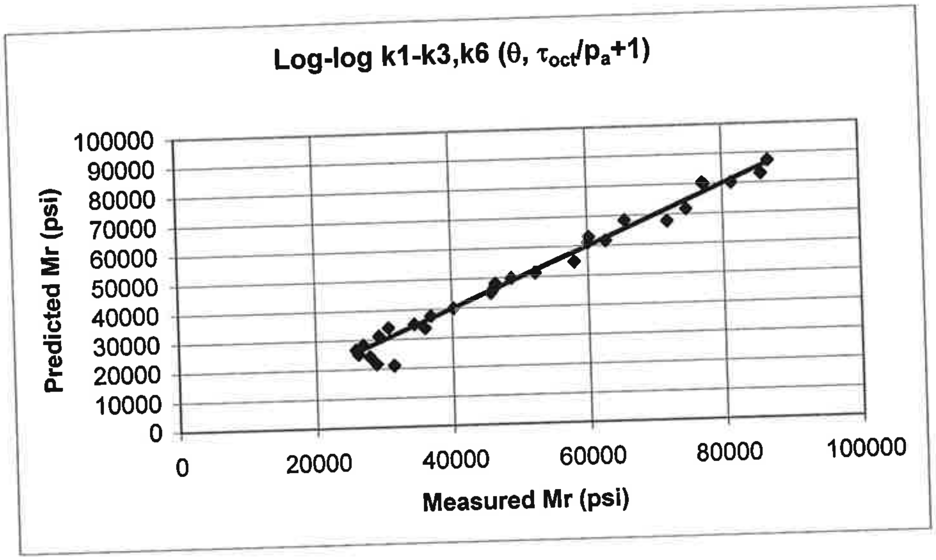
Semi-log k1-k3 (σ_3, σ_{cyc})

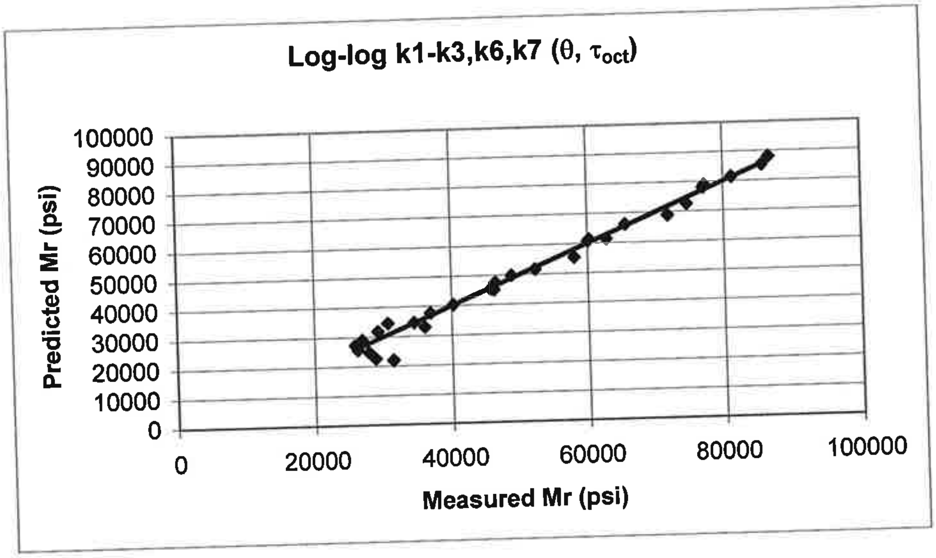
Semi-log k1-k3,k6 (θ, τ_{oct})

Measured Vs. Predicted M_R for Test S12_6

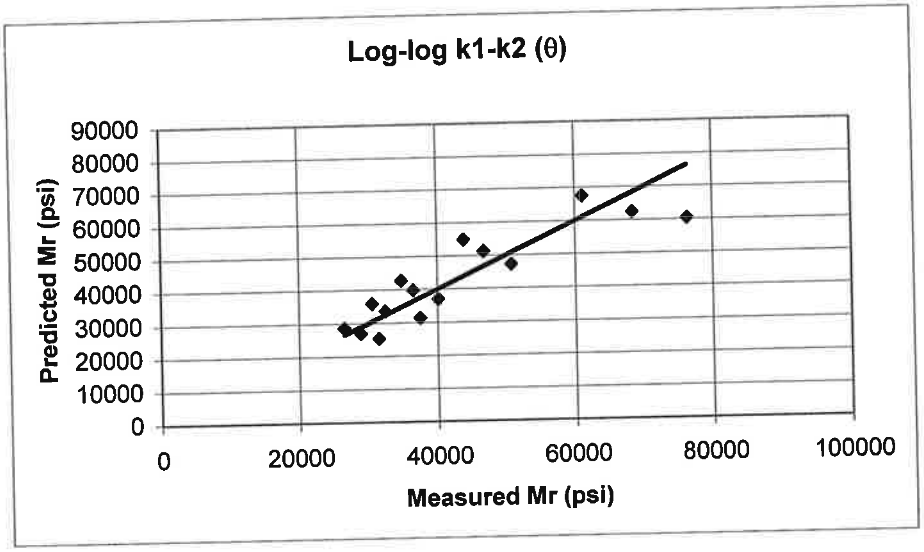


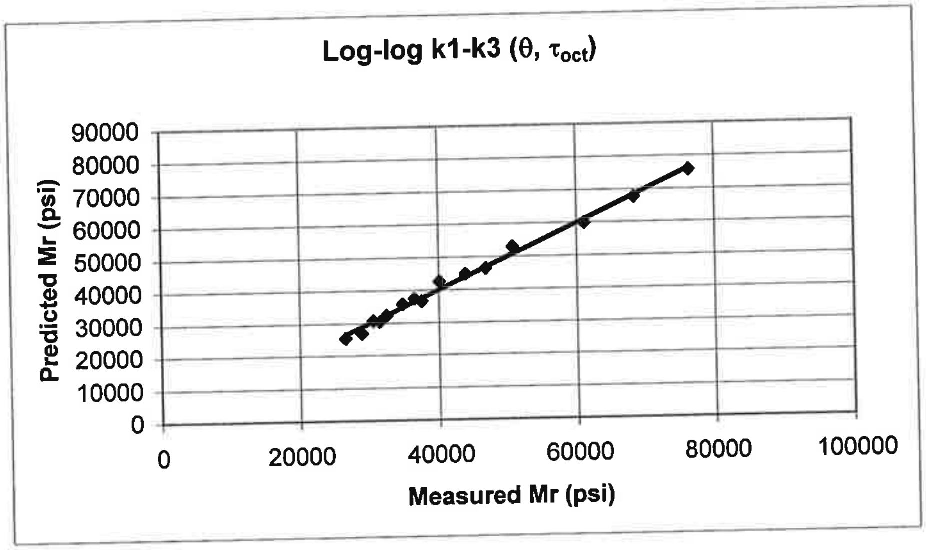
Measured Vs. Predicted M_R for Test S12_6

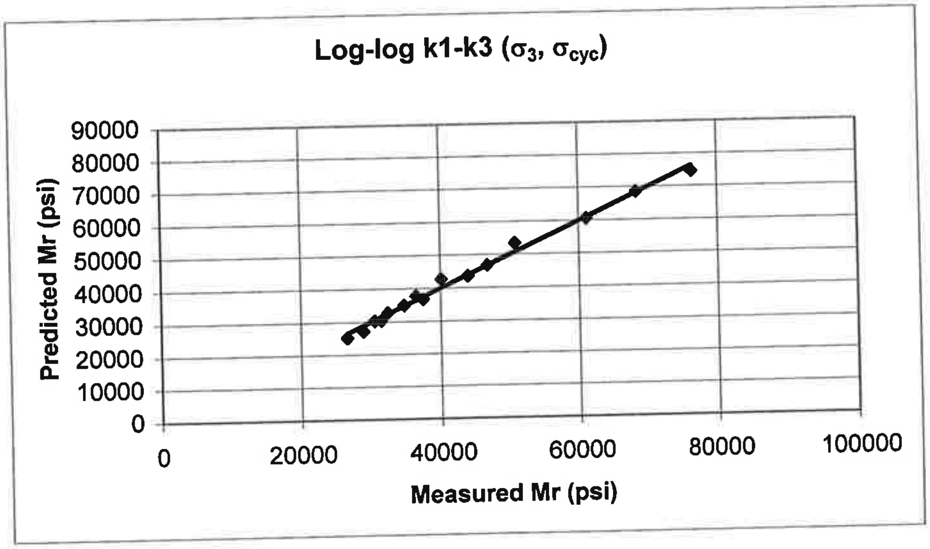




Measured Vs. Predicted M_R for Test S12_6







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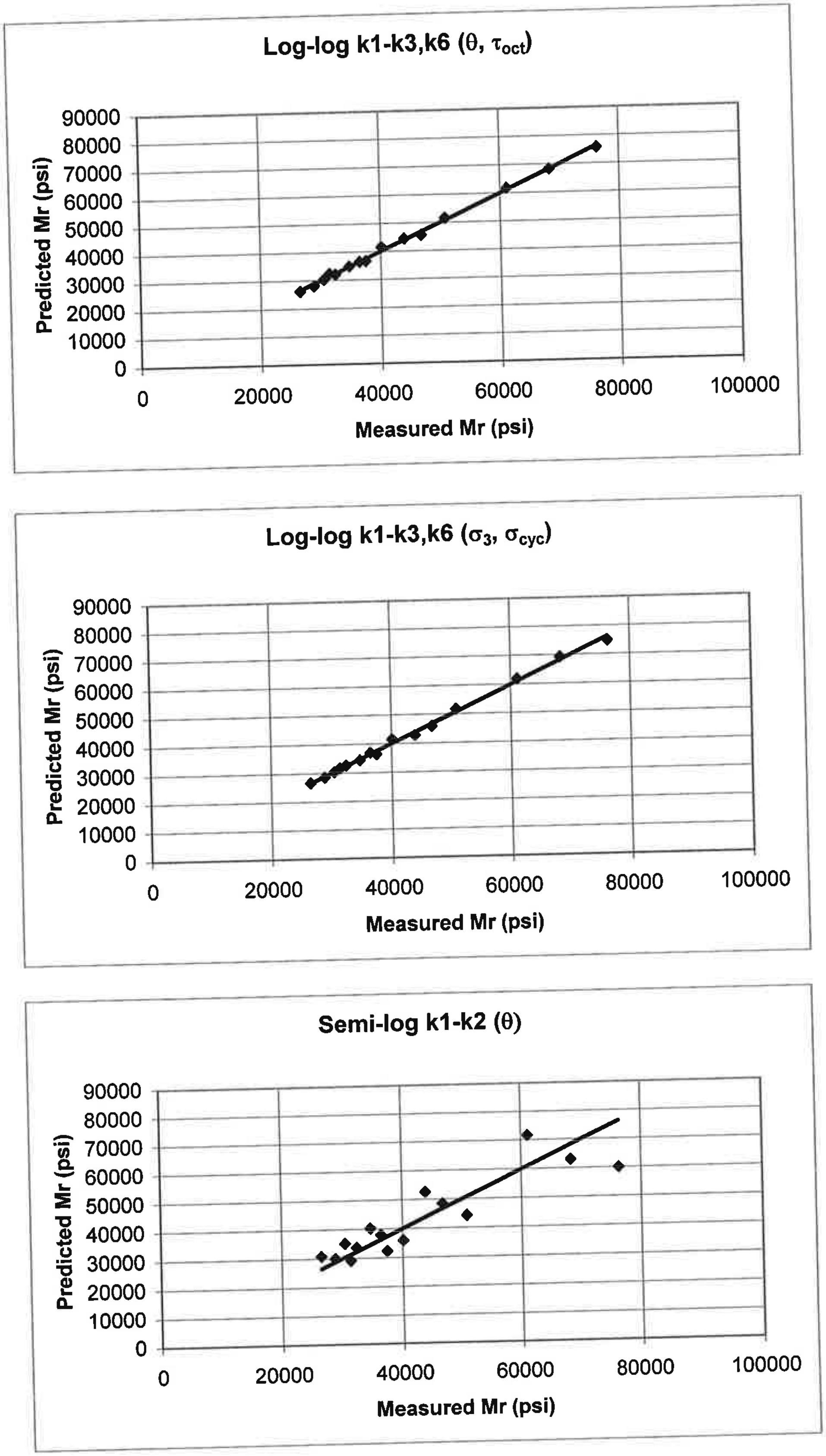
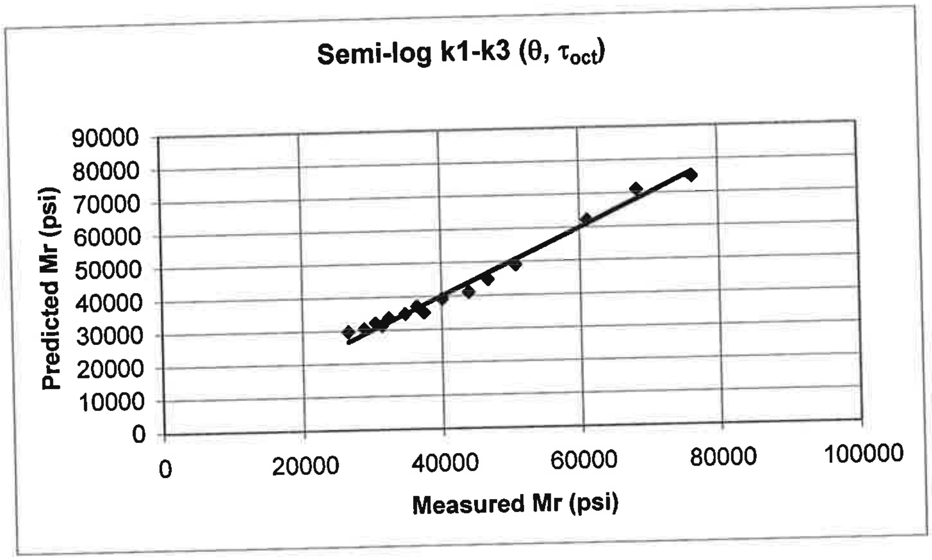
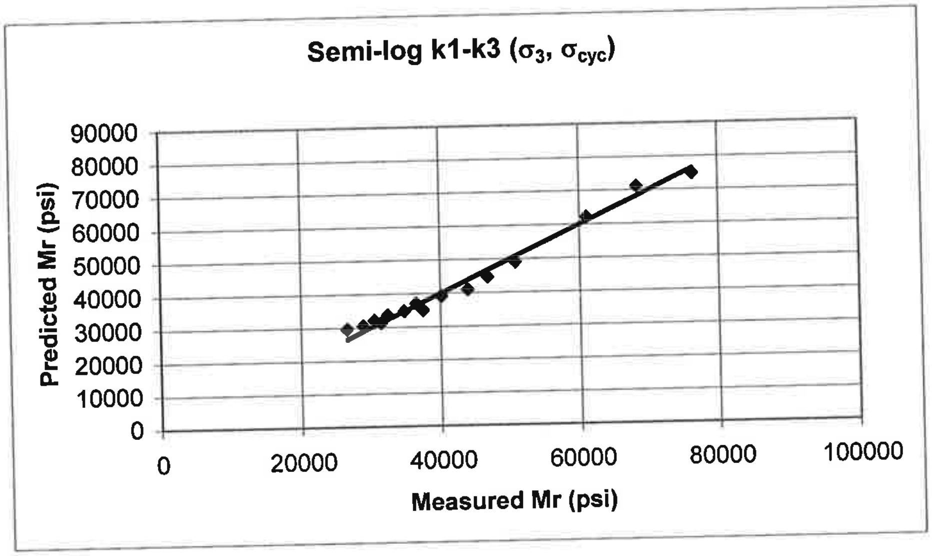
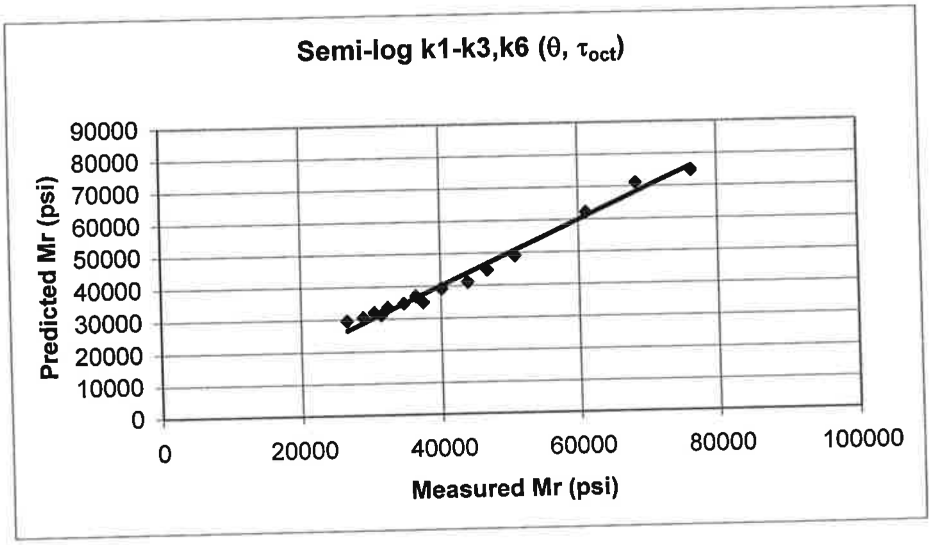


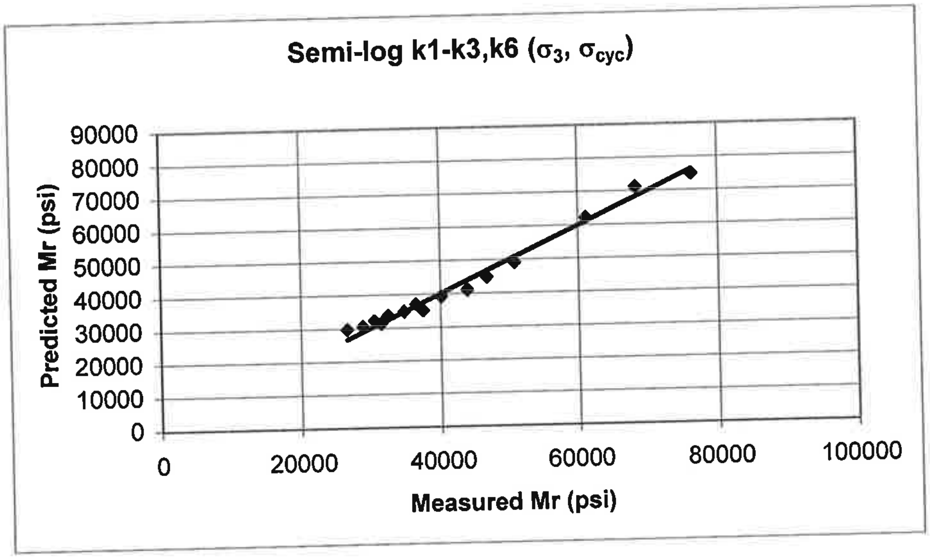
Measured Vs. Predicted M_R for Test NS12_2

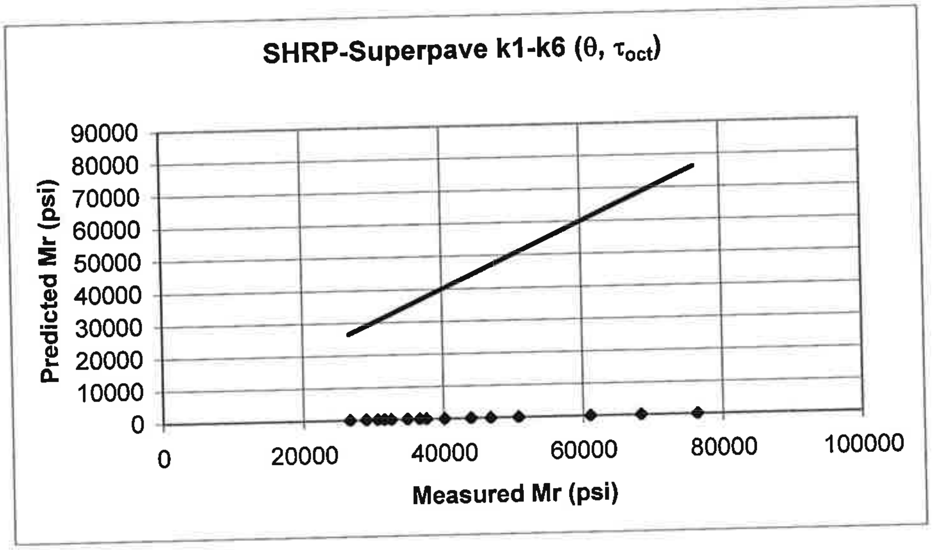


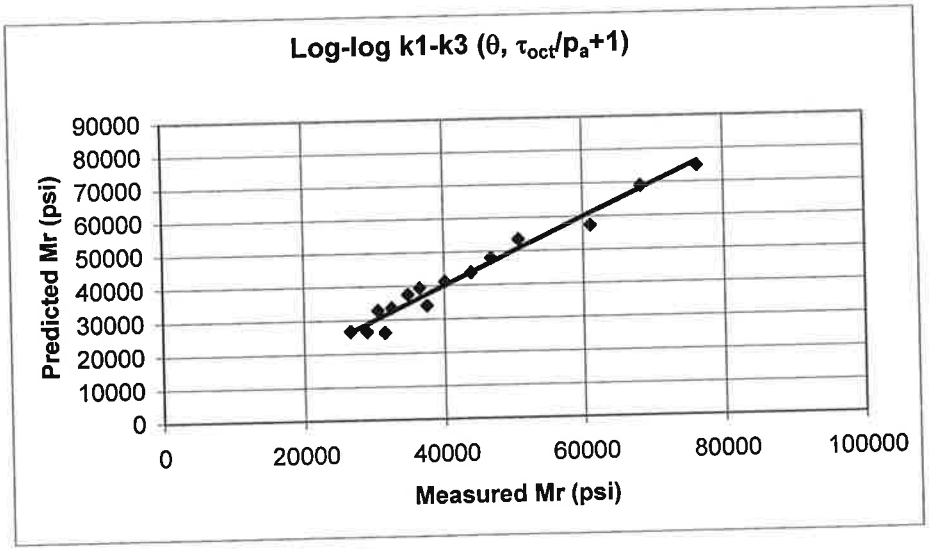




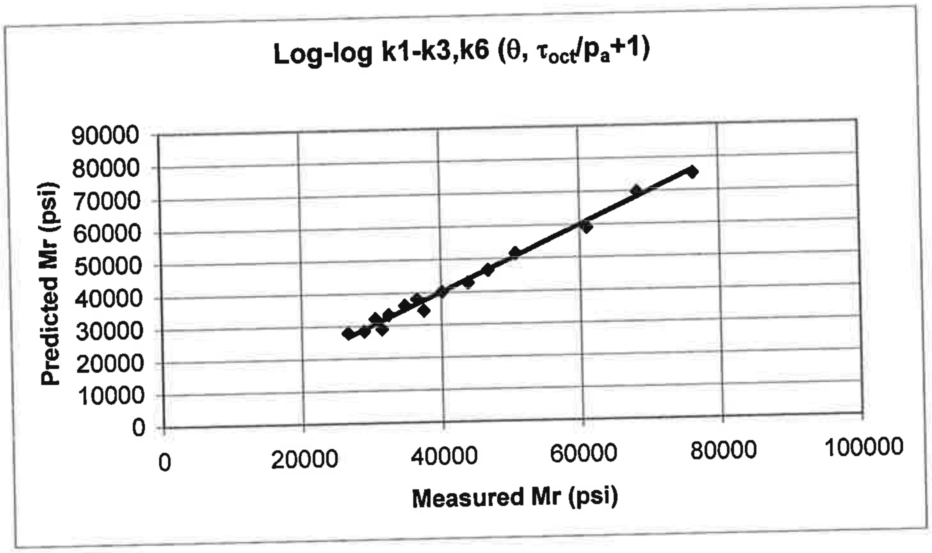
Measured Vs. Predicted M_R for Test NS12_2

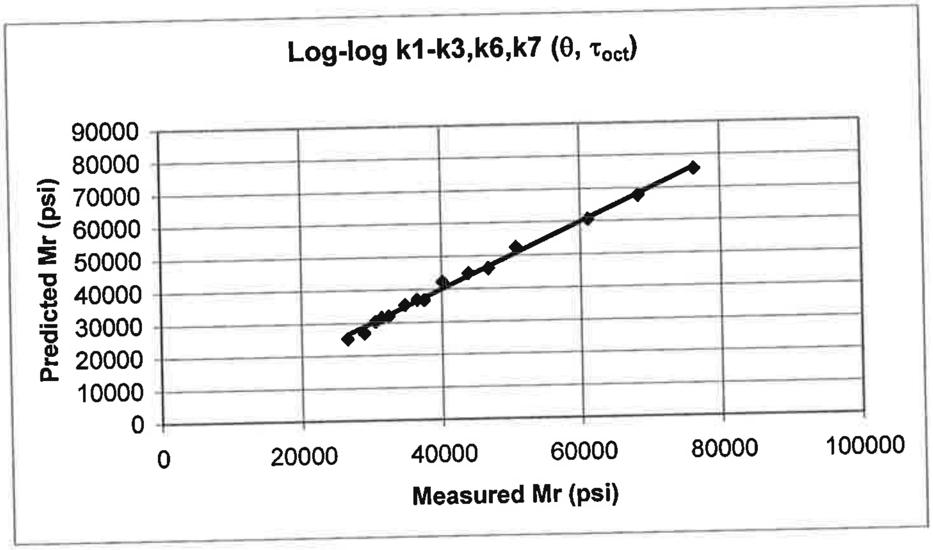




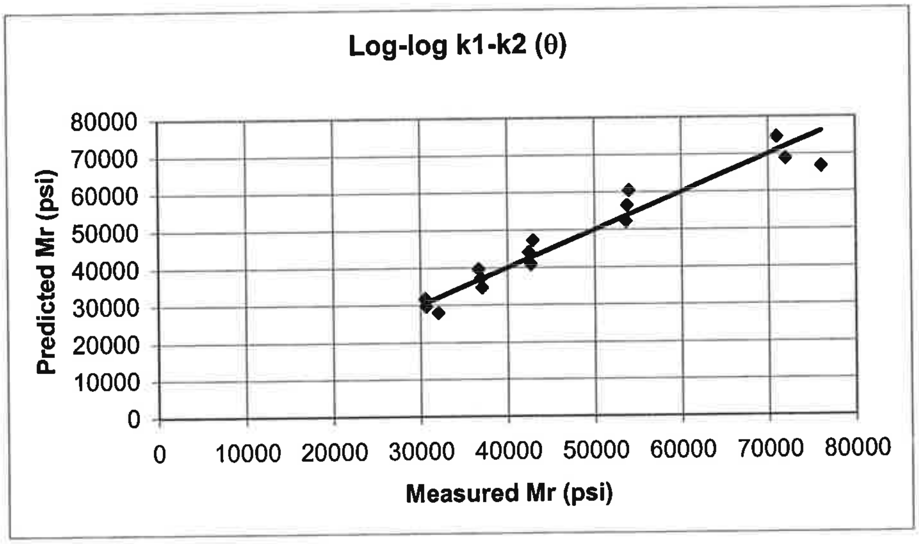


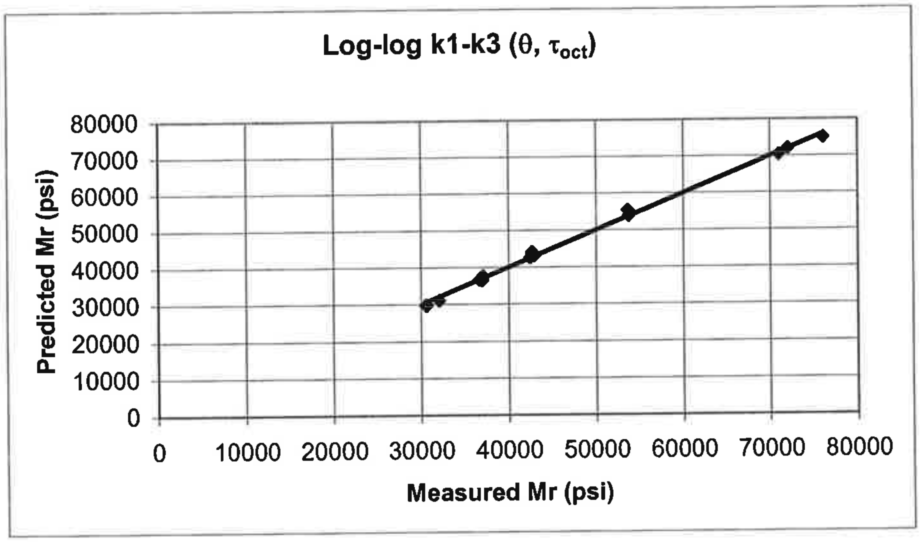
Measured Vs. Predicted M_R for Test NS12_2

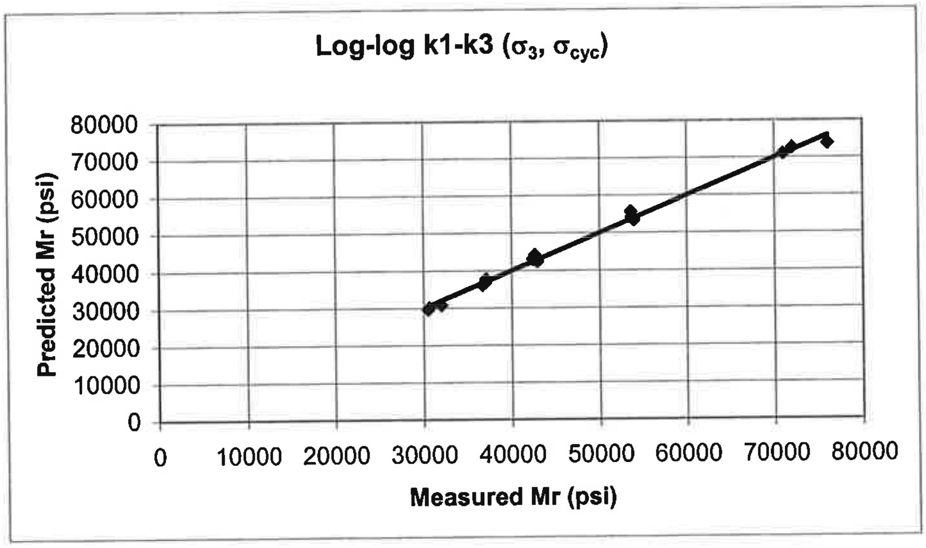




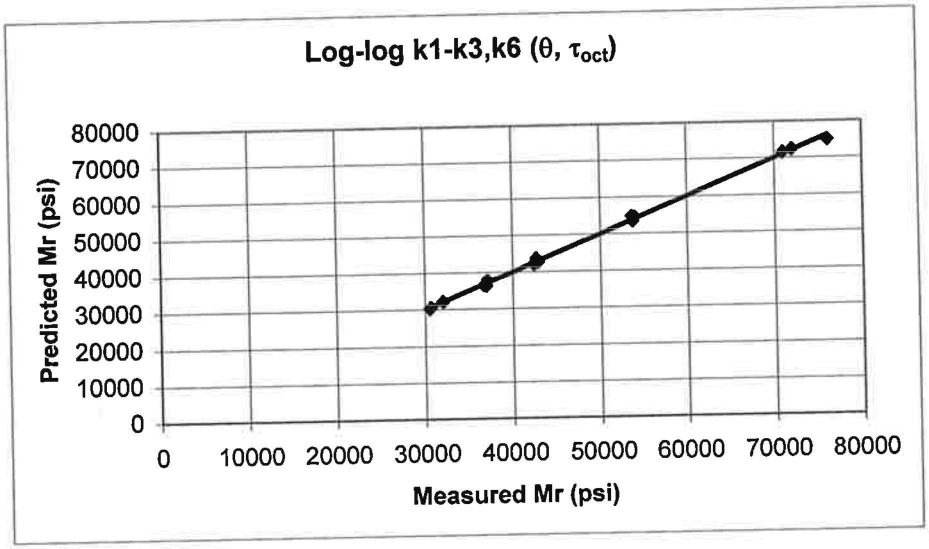
Measured Vs. Predicted M_R for Test NS12_2

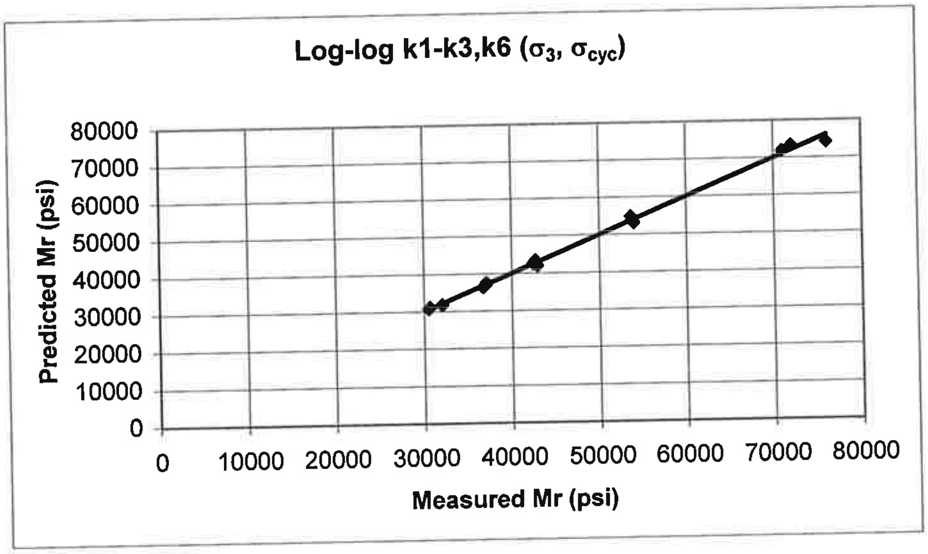

Log-log k1-k2 (θ)

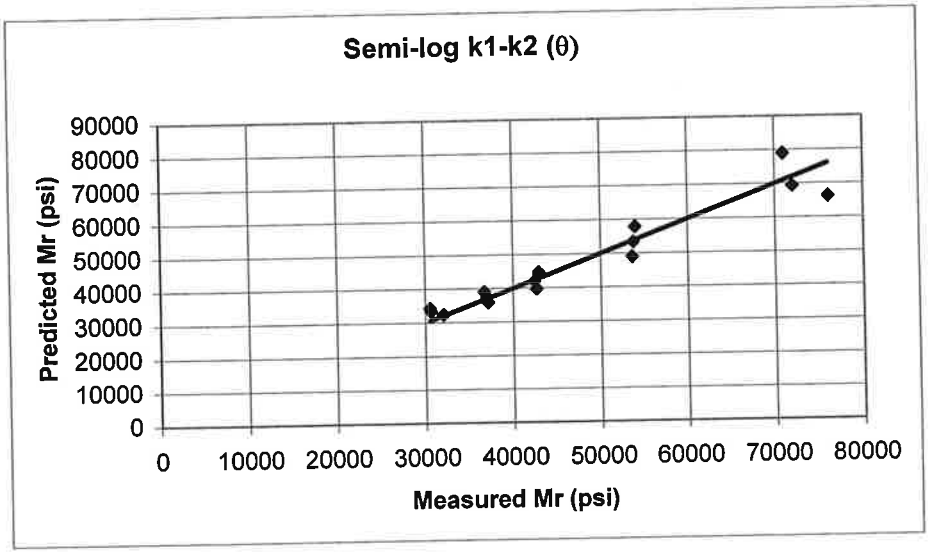

Log-log k1-k3 (θ, τ_{oct})


Log-log k1-k3 (σ_3, σ_{cyc})

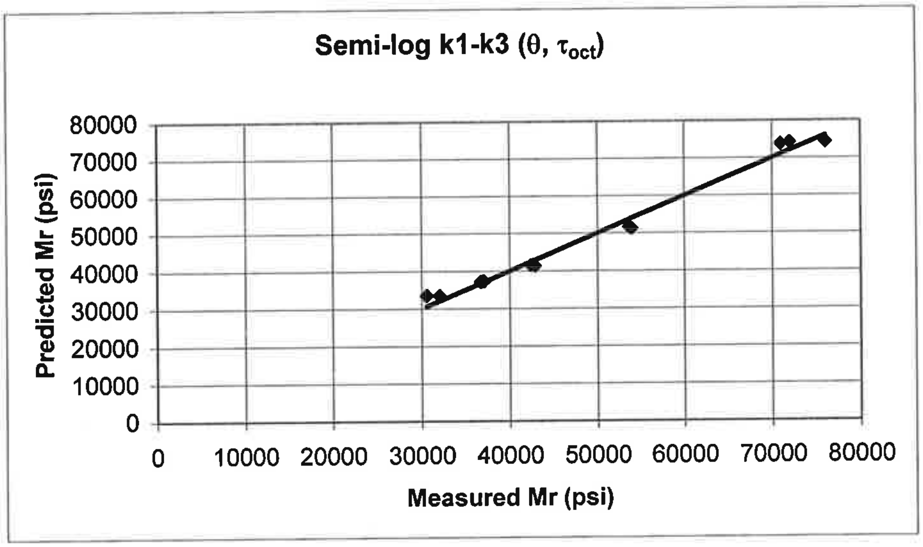
Measured Vs. Predicted MR for Test NS12-3

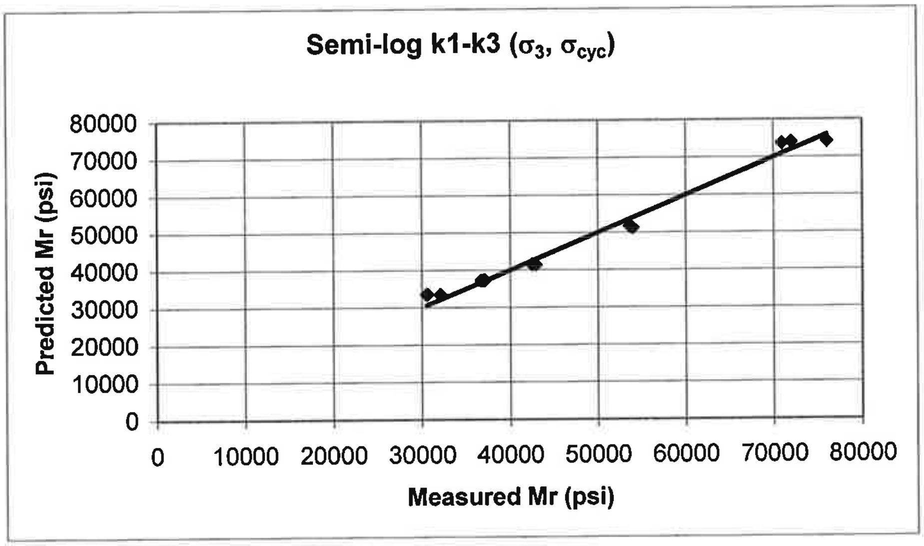


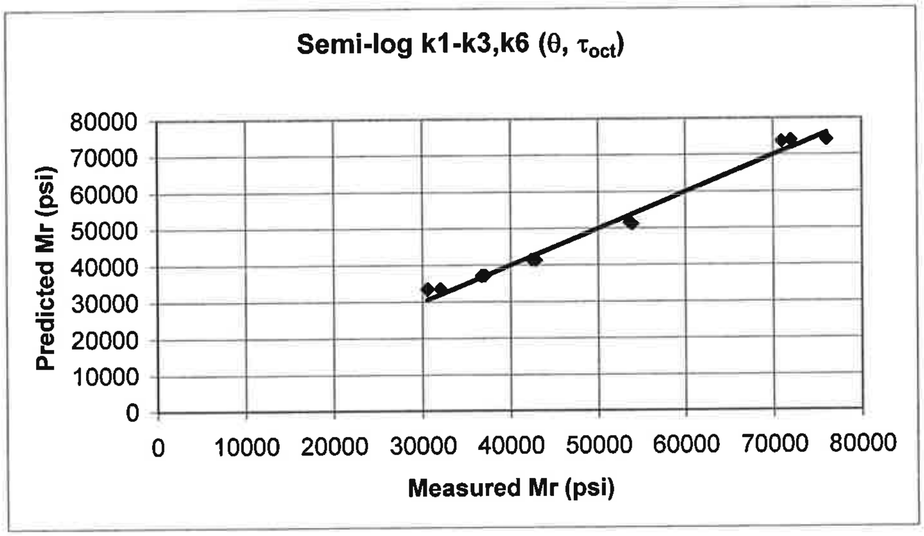




Measured Vs. Predicted MR for Test NS12-3







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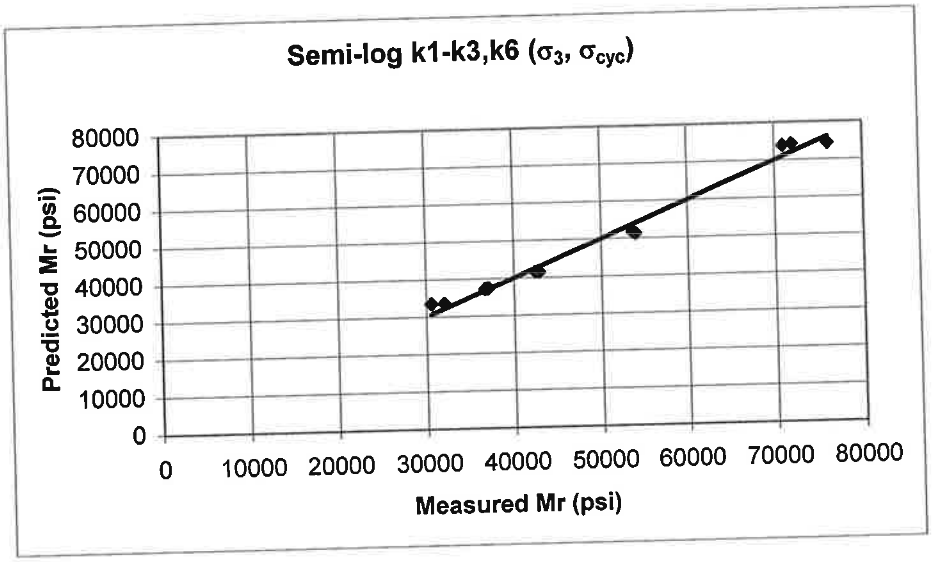
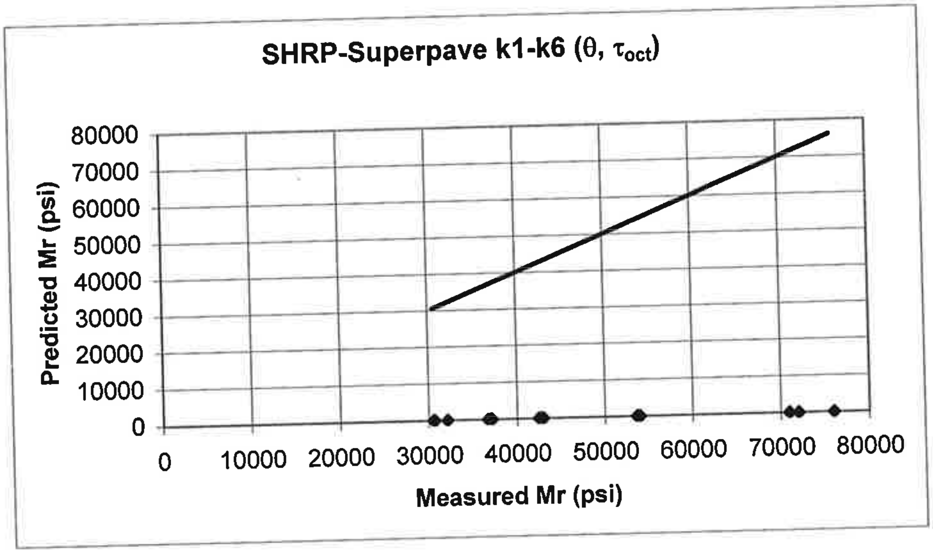
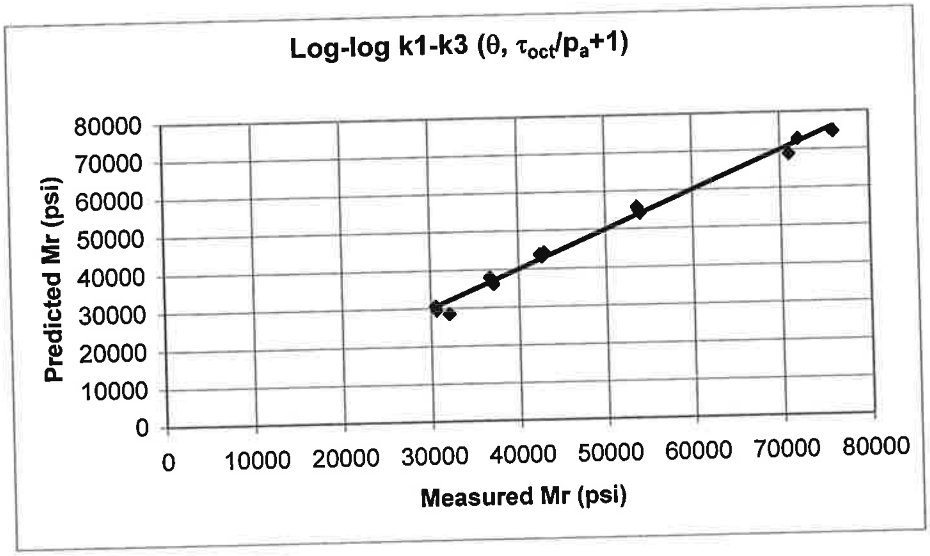
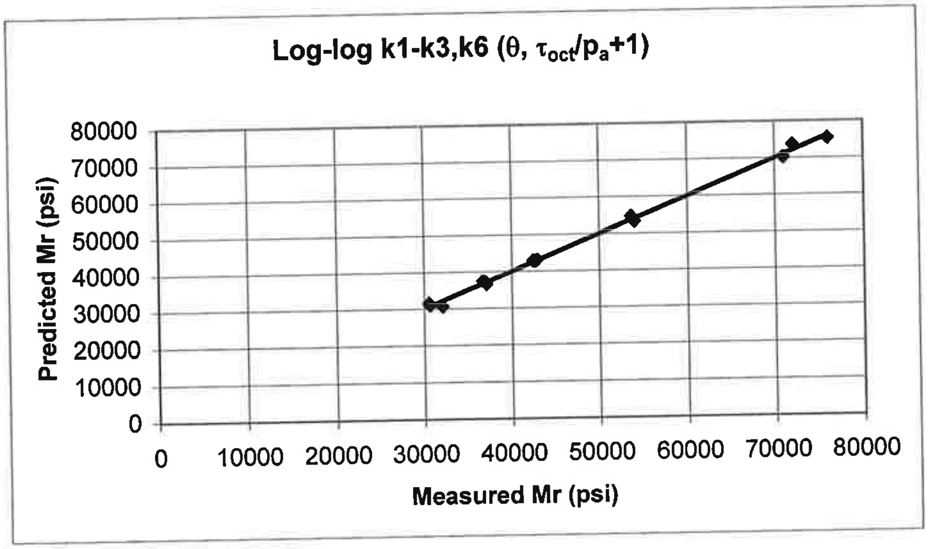
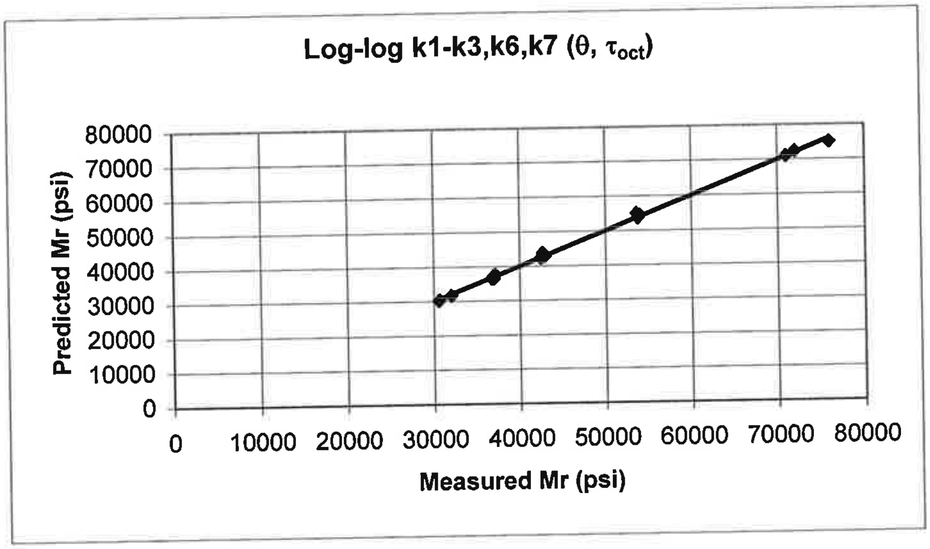






Measured Vs. Predicted MR for Test NS12-3





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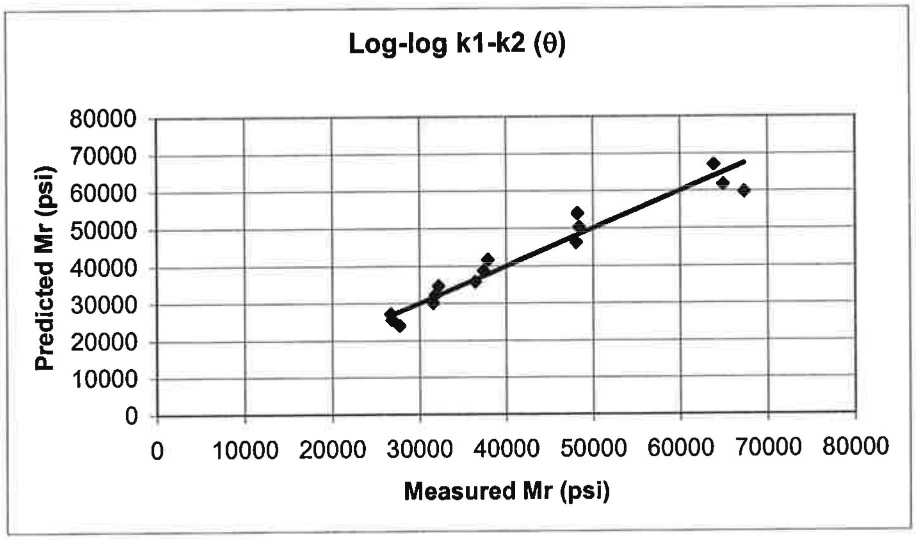
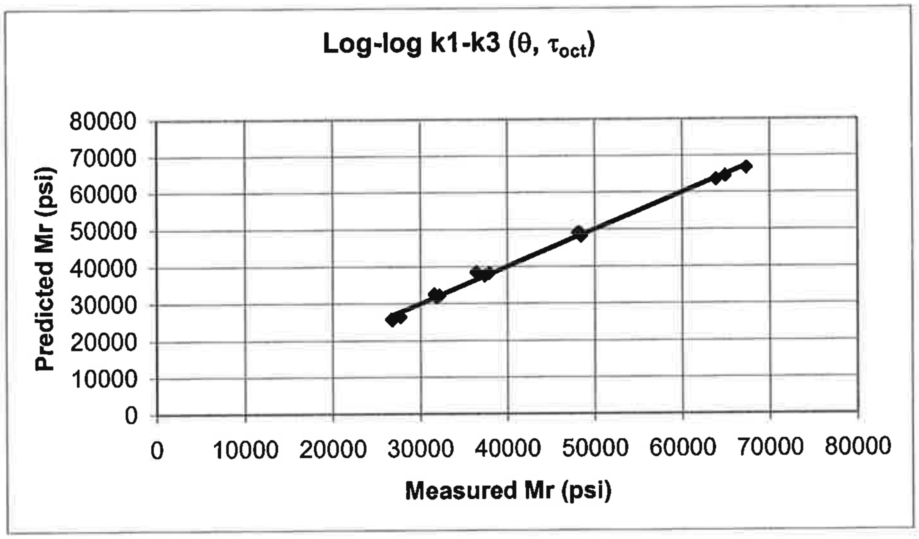
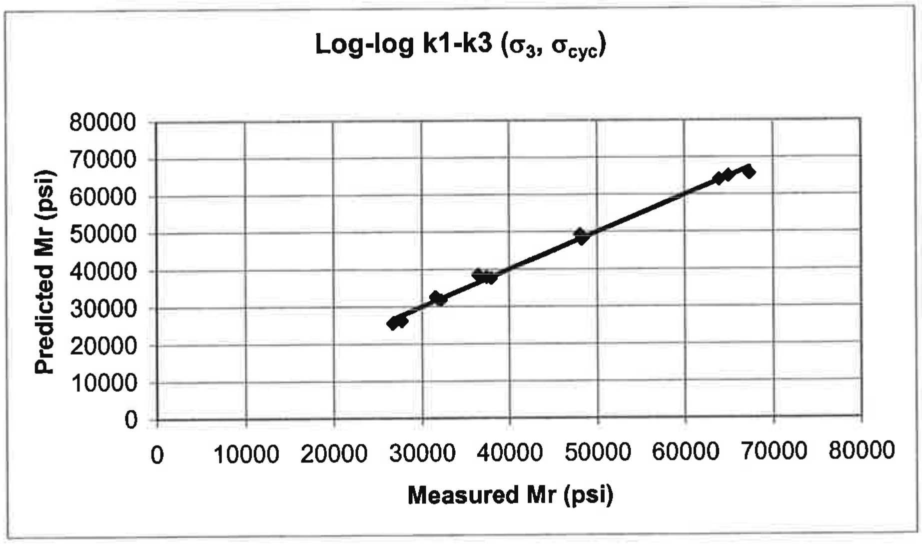
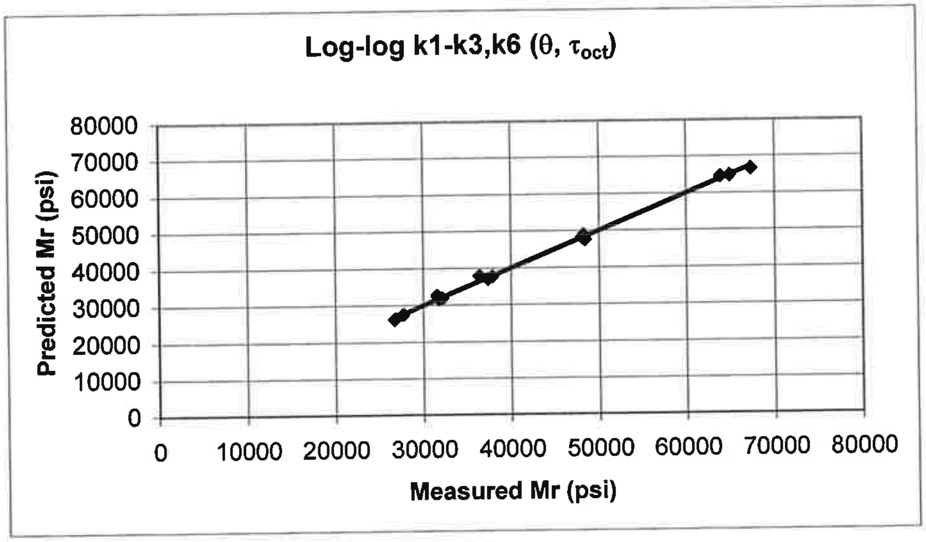
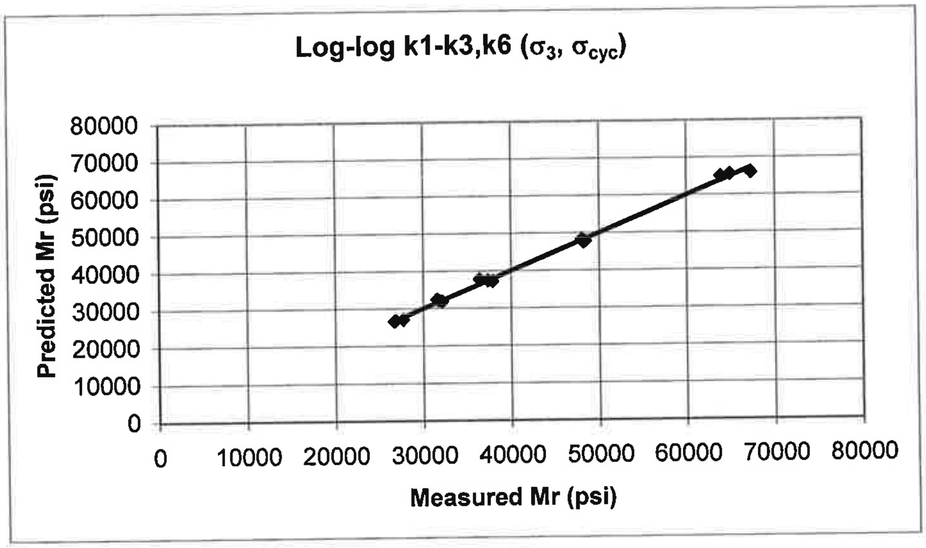


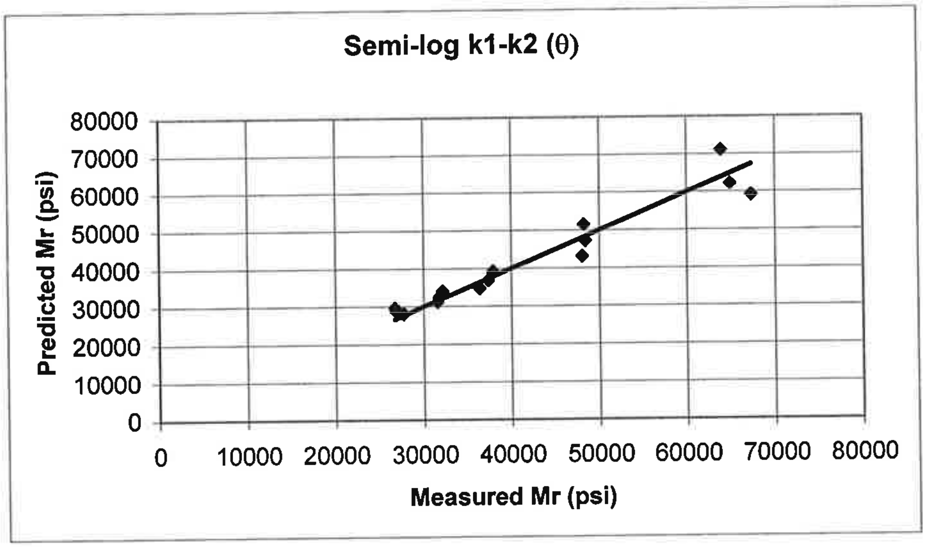




Measured Vs. Predicted M_R for Test NS12_4







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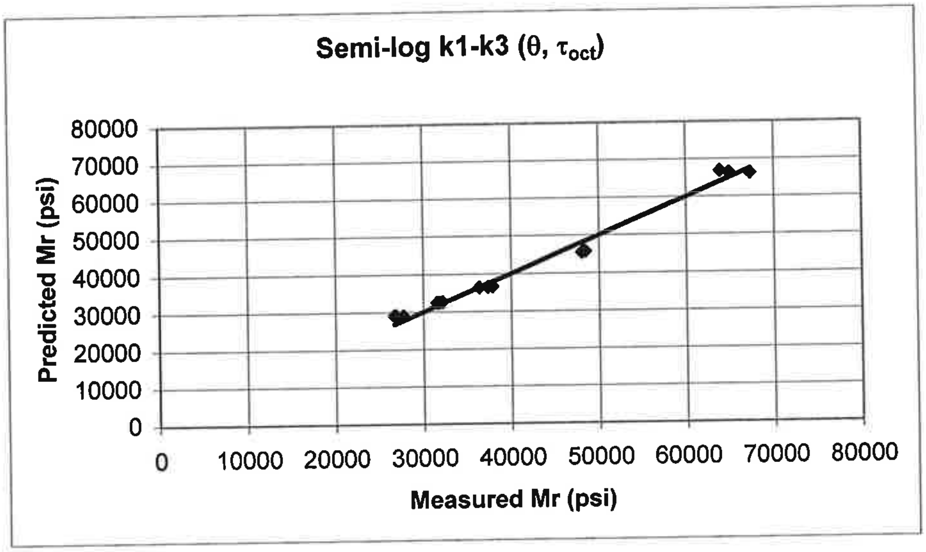

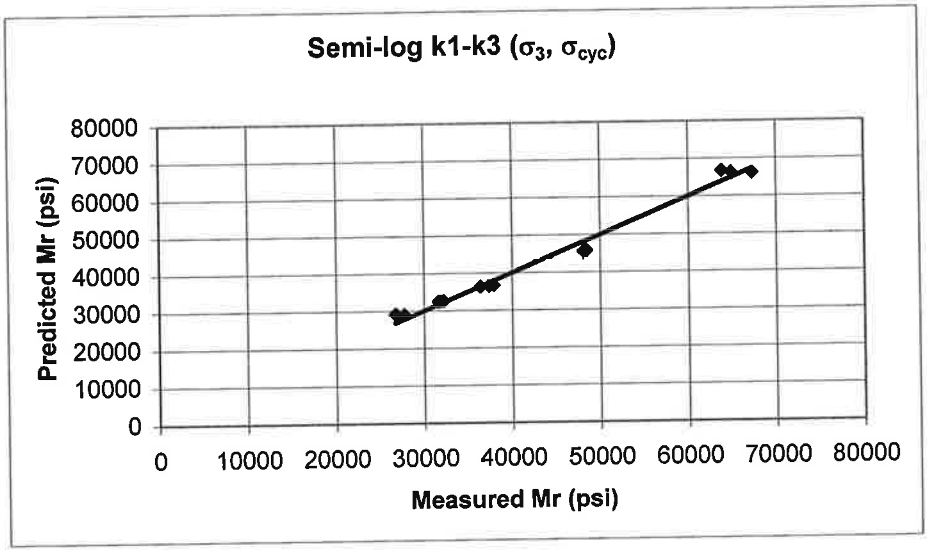

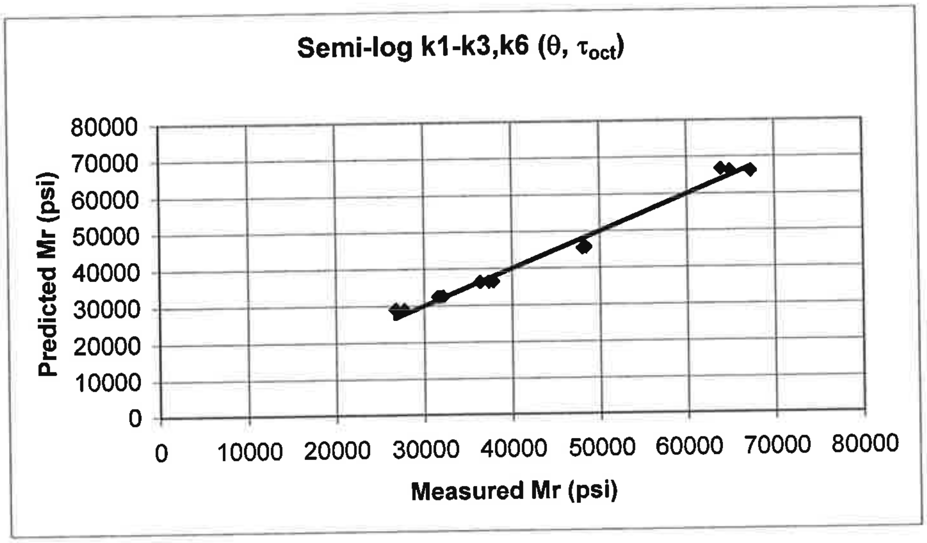

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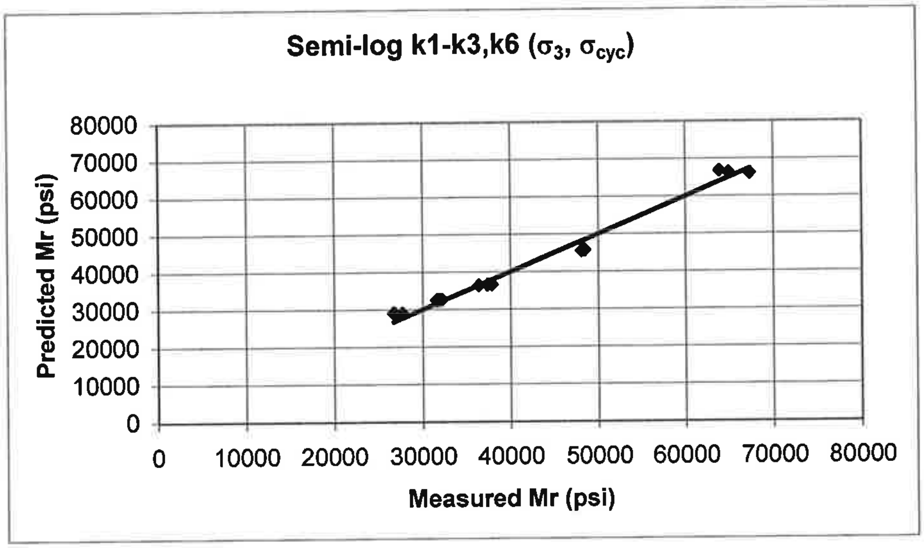

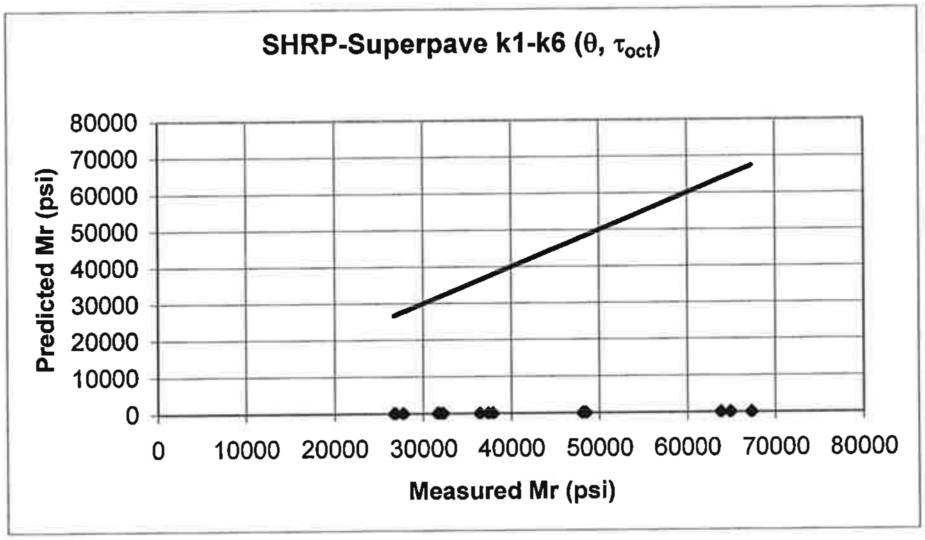

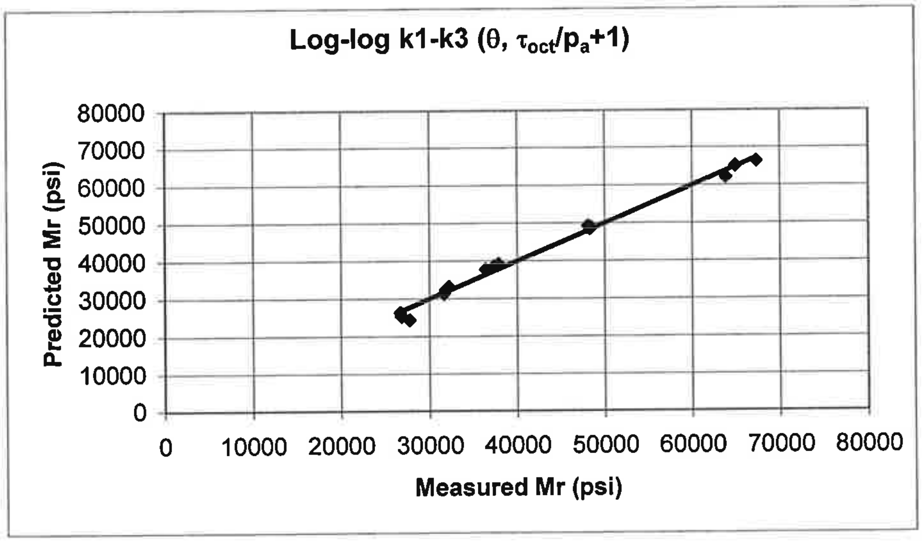

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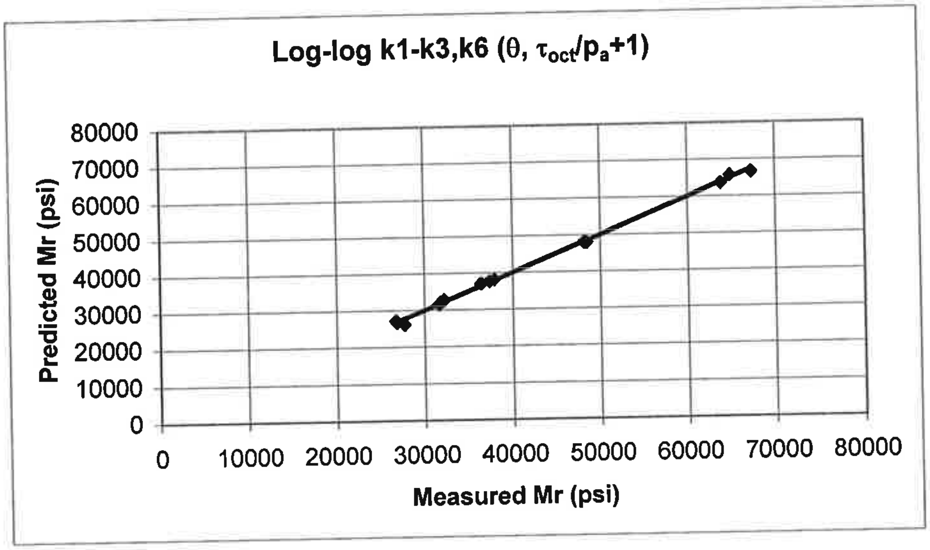

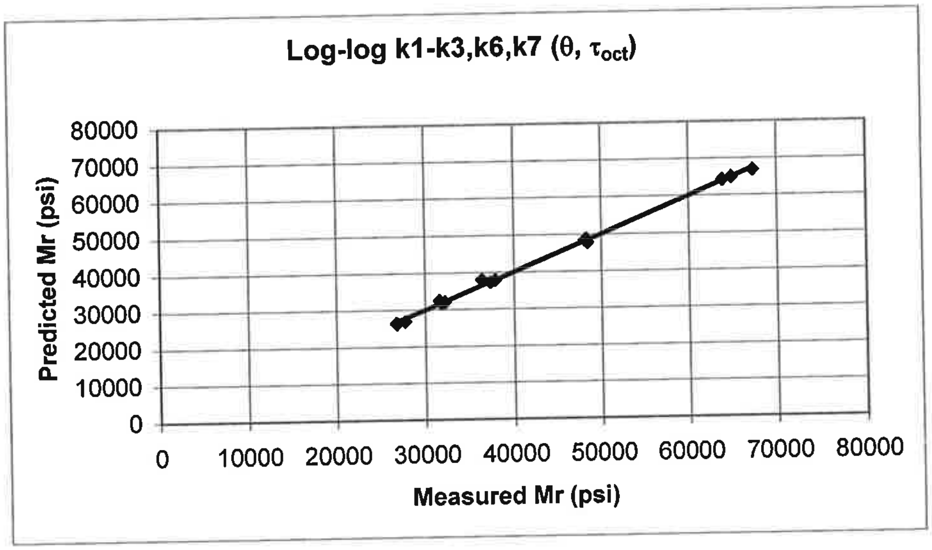

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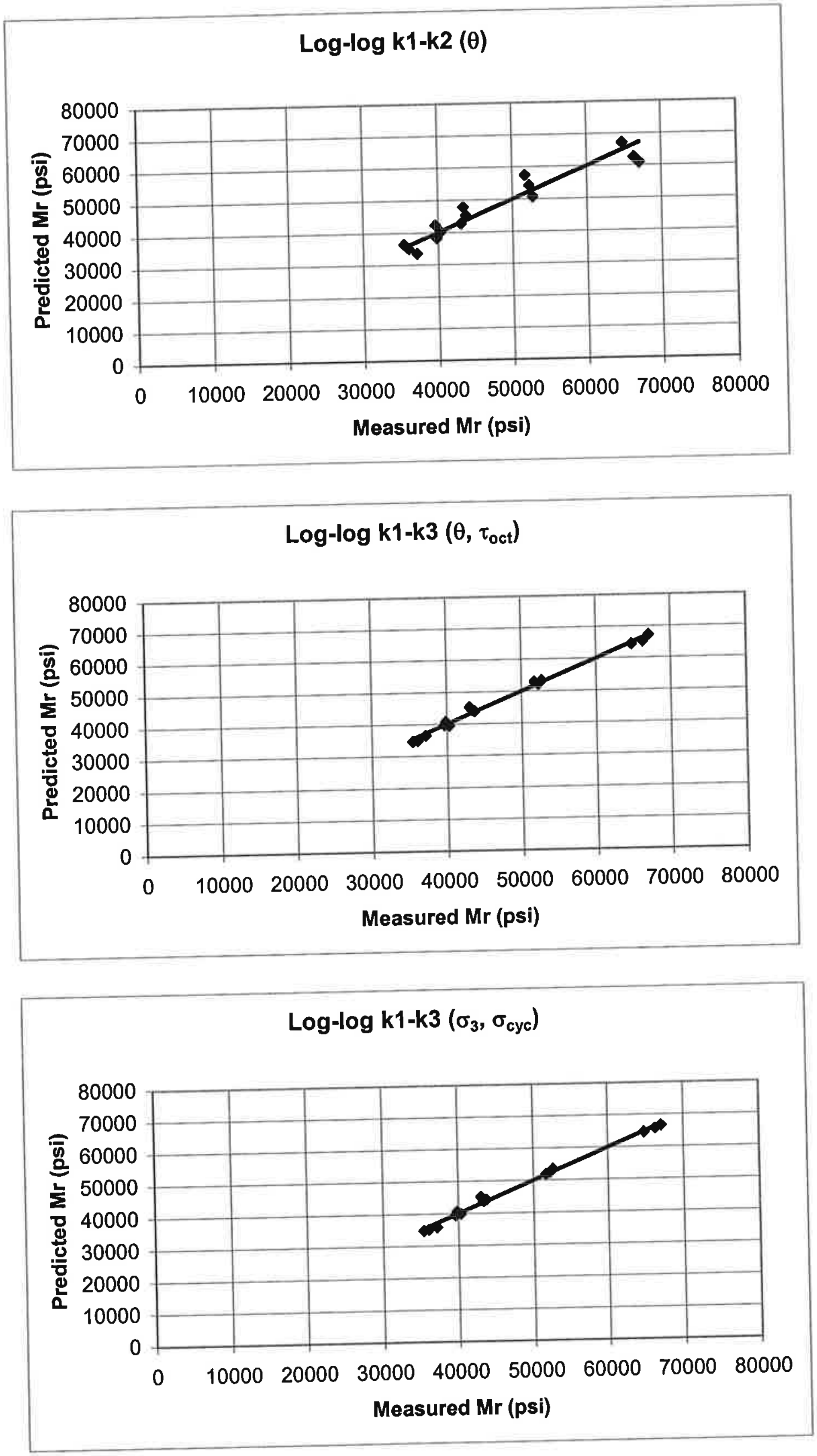
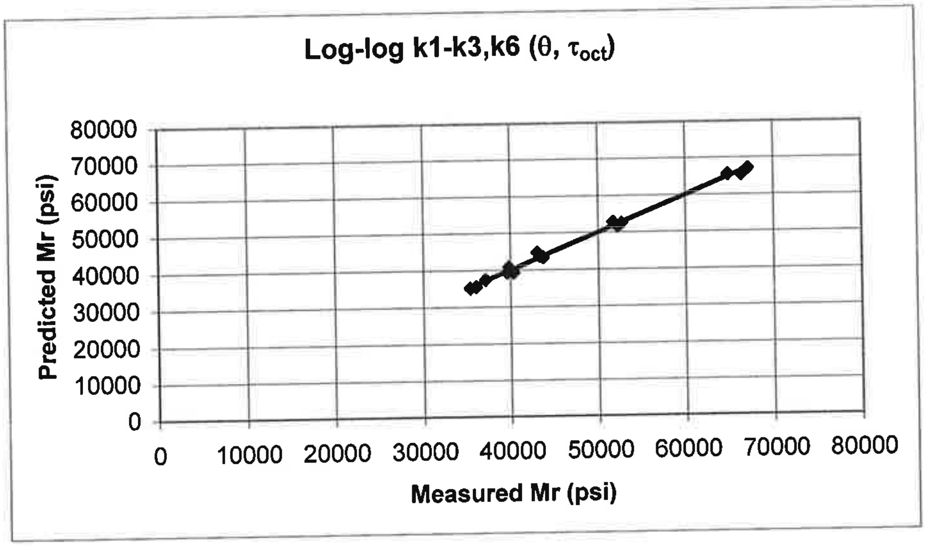
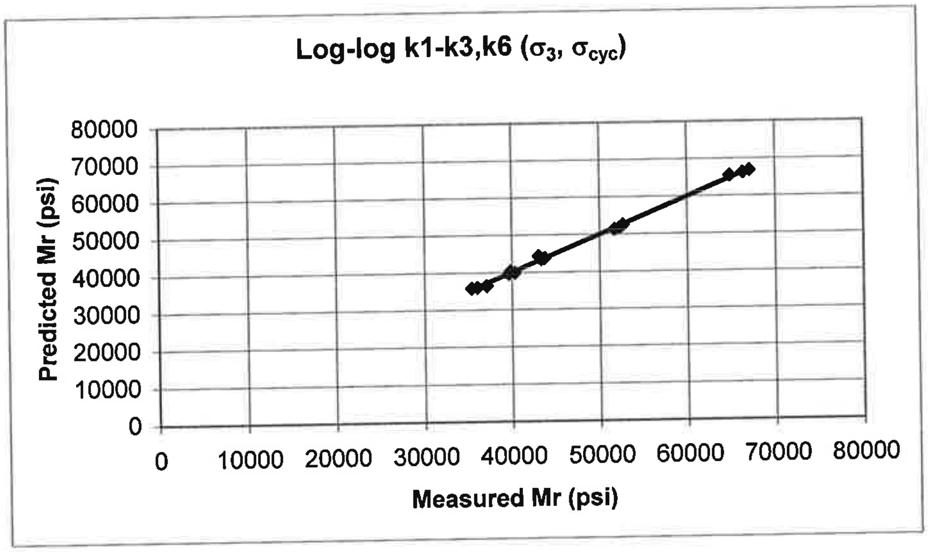
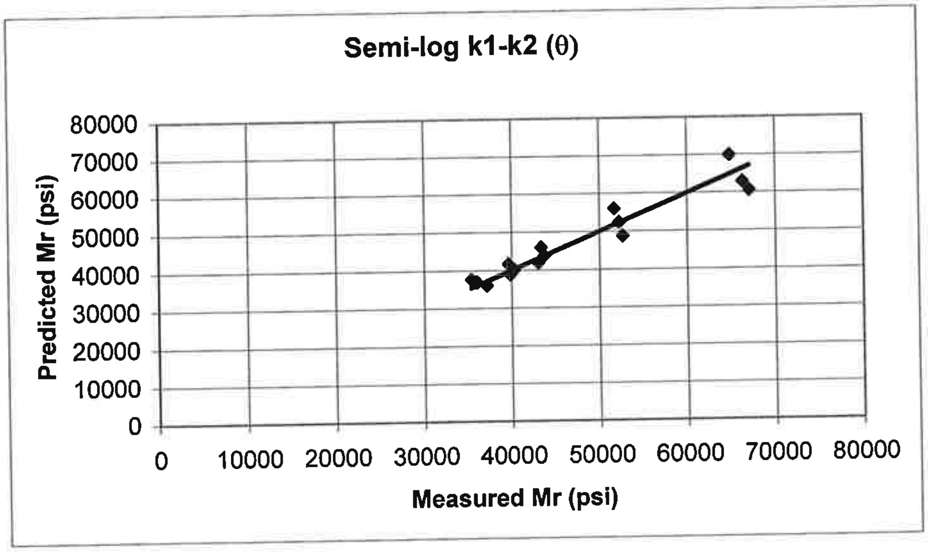


Measured Vs. Predicted M_R for Test NS12_5







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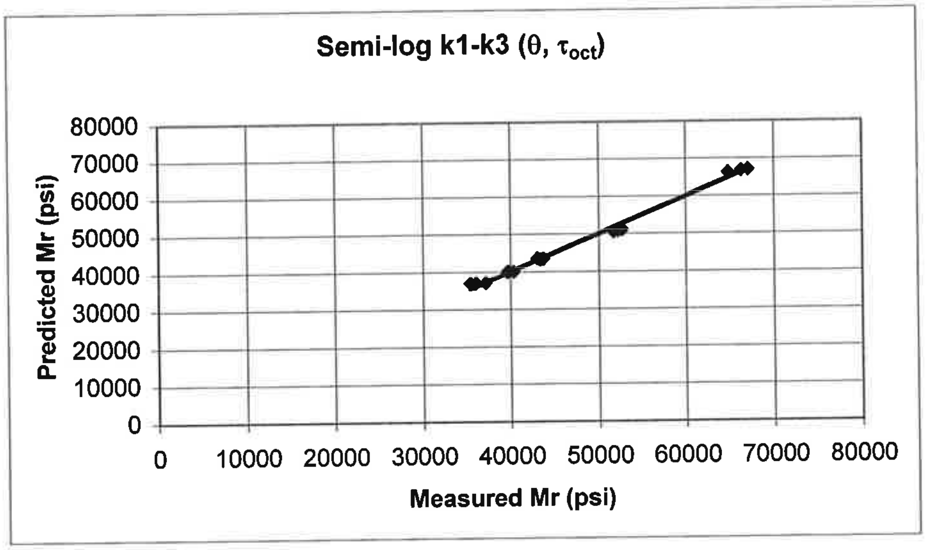
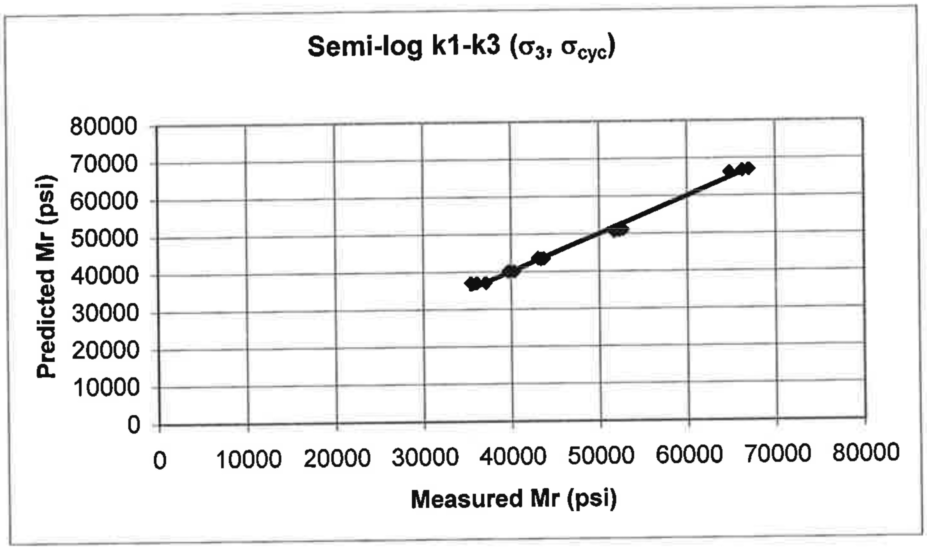
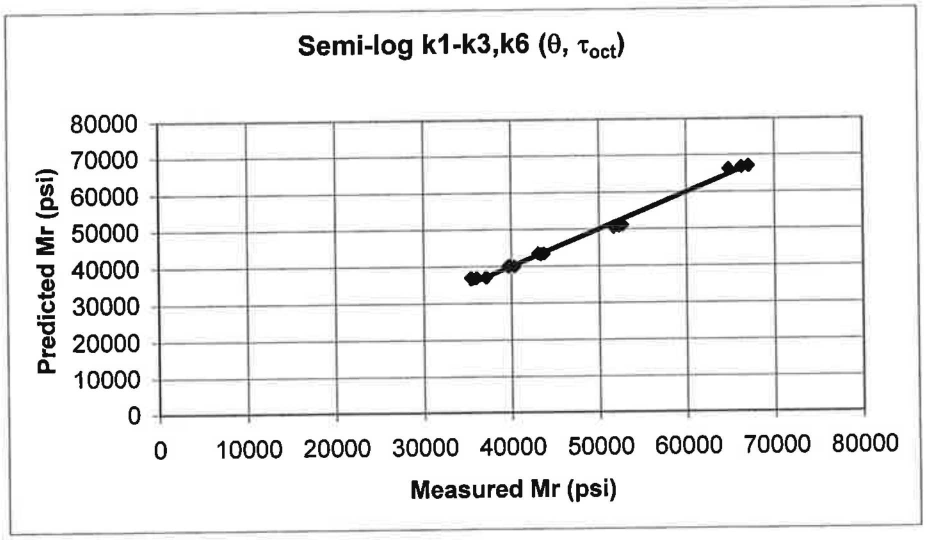


Semi-log k1-k3 (θ, τ_{oct})

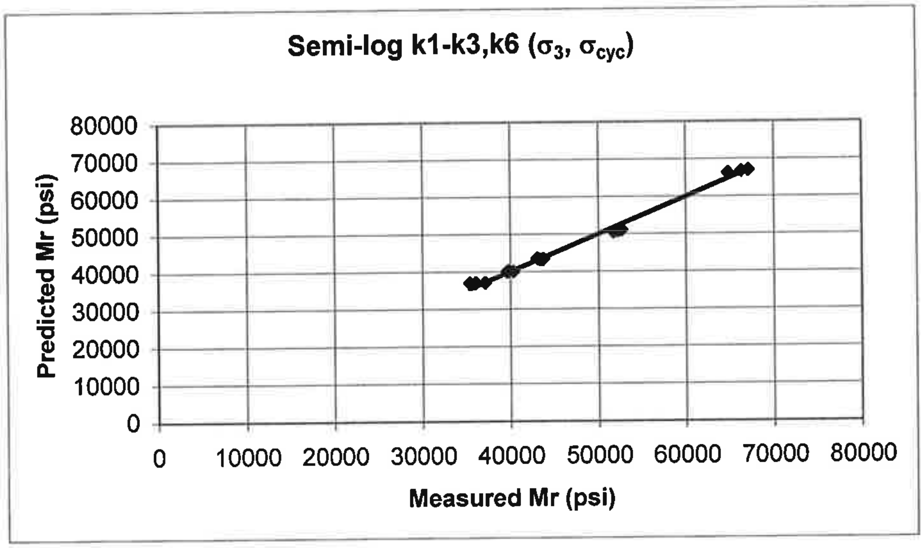


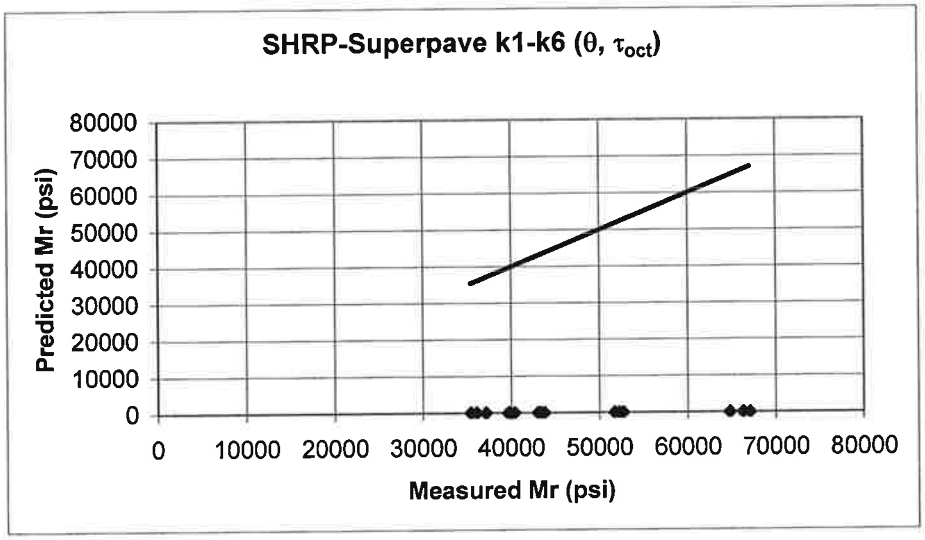
Semi-log k1-k3 (σ_3, σ_{cyc})

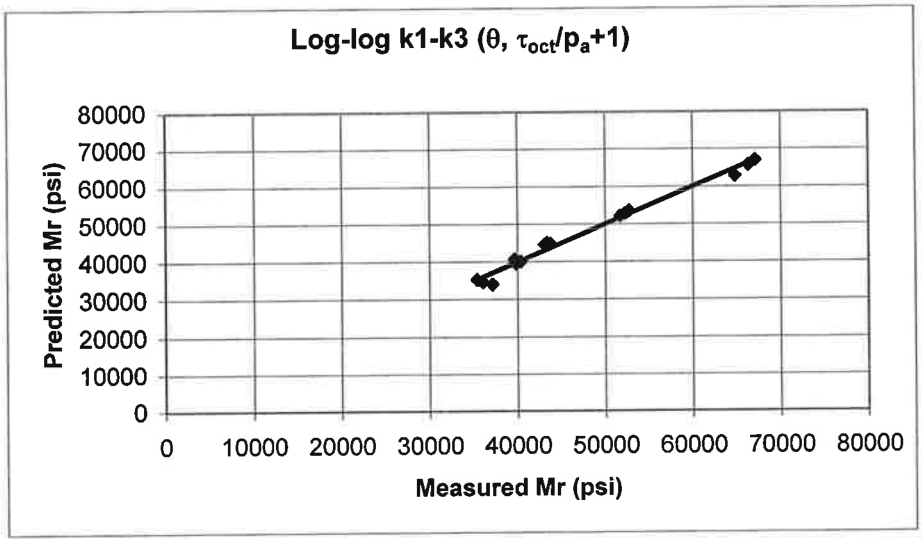


Semi-log k1-k3,k6 (θ, τ_{oct})

Measured Vs. Predicted M_R for Test NS12_5







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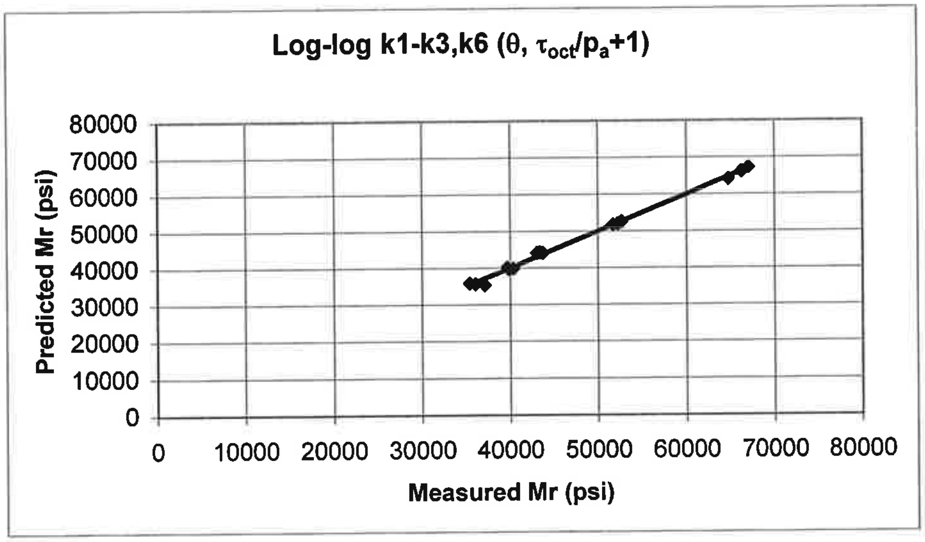

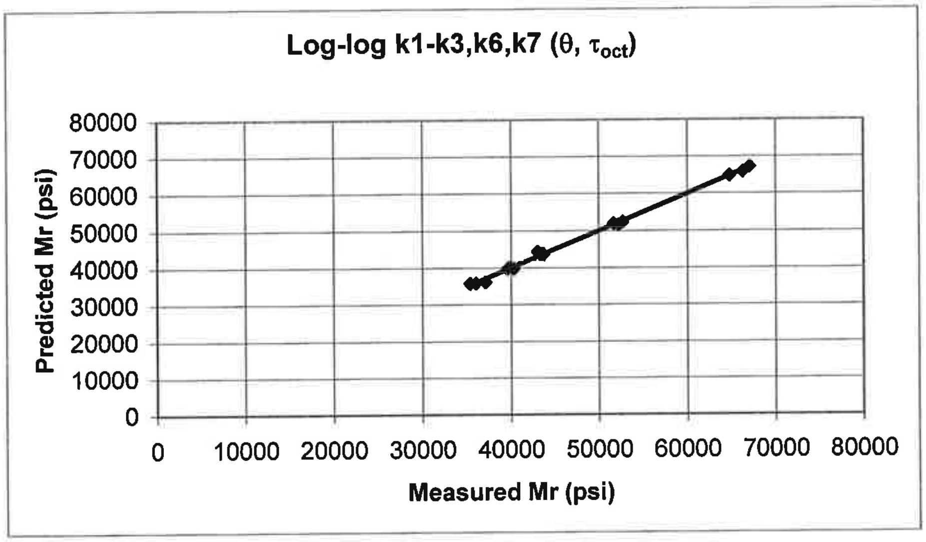

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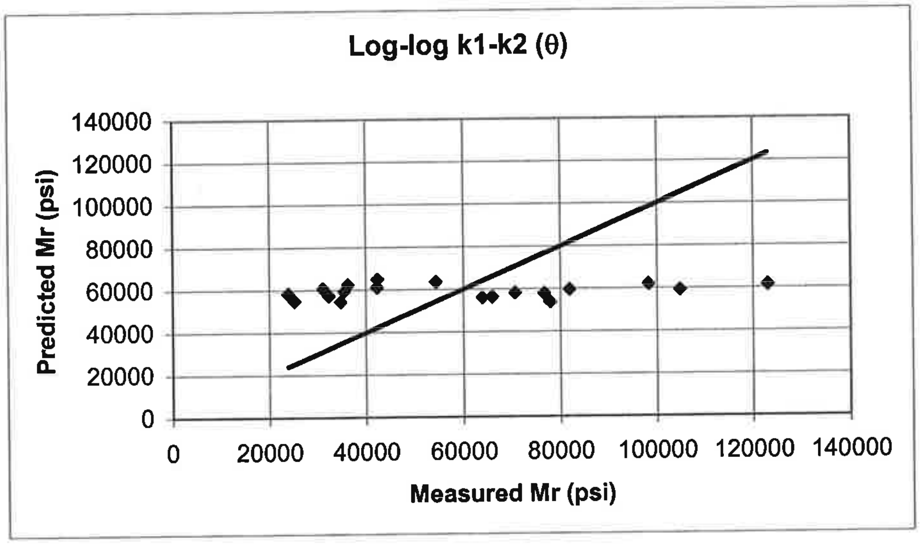
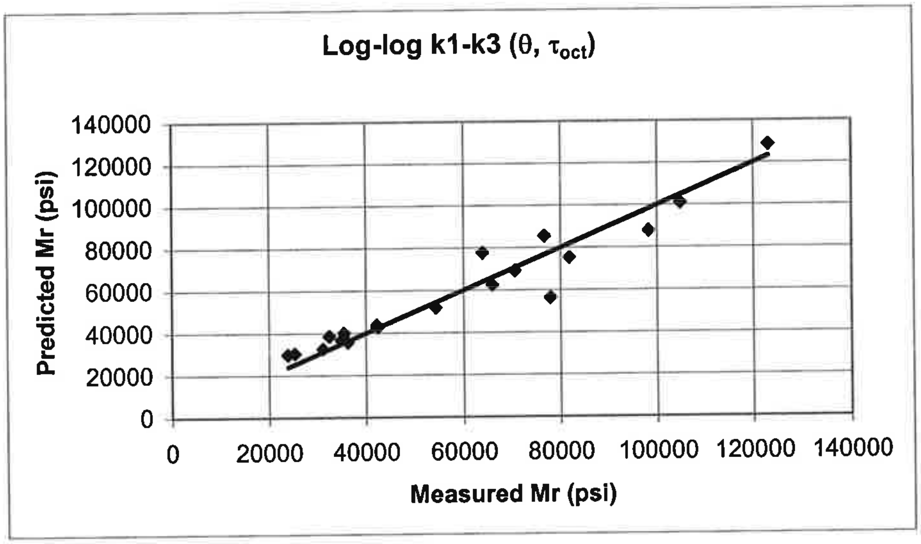
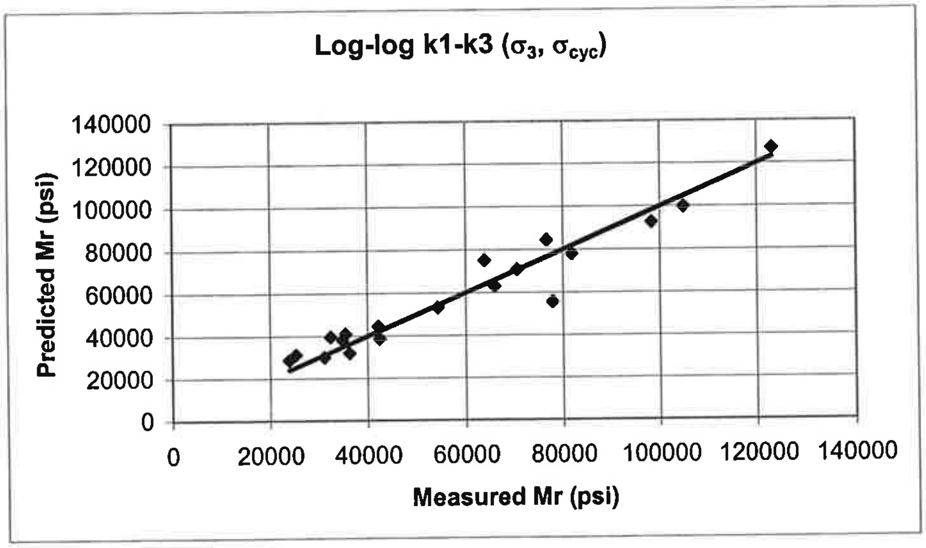
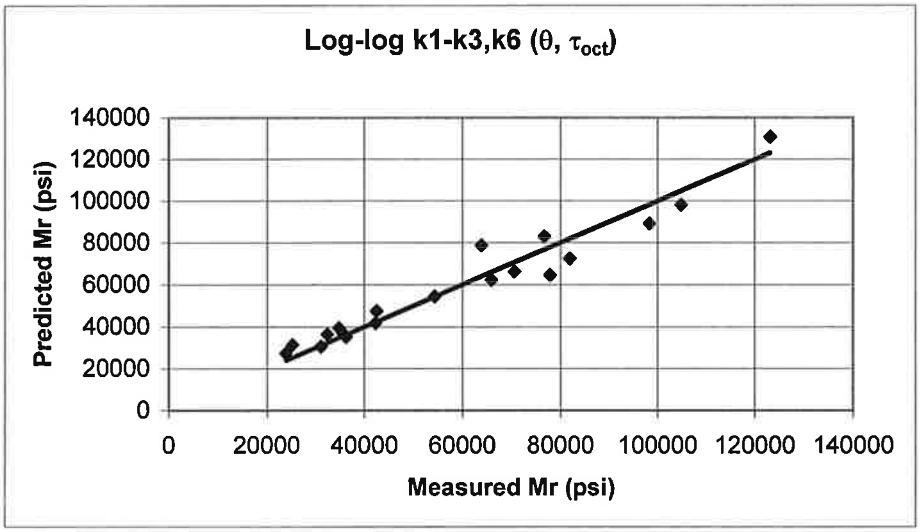
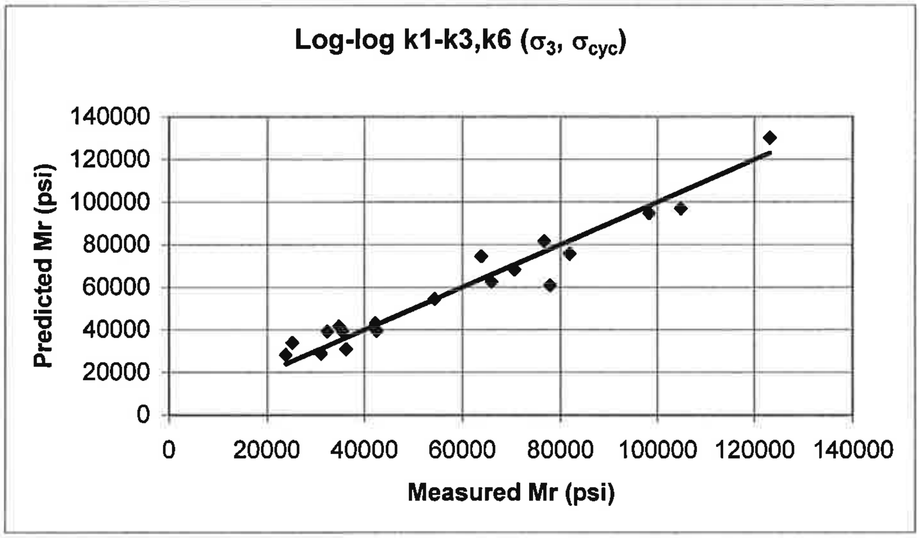


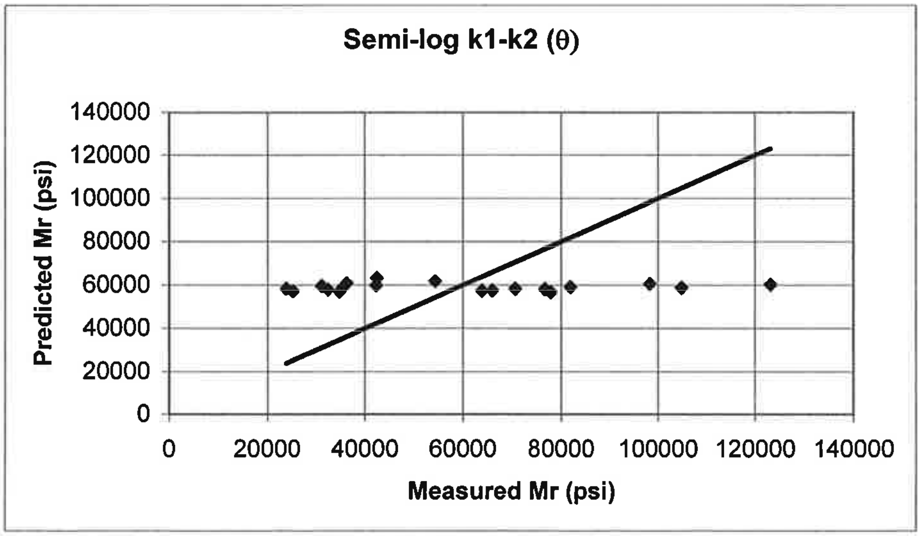




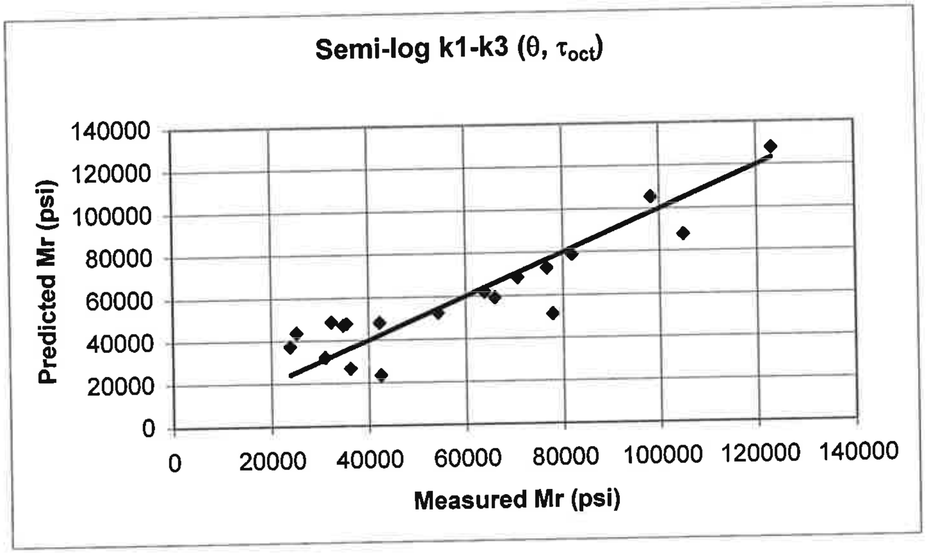
Measured Vs. Predicted M_R for Test S1_1

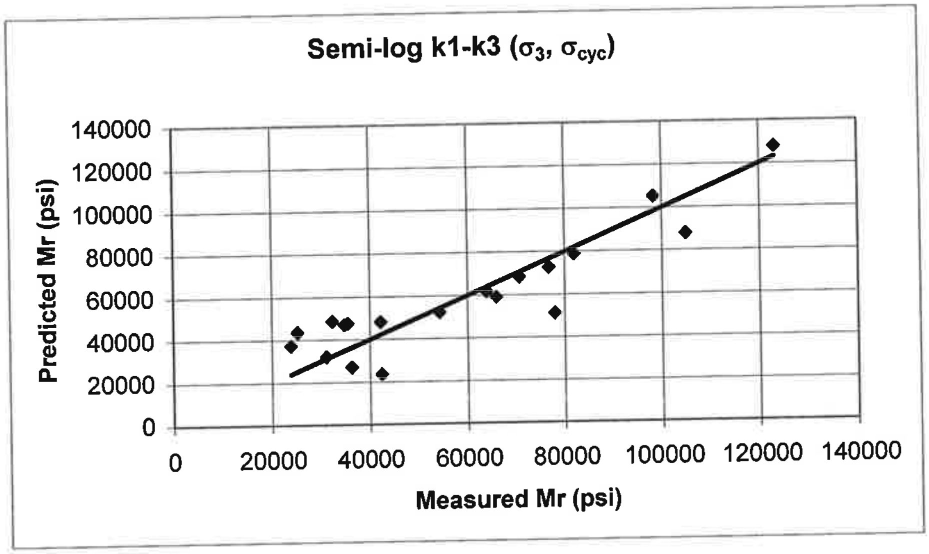


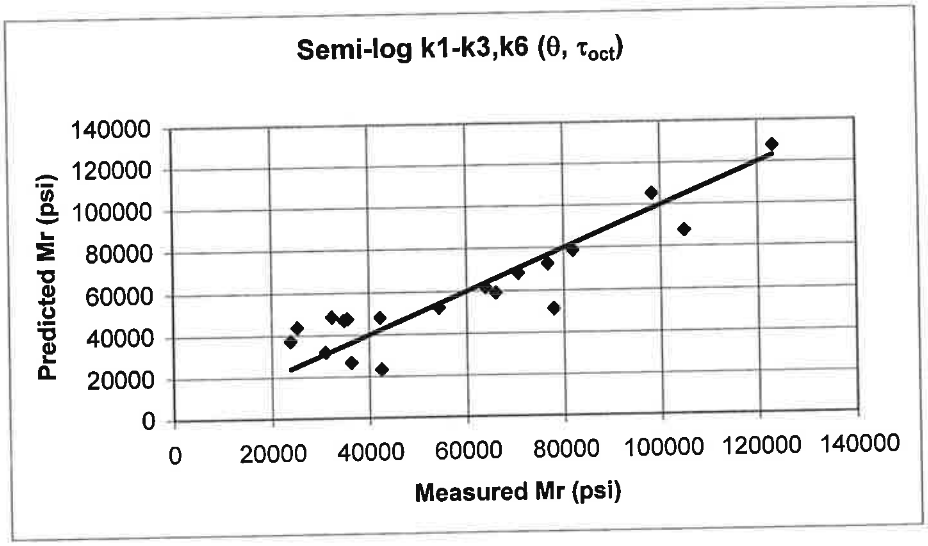




Measured Vs. Predicted M_R for Test S1_1







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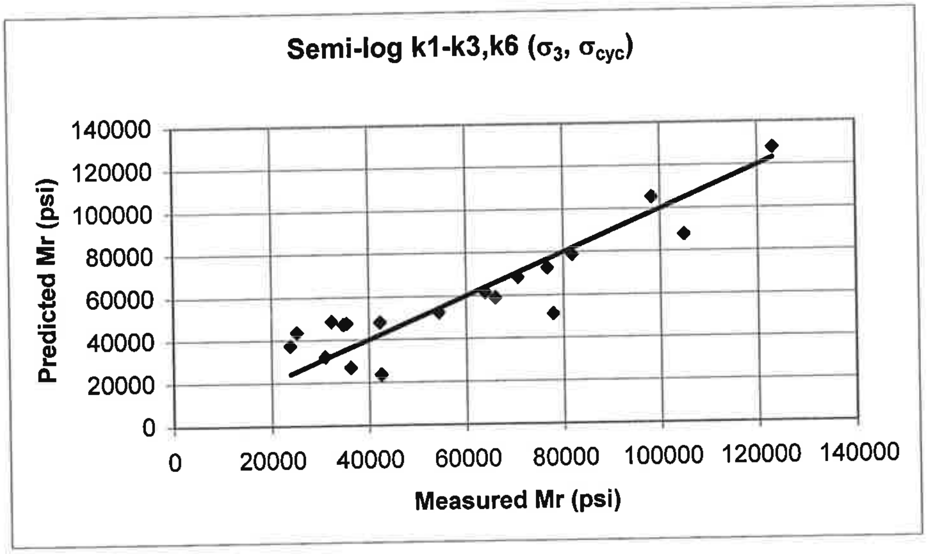
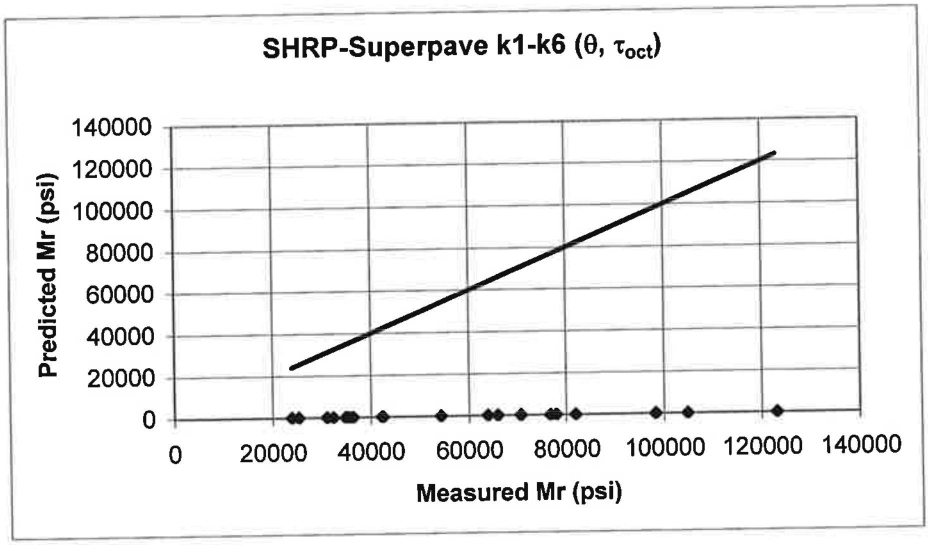
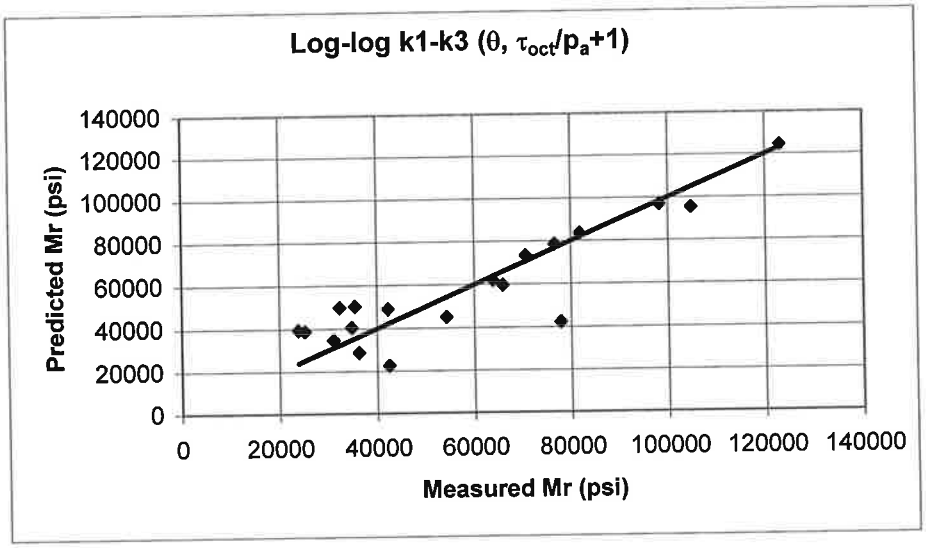
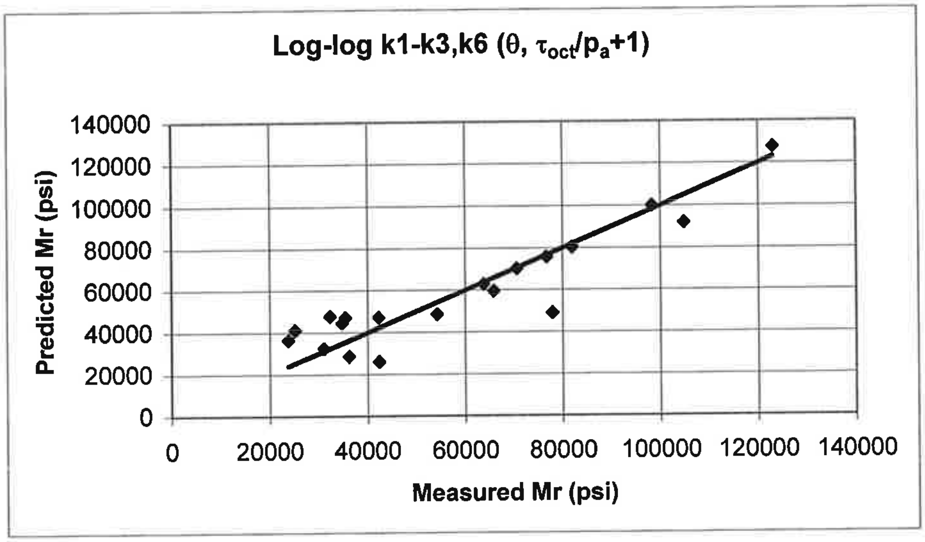
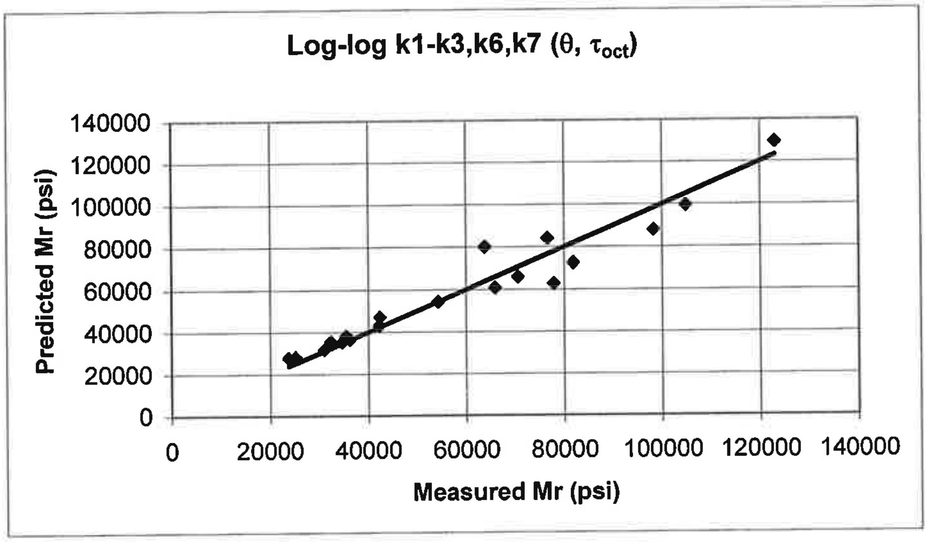




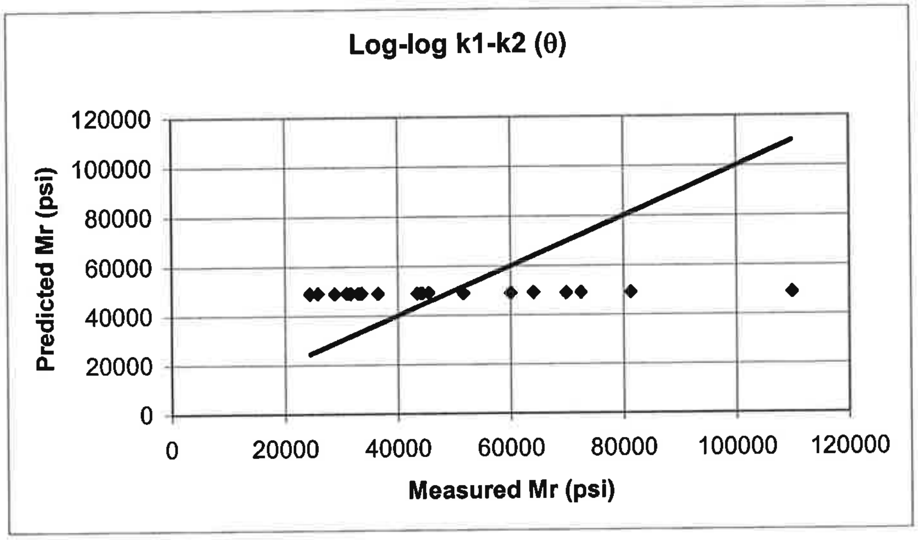


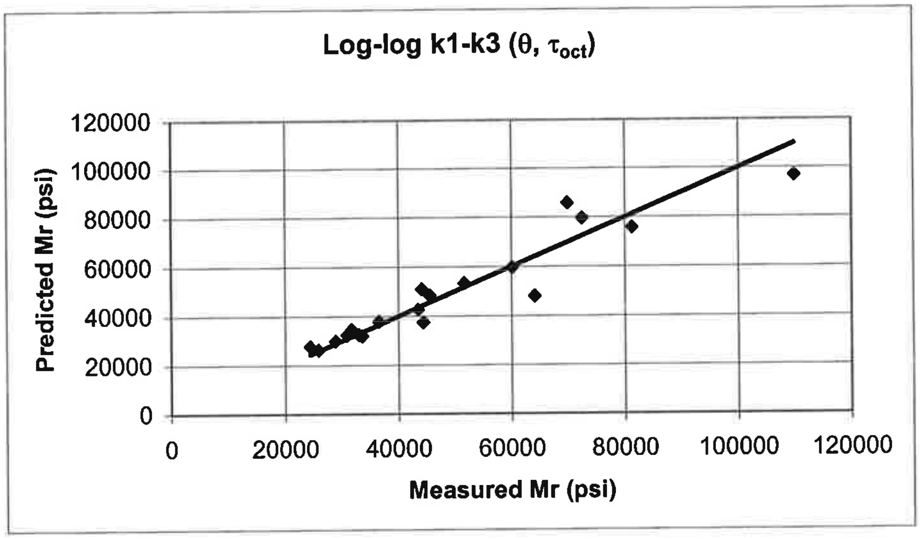
Measured Vs. Predicted M_R for Test S1_1

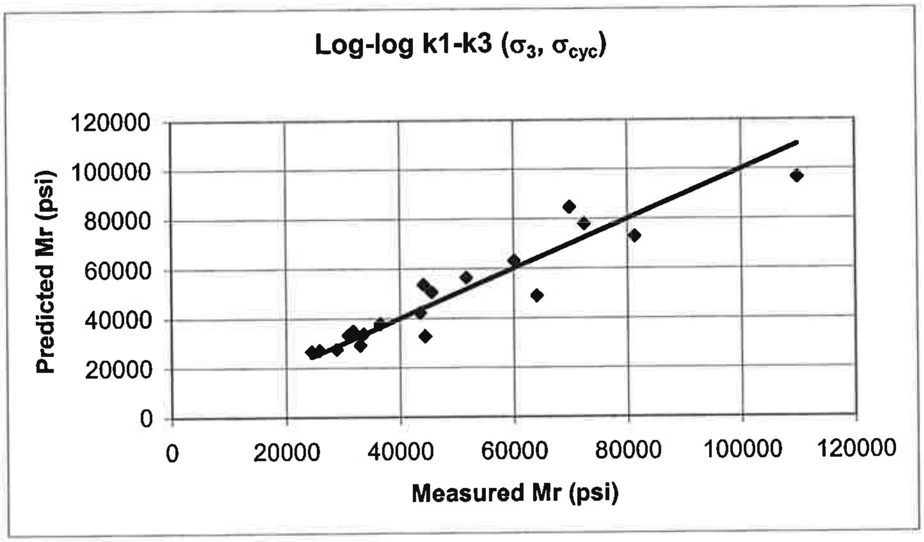




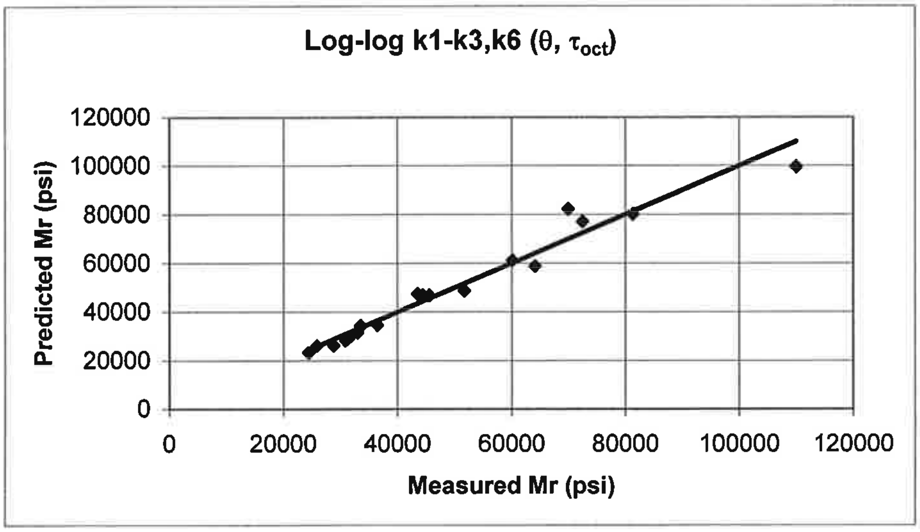
Measured Vs. Predicted M_R for Test S1_1

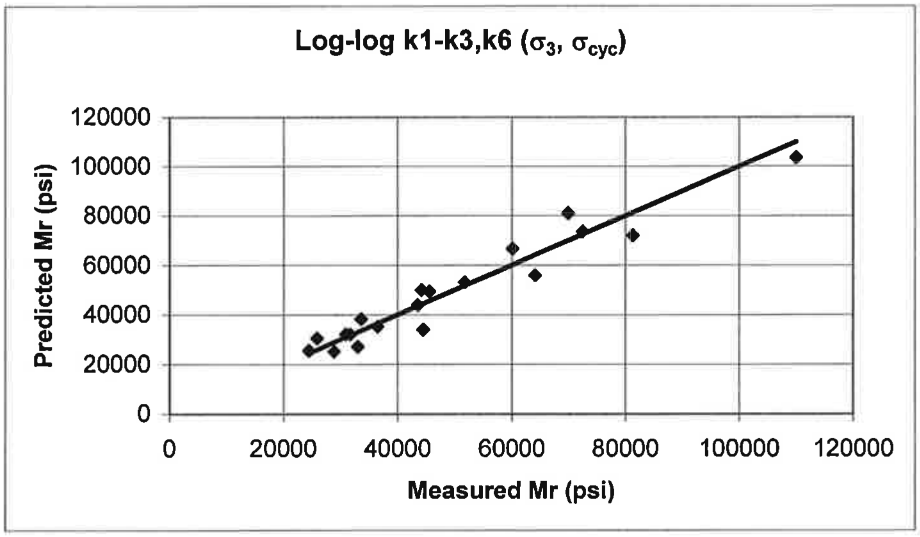


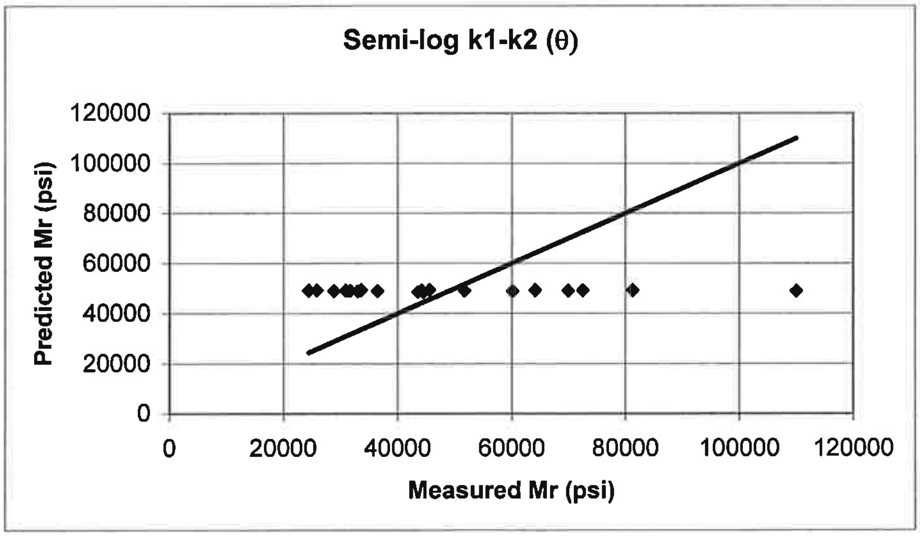




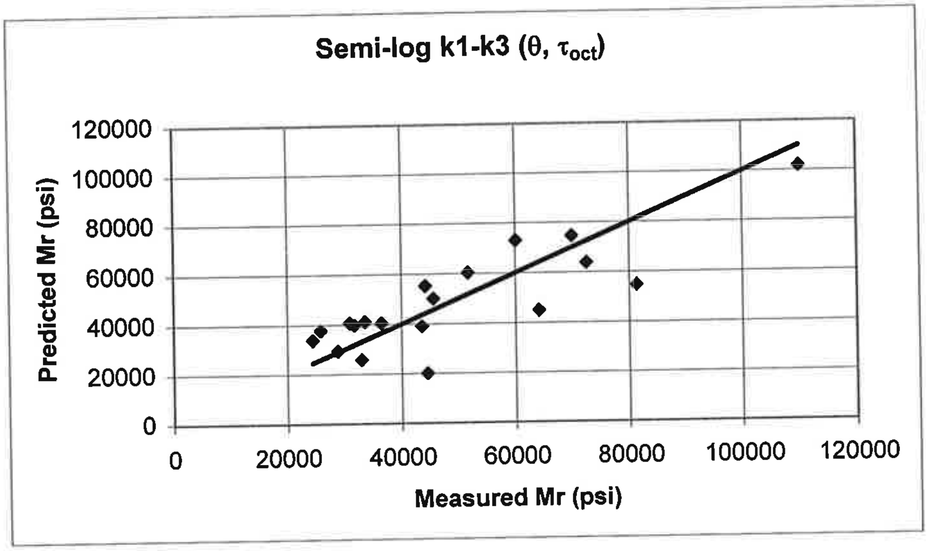
Measured Vs. Predicted M_R for Test S1_2

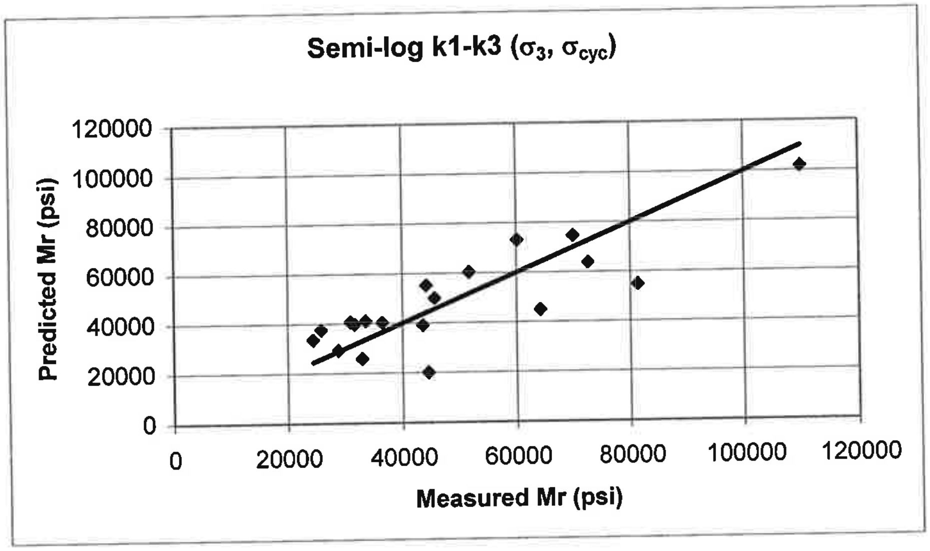


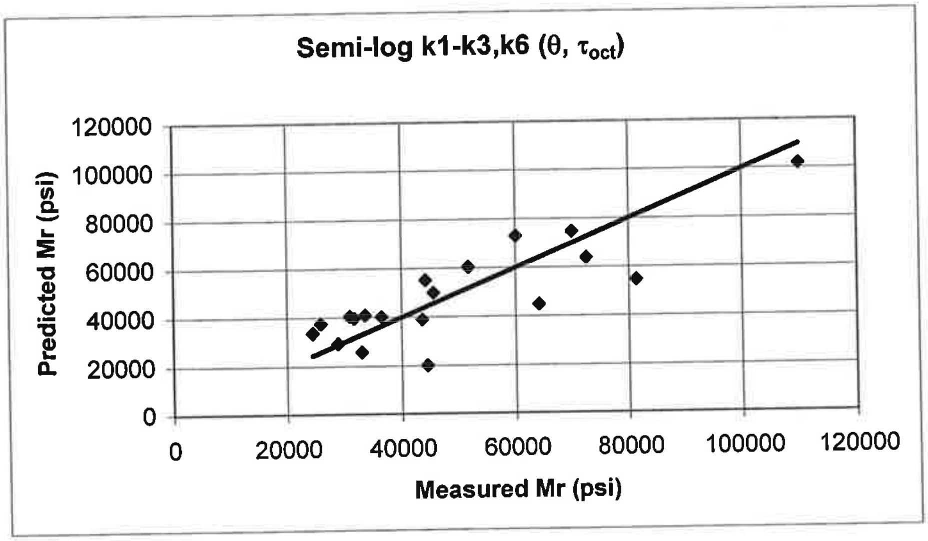




Measured Vs. Predicted M_R for Test S1_2







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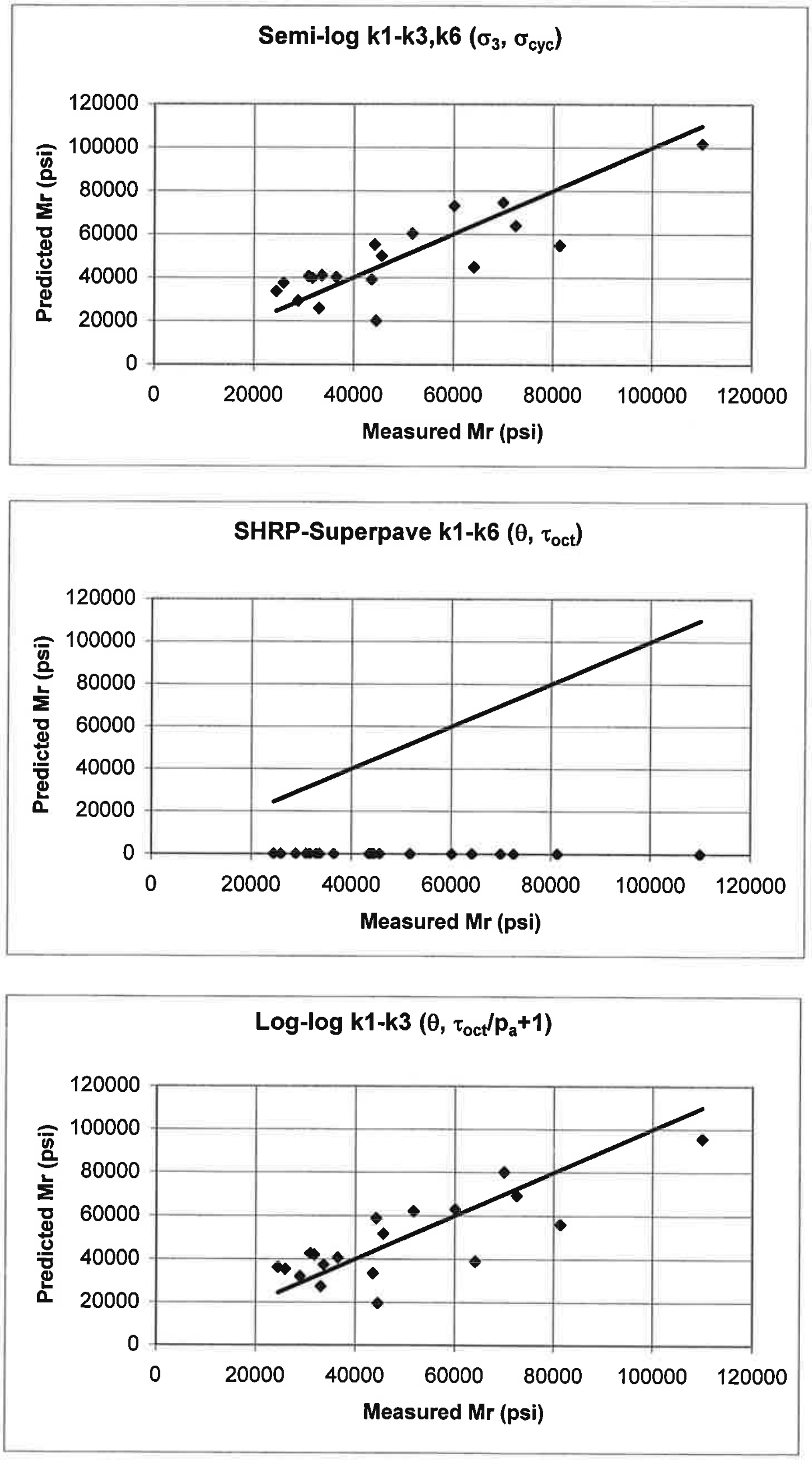

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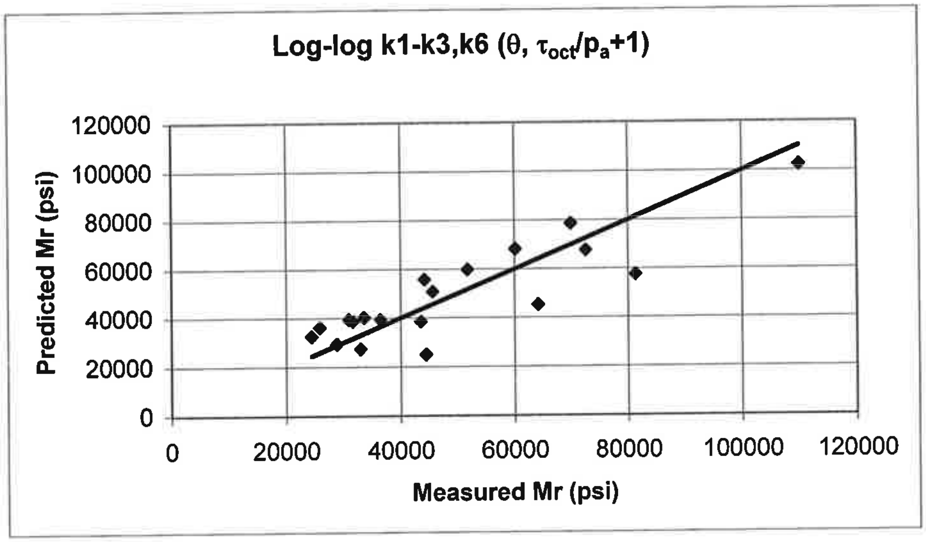
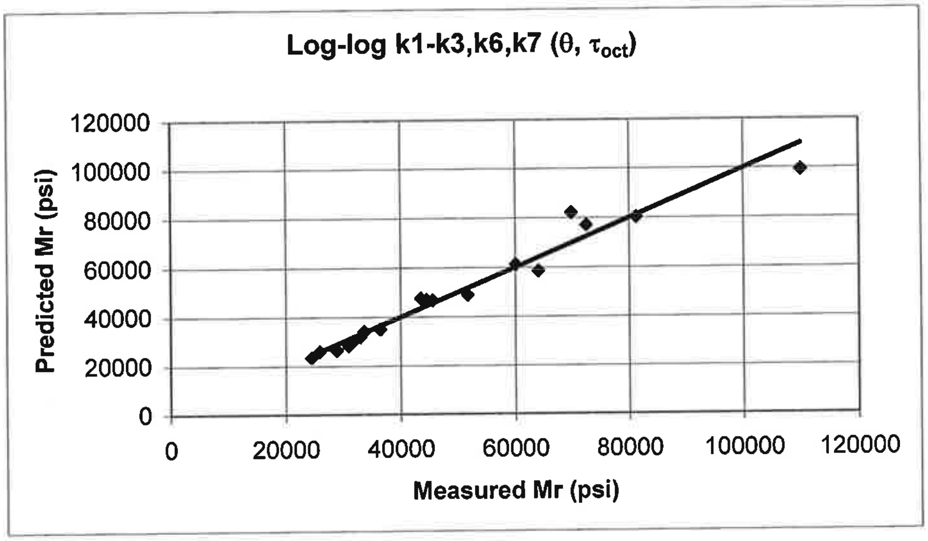
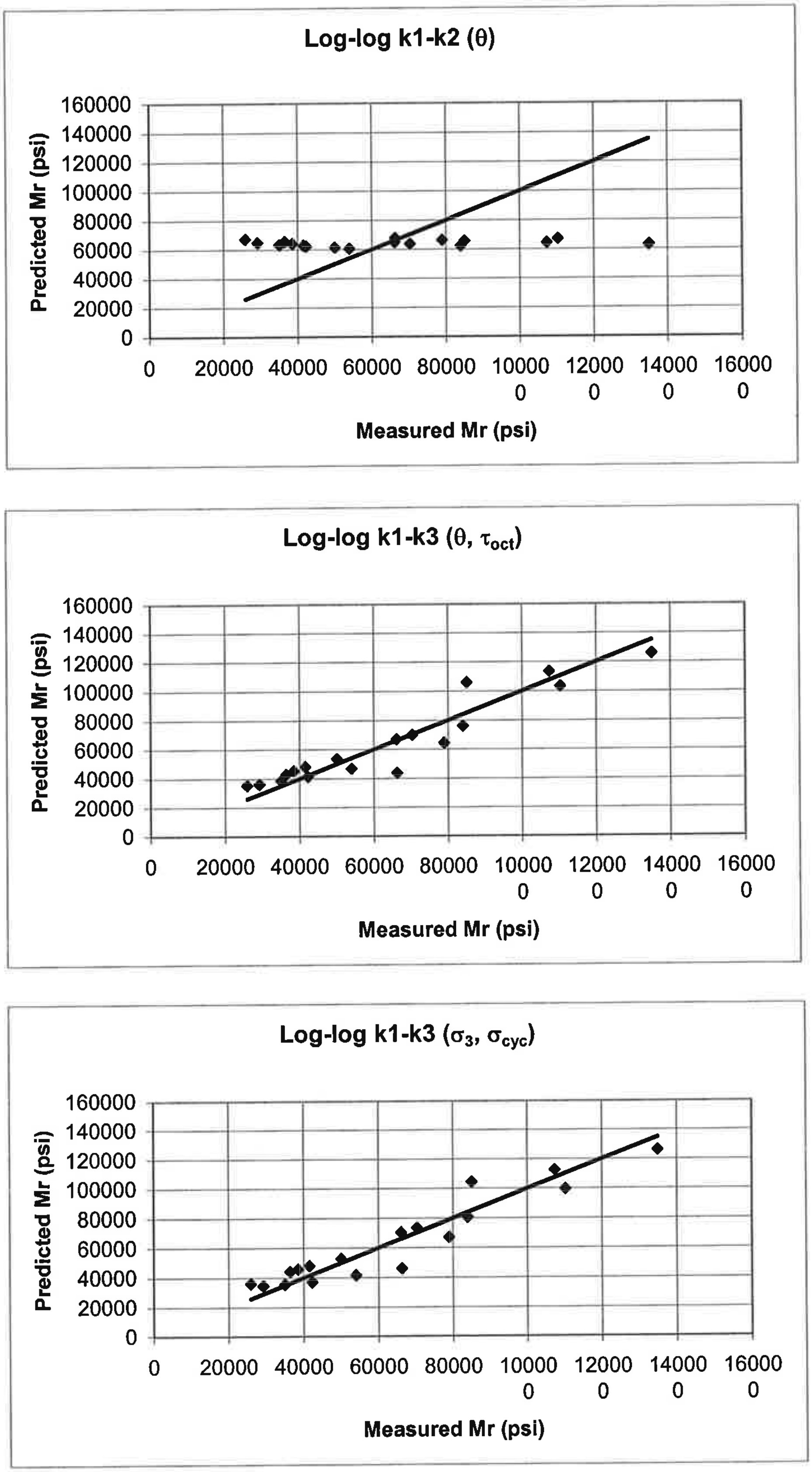
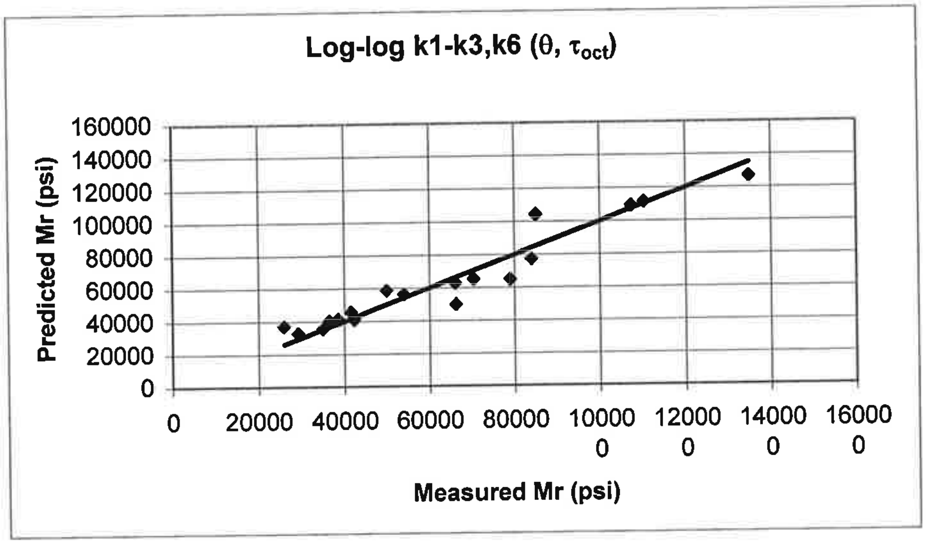


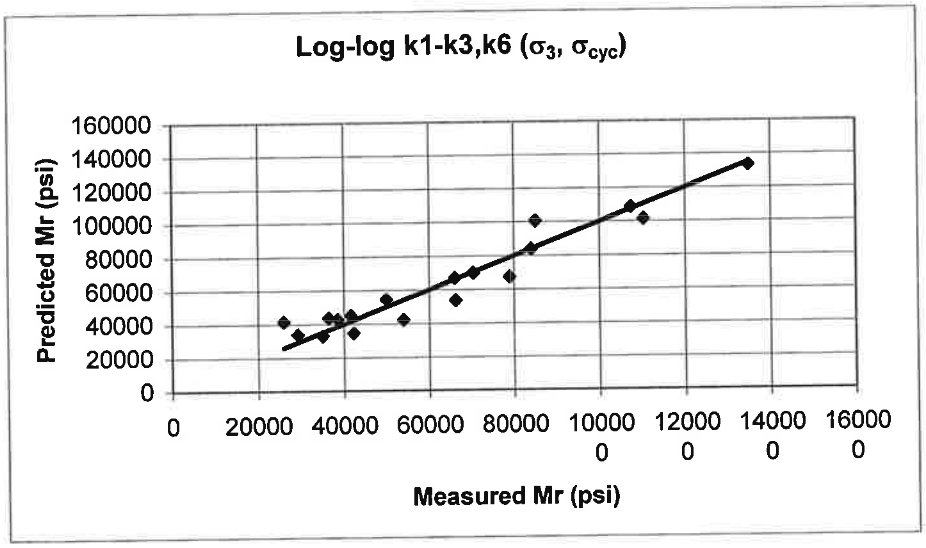


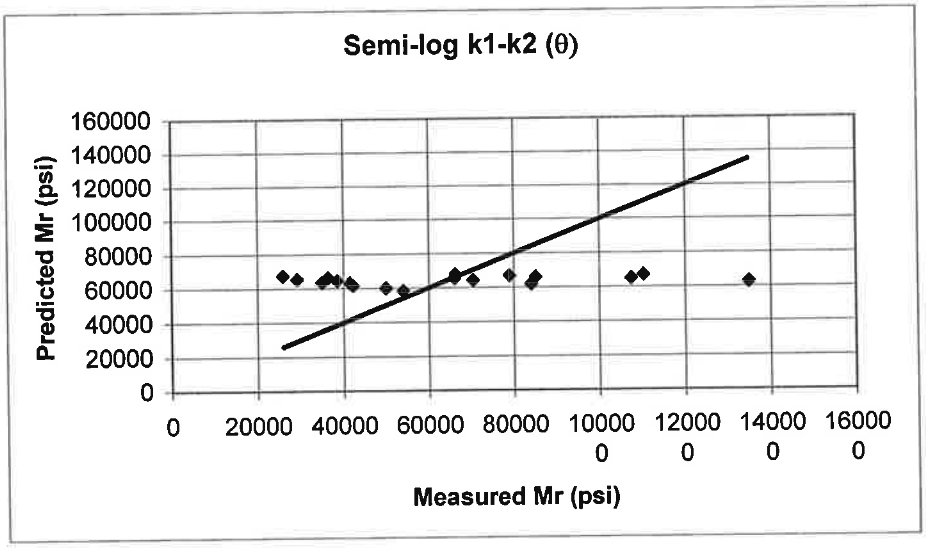
Measured Vs. Predicted M_R for Test S1_2



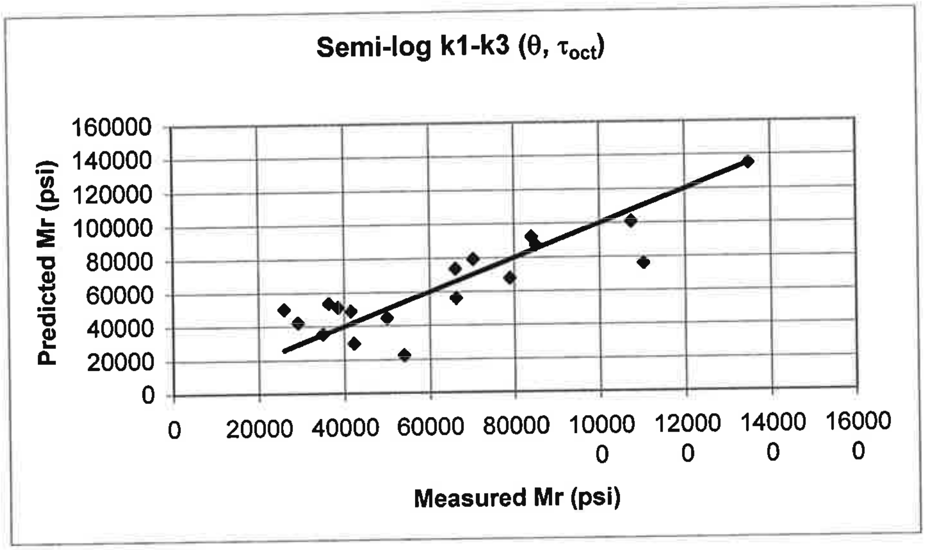
Measured Vs. Predicted M_R for Test S1_3

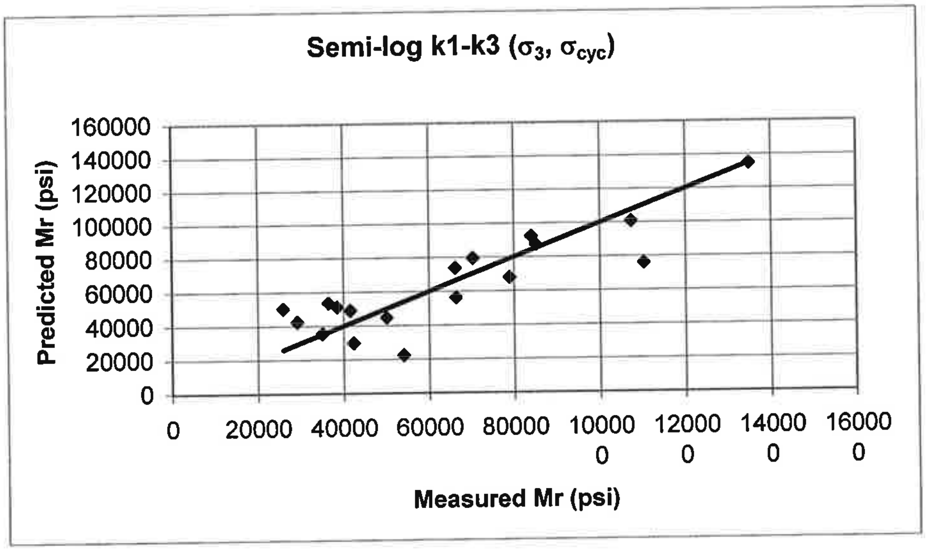


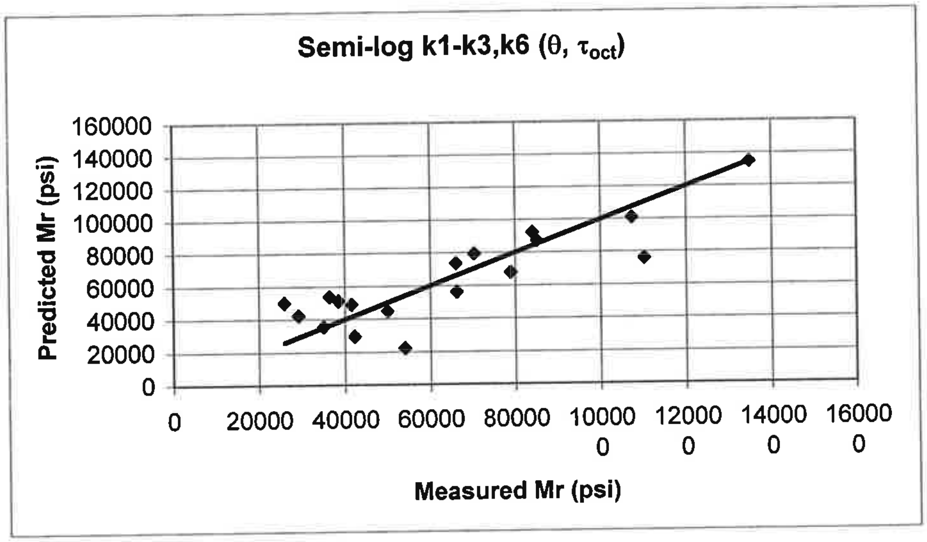




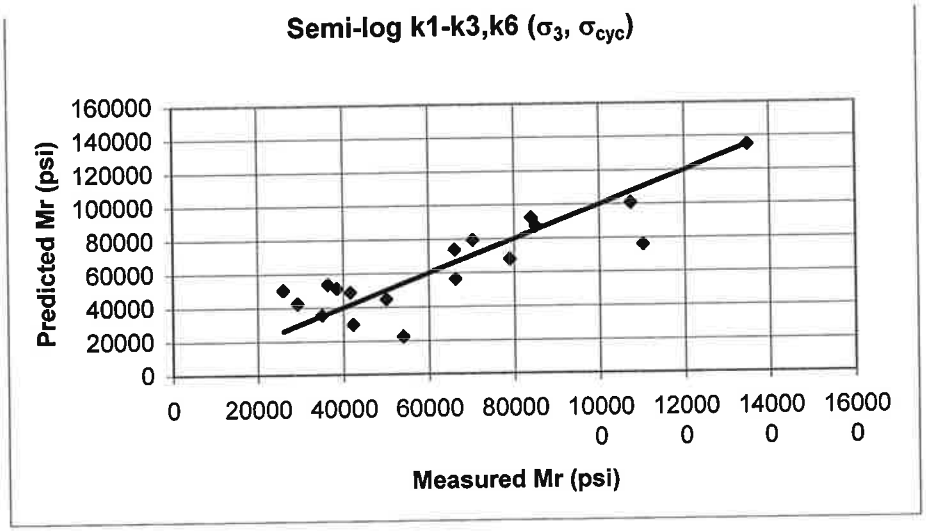
Measured Vs. Predicted M_R for Test S1_3

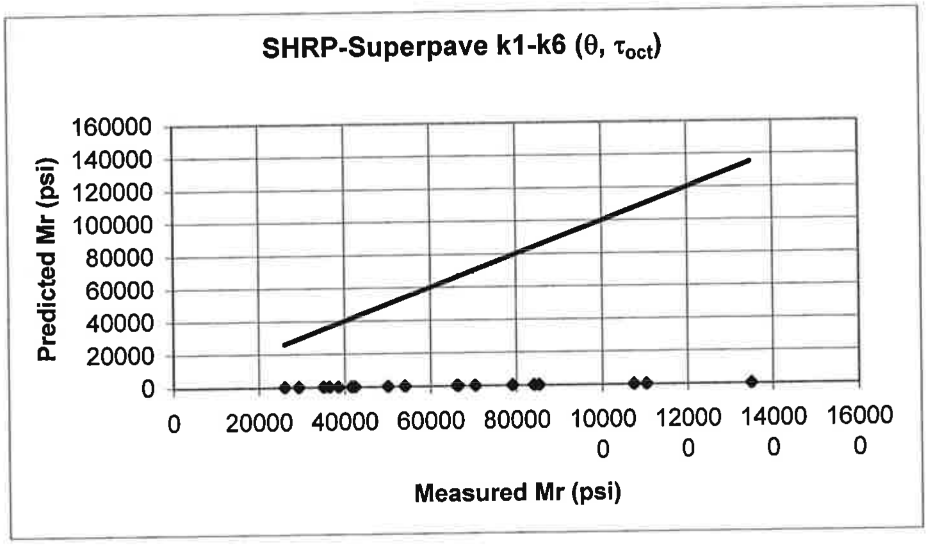


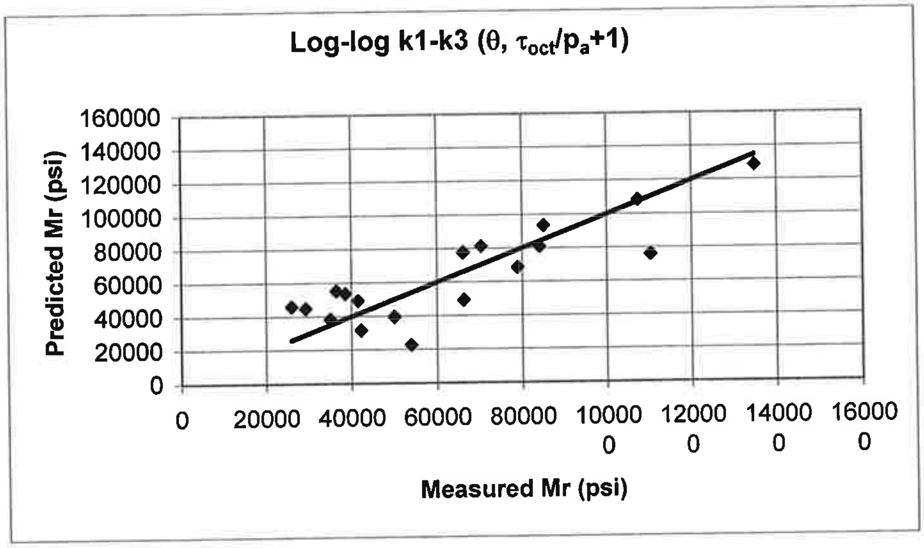




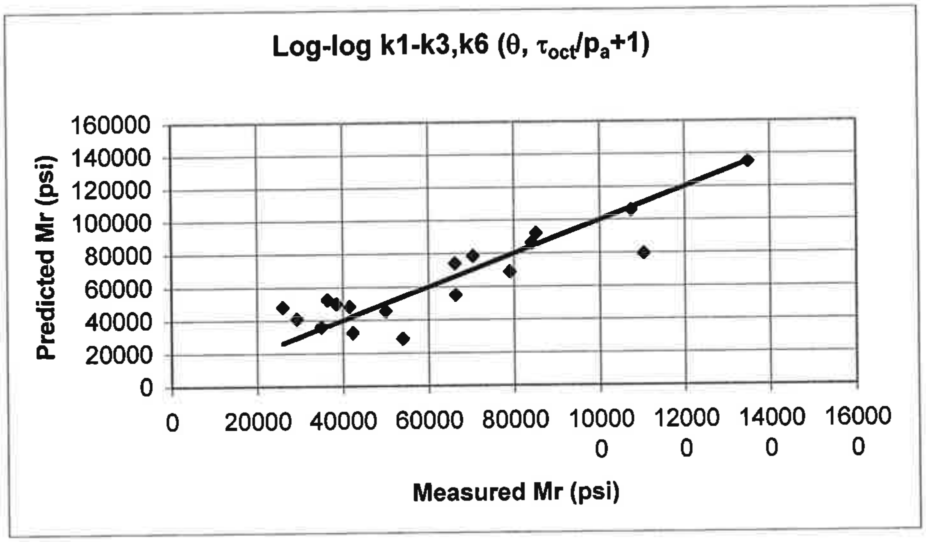
Measured Vs. Predicted M_R for Test S1_3

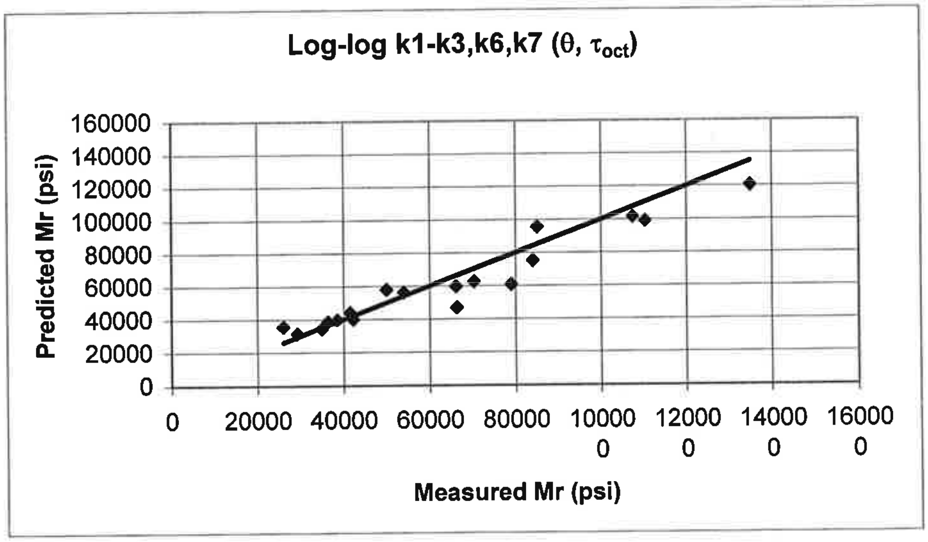

Semi-log k1-k3,k6 (σ_3, σ_{cyc})


SHRP-Superpave k1-k6 (θ, τ_{oct})


Log-log k1-k3 (θ, τ_{oct}/p_a+1)

Measured Vs. Predicted M_R for Test S1_3





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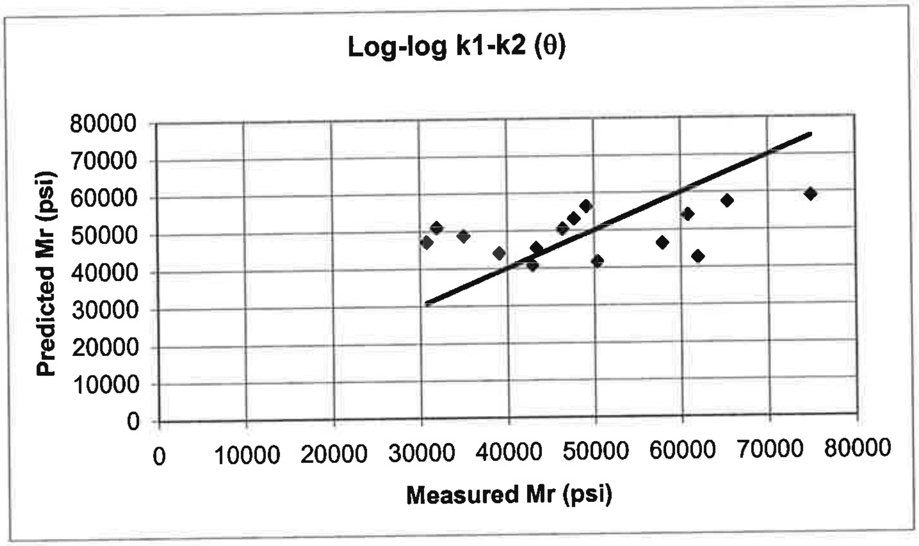
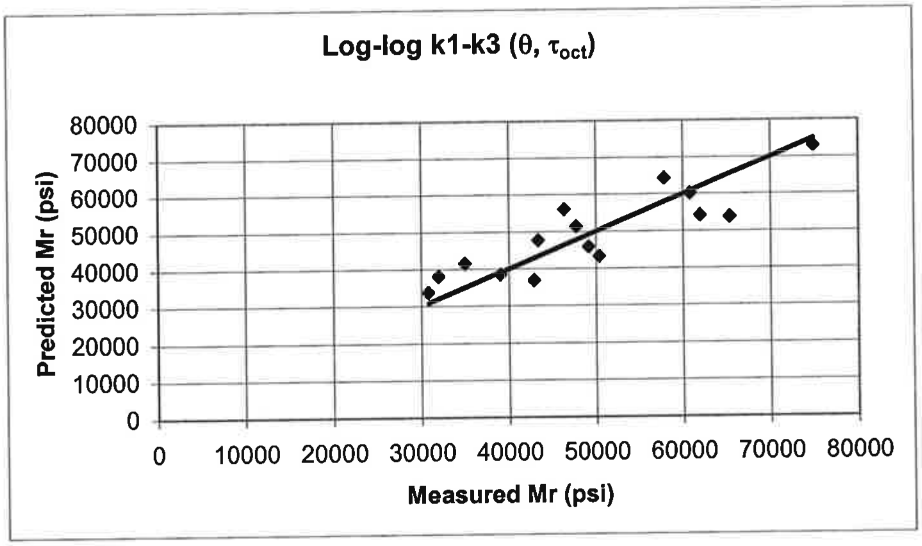
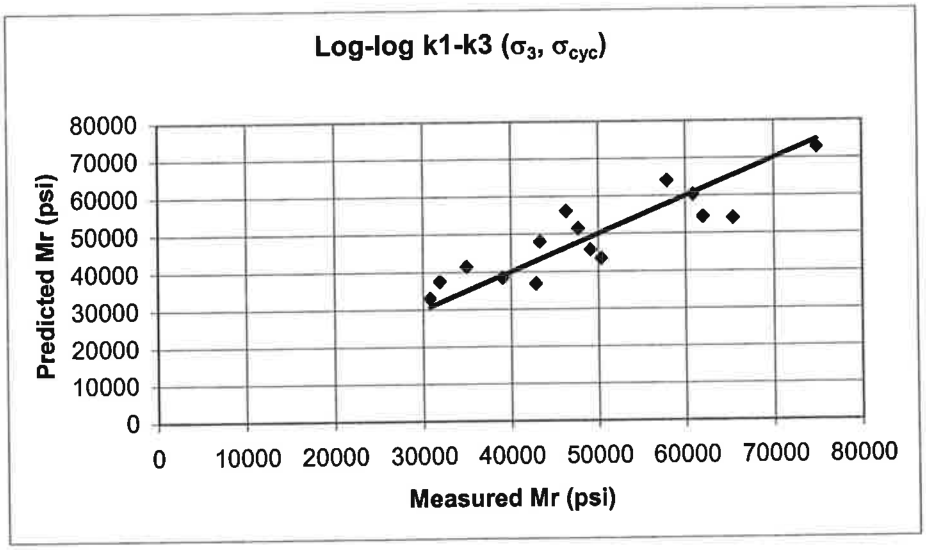
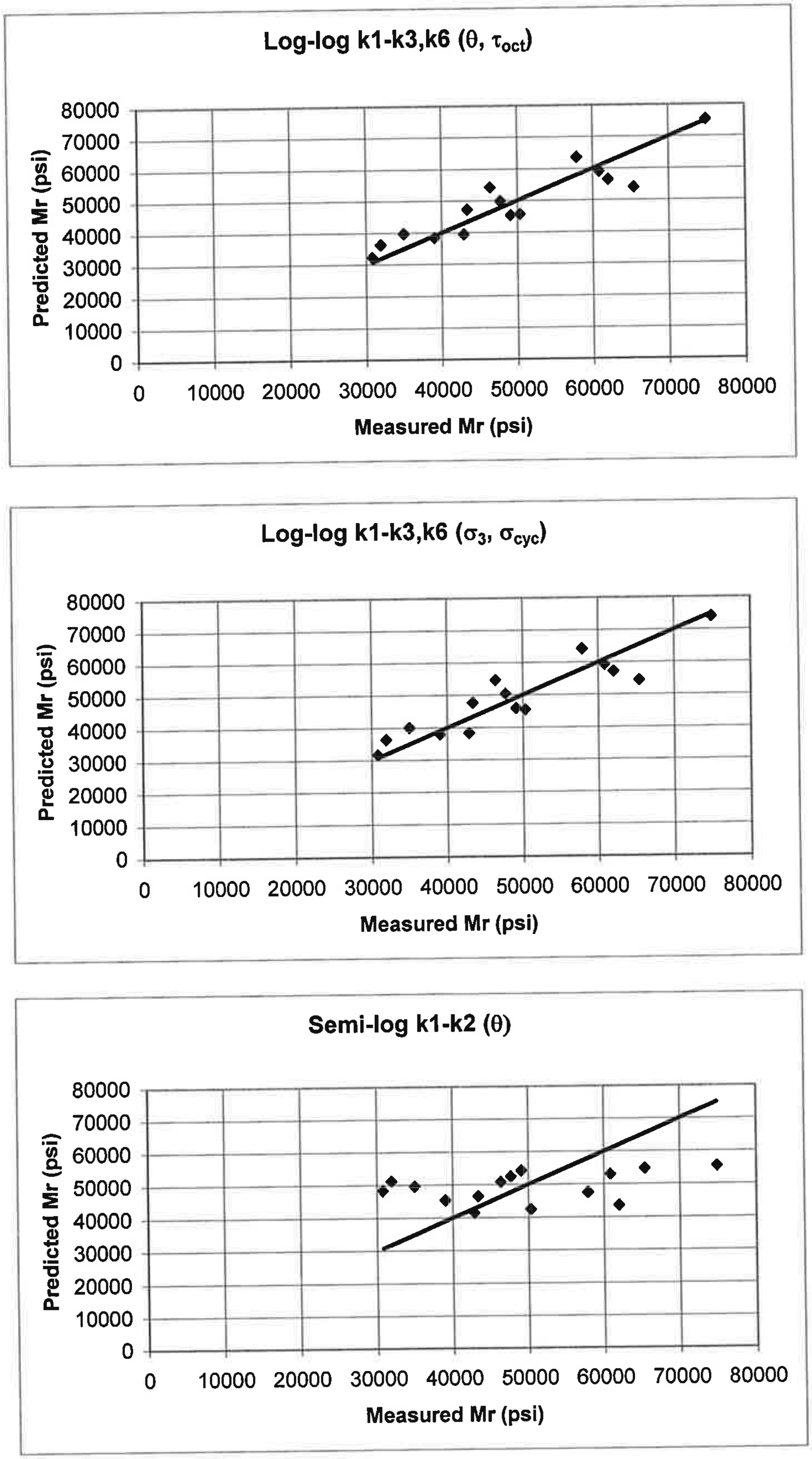


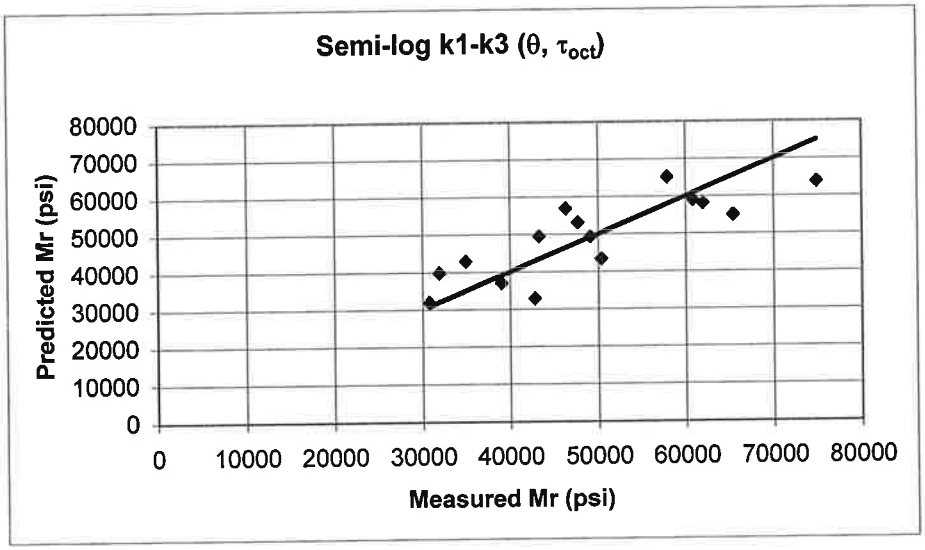


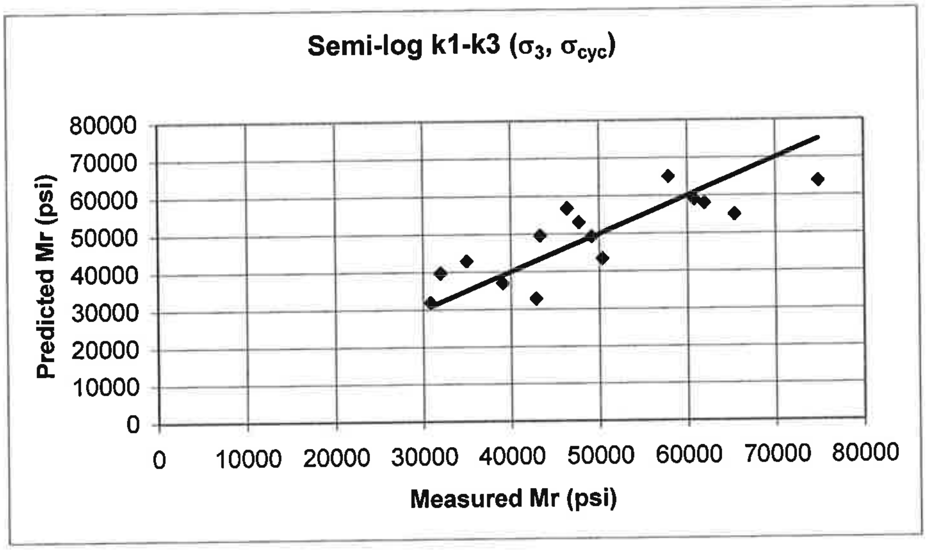


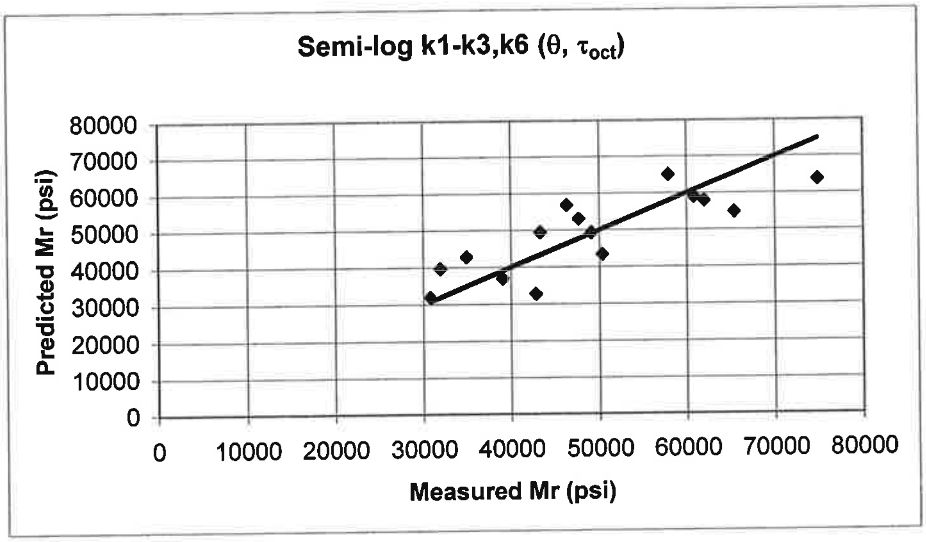
Measured Vs. Predicted M_R for Test NS1_1



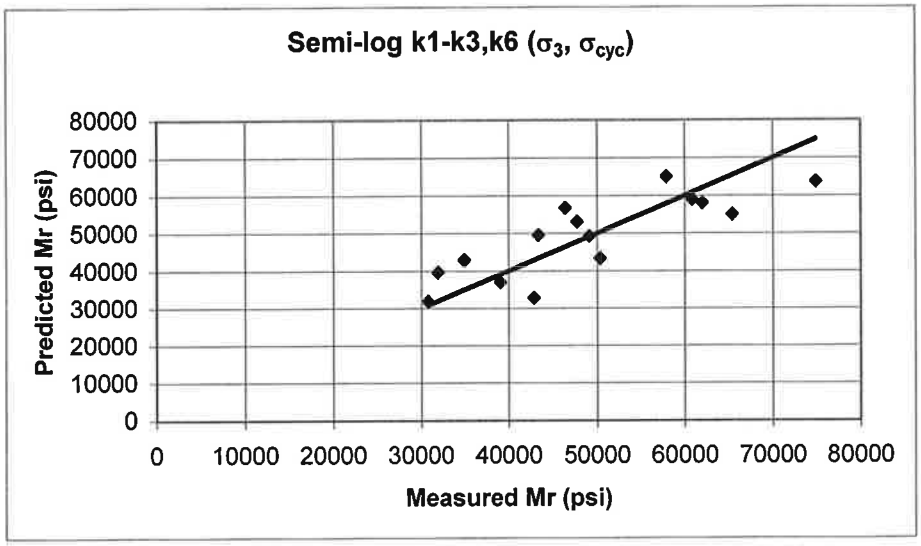
Measured Vs. Predicted M_R for Test NS1_1

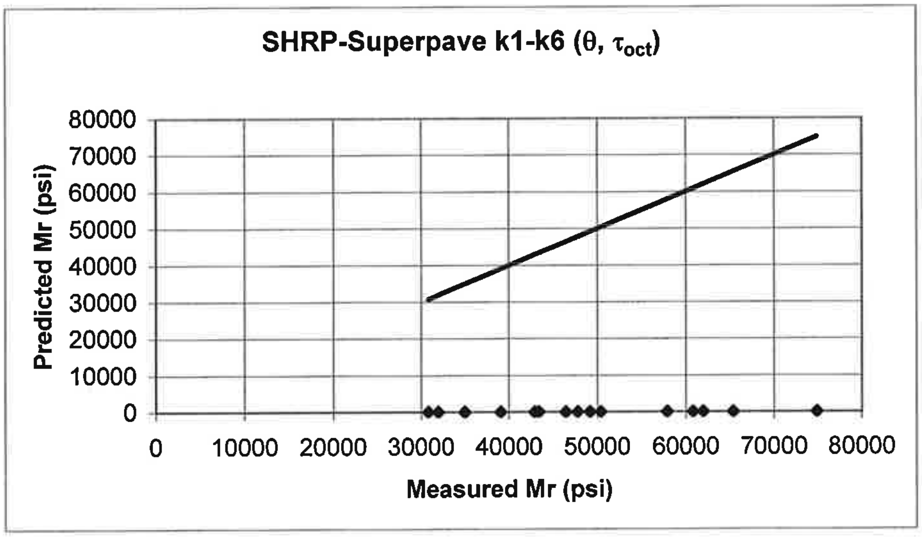


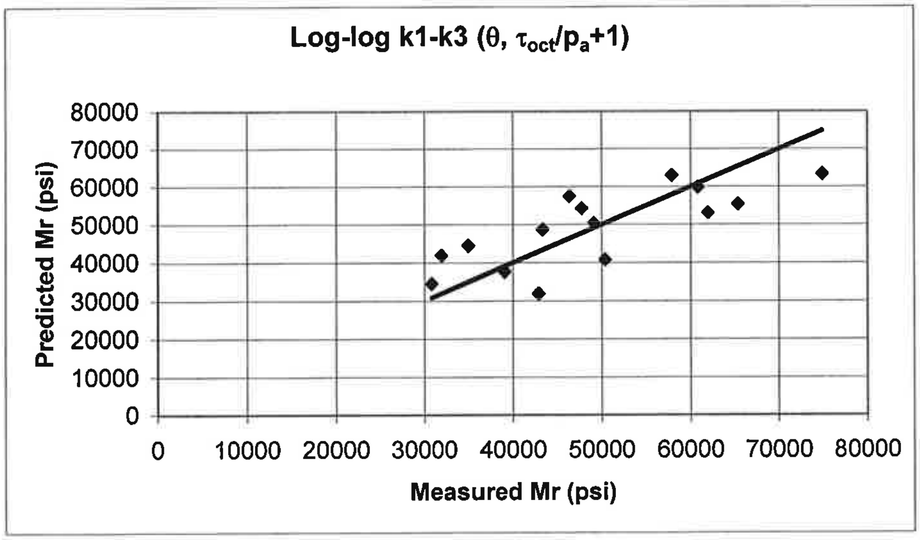




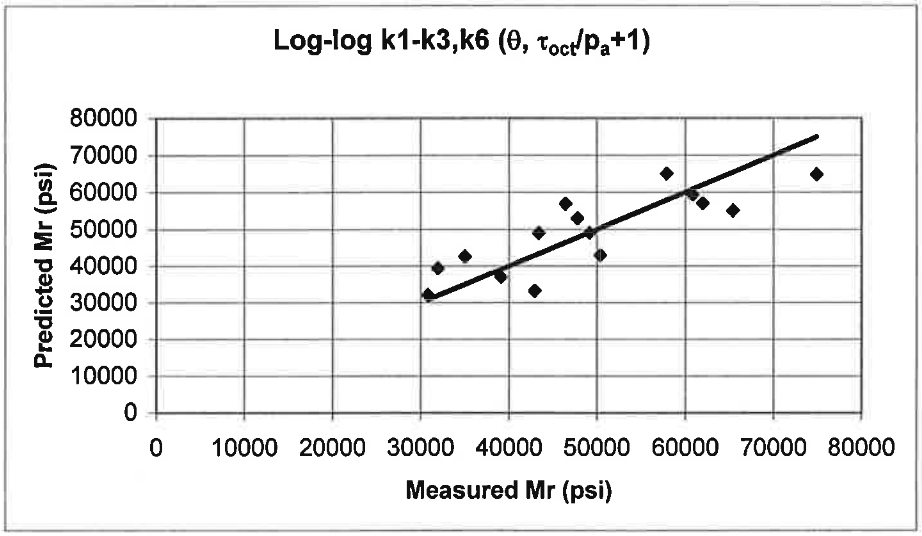
Measured Vs. Predicted M_R for Test NS1_1

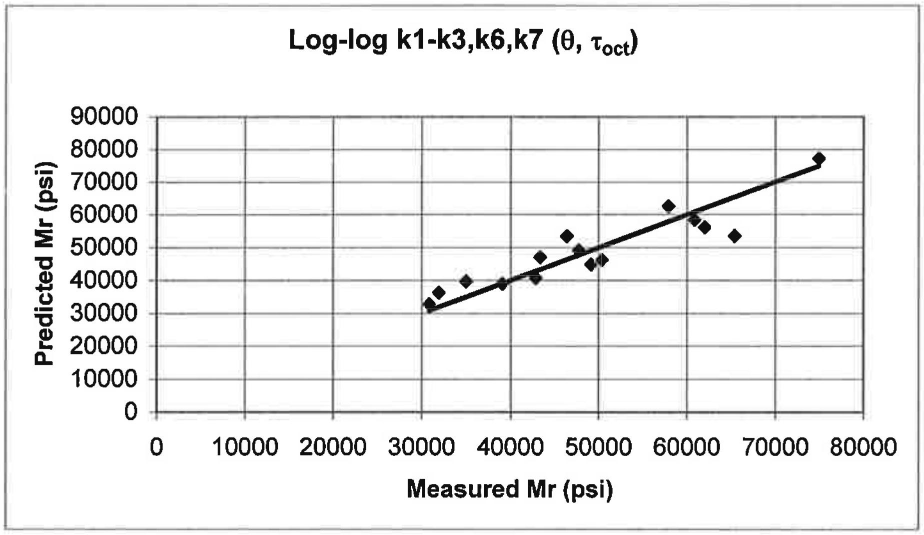




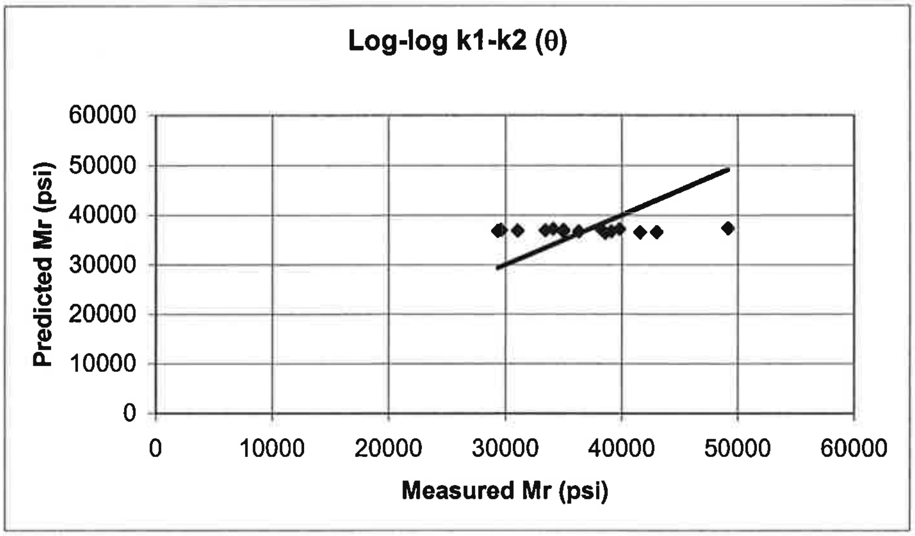


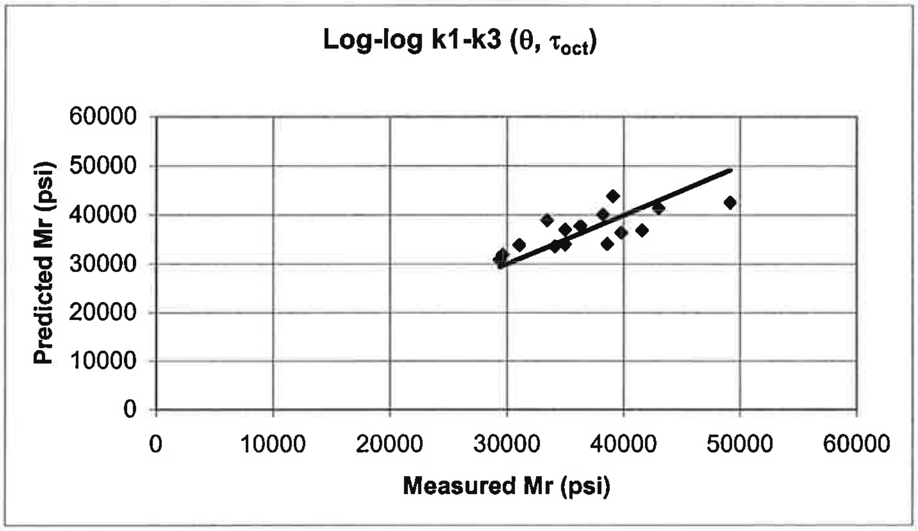
Measured Vs. Predicted M_R for Test NS1_1

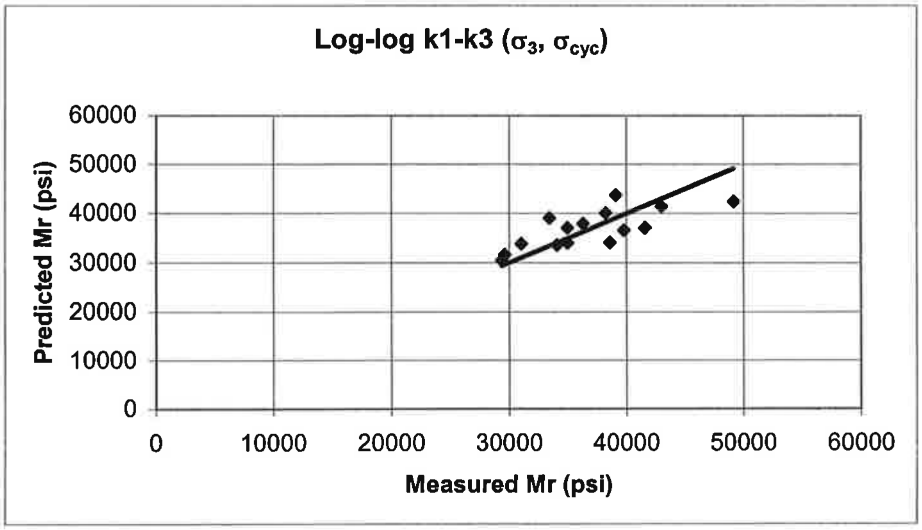




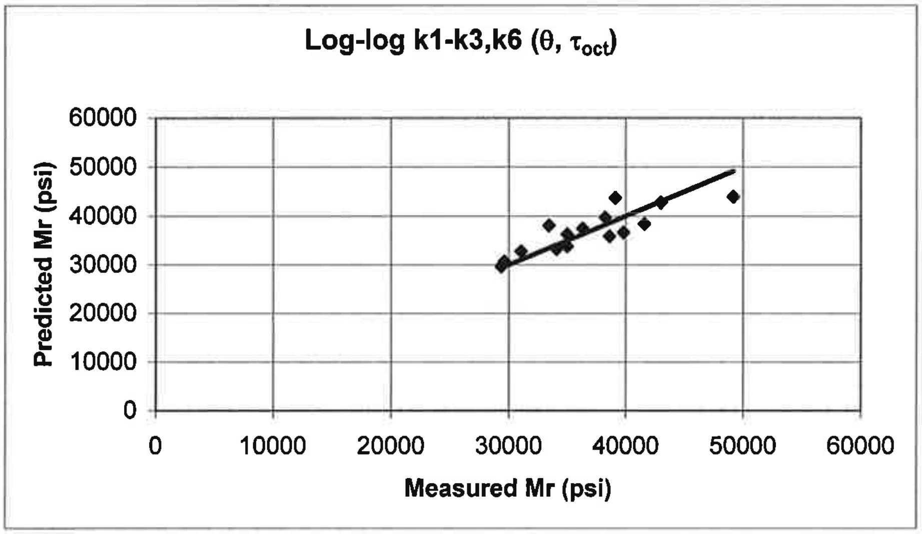
Measured Vs. Predicted M_R for Test NS1_1

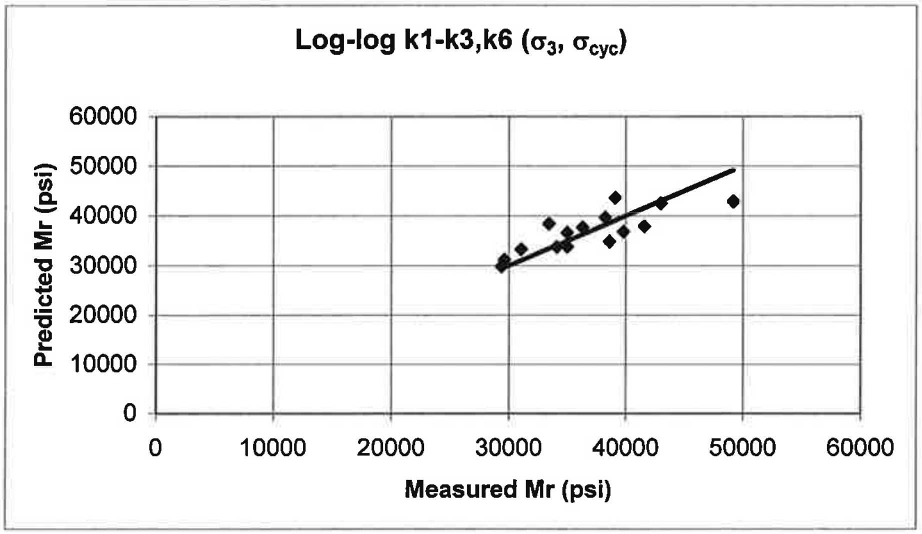


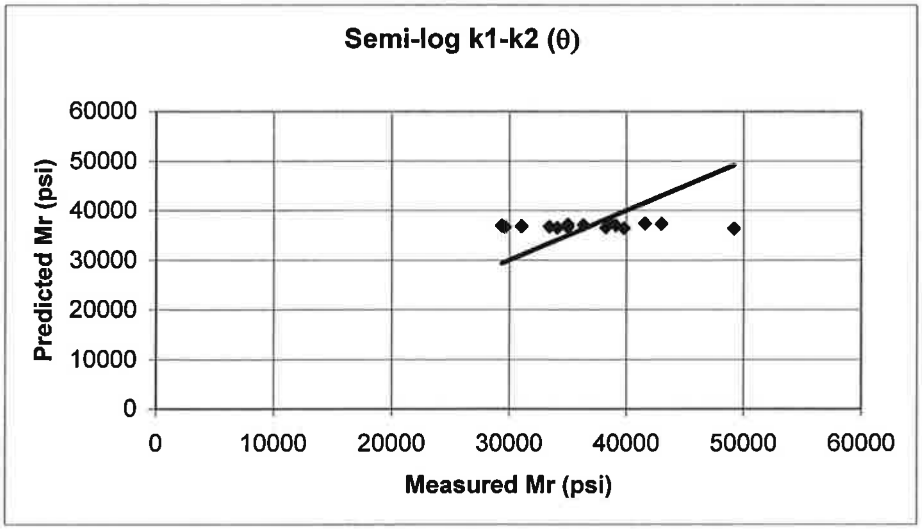




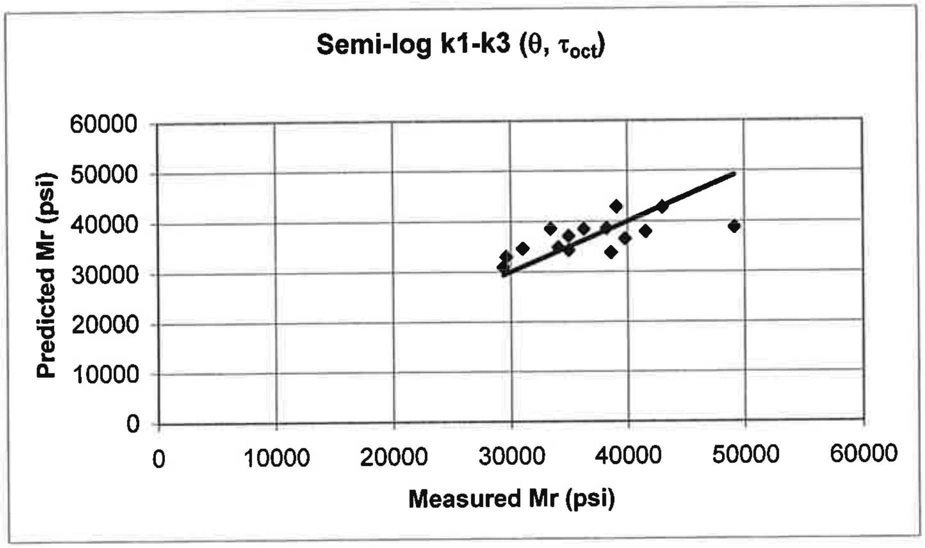
Measured Vs. Predicted M_R for Test NS1_2

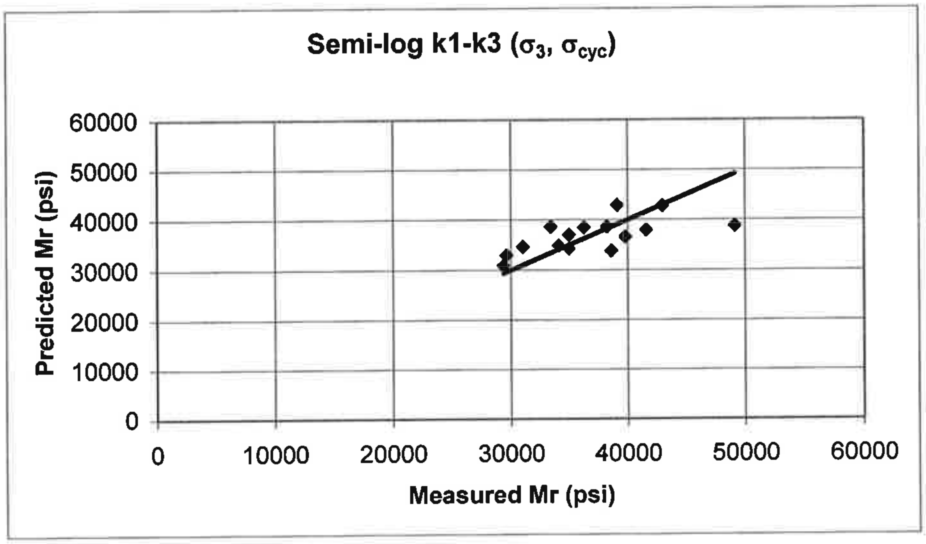


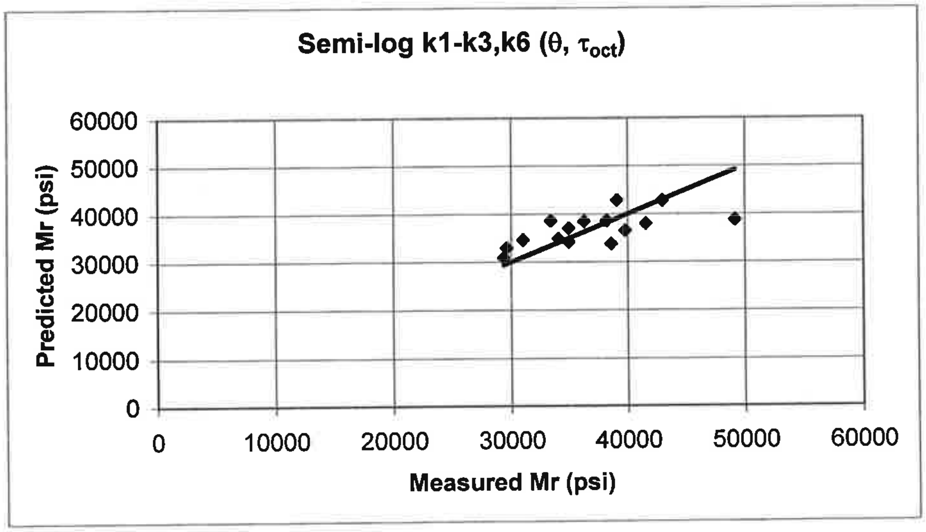




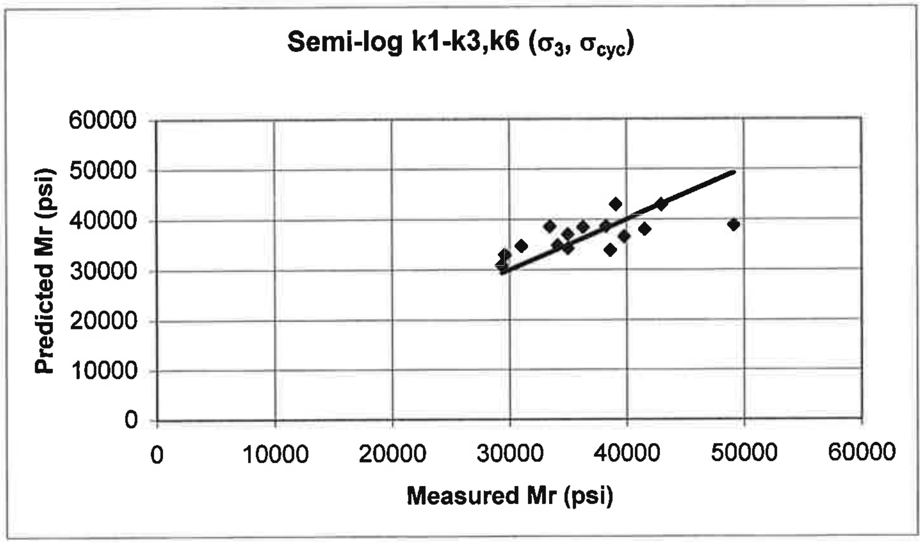
Measured Vs. Predicted M_R for Test NS1_2

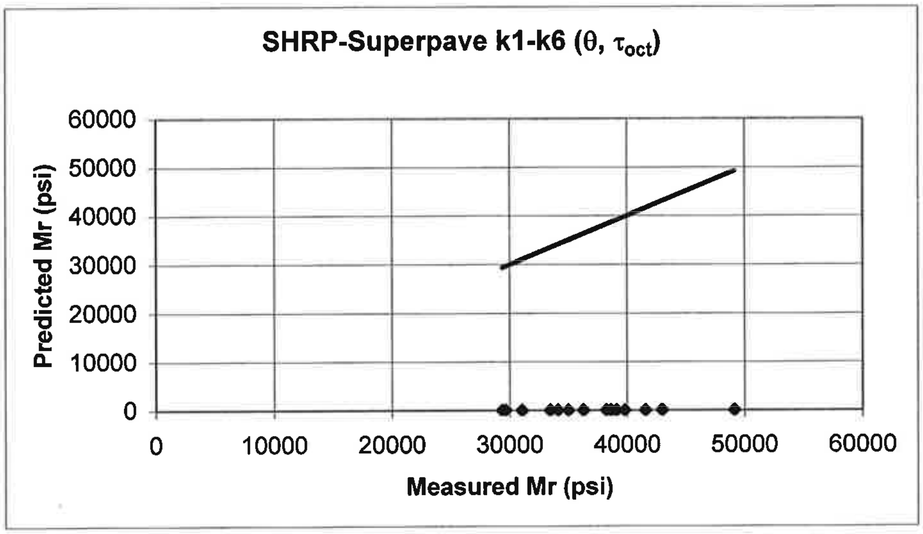


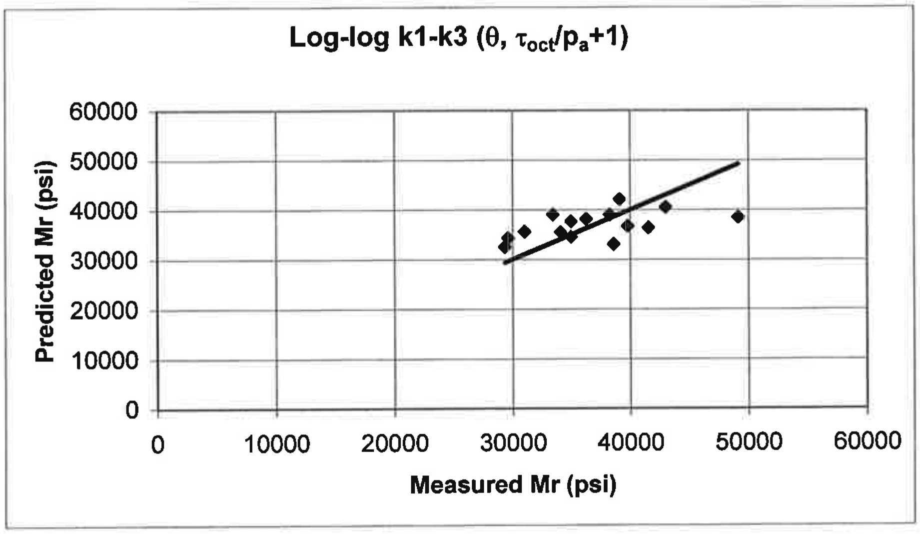




Measured Vs. Predicted M_R for Test NS1_2







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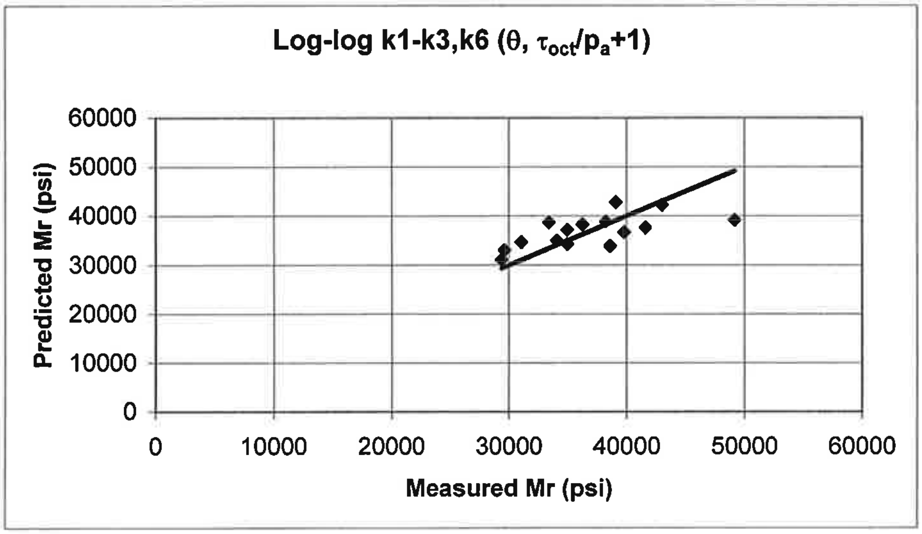

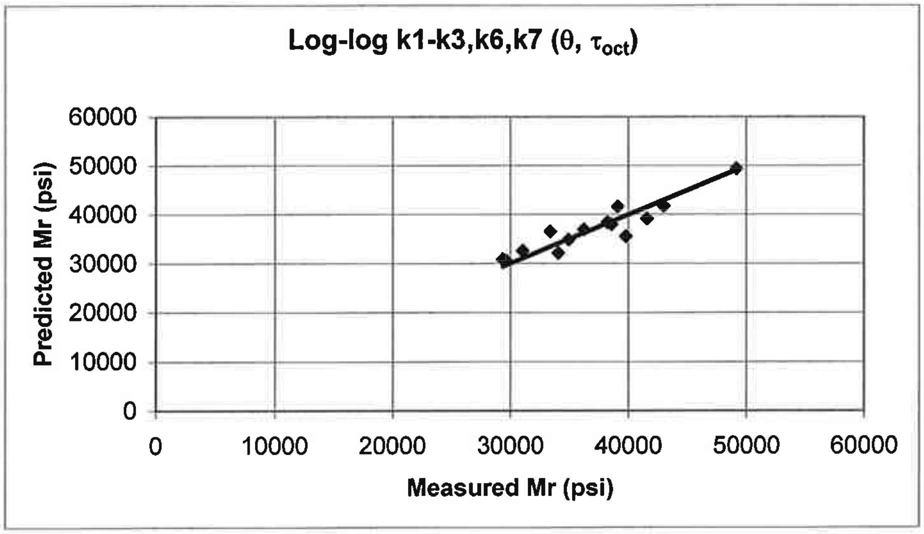

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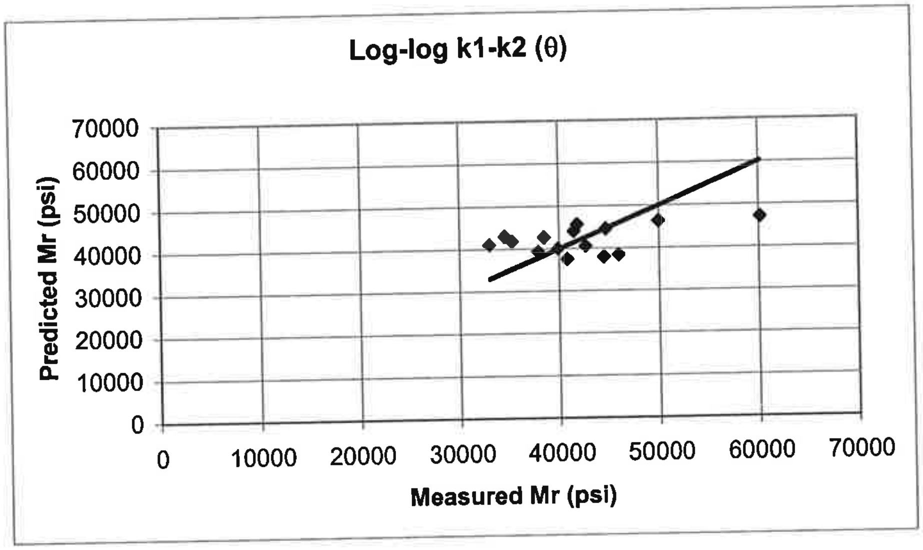
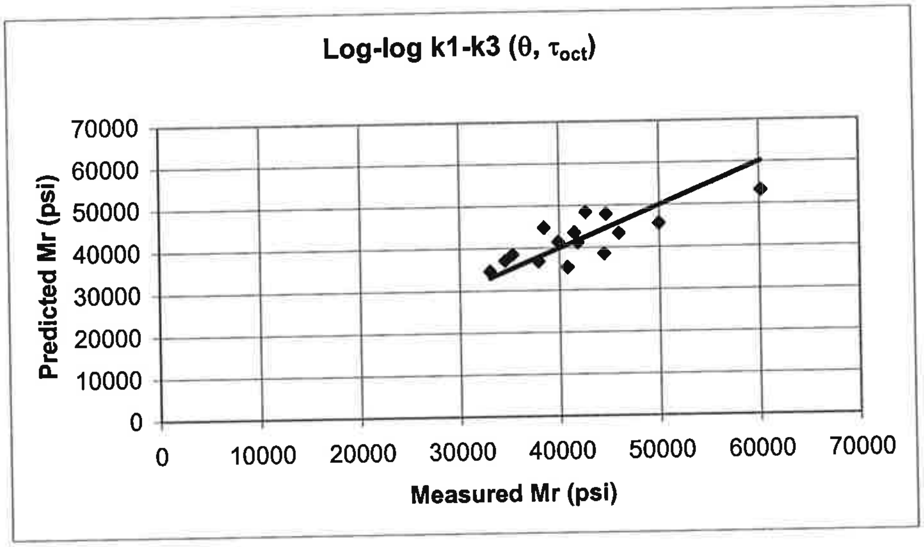
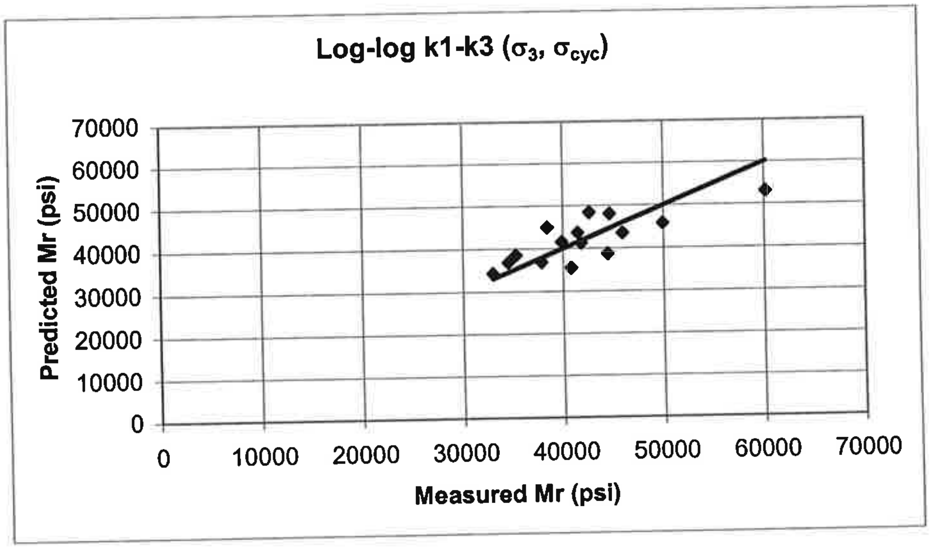
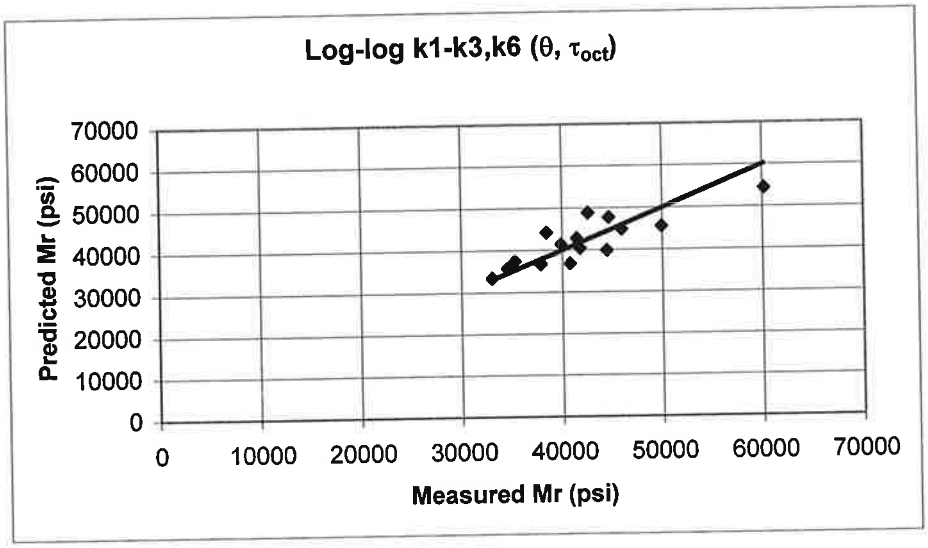
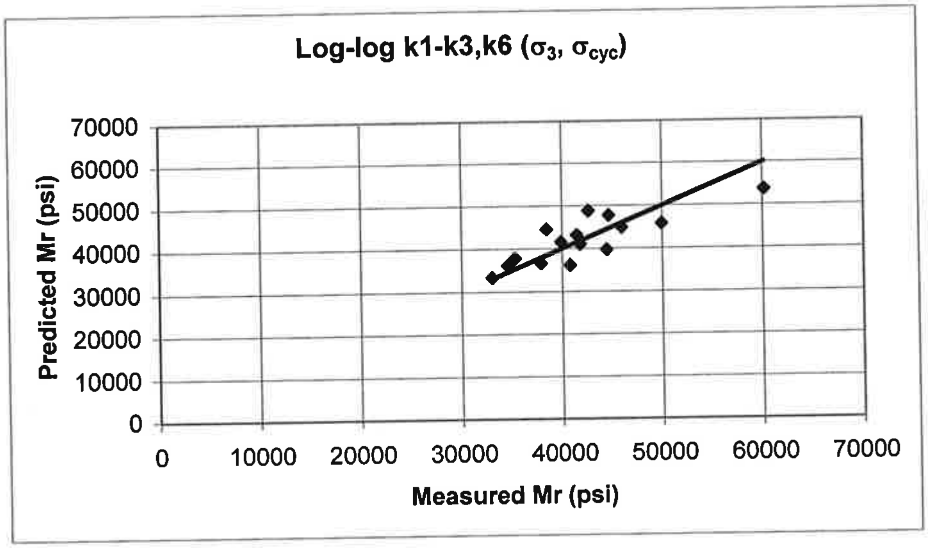


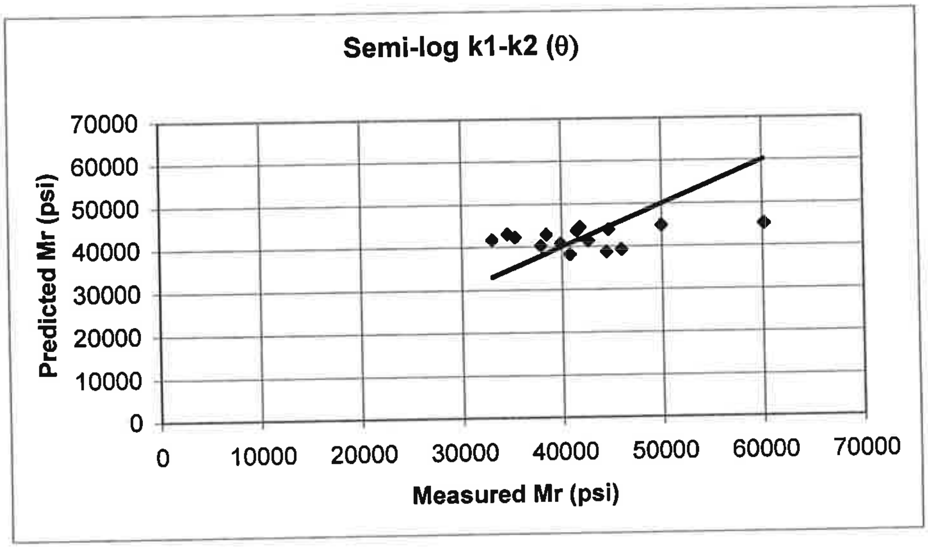




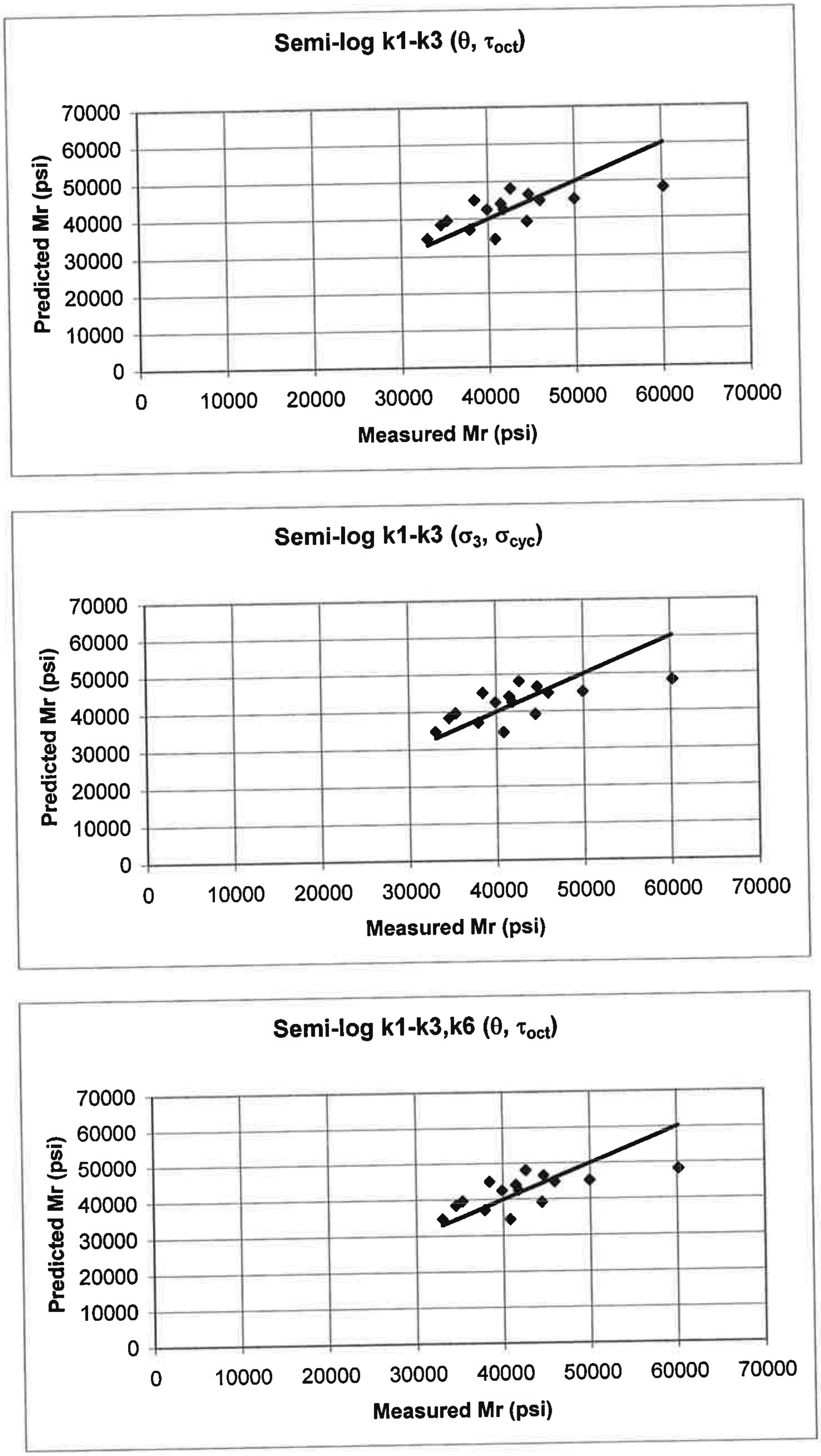
Measured Vs. Predicted M_R for Test NS1_3







Measured Vs. Predicted M_R for Test NS1_3

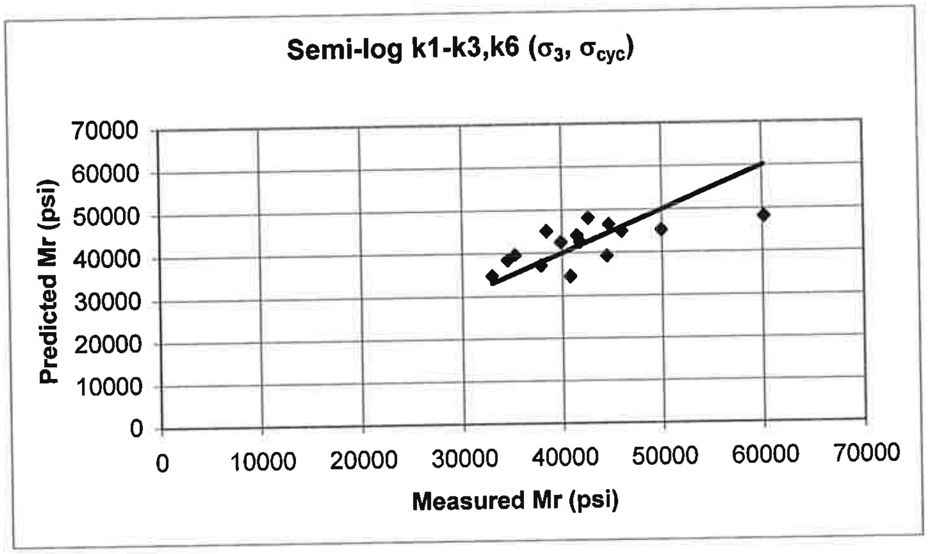


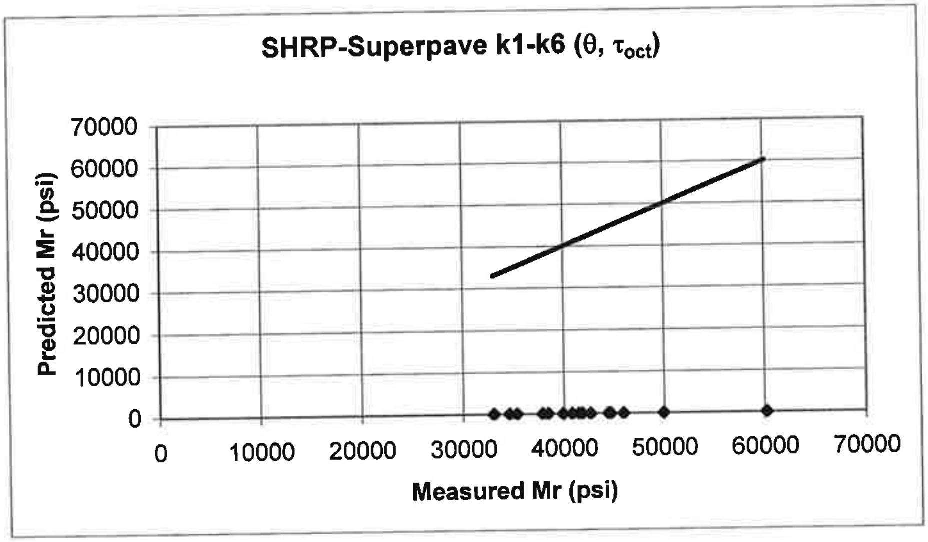
Semi-log k1-k3 (θ, τ_{oct})

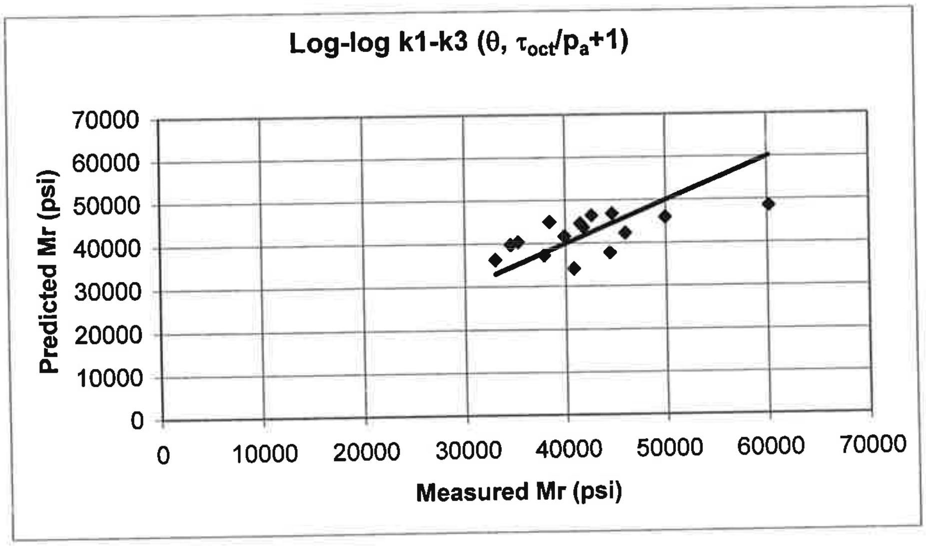
Semi-log k1-k3 (σ_3, σ_{cyc})

Semi-log k1-k3,k6 (θ, τ_{oct})

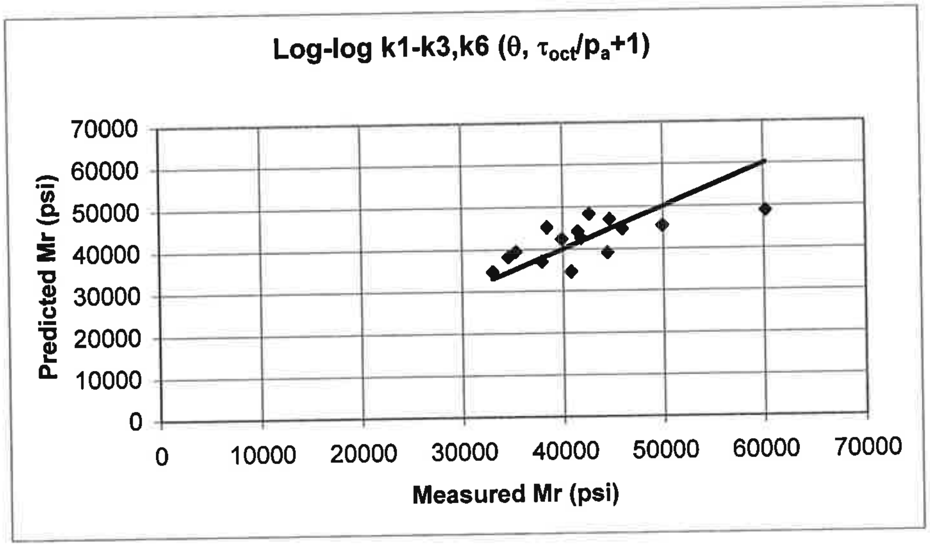
Measured Vs. Predicted M_R for Test NS1_3

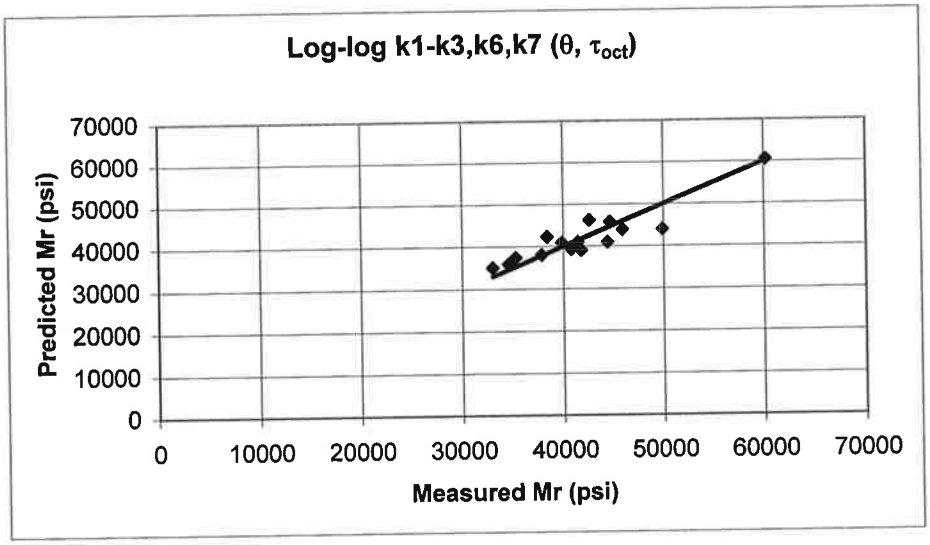




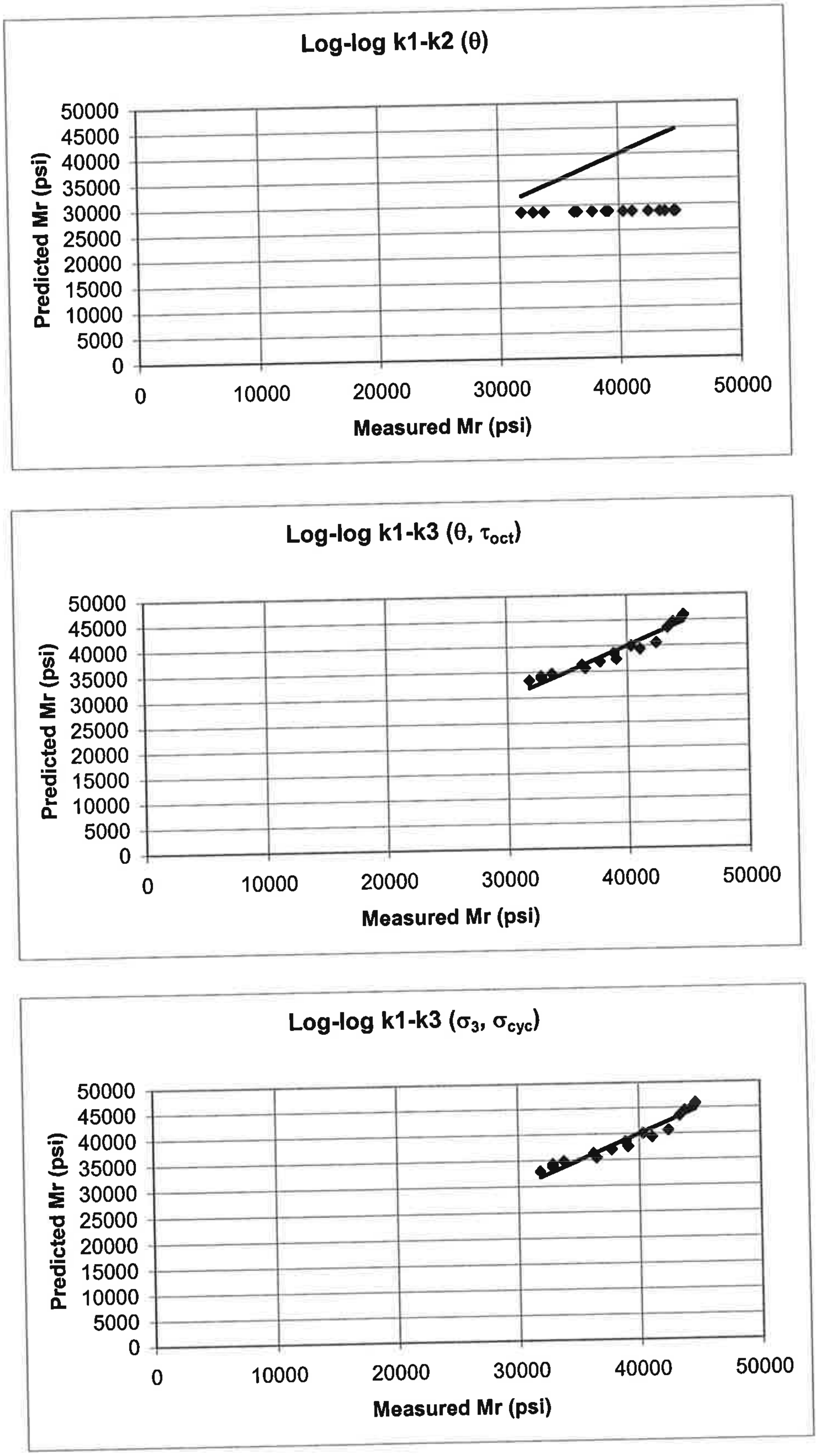


Measured Vs. Predicted M_R for Test NS1_3





Measured Vs. Predicted M_R for Test NS1_3

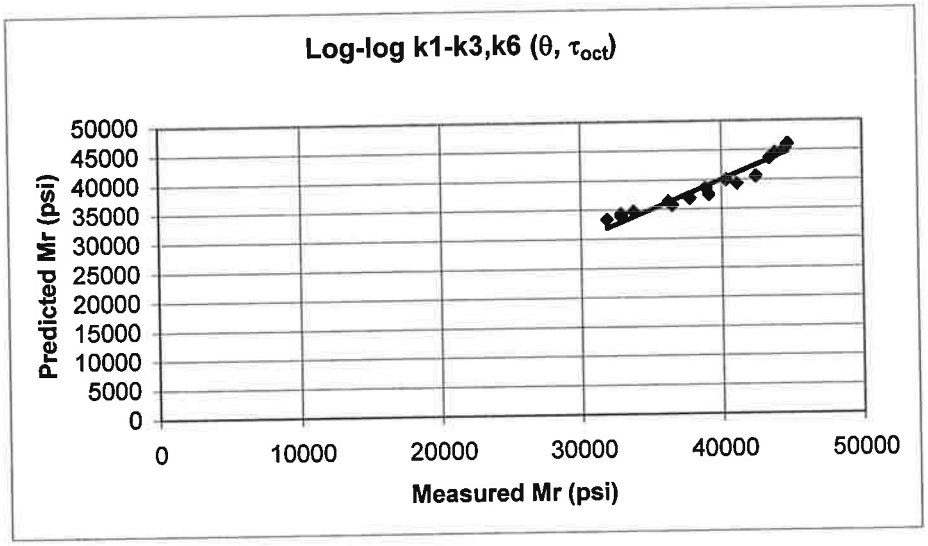


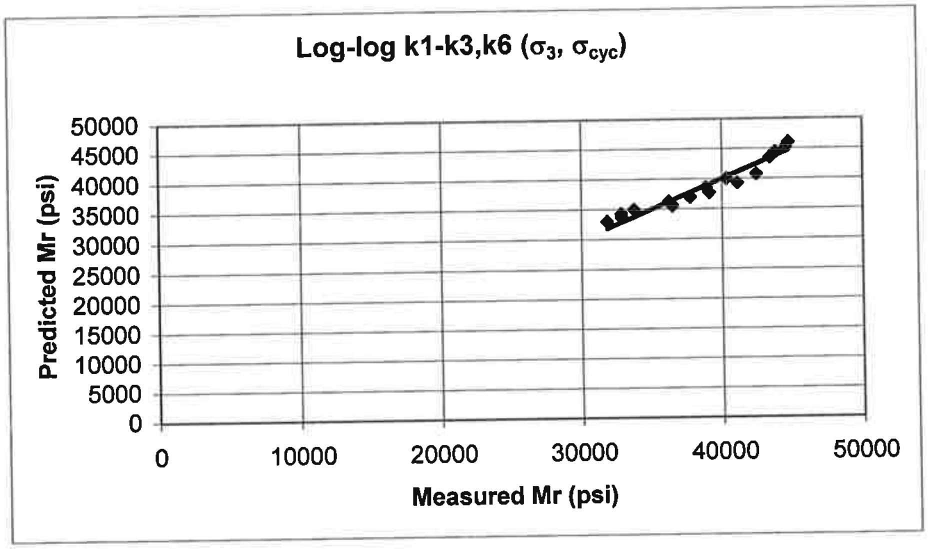
Log-log k1-k2 (θ)

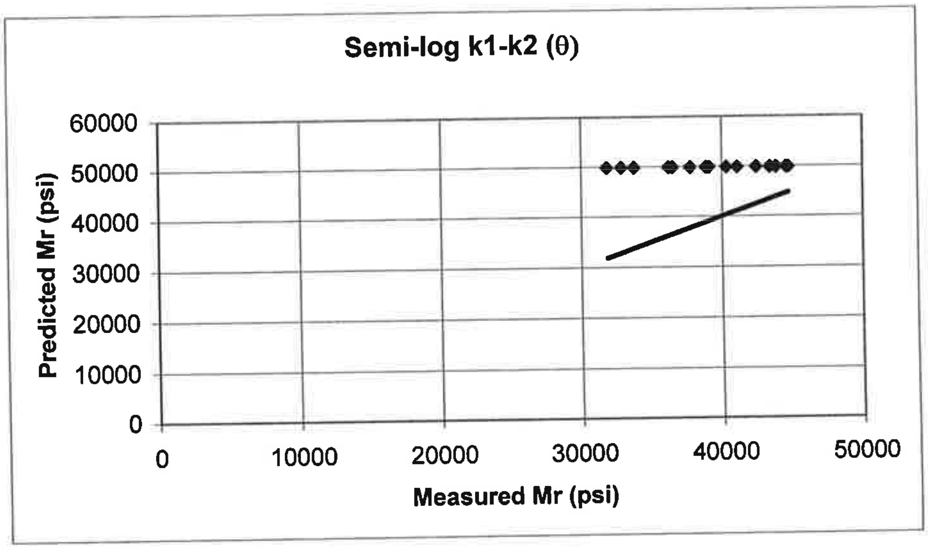
Log-log k1-k3 (θ, τ_{oct})

Log-log k1-k3 (σ_3, σ_{cyc})

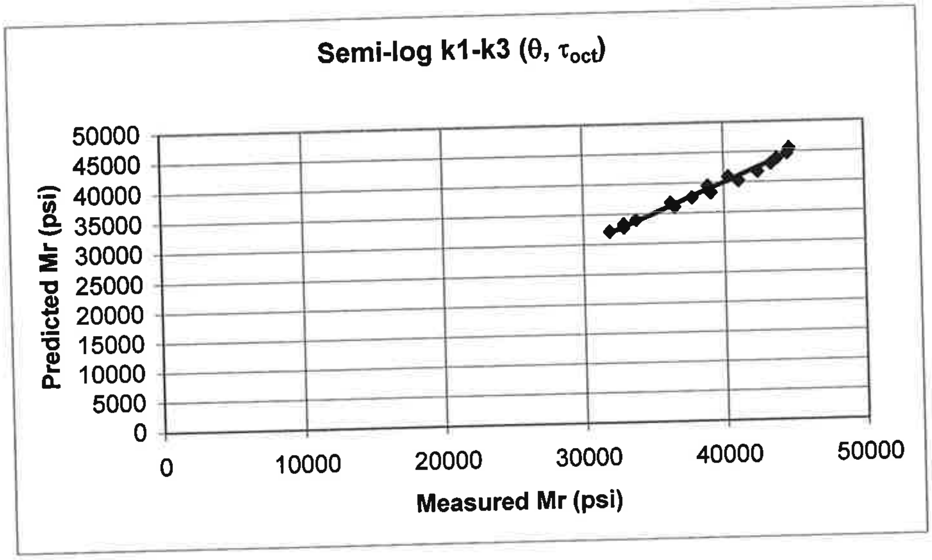
Measured Vs. Predicted M_R for Test S3_1

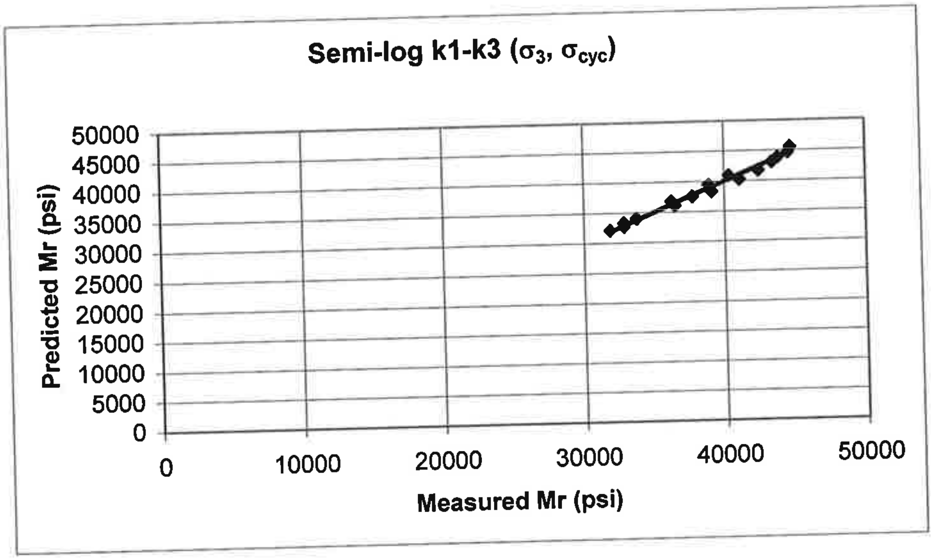


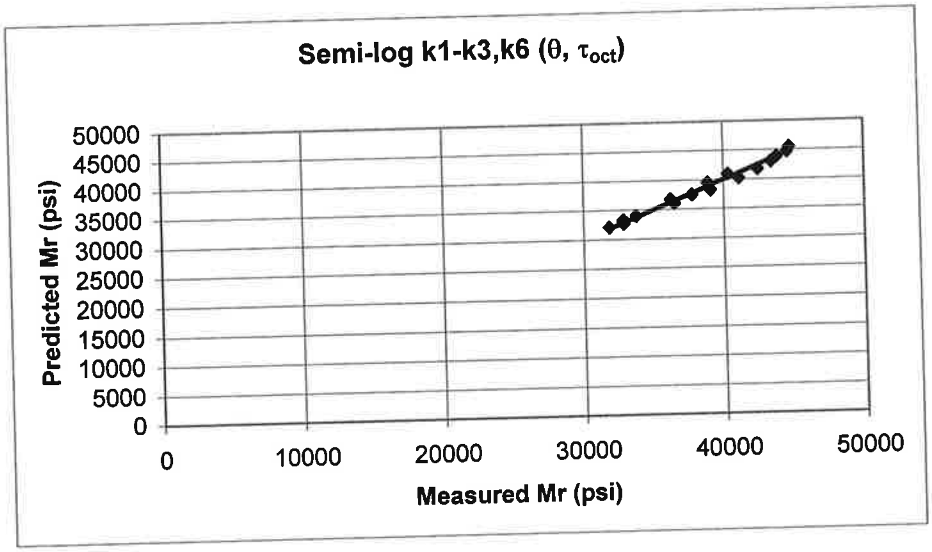




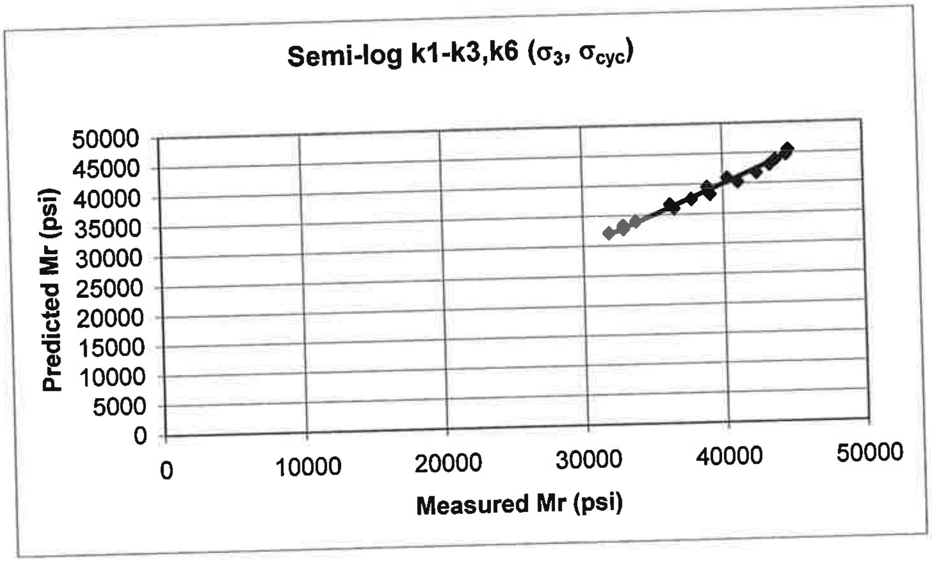
Measured Vs. Predicted M_R for Test S3_1



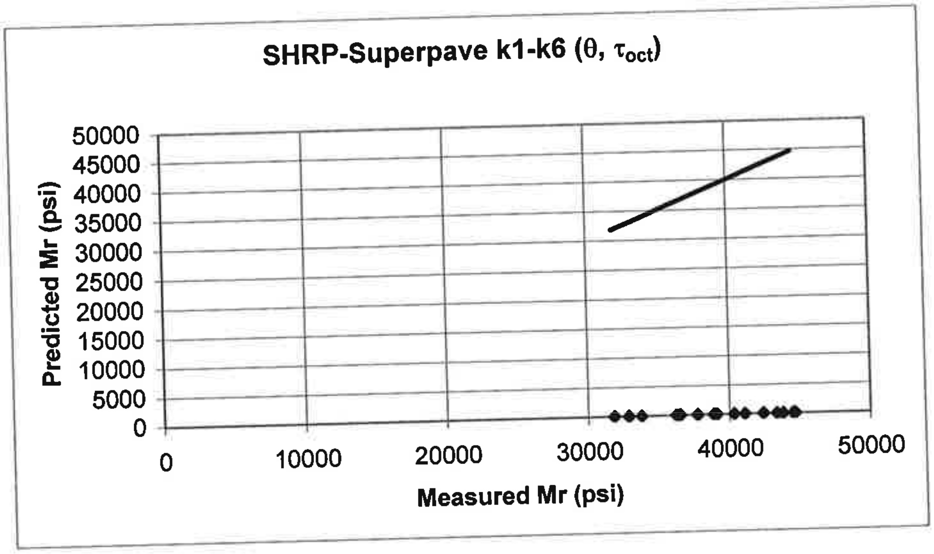




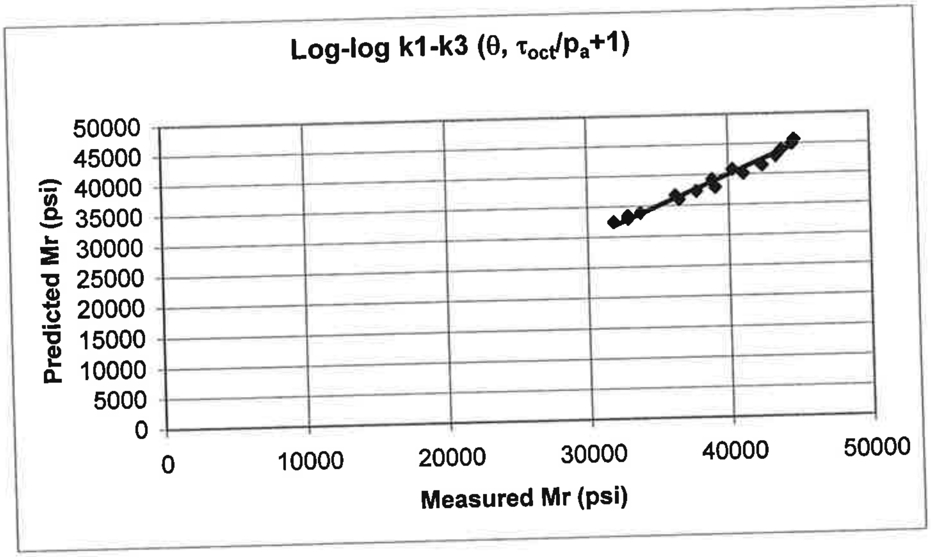
Measured Vs. Predicted M_R for Test S3_1



Semi-log k1-k3,k6 (σ_3, σ_{cyc})

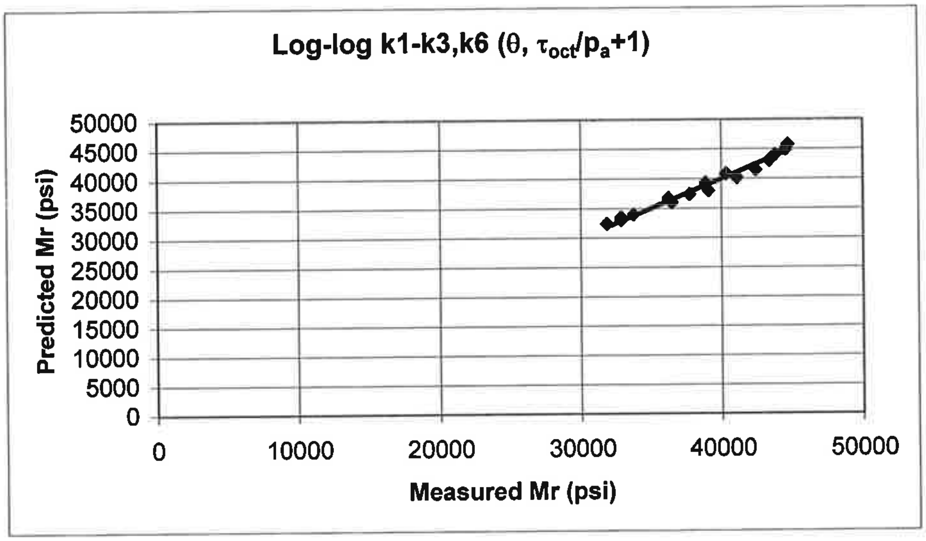


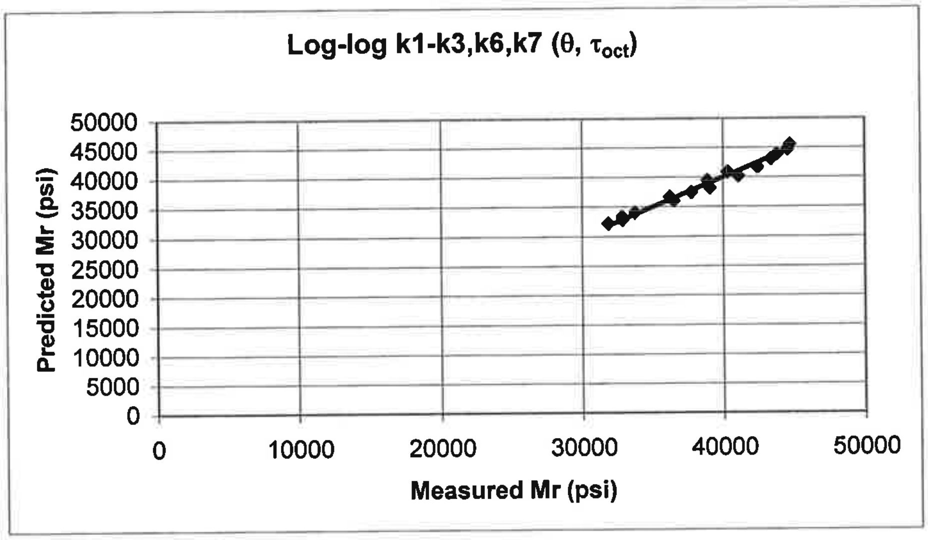
SHRP-Superpave k1-k6 (θ, τ_{oct})



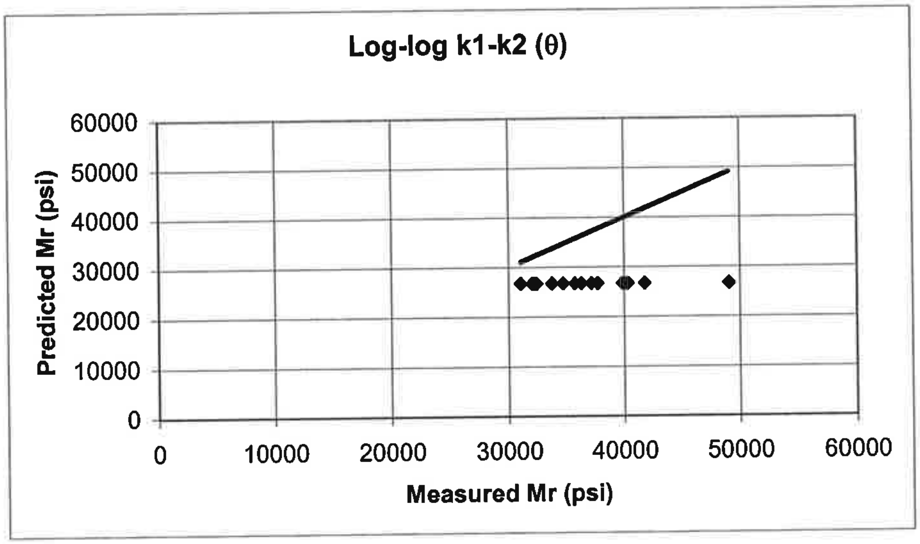
Log-log k1-k3 (θ, τ_{oct}/p_a+1)

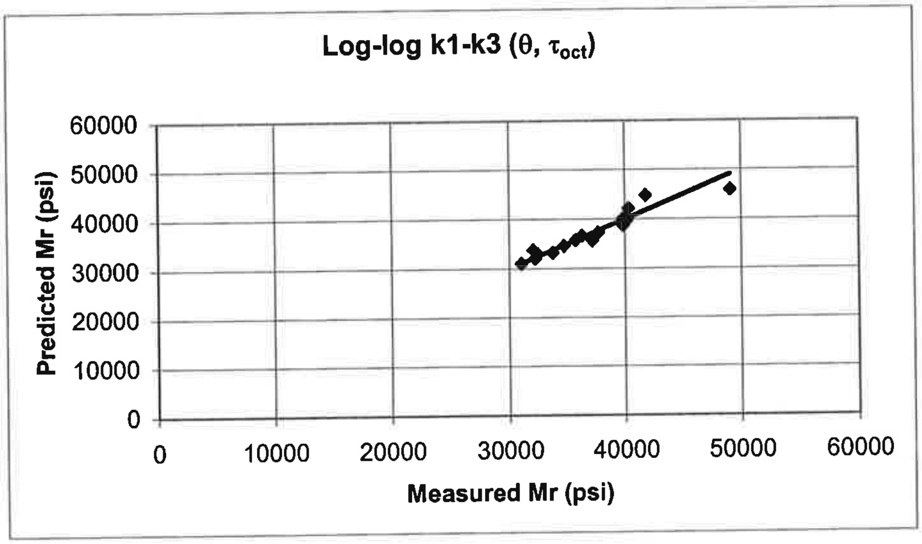
Measured Vs. Predicted M_R for Test S3_1

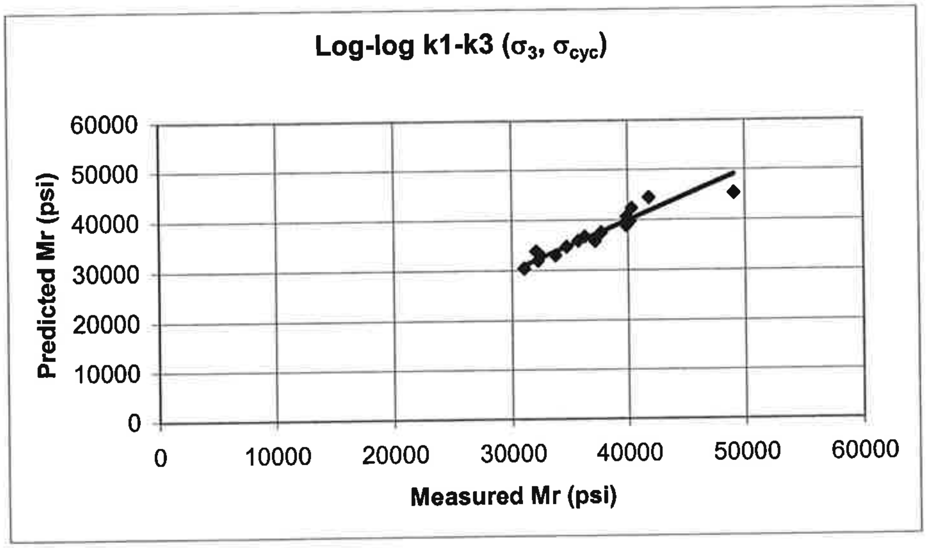




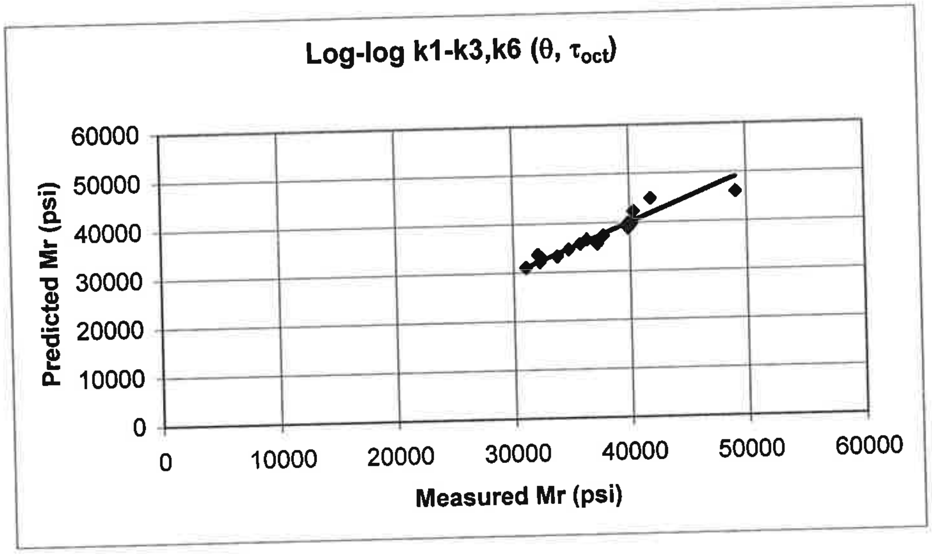
Measured Vs. Predicted M_R for Test S3-1

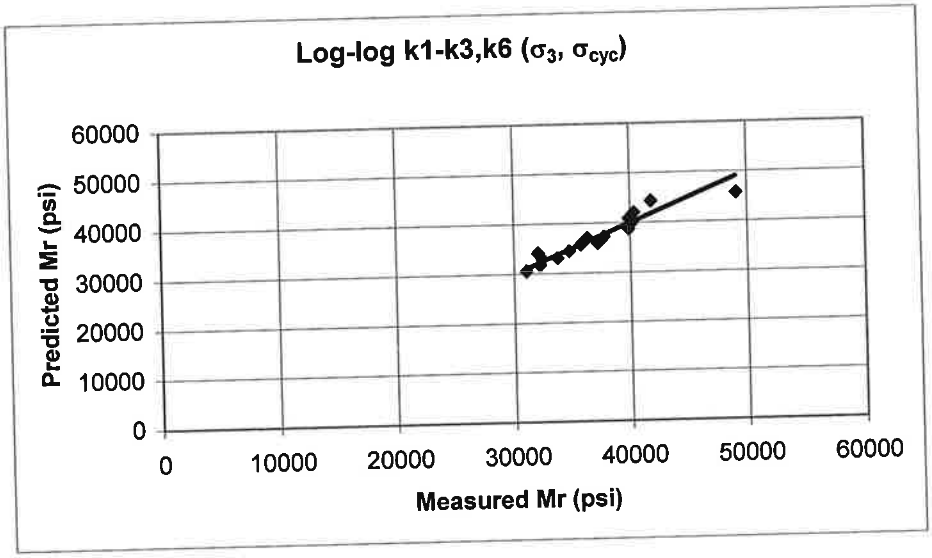


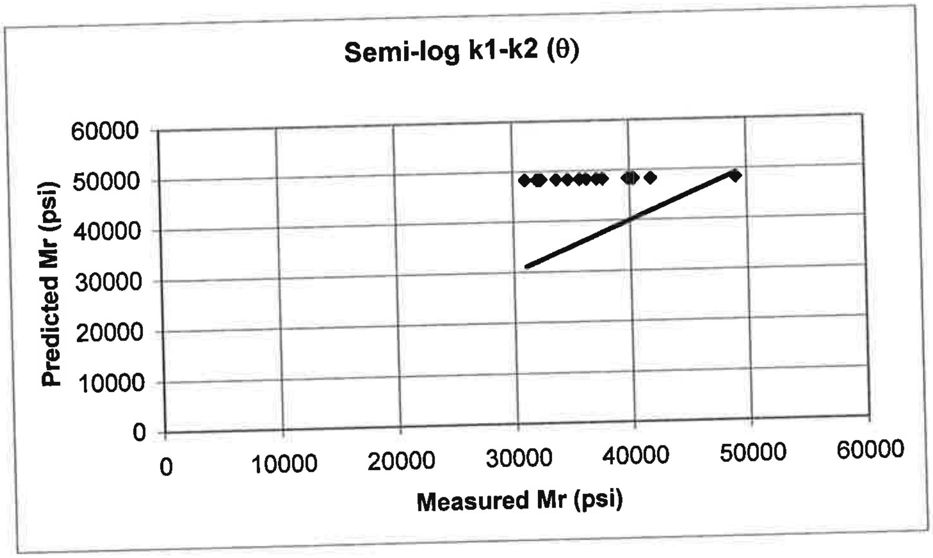




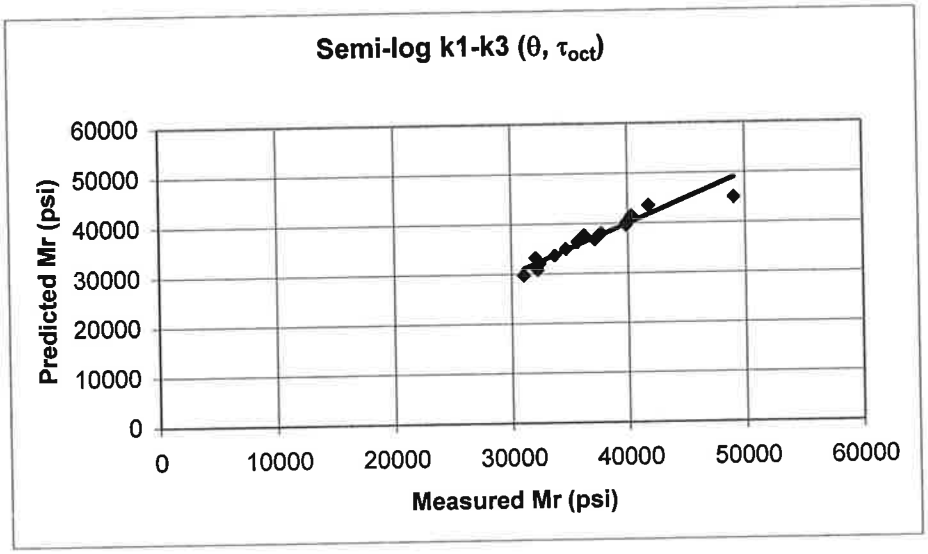
Measured Vs. Predicted M_R for Test S3_2

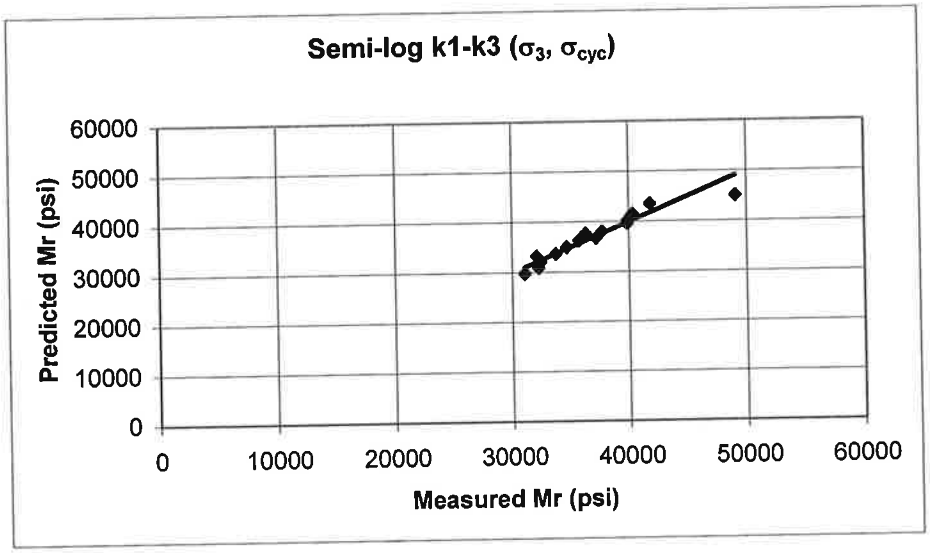


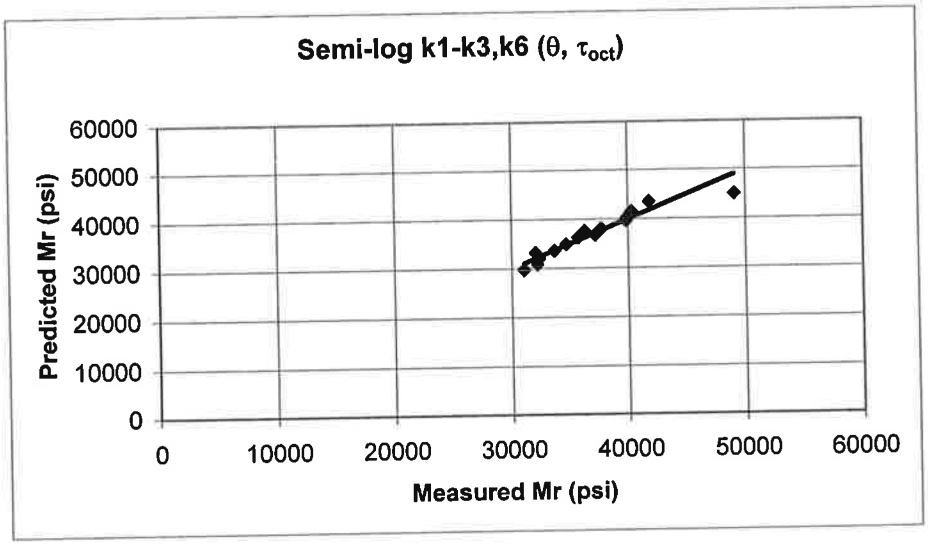




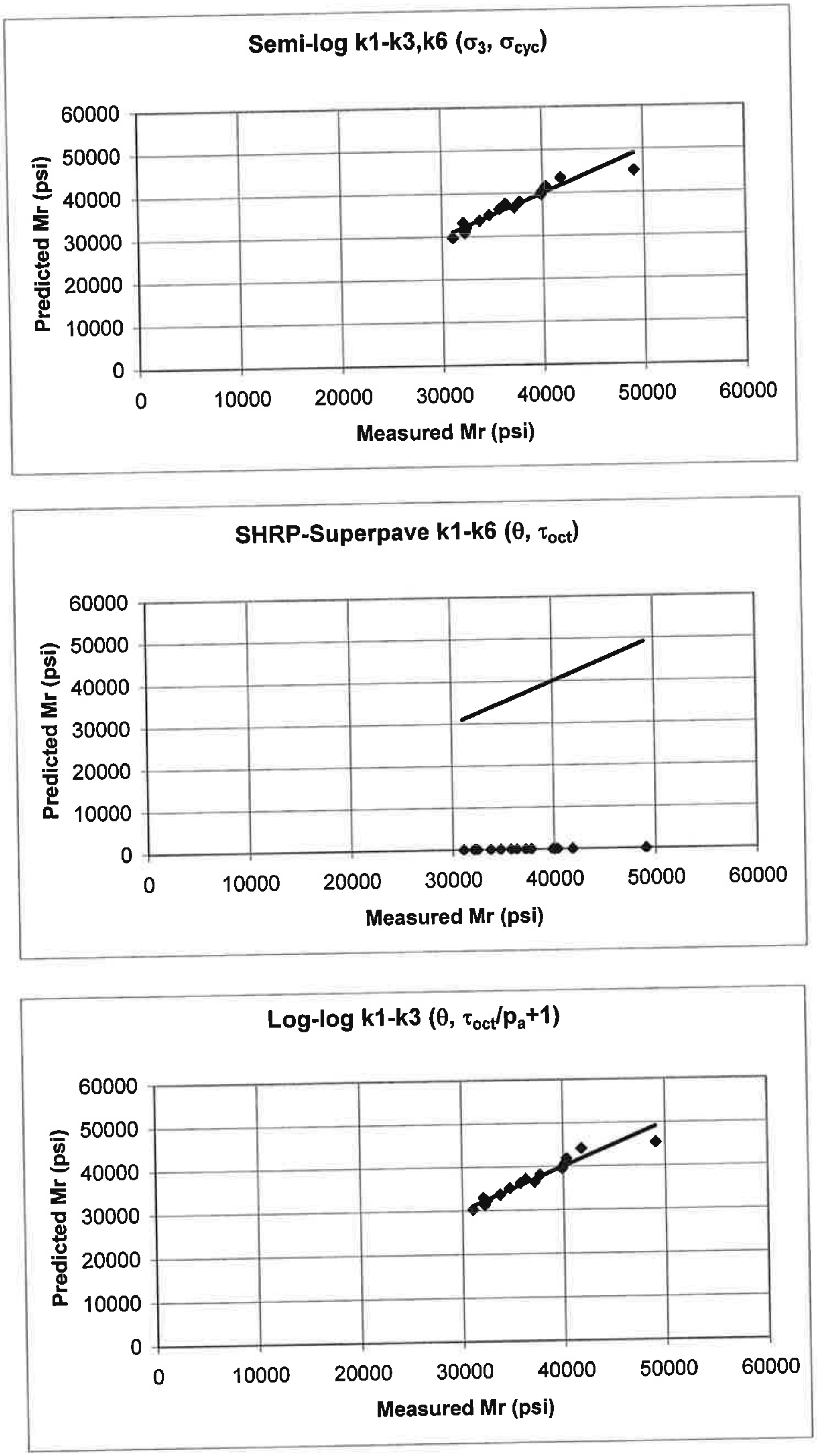
Measured Vs. Predicted M_R for Test S3_2



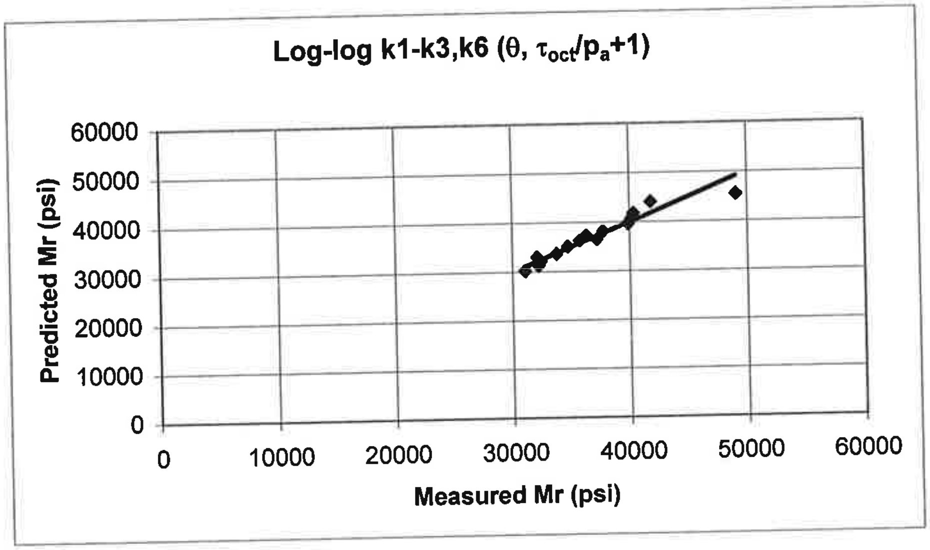


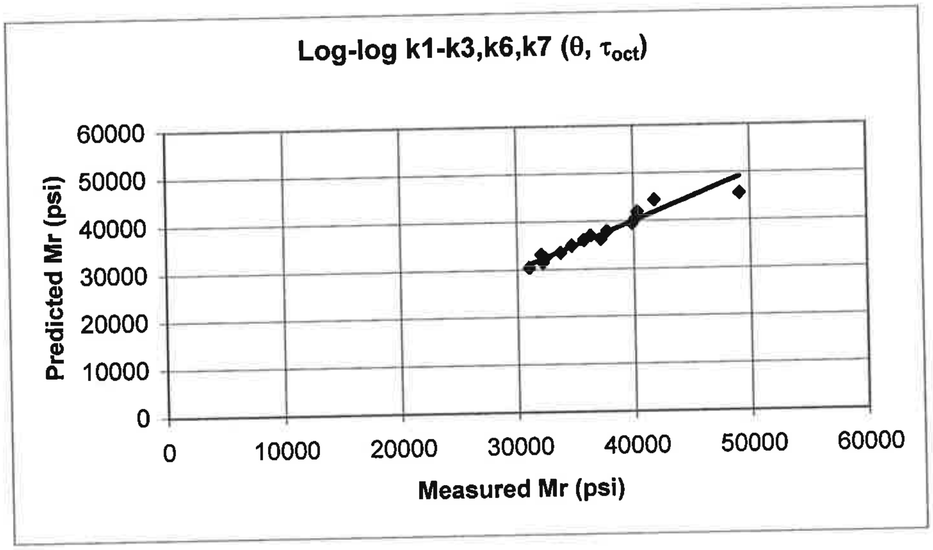


Measured Vs. Predicted M_R for Test S3_2

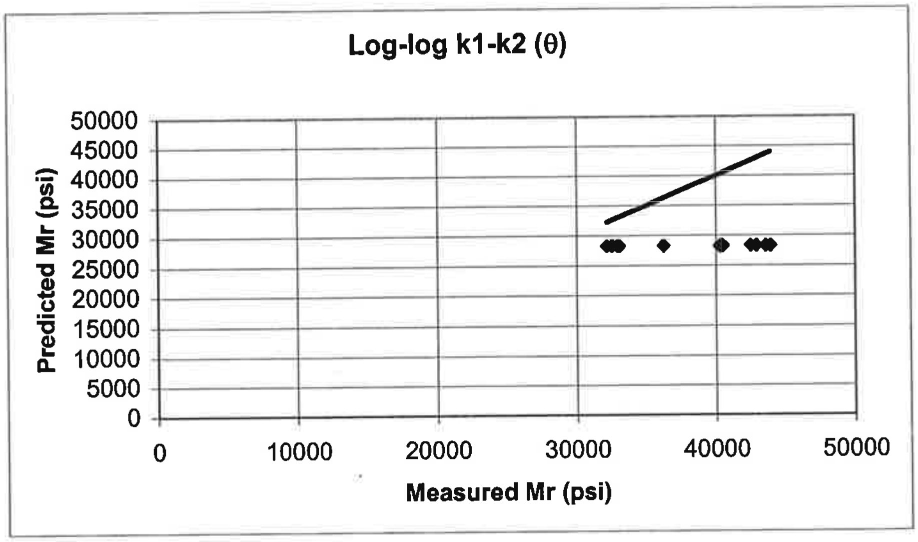


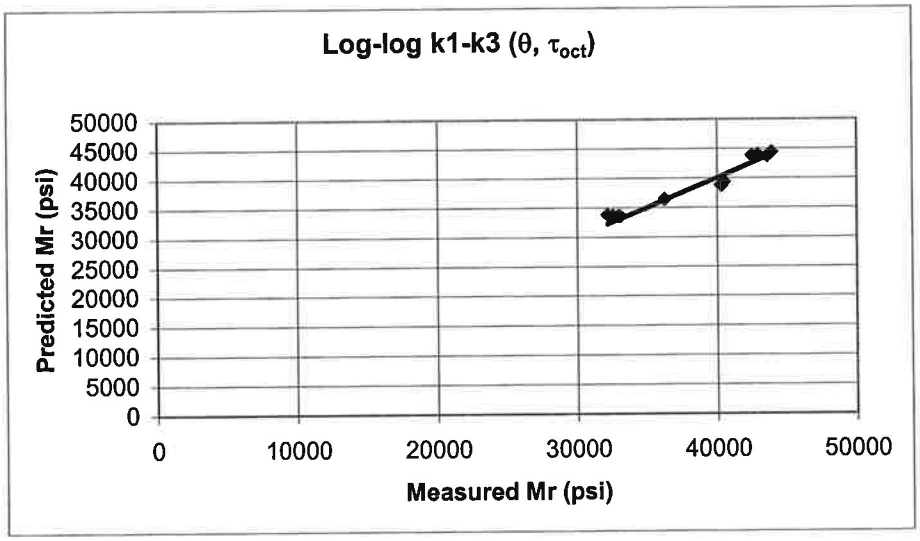
Measured Vs. Predicted M_R for Test S3_2

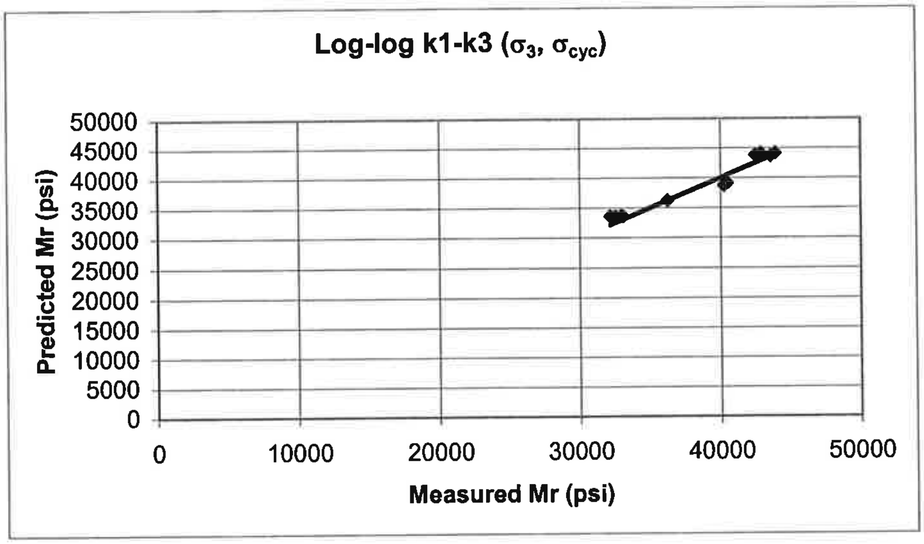




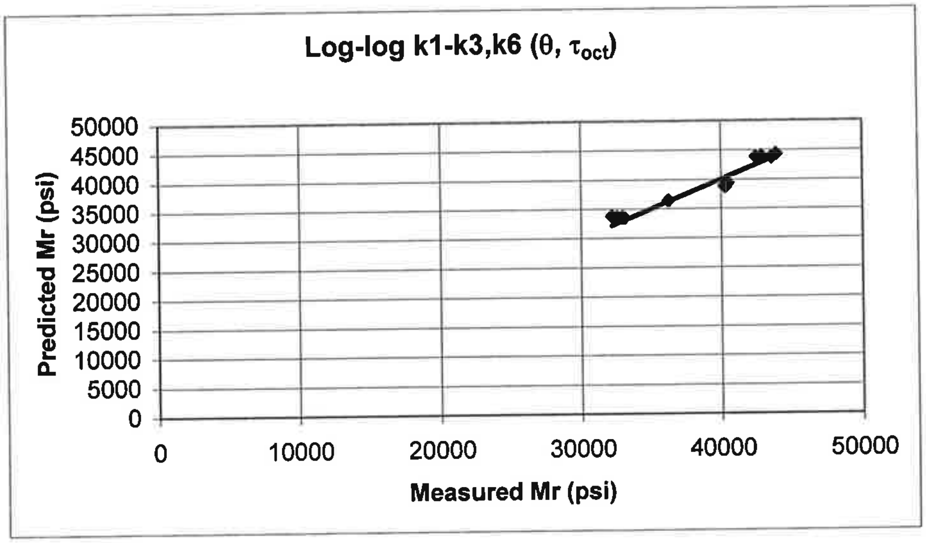
Measured Vs. Predicted M_R for Test S3_2

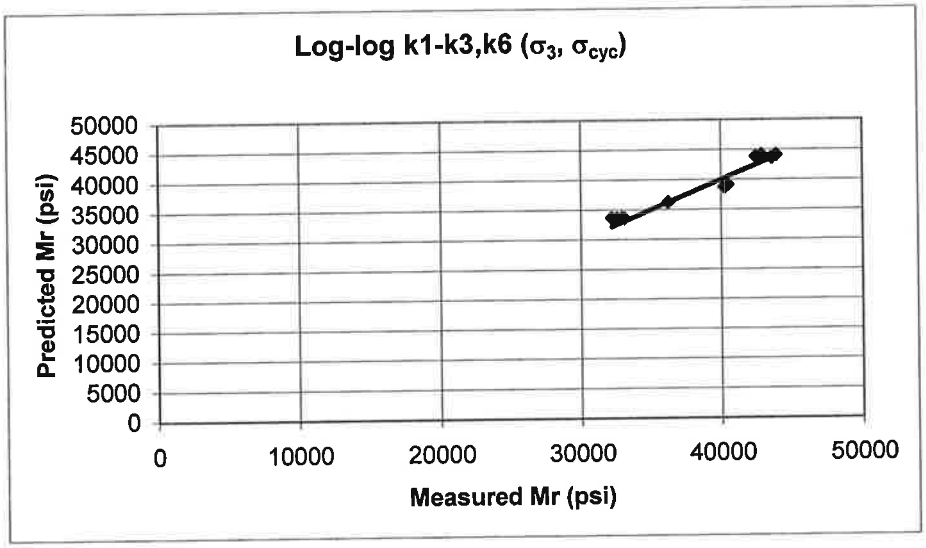


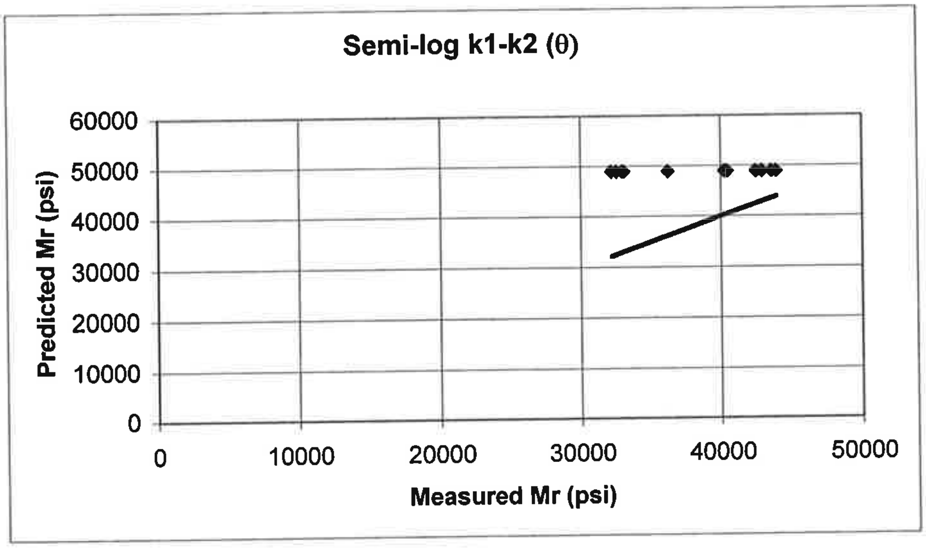




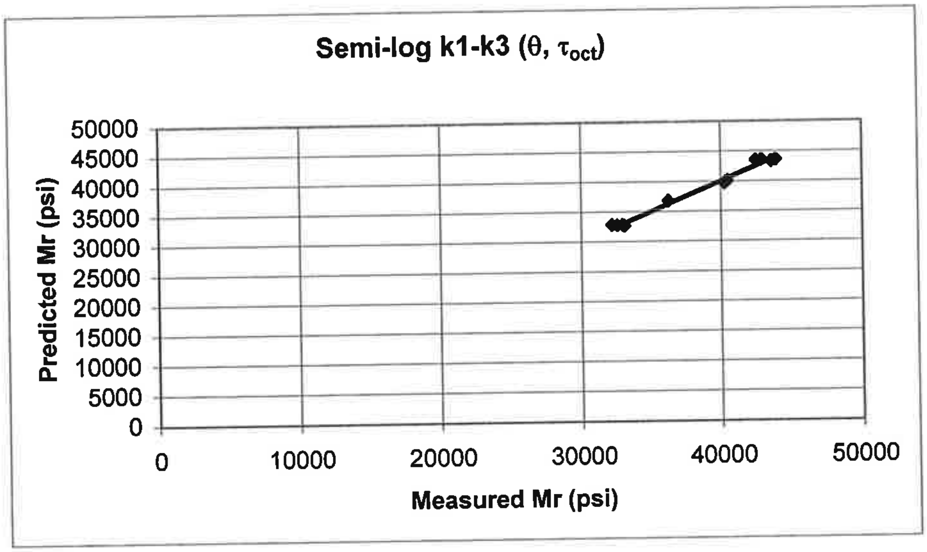
Measured Vs. Predicted M_R for Test S3_3

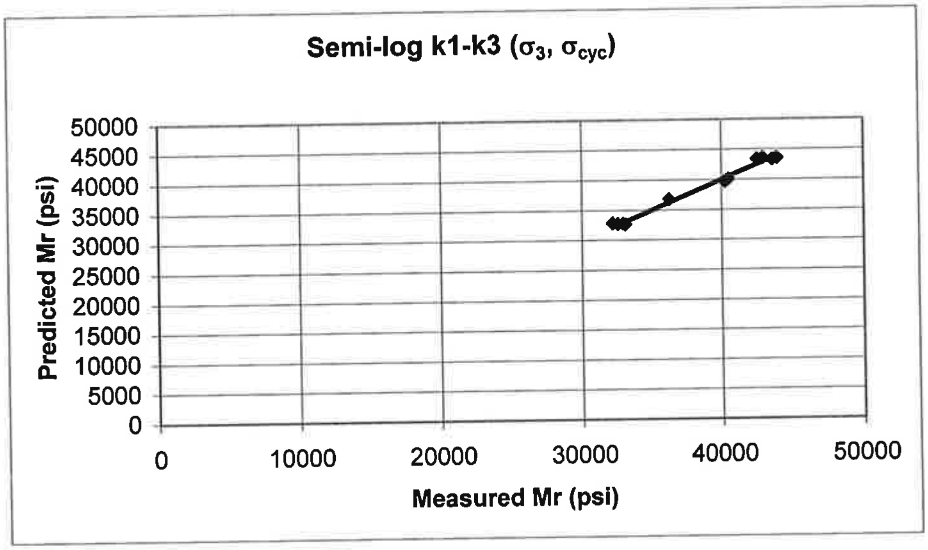


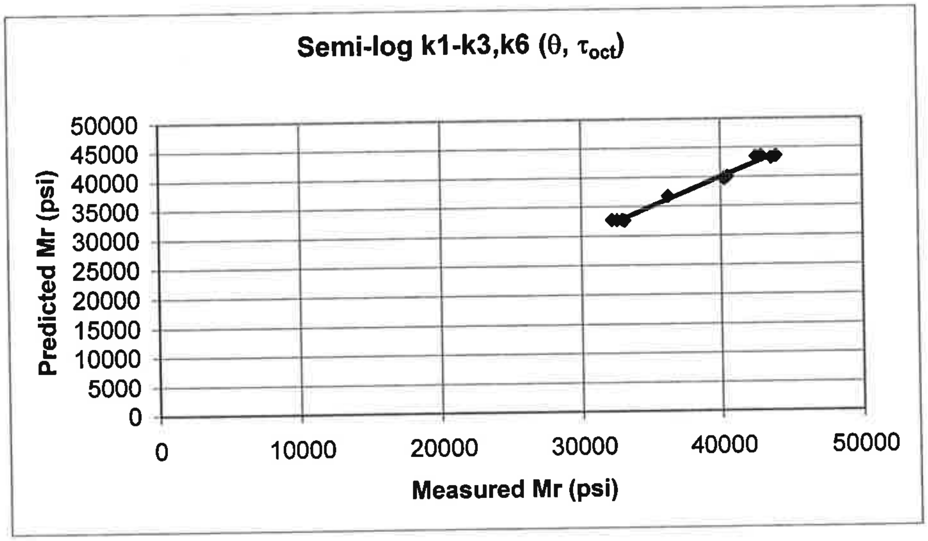




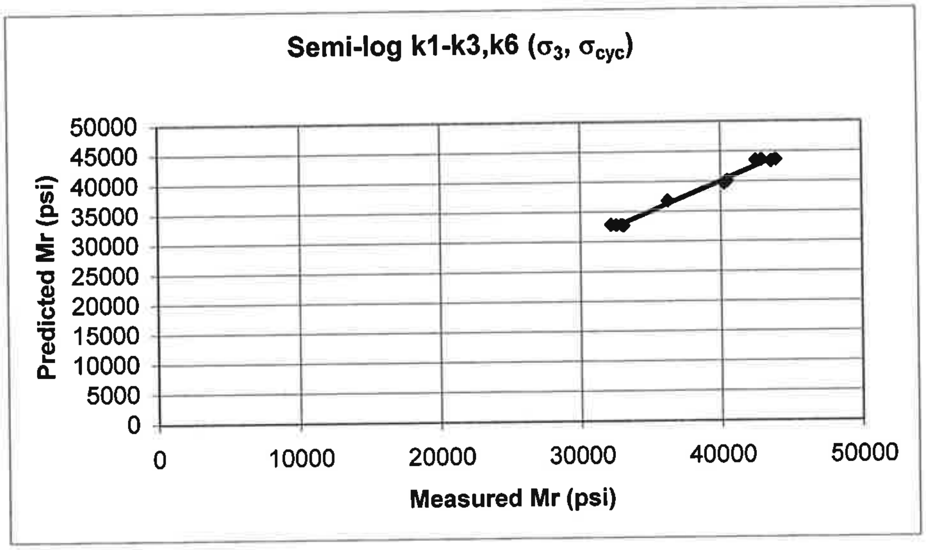
Measured Vs. Predicted M_R for Test S3_3

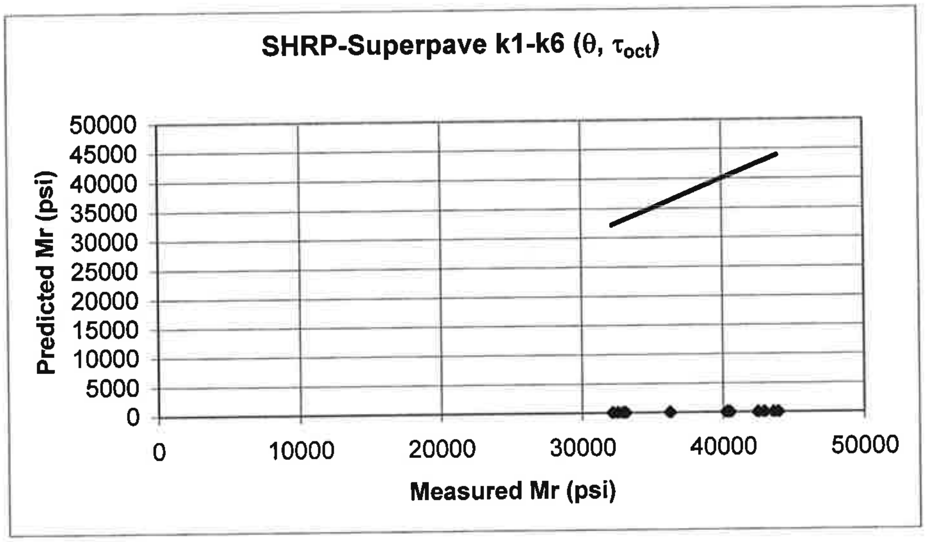


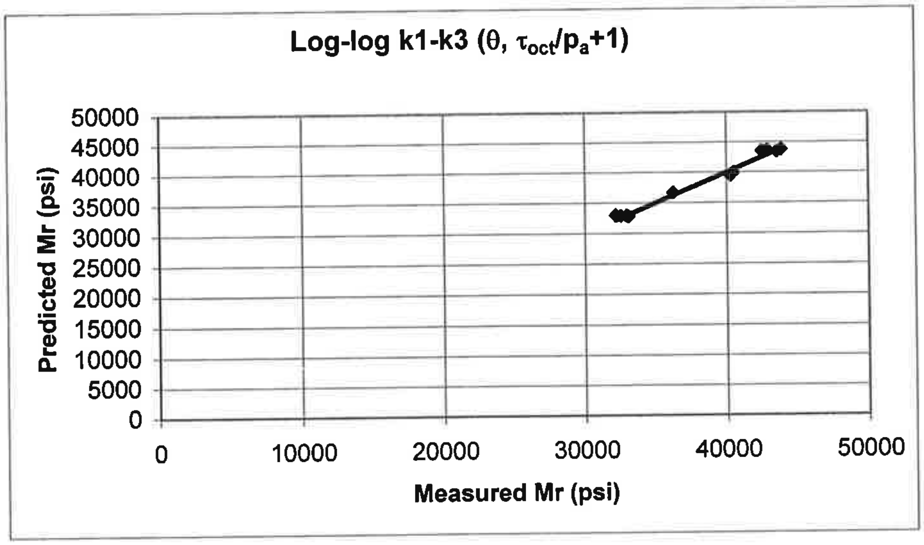




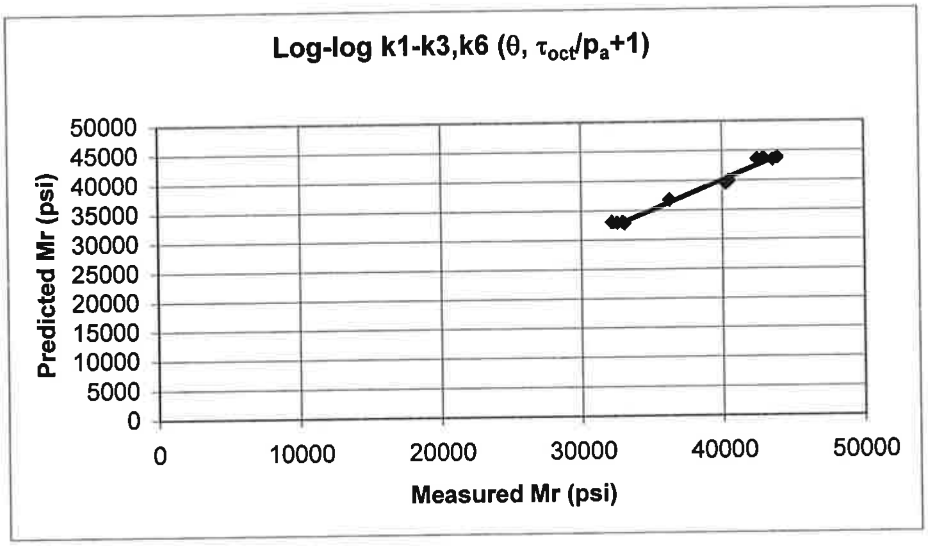
Measured Vs. Predicted M_R for Test S3_3

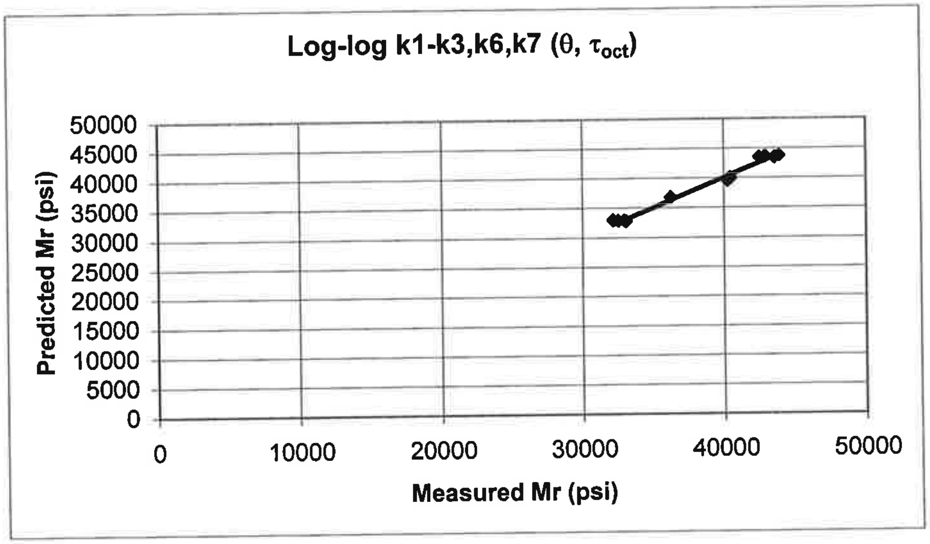




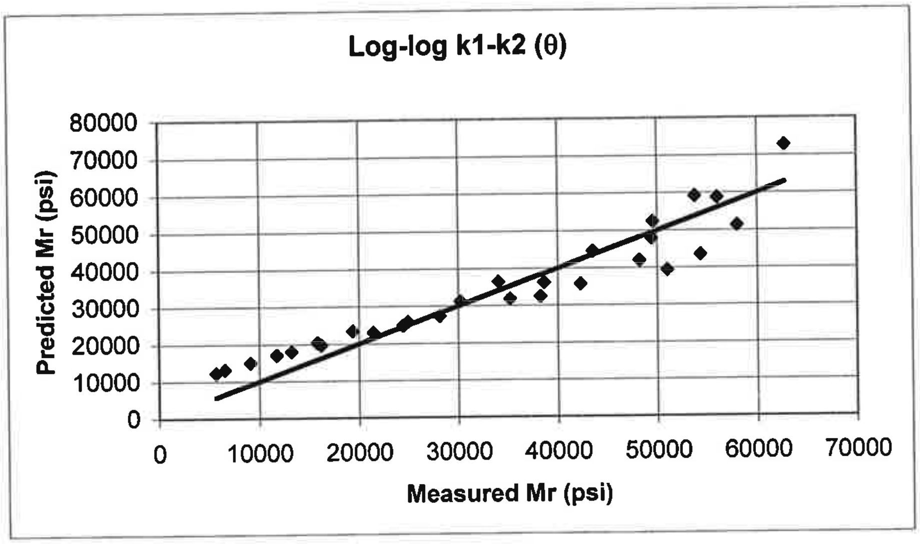


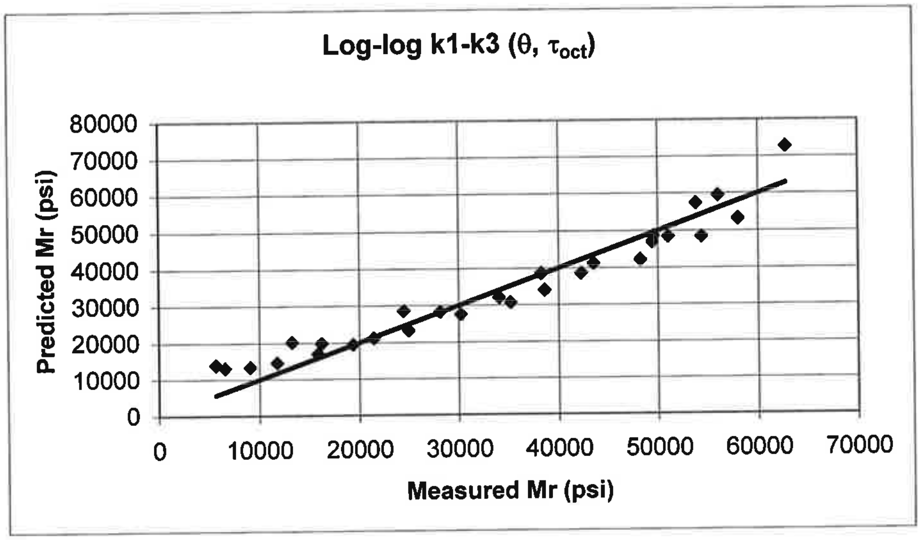
Measured Vs. Predicted M_R for Test S3_3

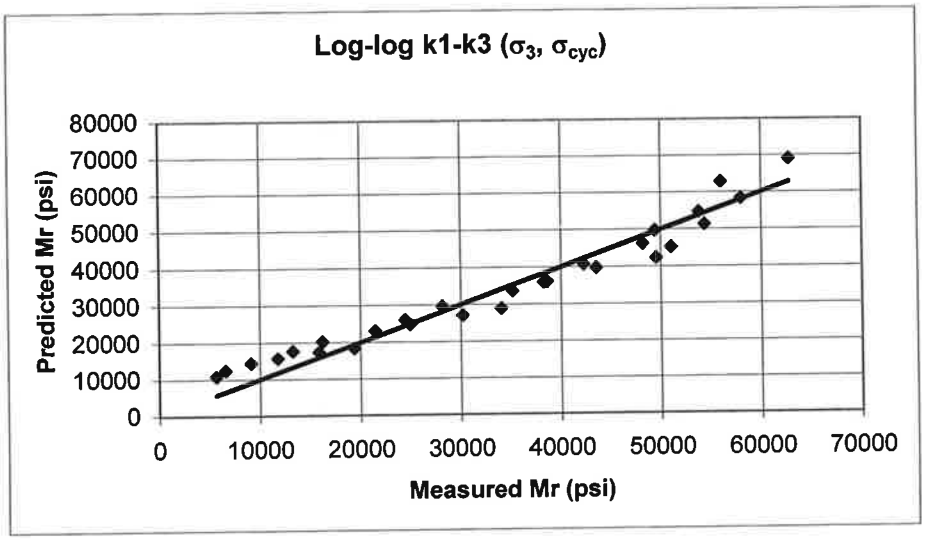




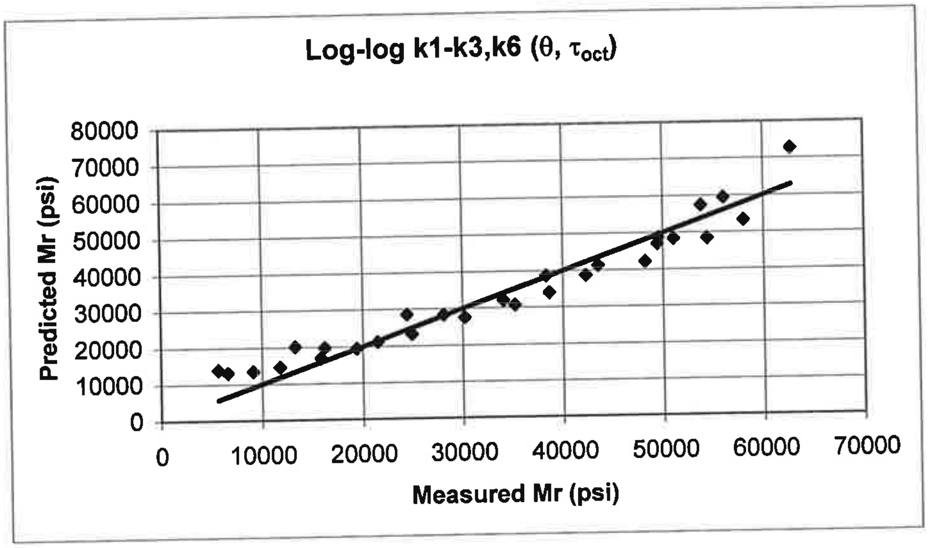
Measured Vs. Predicted M_R for Test S3_3

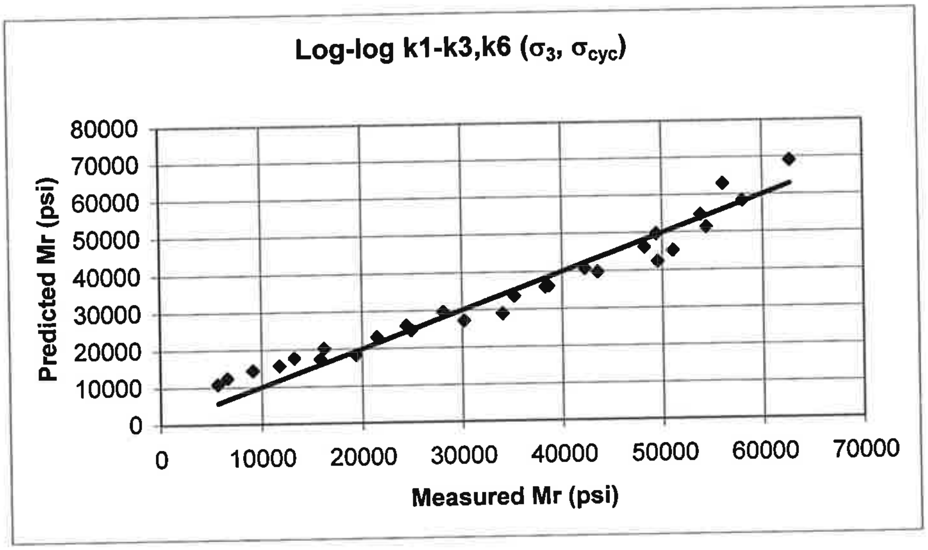


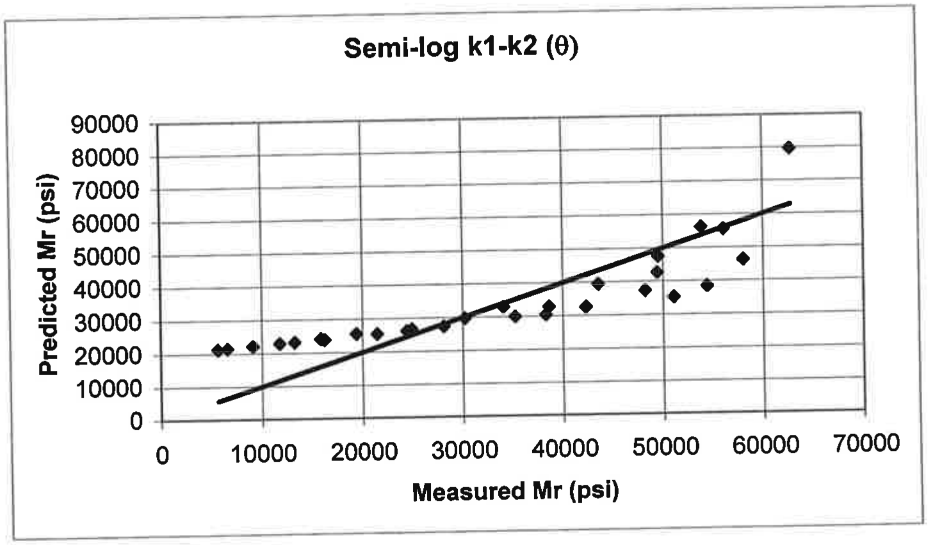




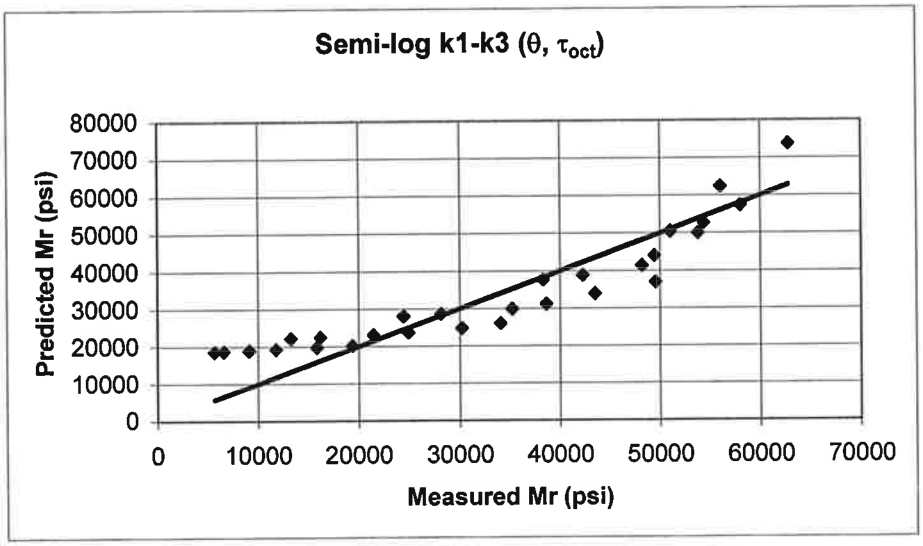
Measured Vs. Predicted M_R for Test S11_high

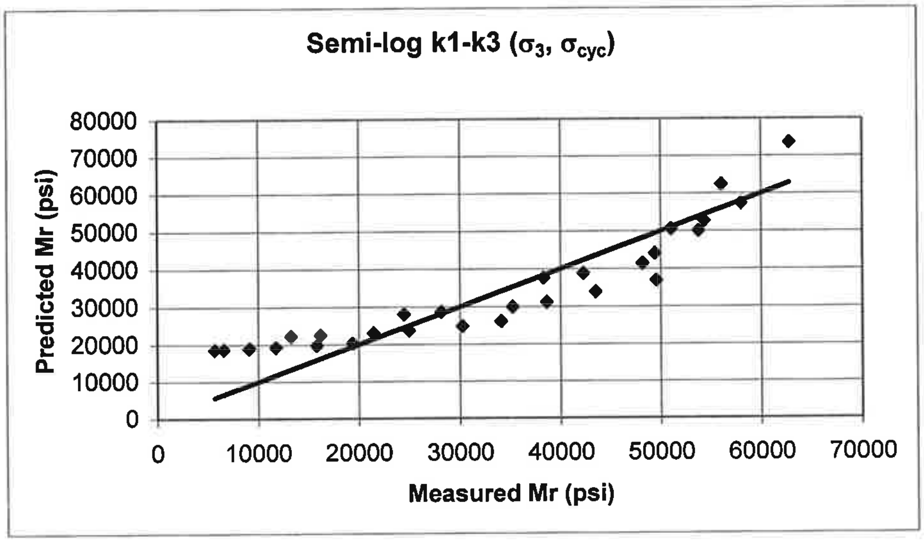


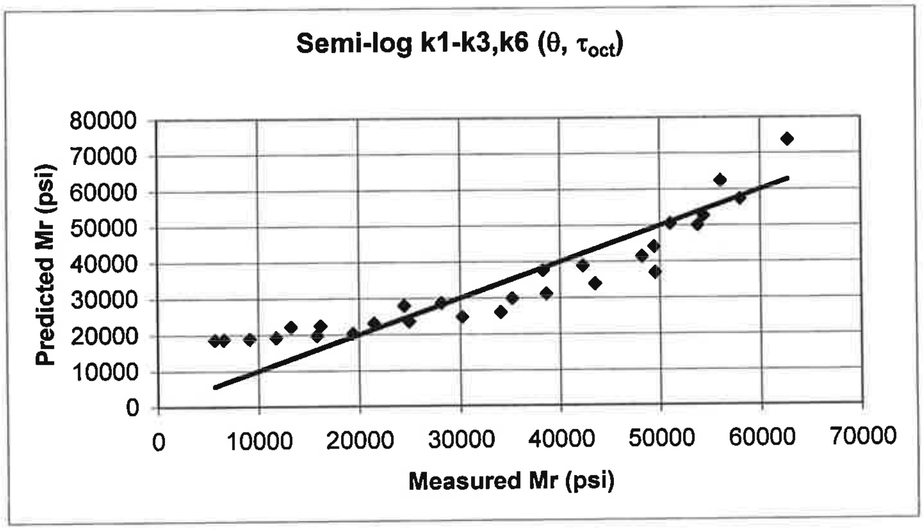




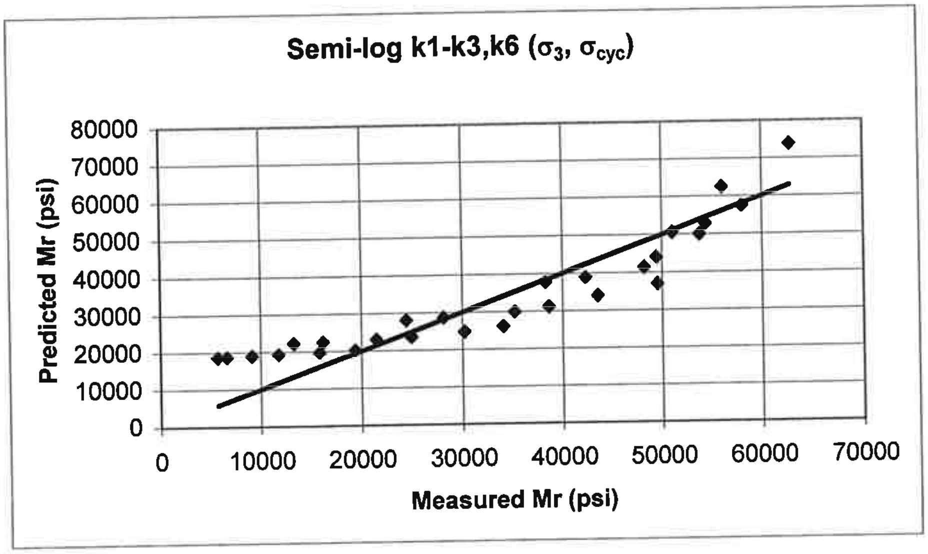
Measured Vs. Predicted M_R for Test S11_high

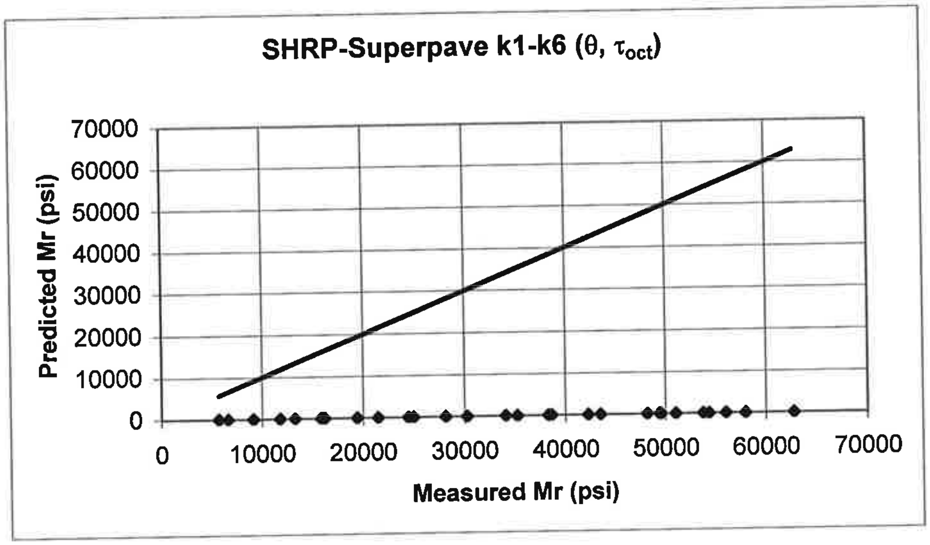


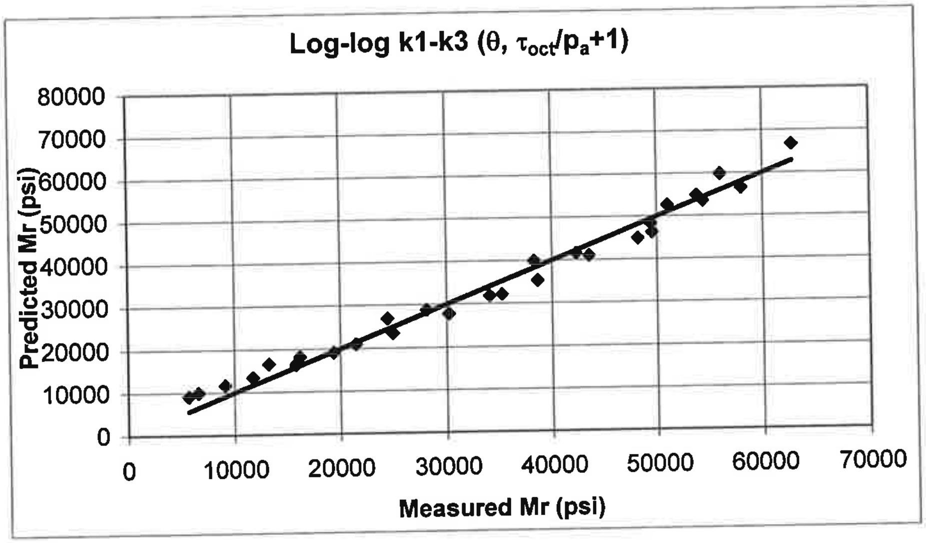




Measured Vs. Predicted M_R for Test S11_high







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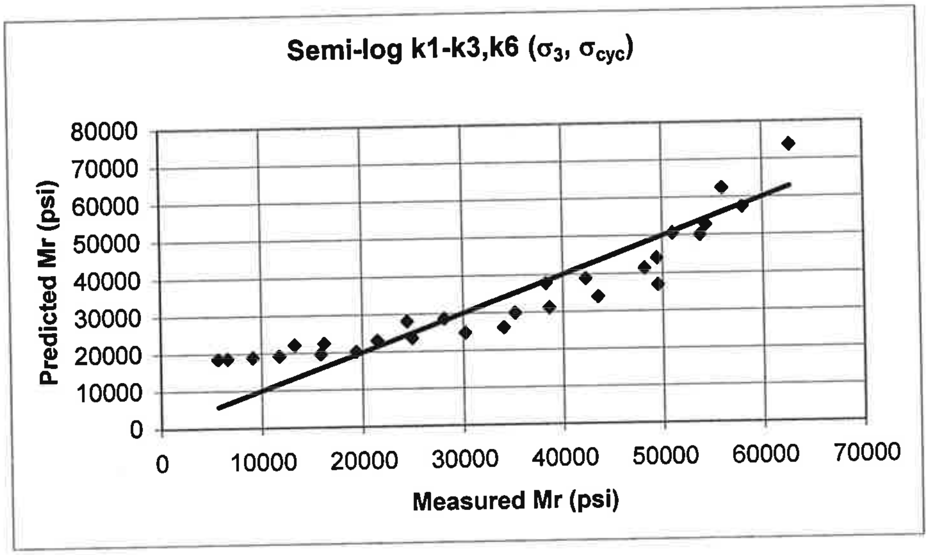

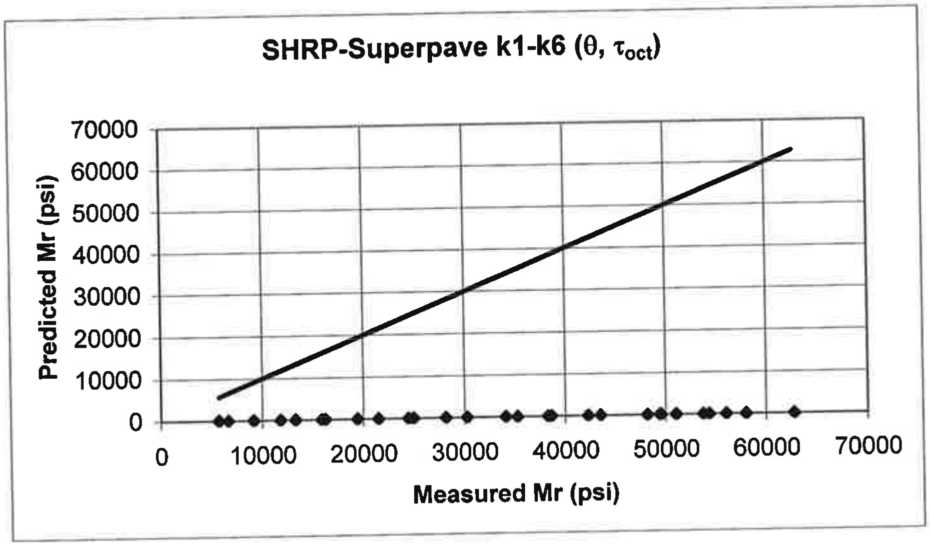

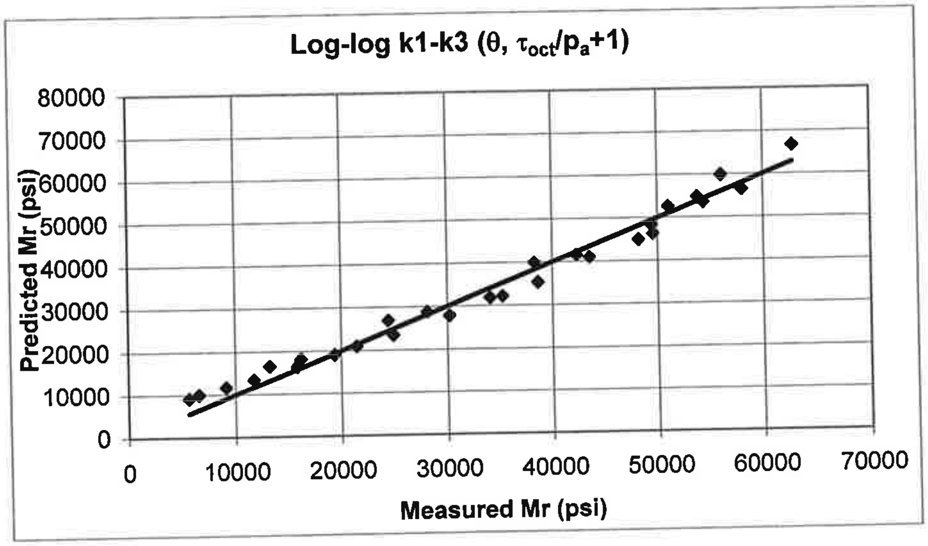

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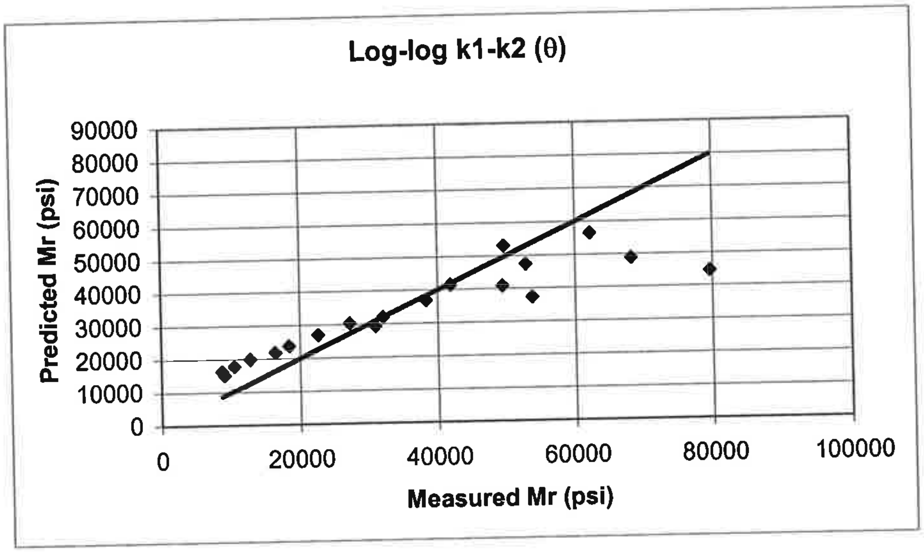
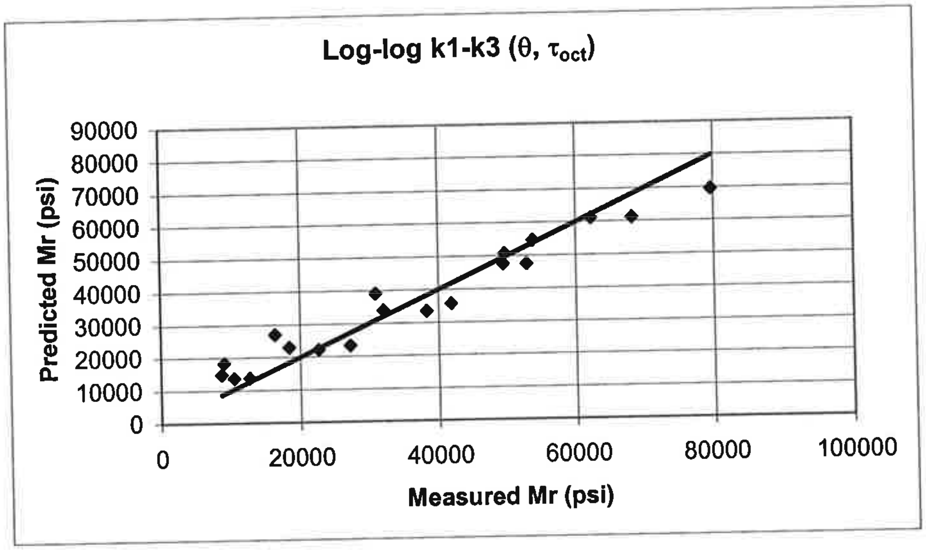
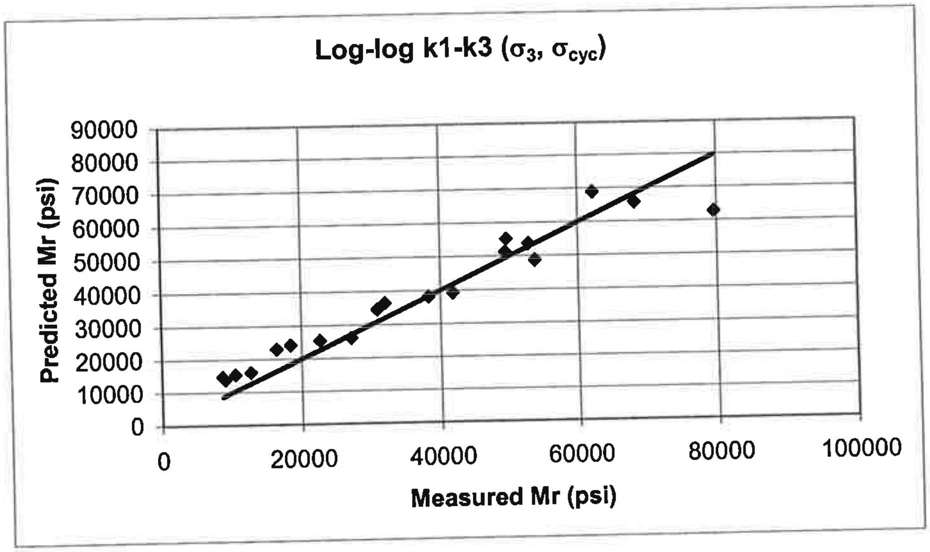
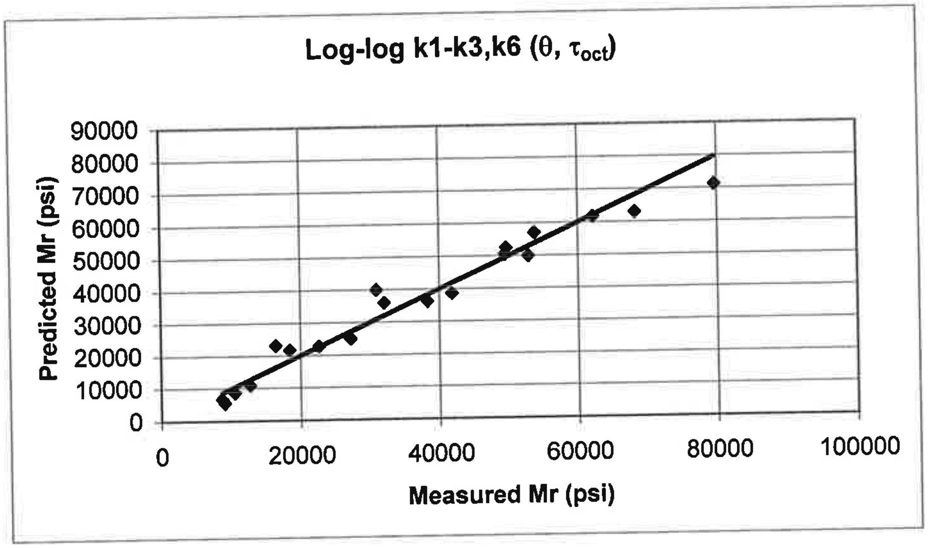
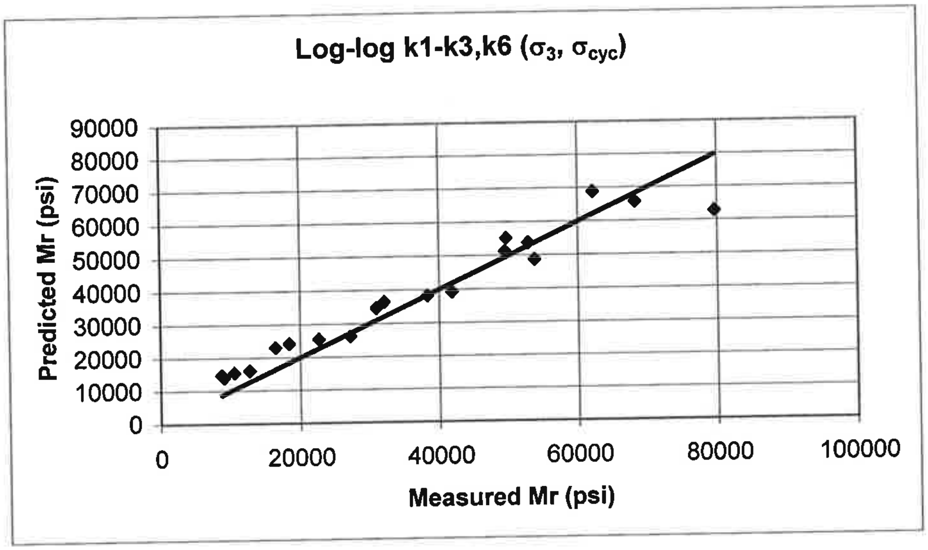


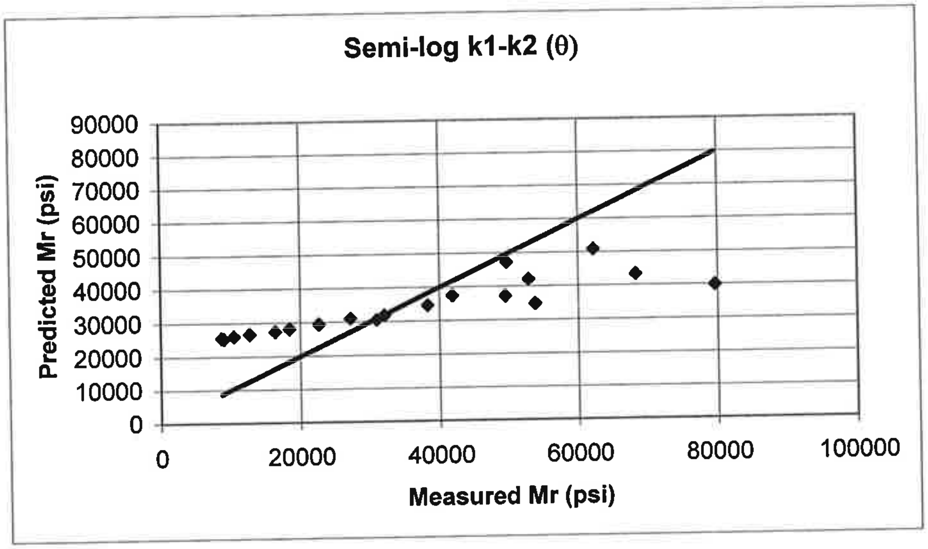




Measured Vs. Predicted M_R for Test S11_mid







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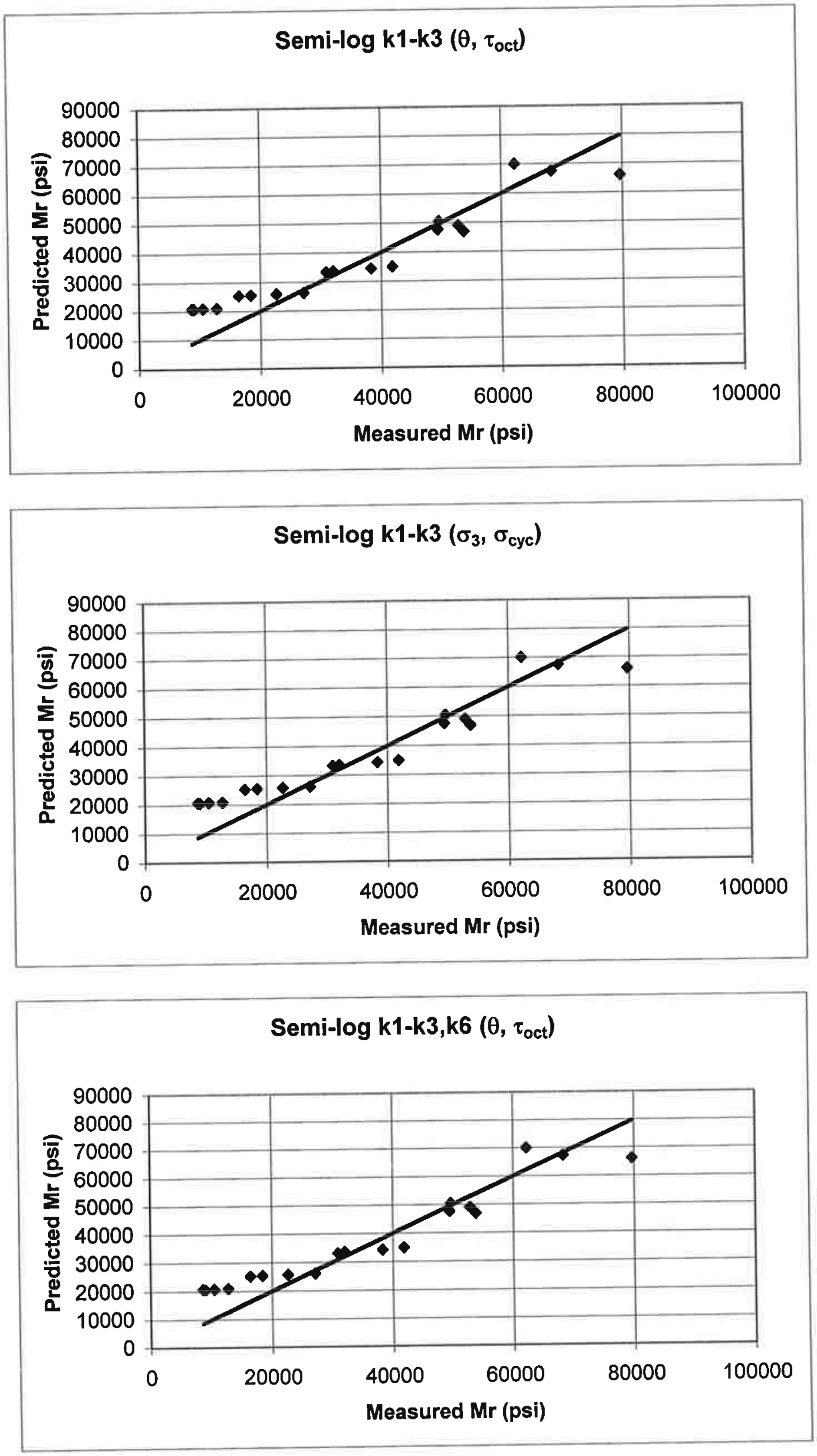

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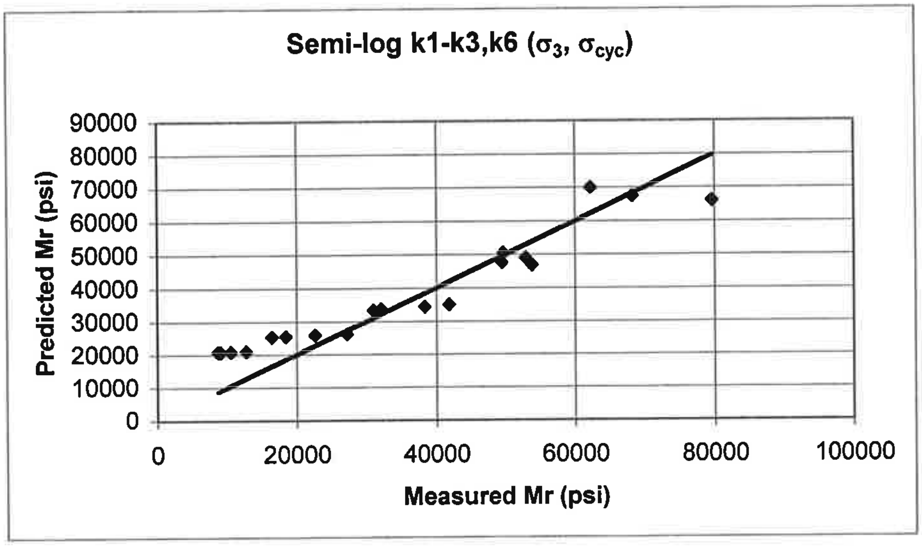

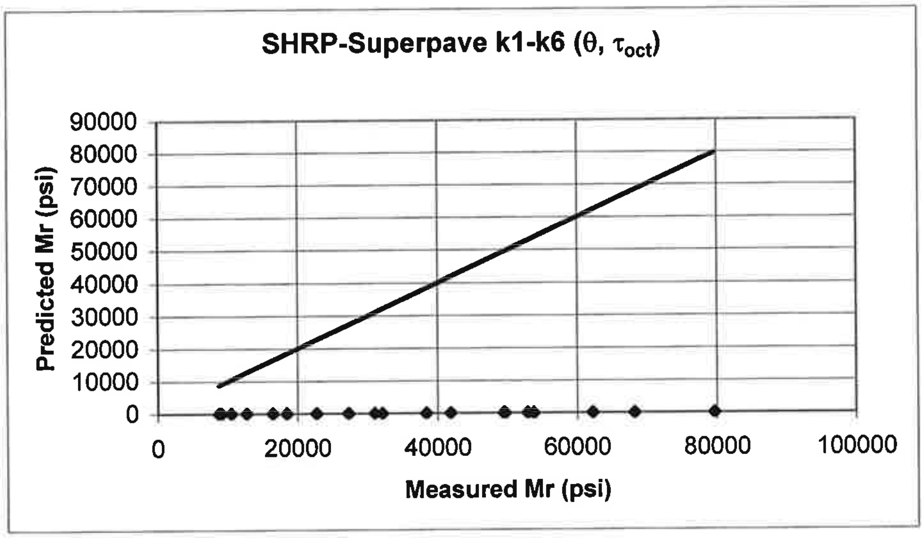

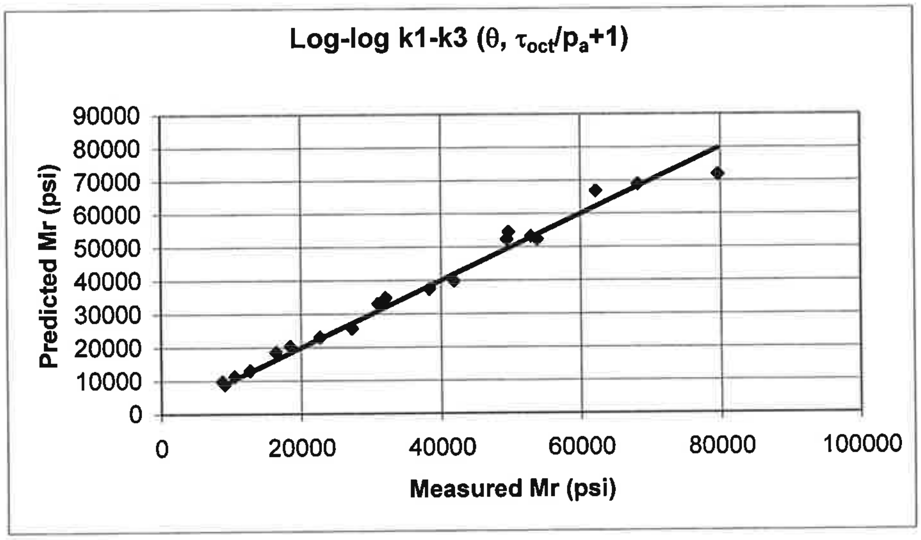

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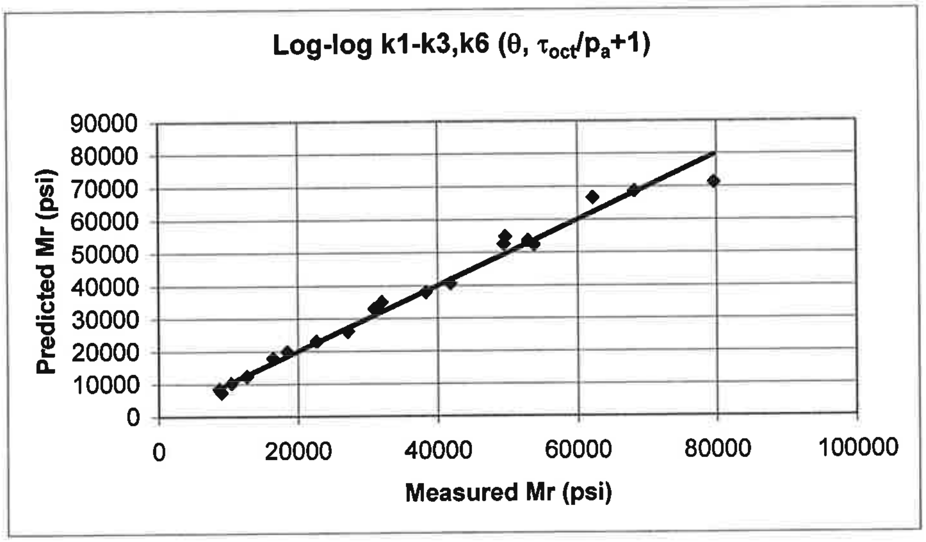

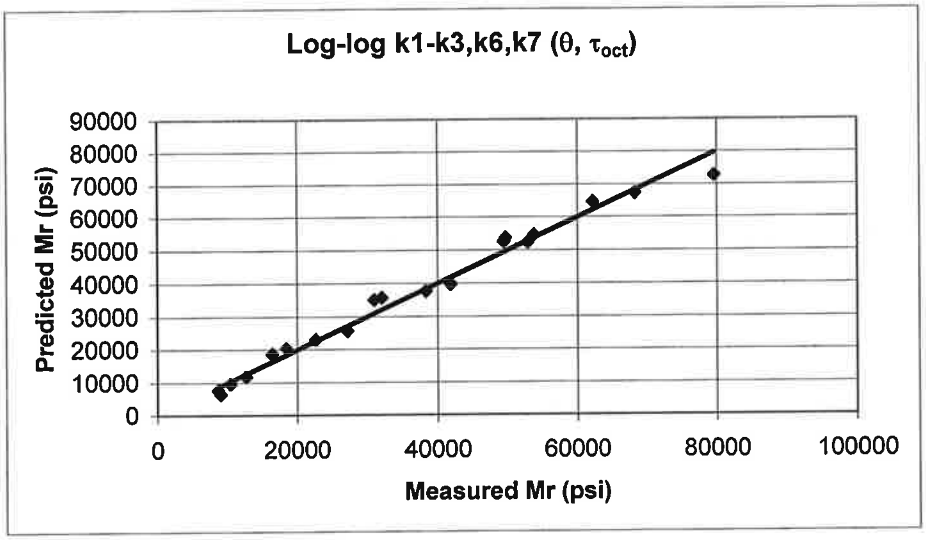

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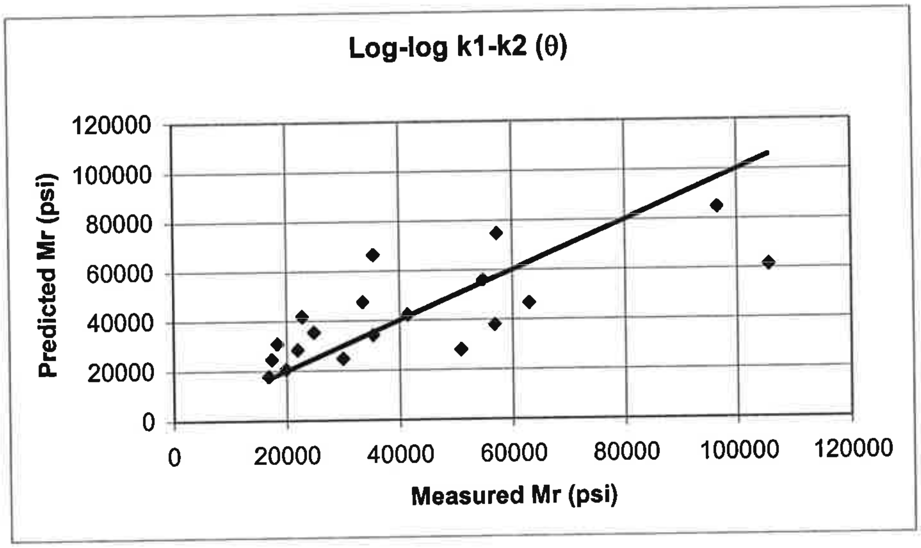
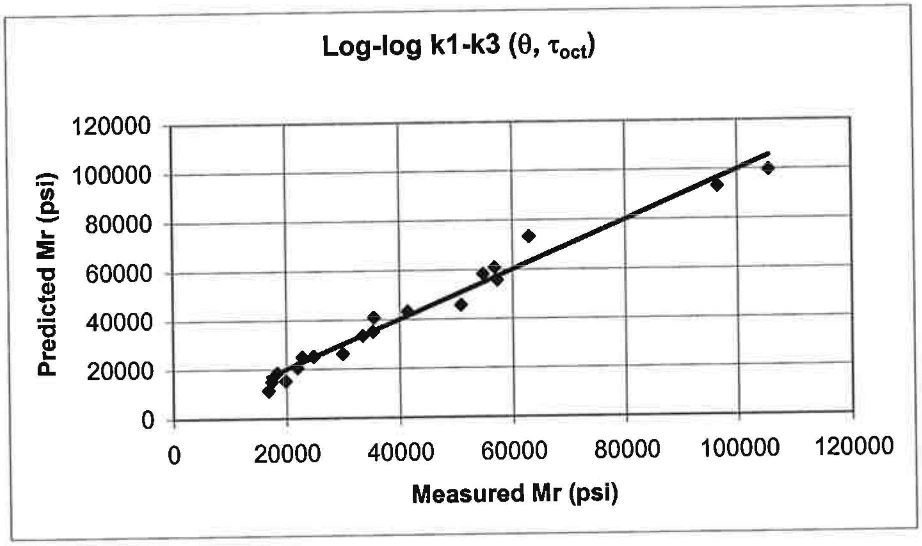
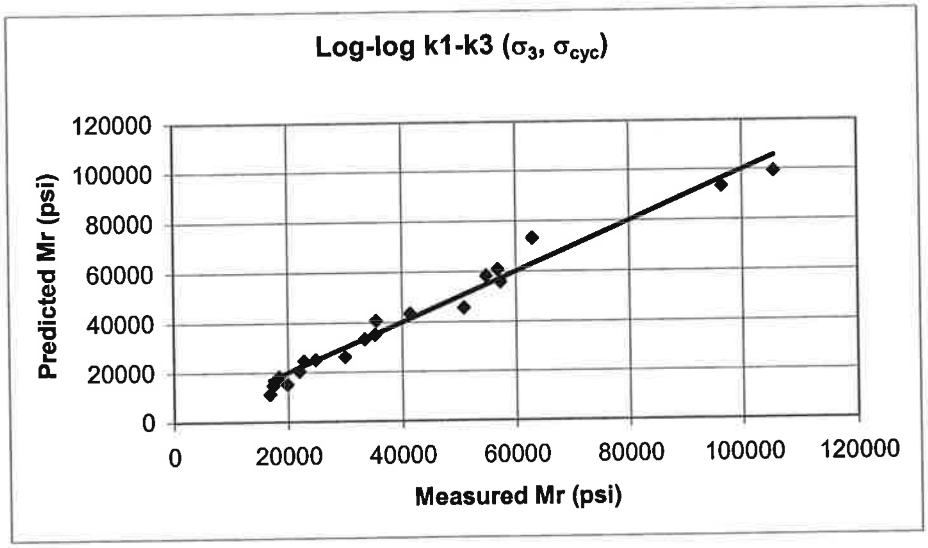
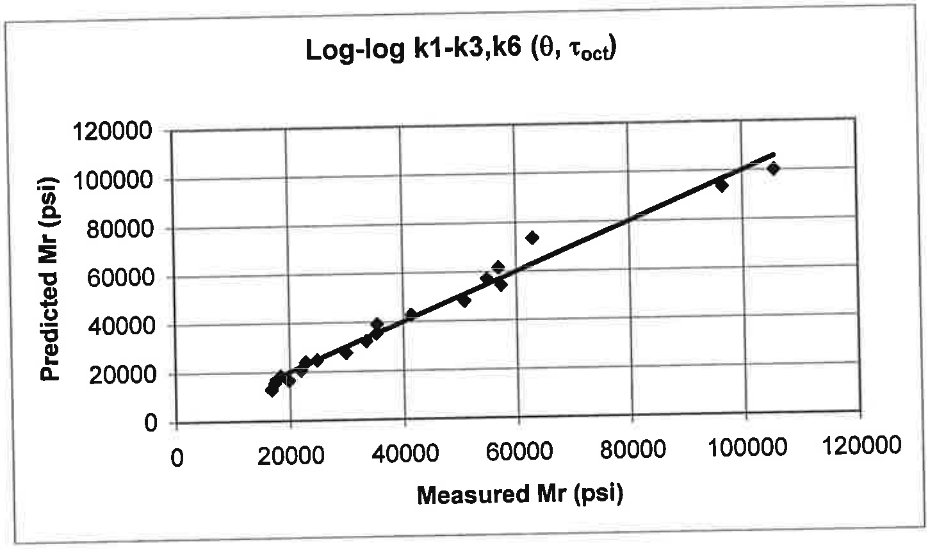
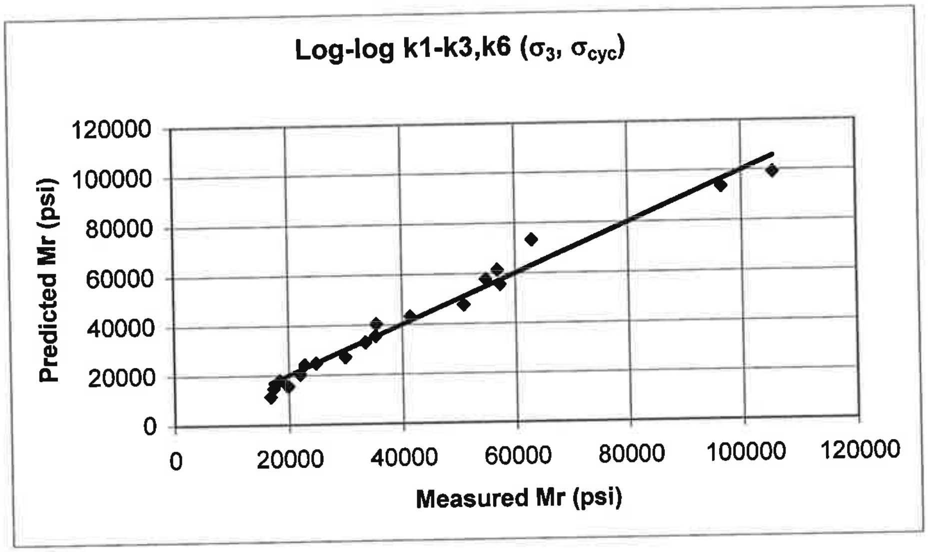


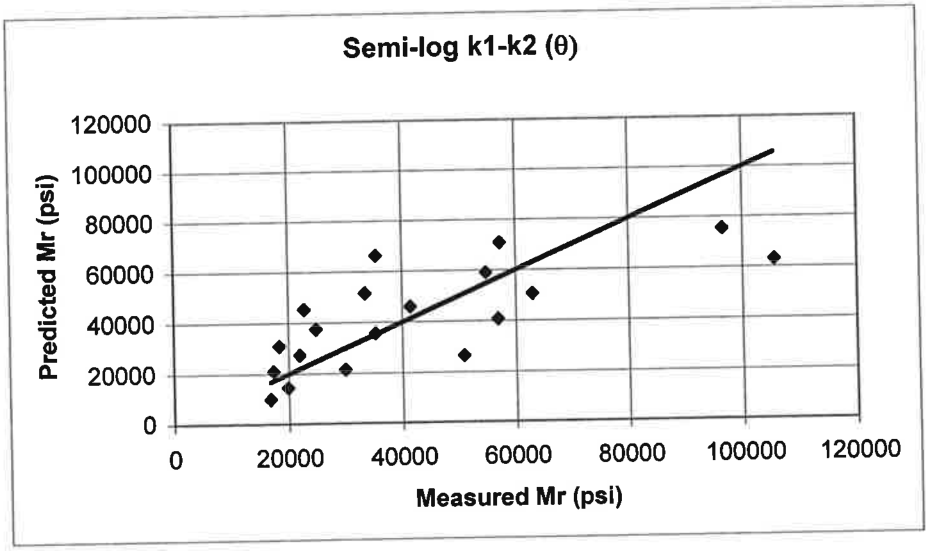




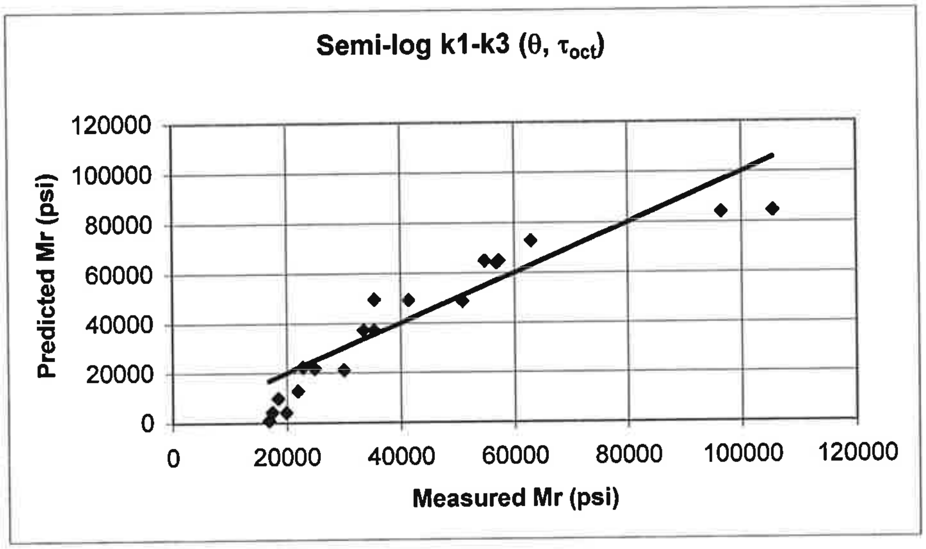
Measured Vs. Predicted M_R for Test S7_dry

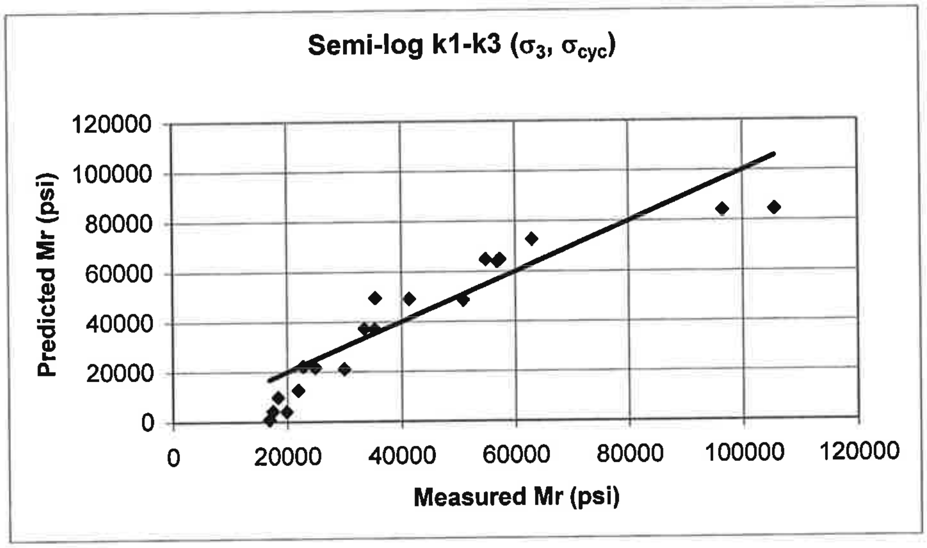


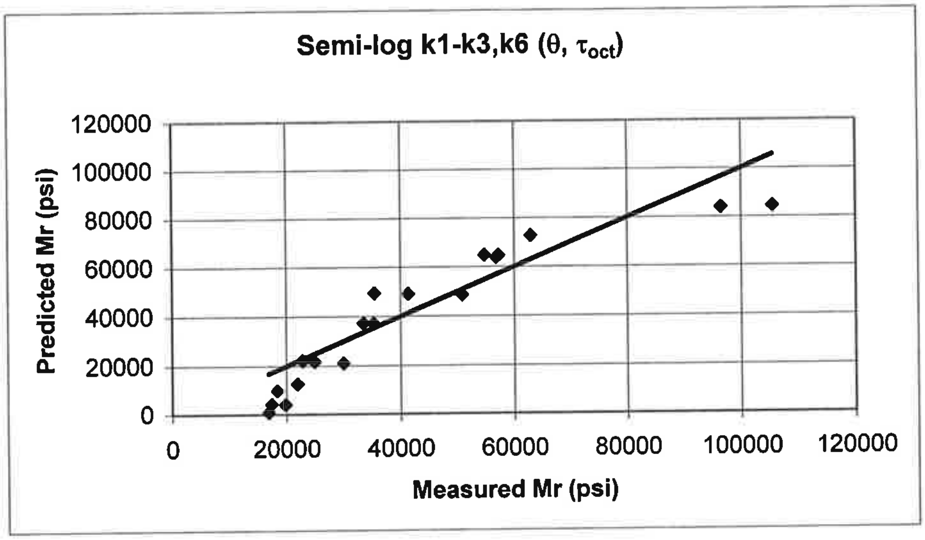




Measured Vs. Predicted M_R for Test S7_dry







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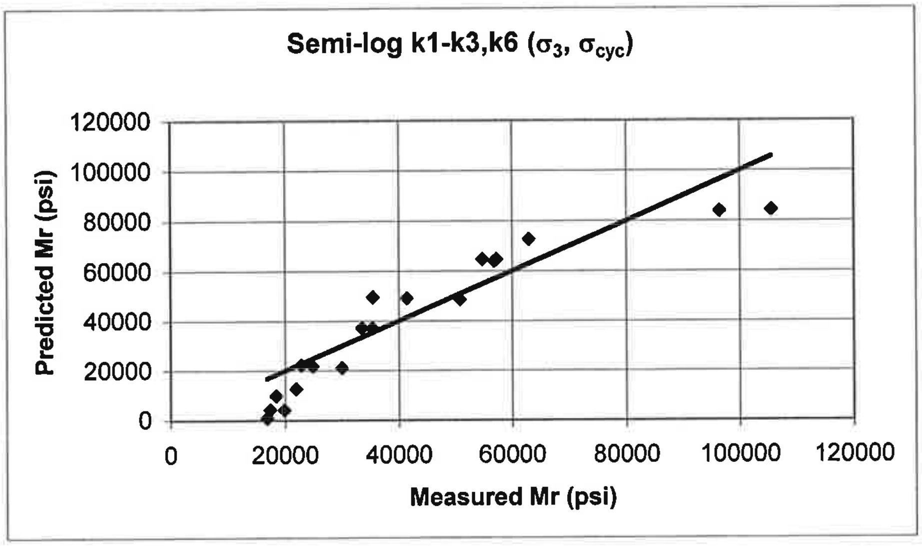
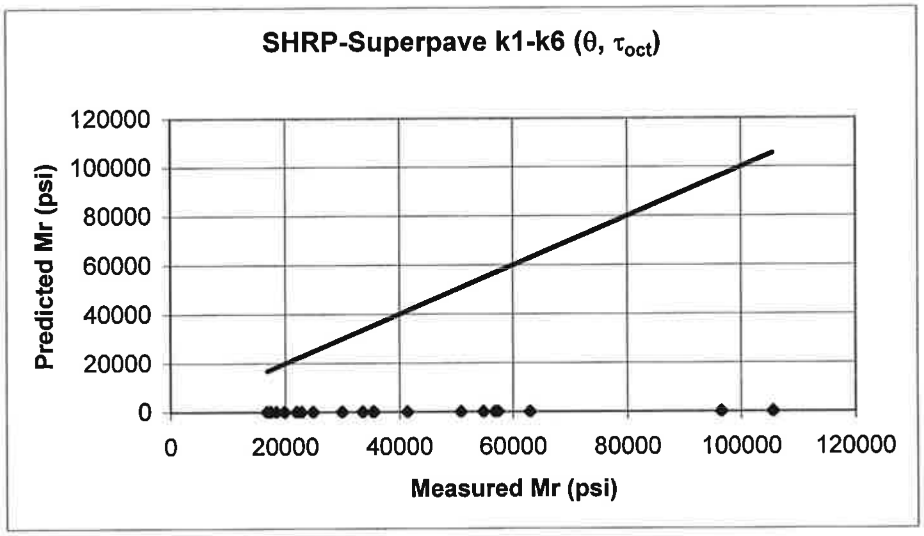
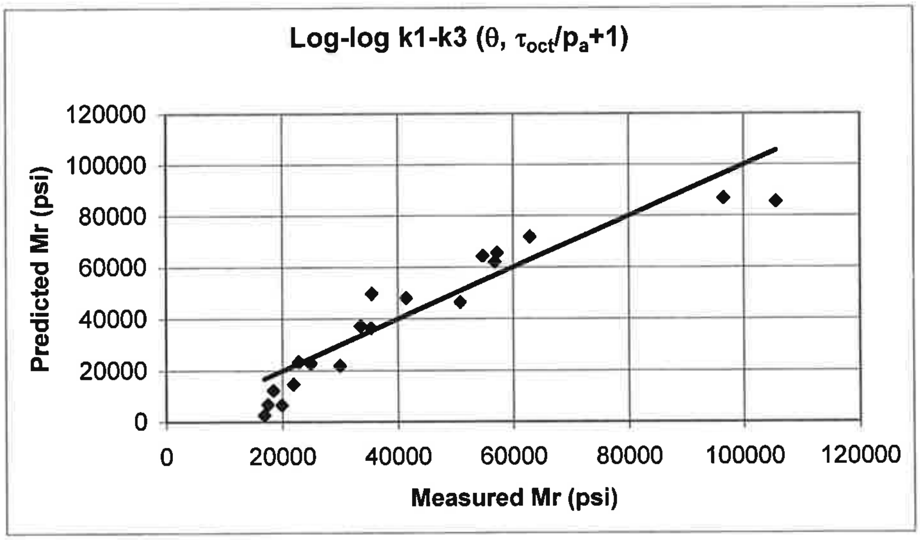
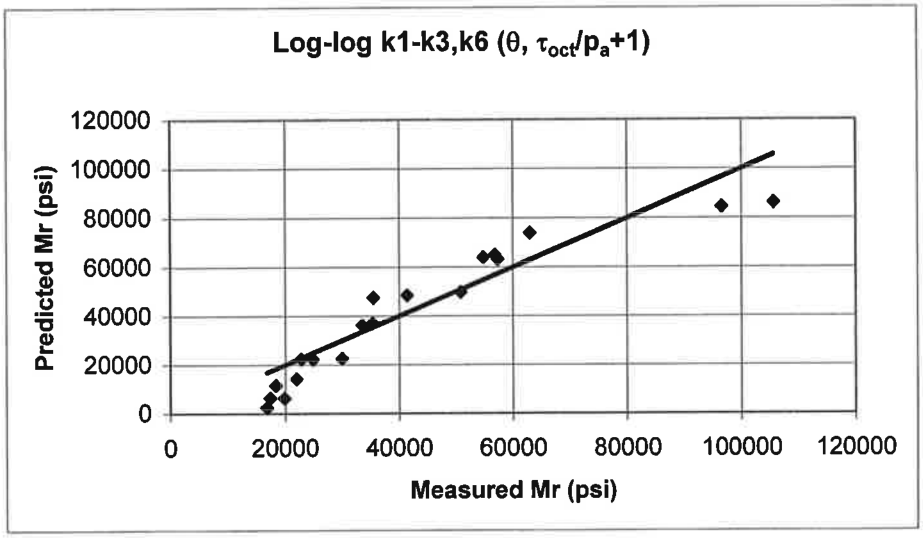
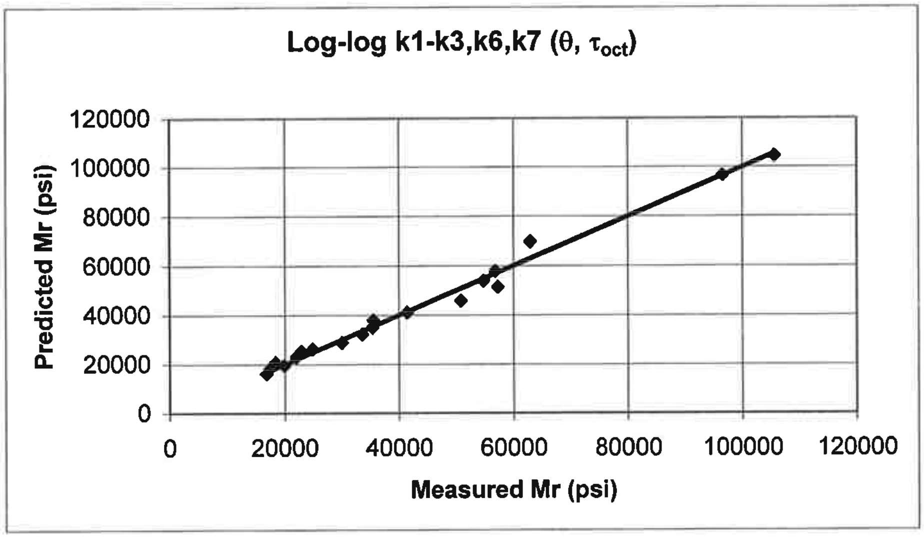




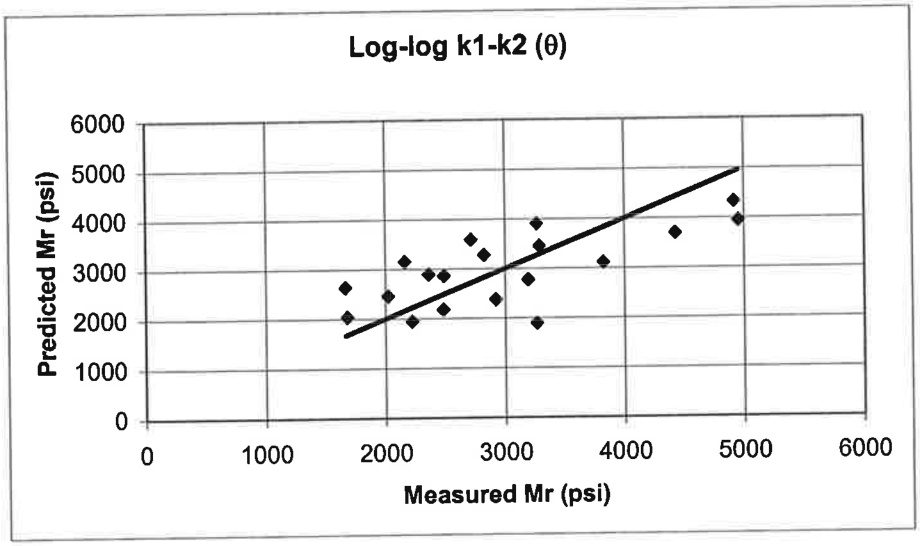


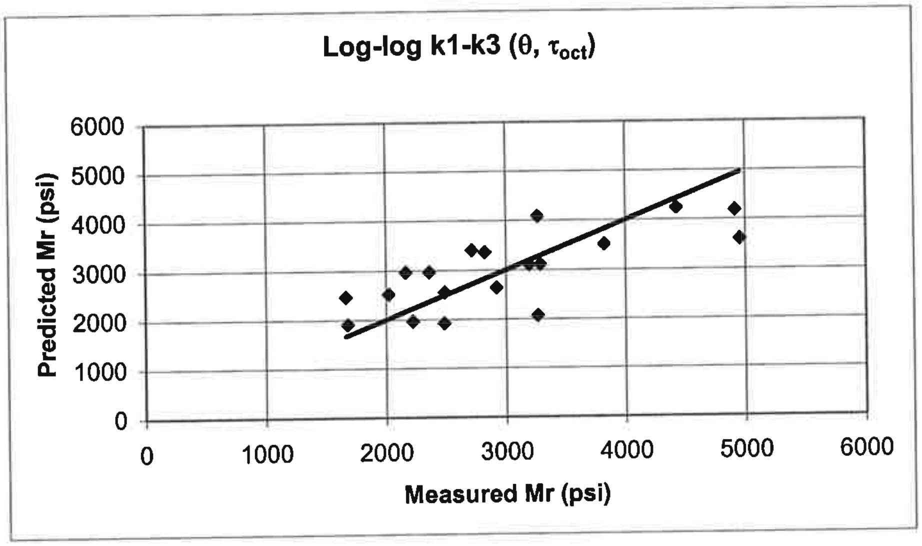
Measured Vs. Predicted M_R for Test S7_dry

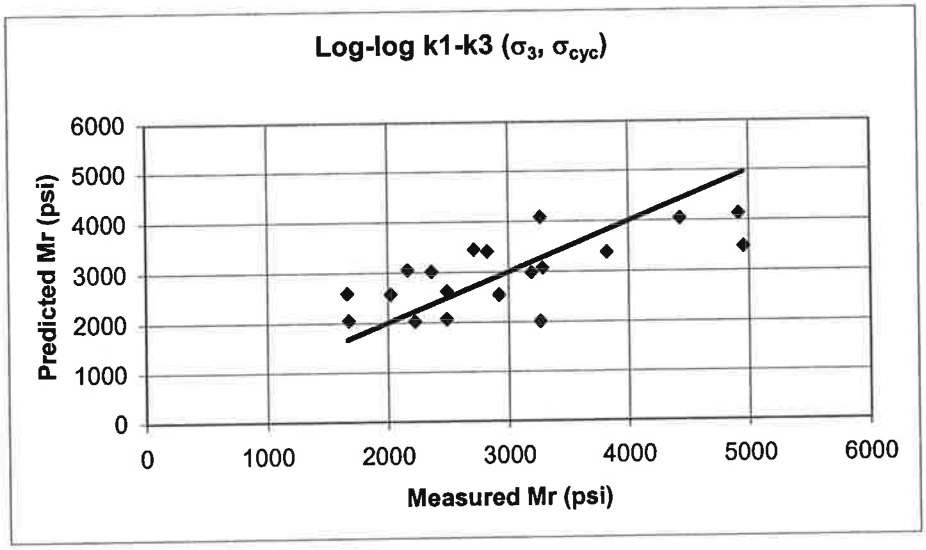




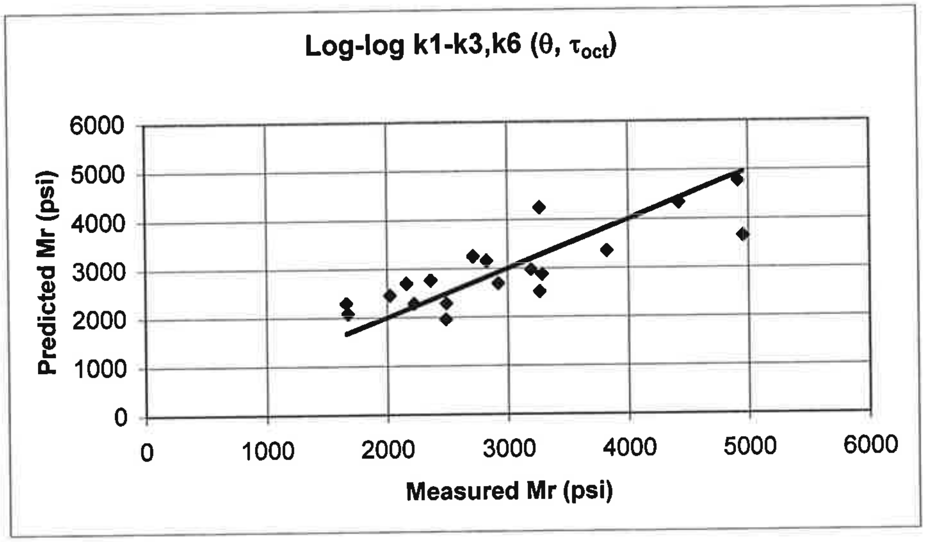
Measured Vs. Predicted M_R for Test S7_dry

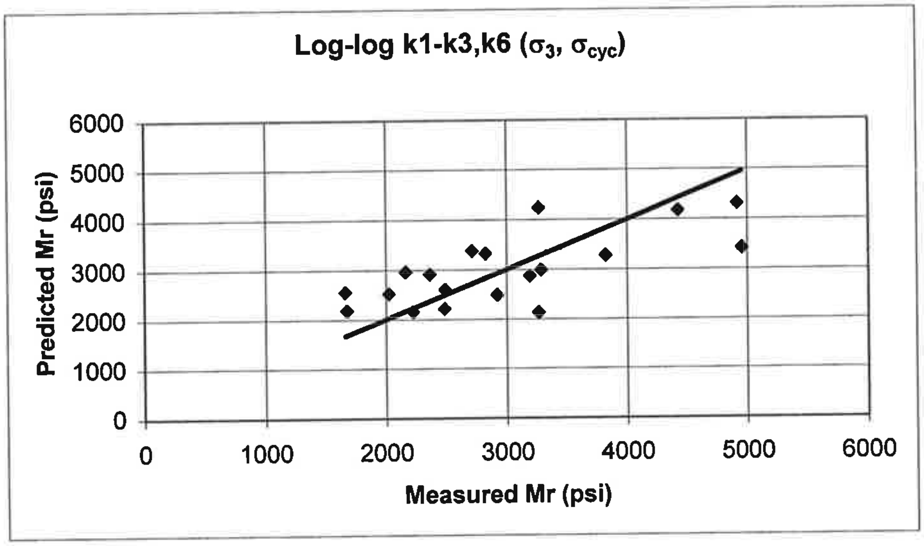

Log-log k1-k2 (θ)

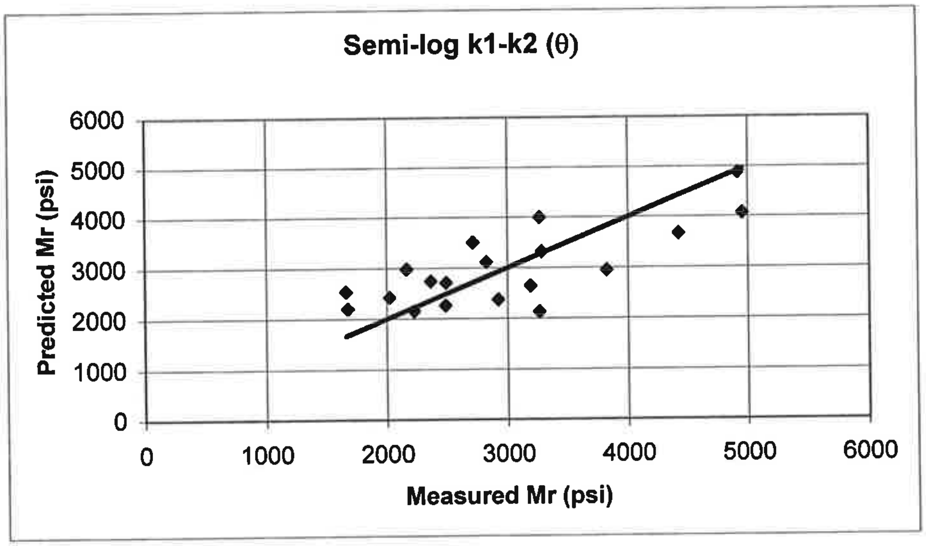

Log-log k1-k3 (θ, τ_{oct})


Log-log k1-k3 (σ_3, σ_{cyc})

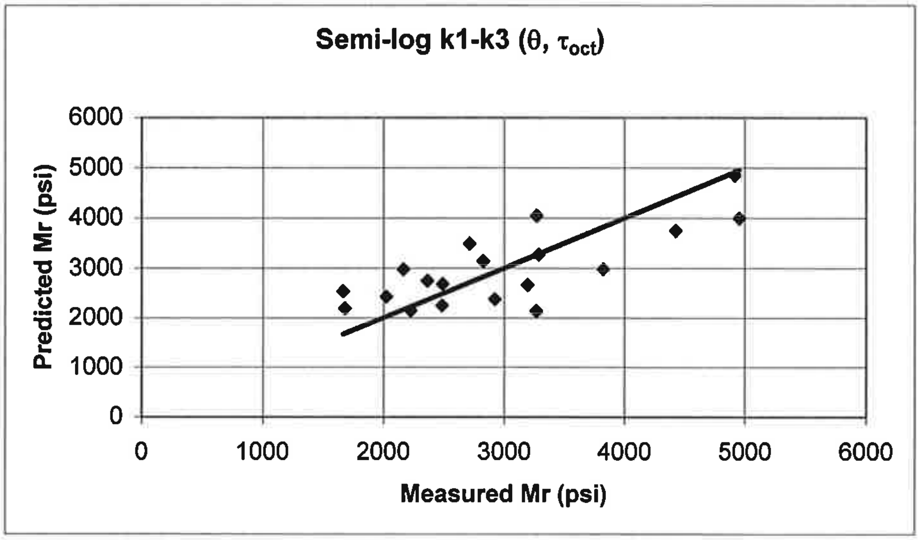
Measured Vs. Predicted M_R for Test S7_low

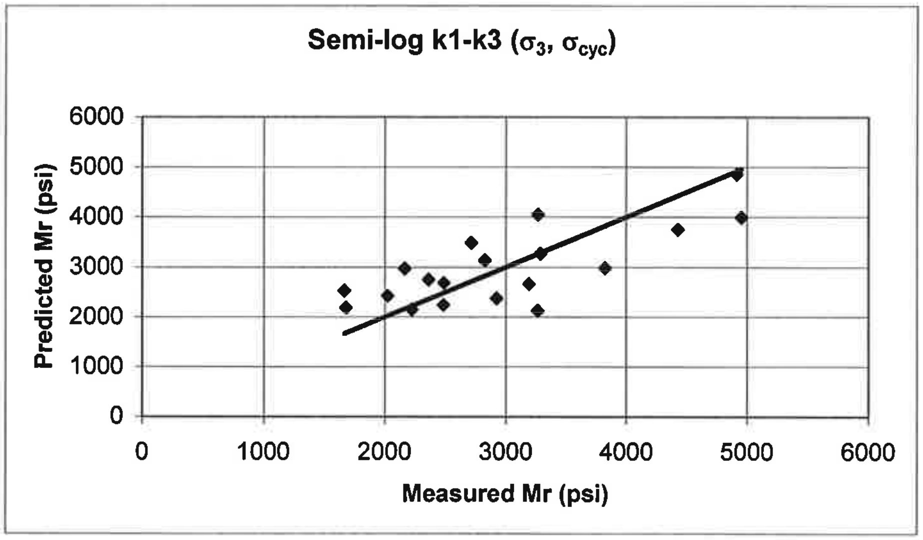


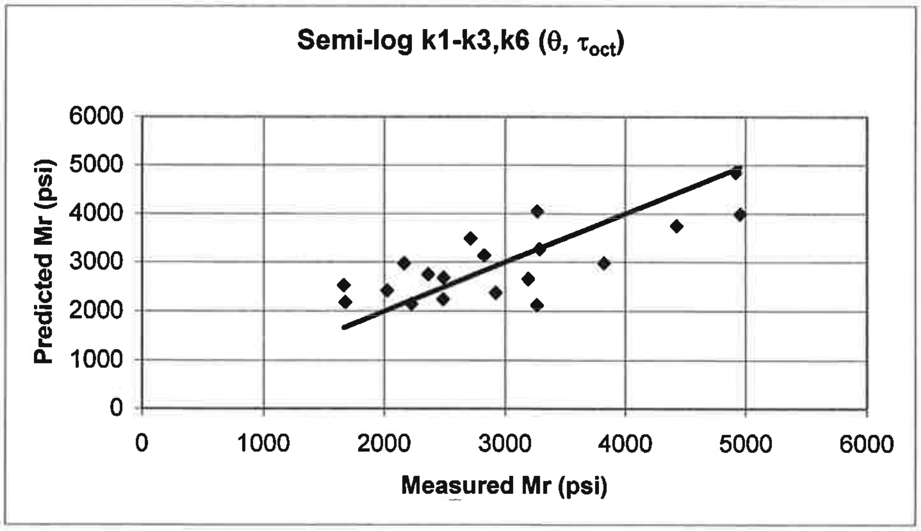




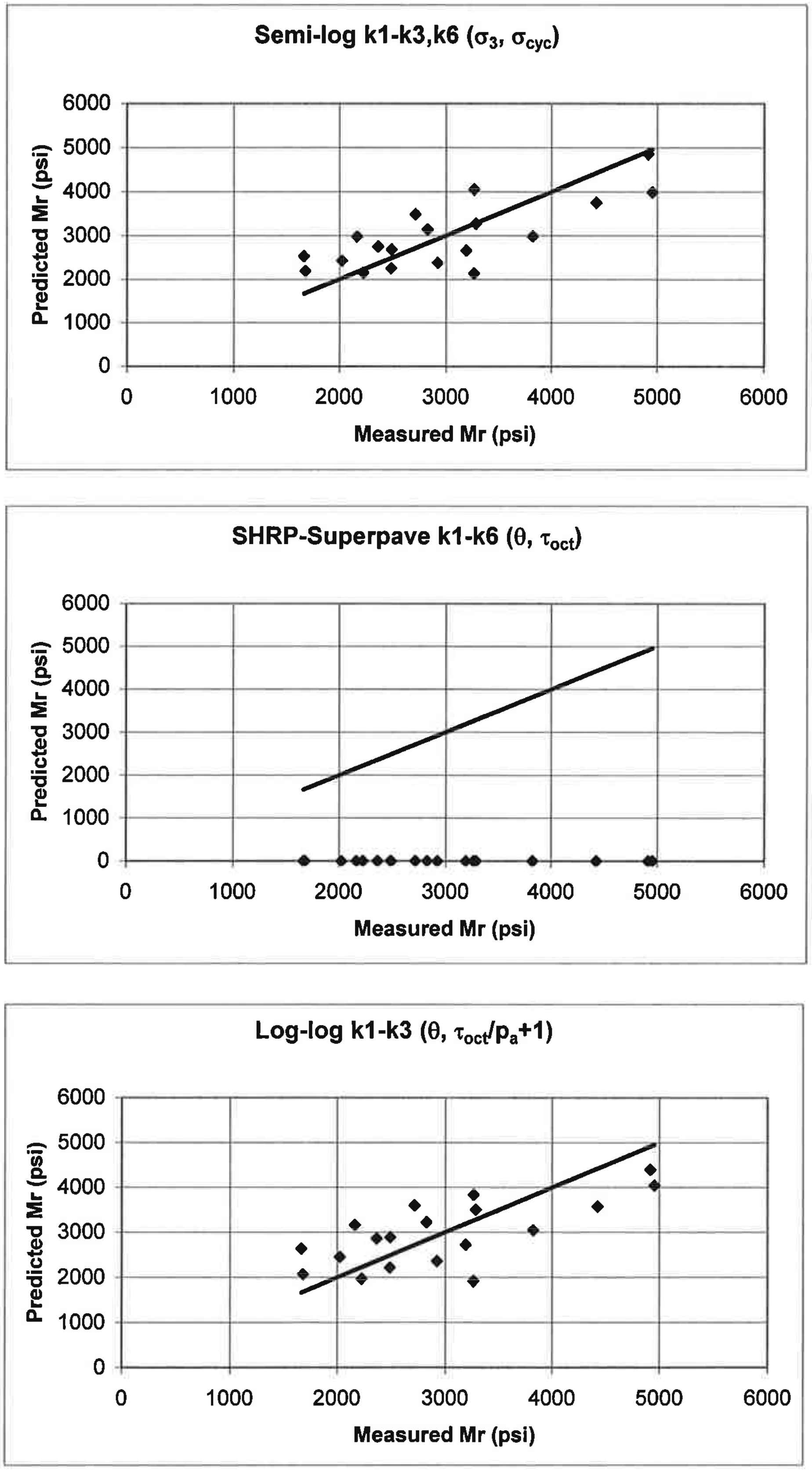
Measured Vs. Predicted M_R for Test S7_low



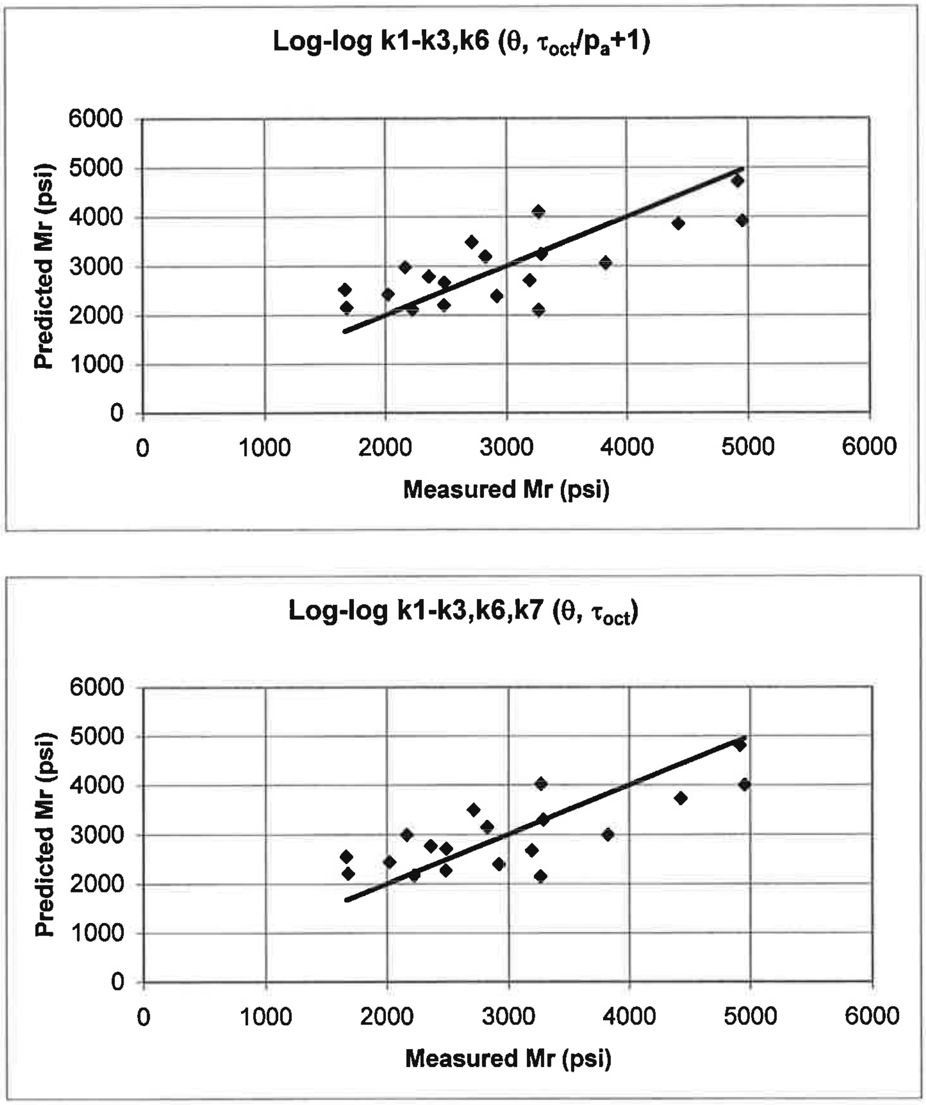




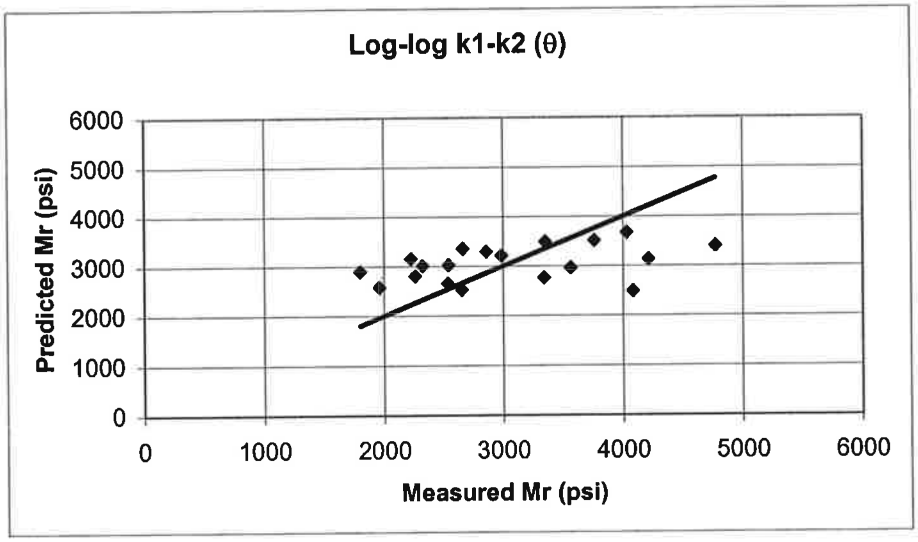
Measured Vs. Predicted M_R for Test S7_low

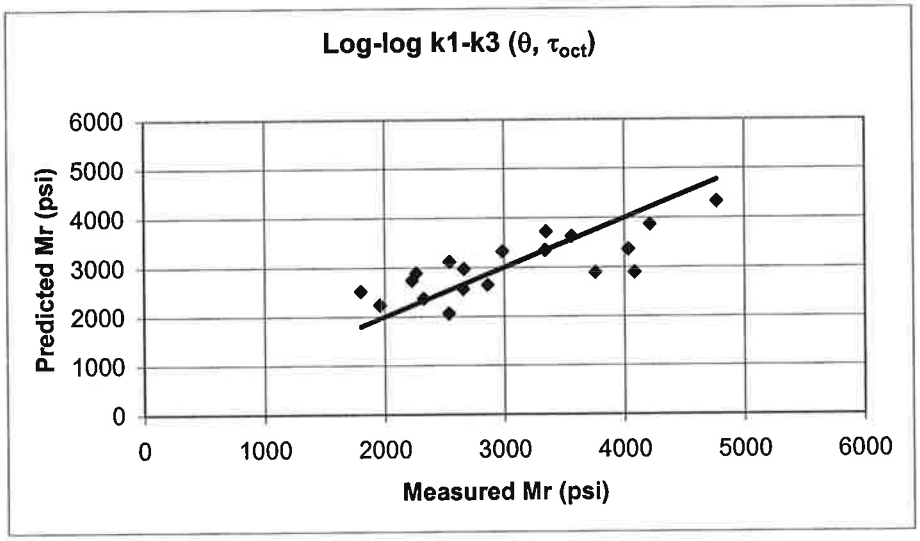


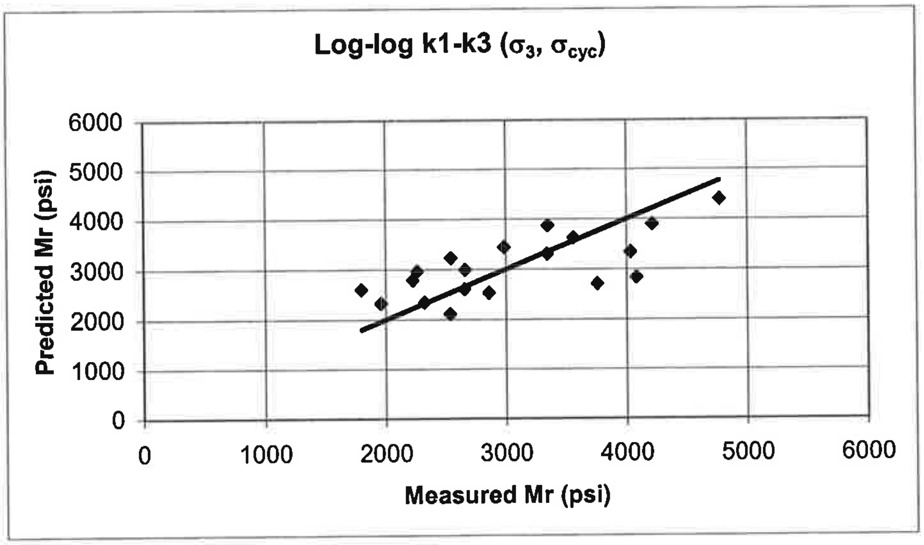
Measured Vs. Predicted M_R for Test S7_low



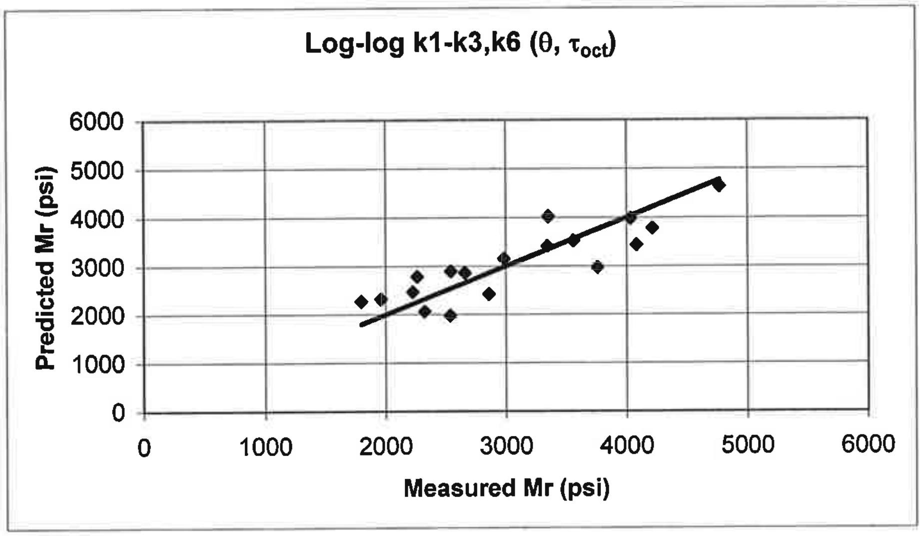
Measured Vs. Predicted M_R for Test S7_low

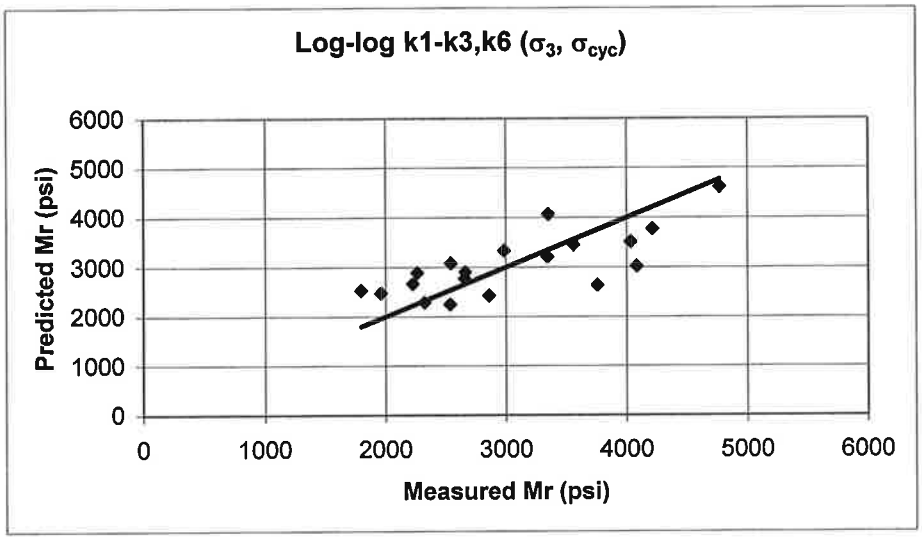


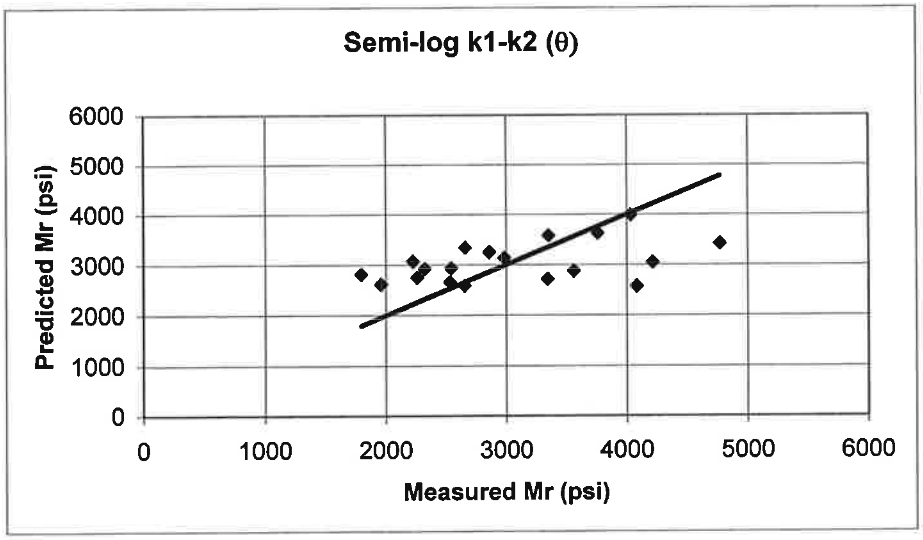




Measured Vs. Predicted M_R for Test S7_wet







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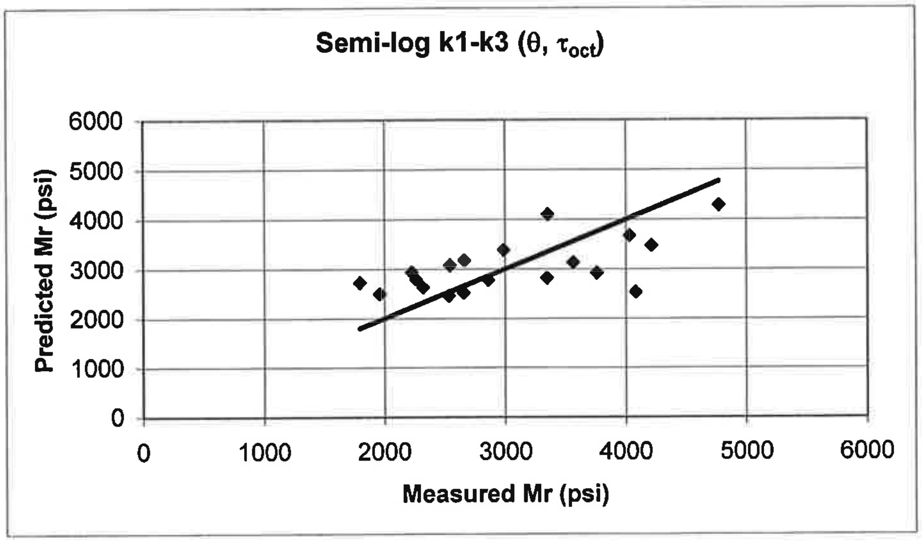

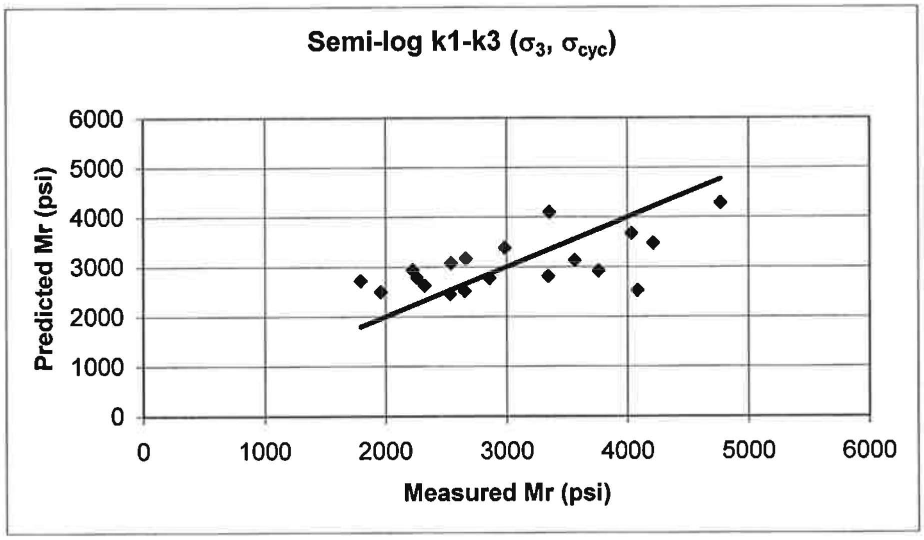

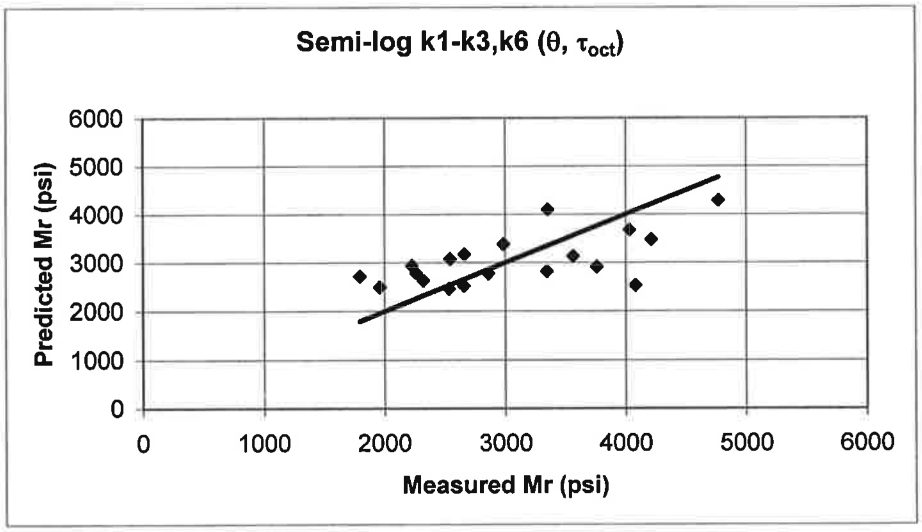

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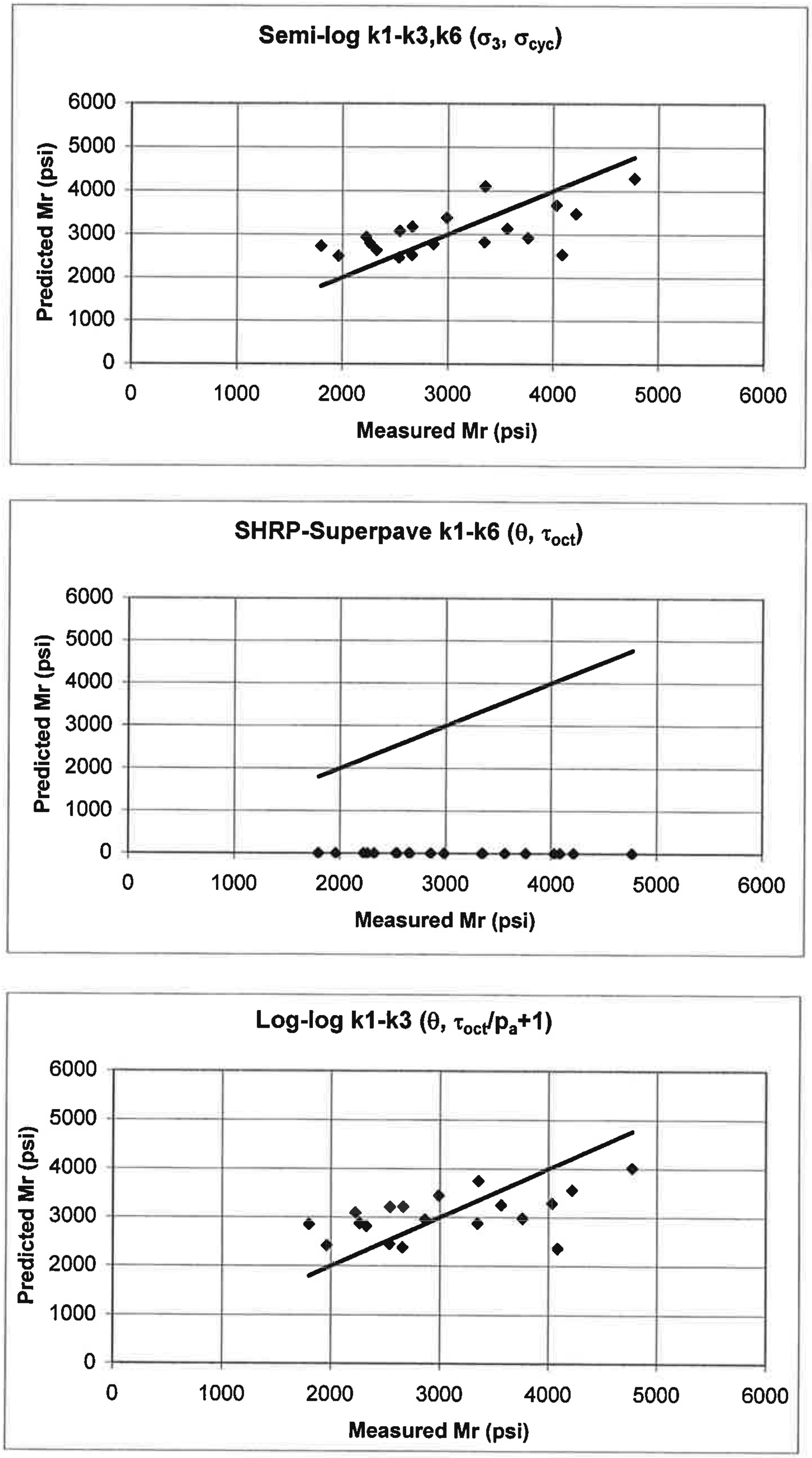

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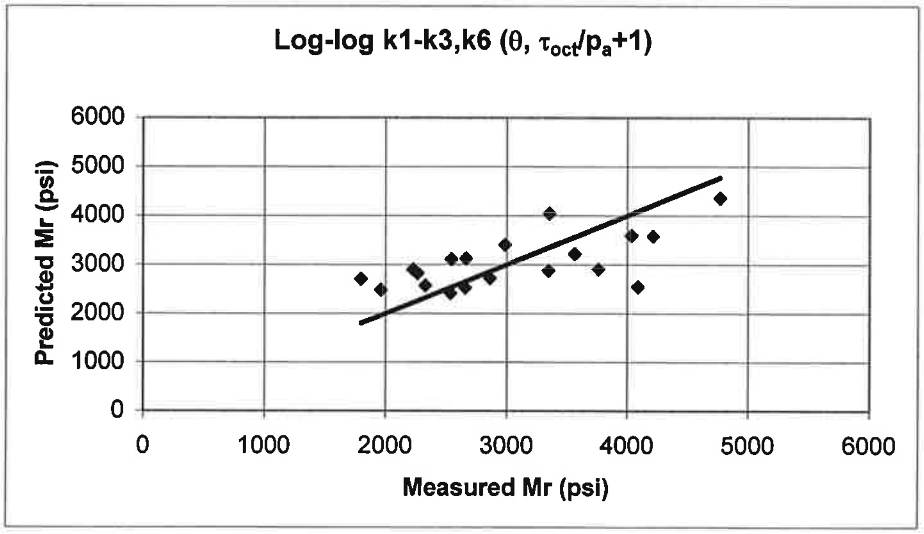

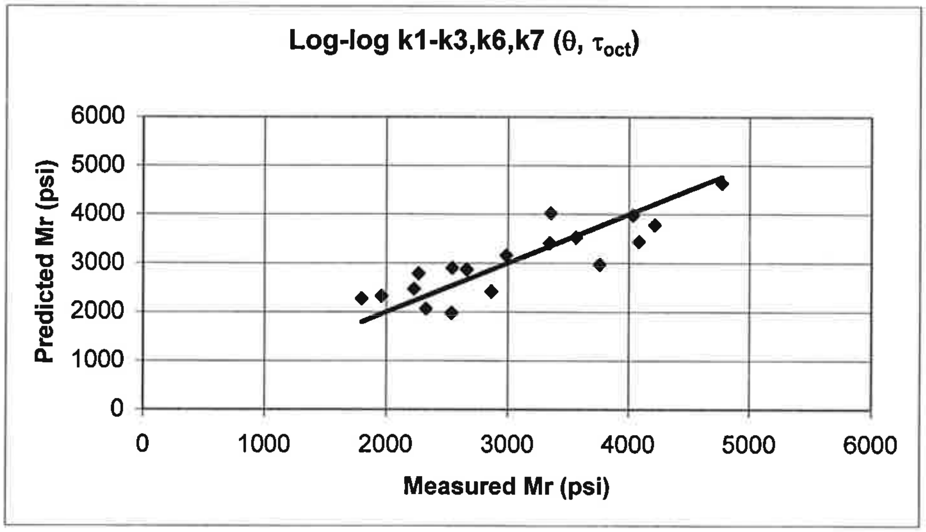

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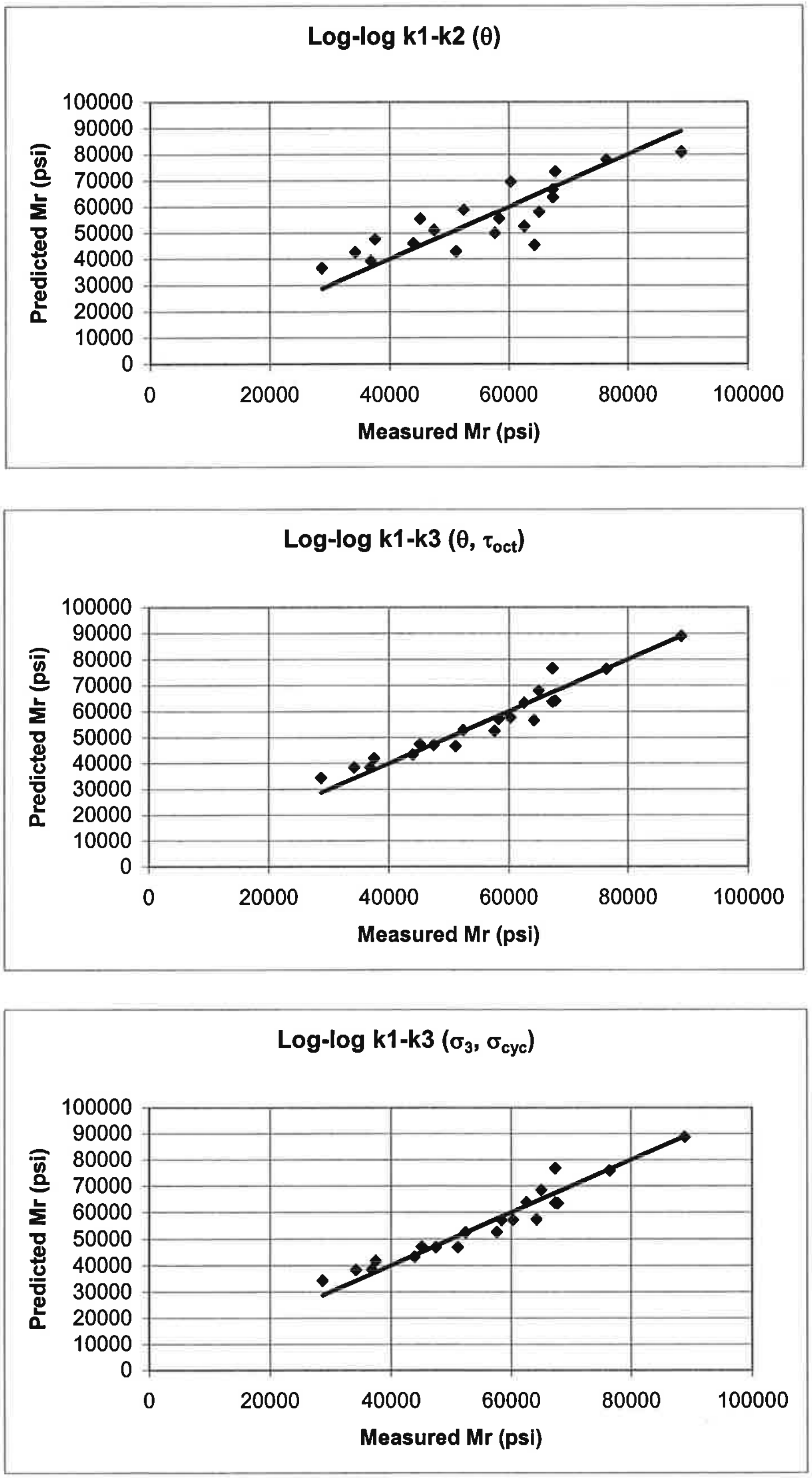

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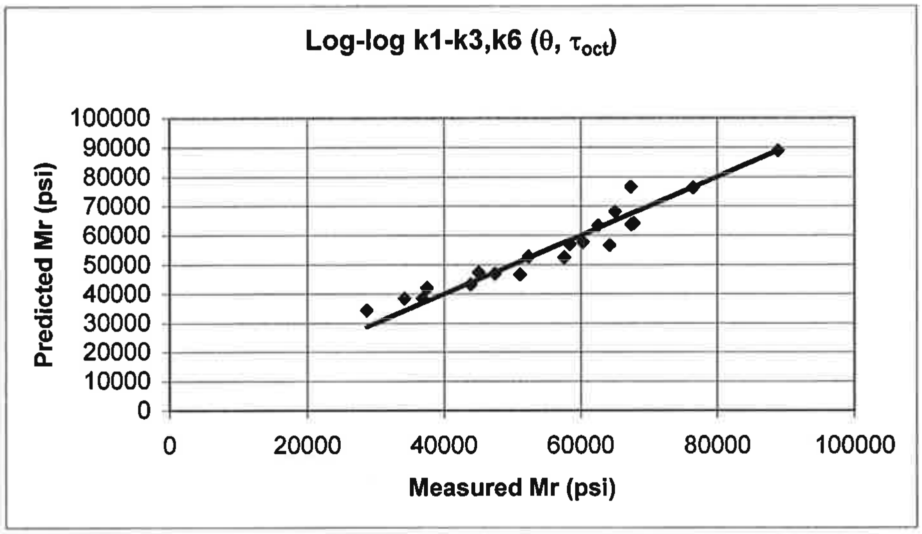

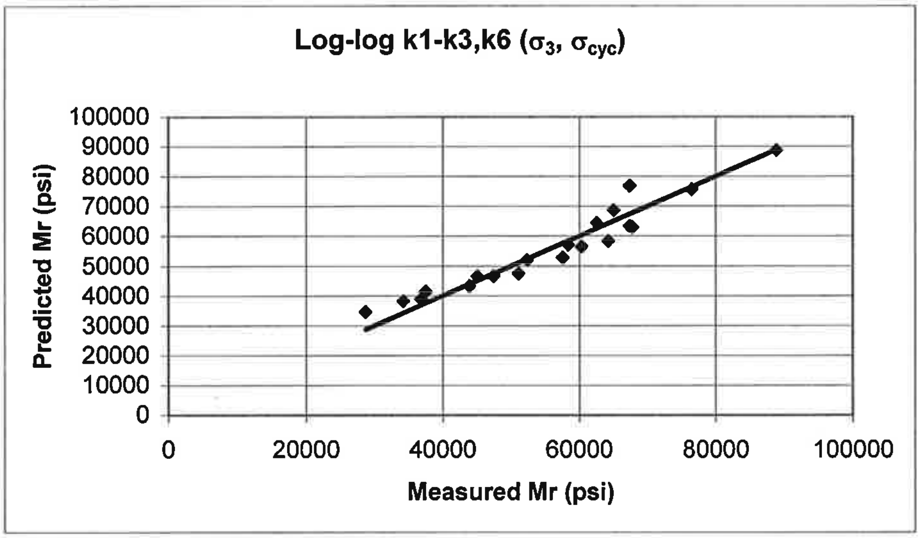

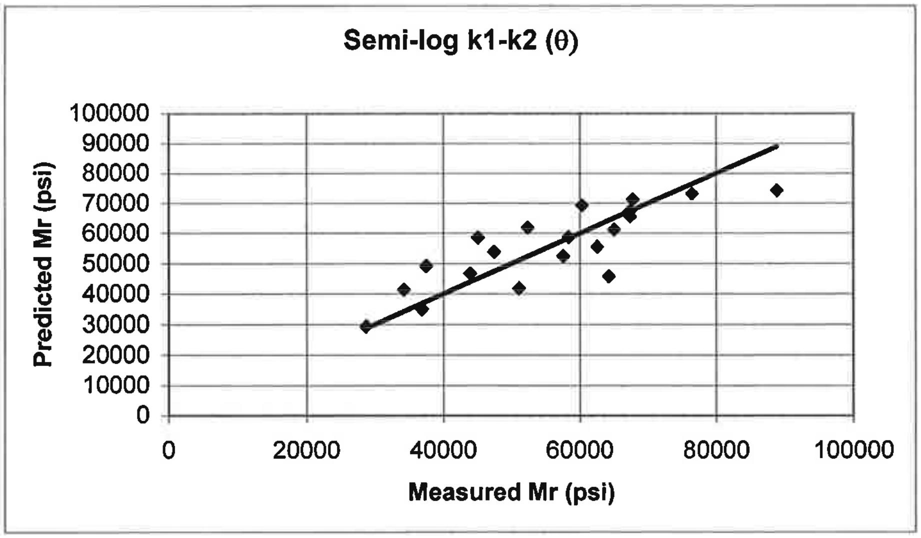

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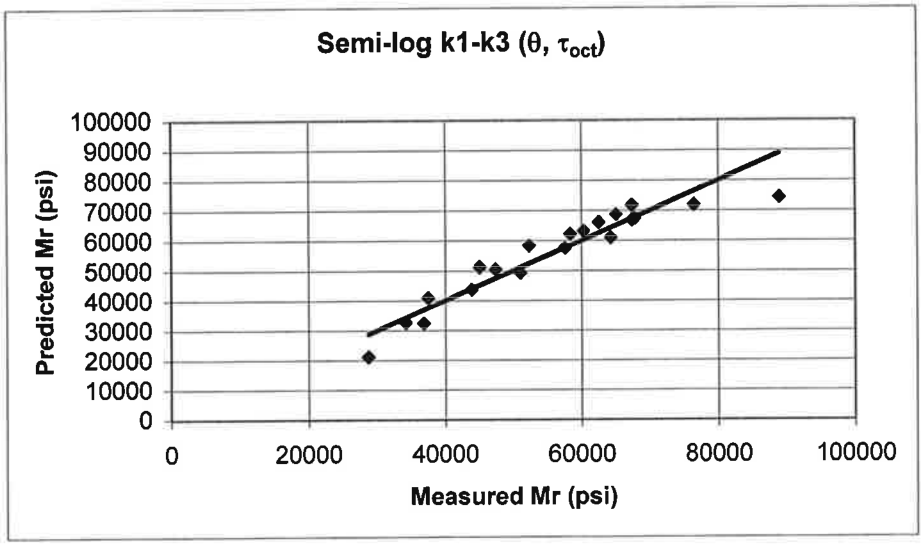

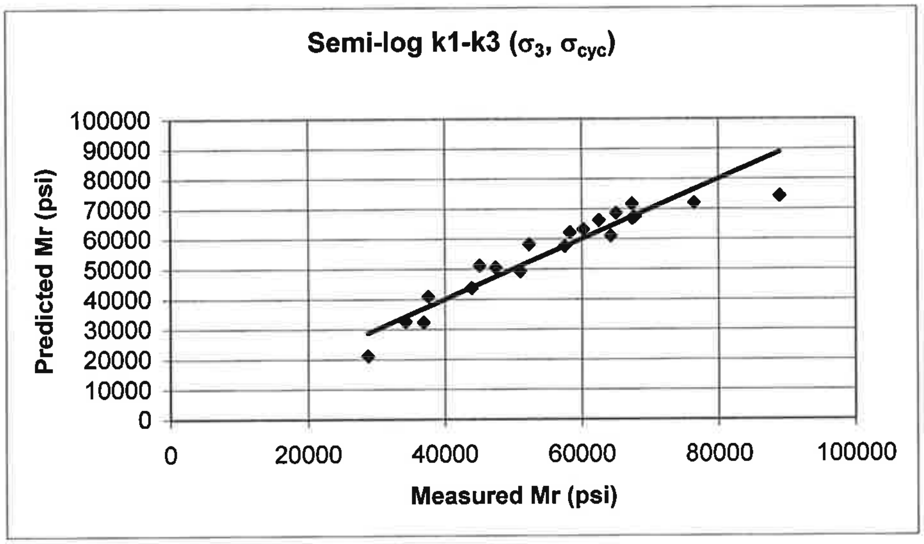

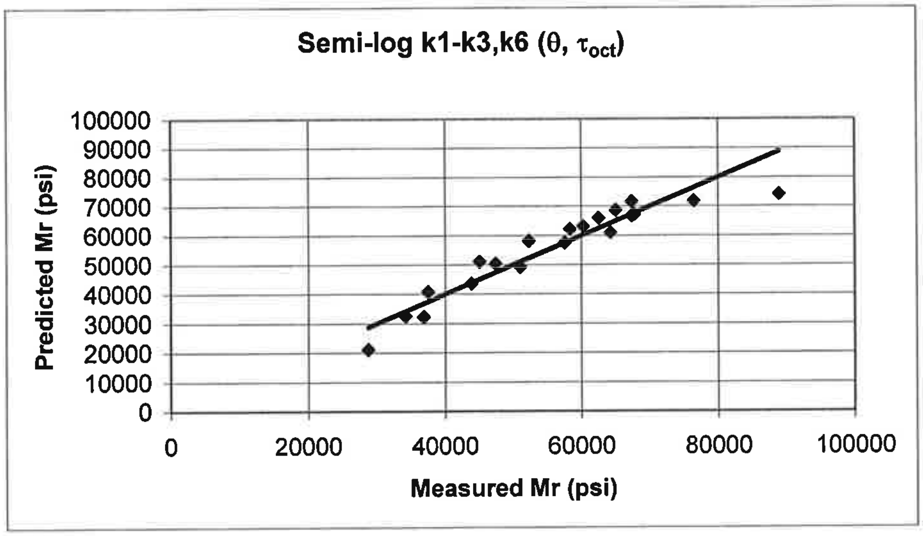

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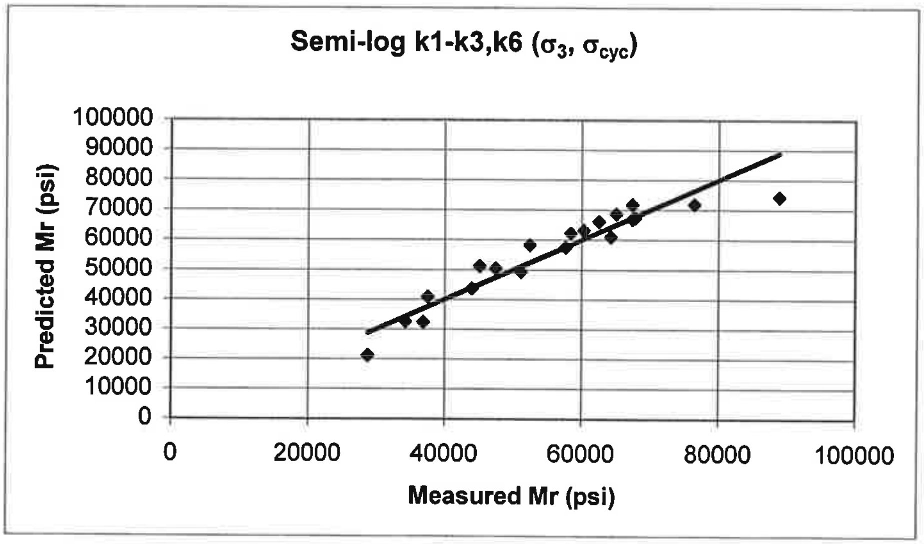

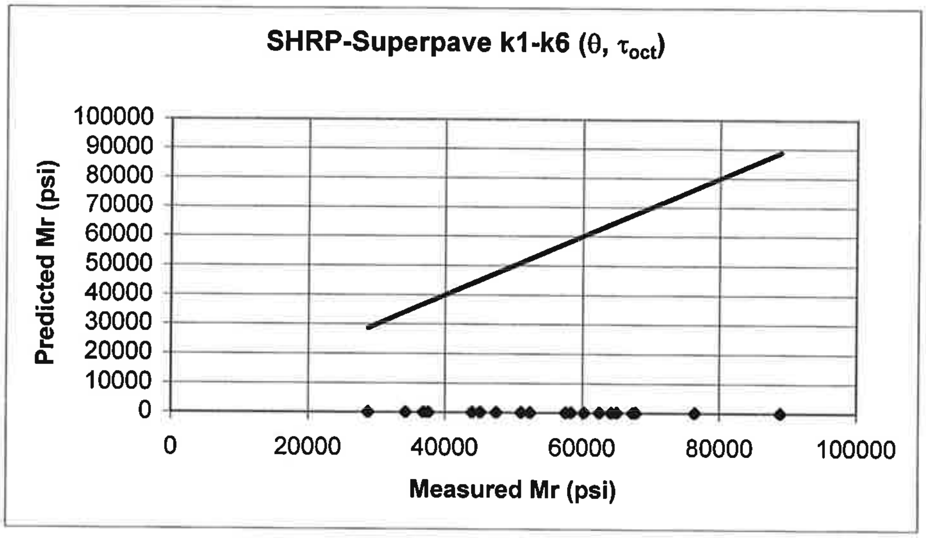

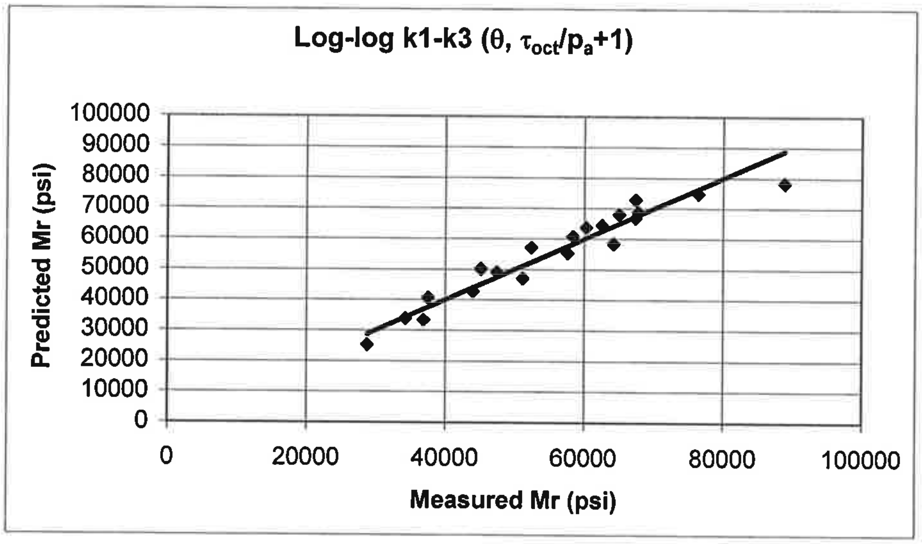

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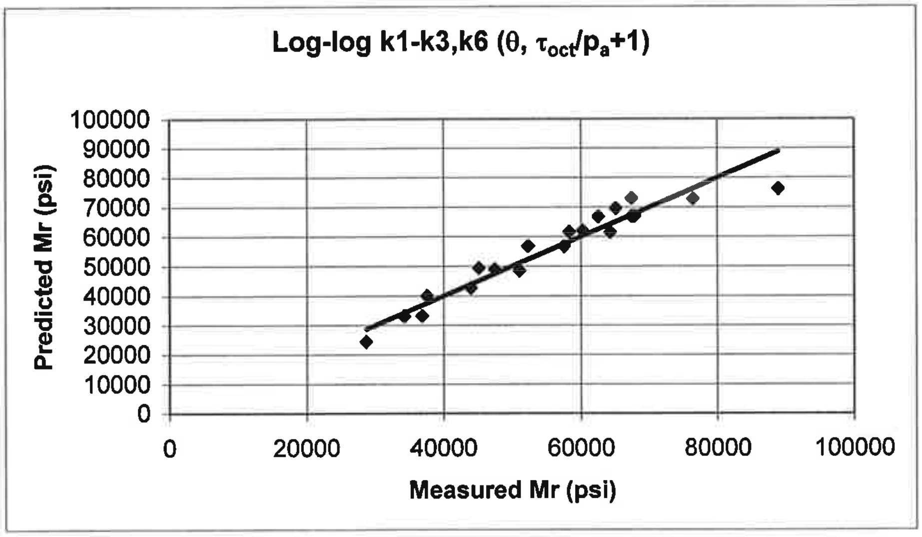

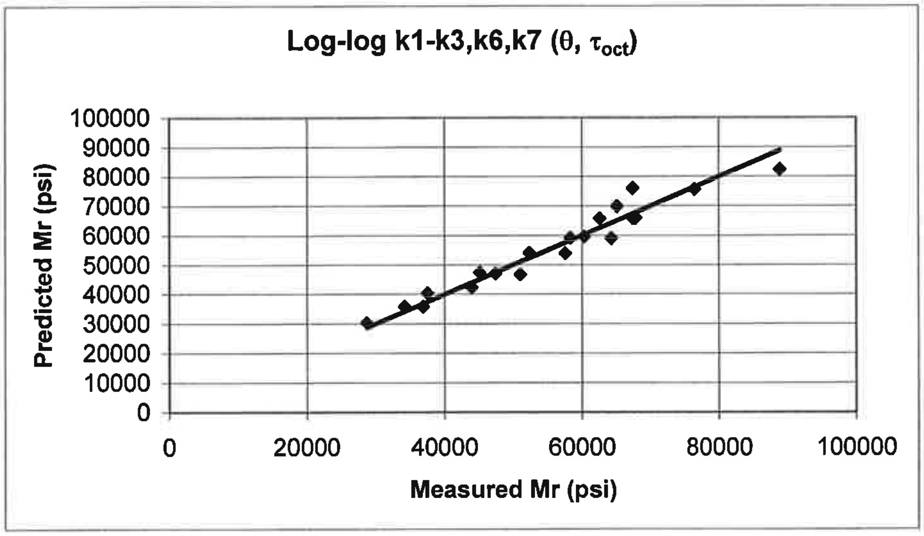

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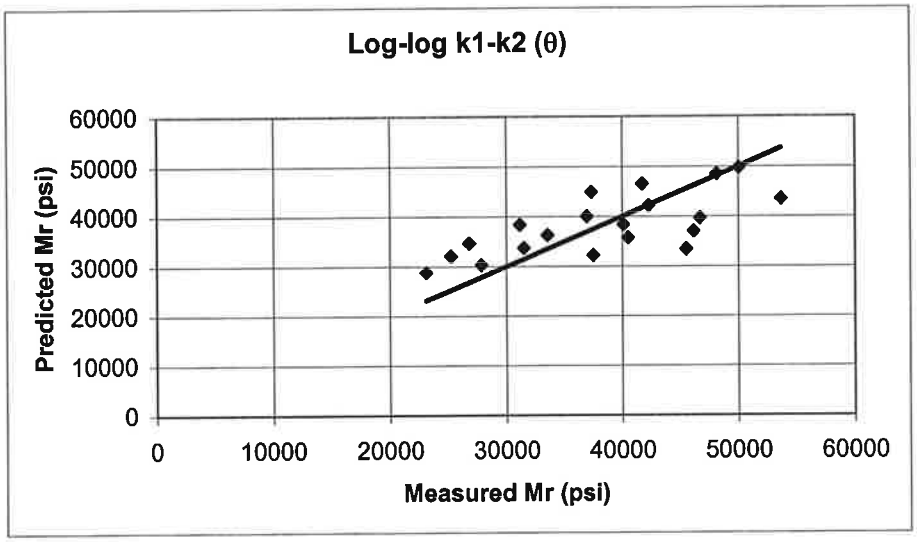

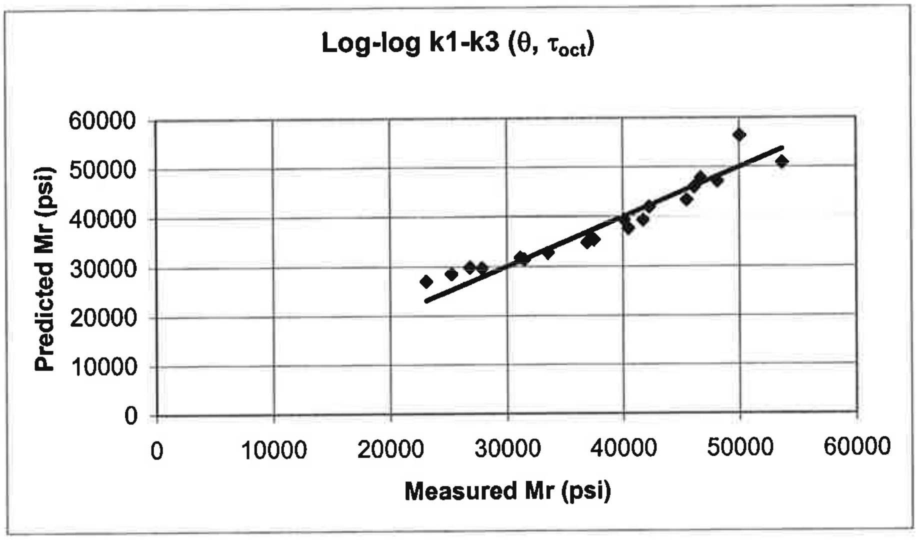

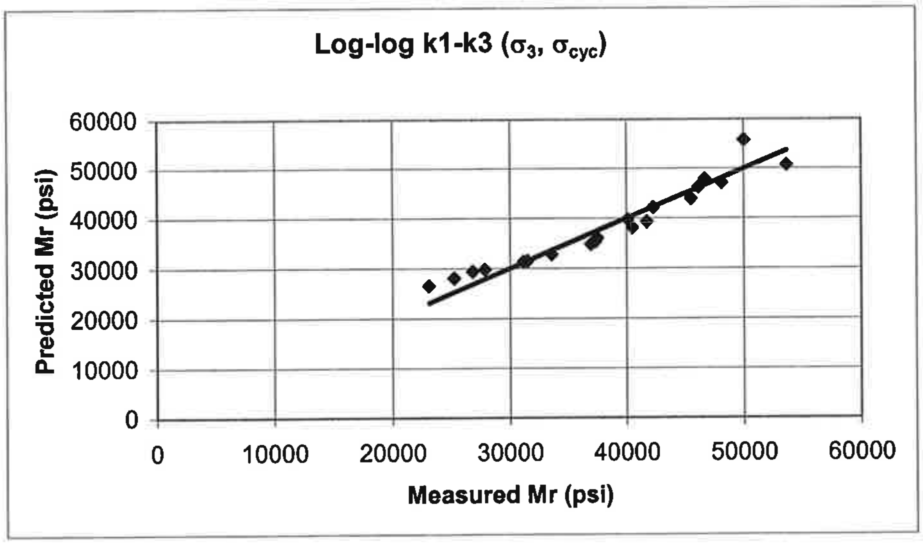

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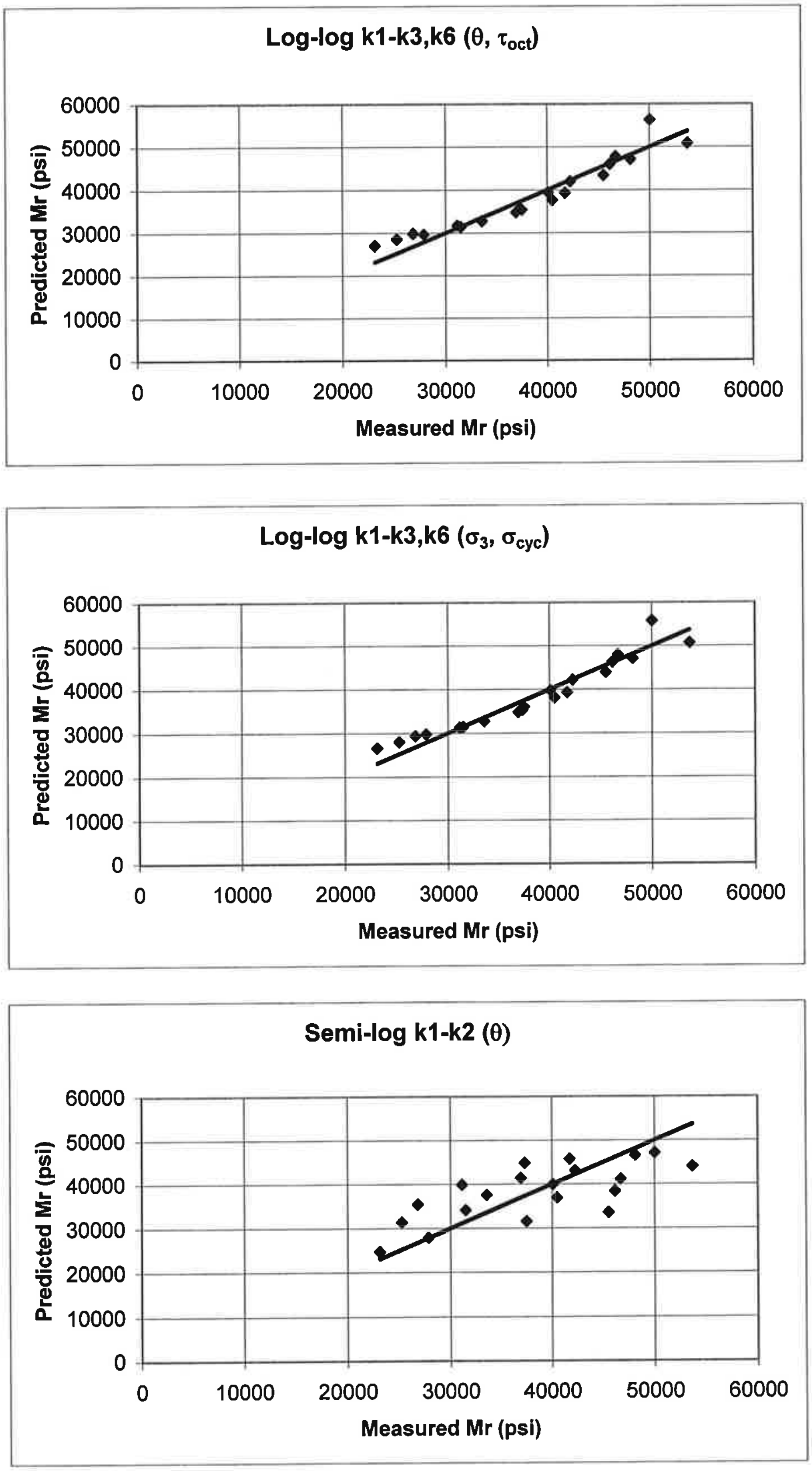

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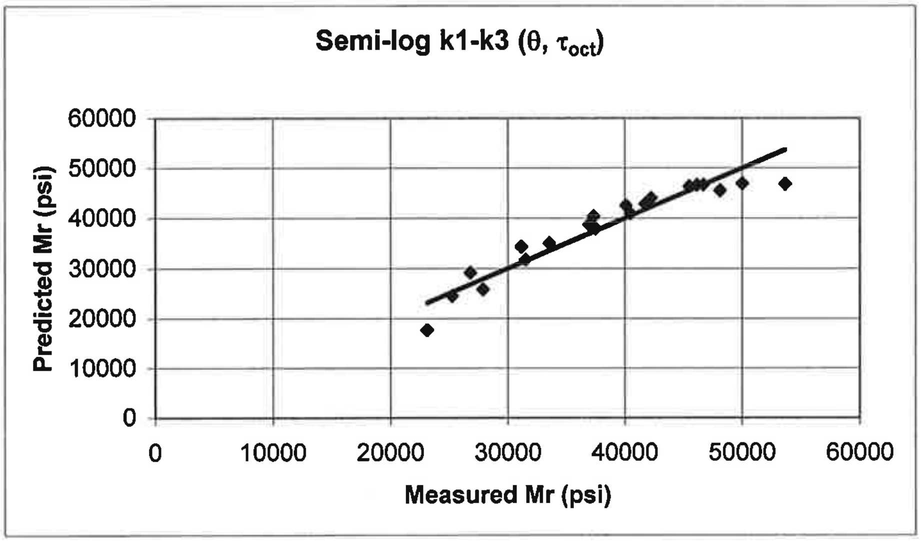

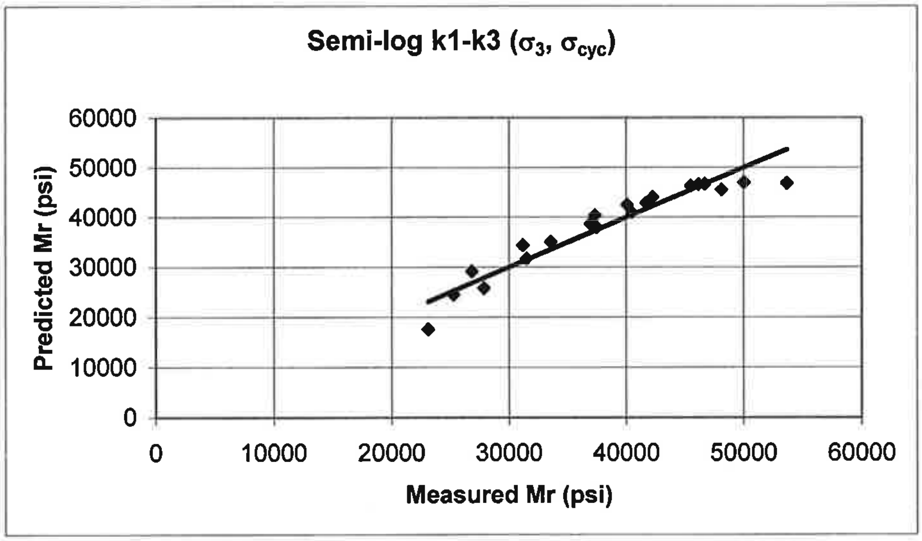

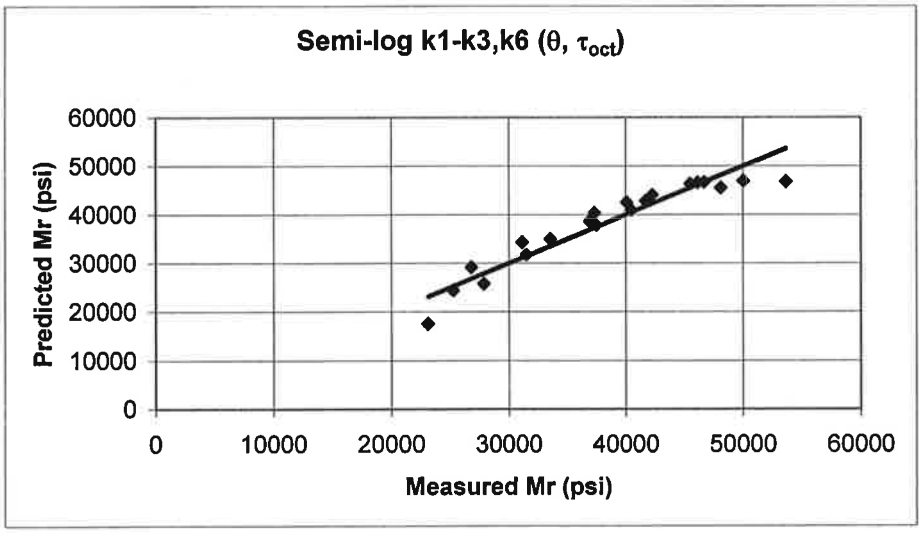

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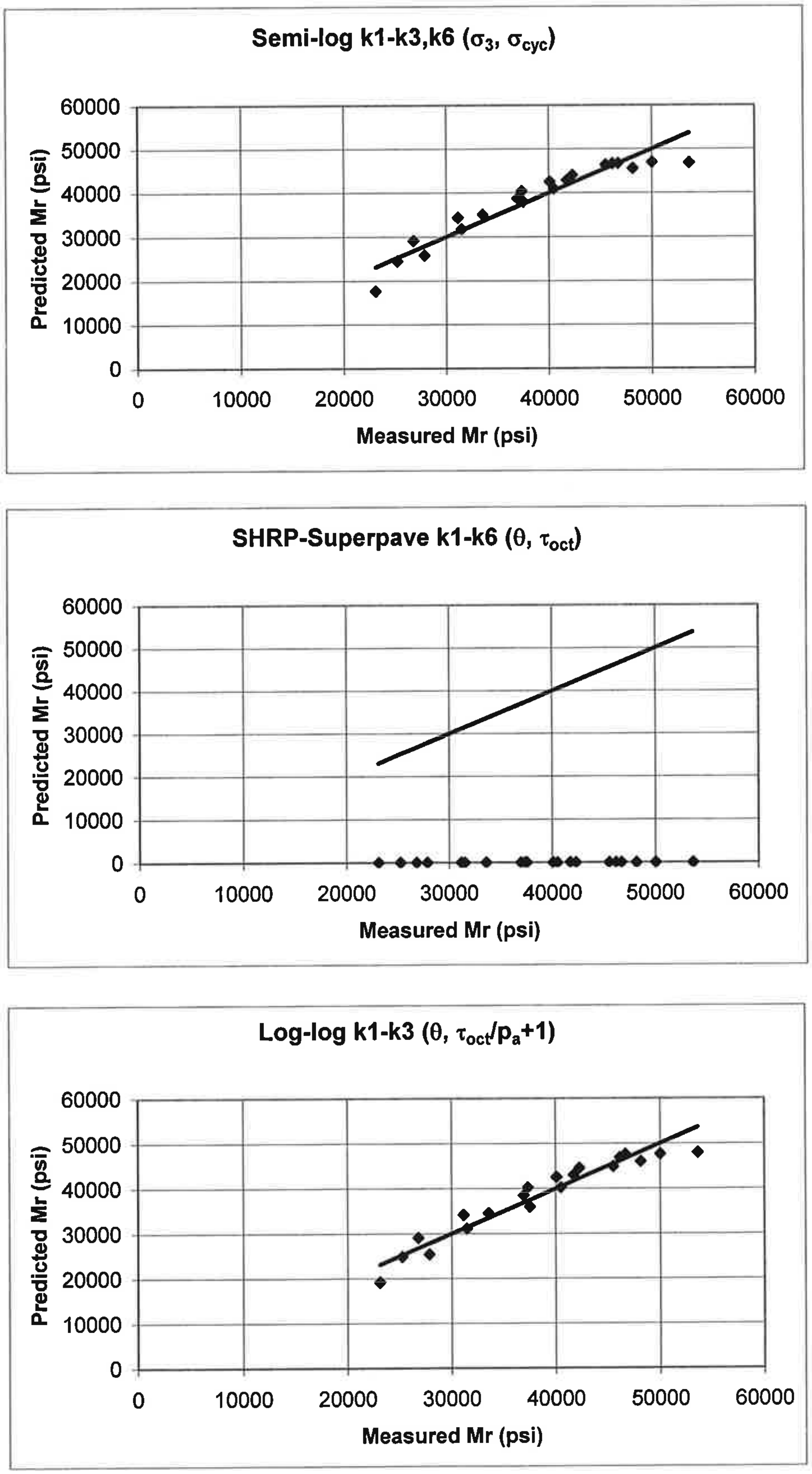

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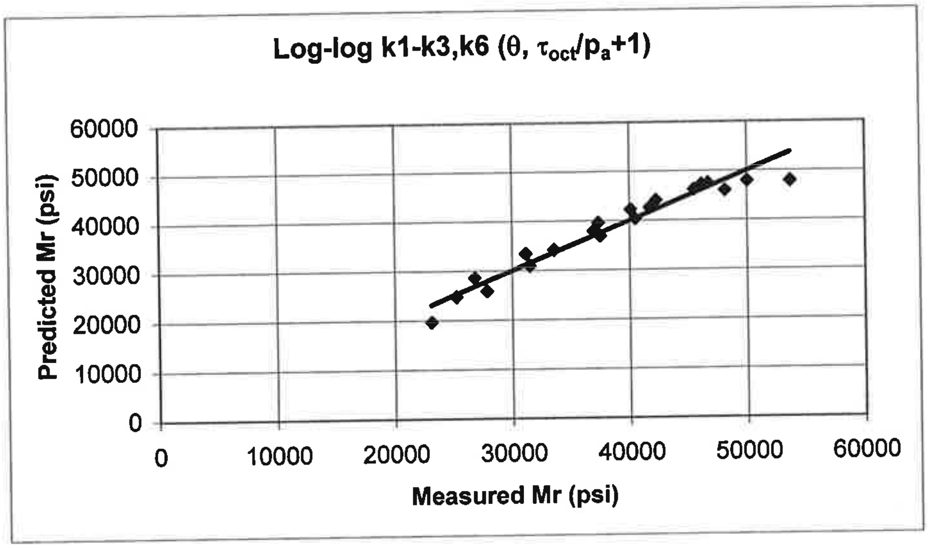

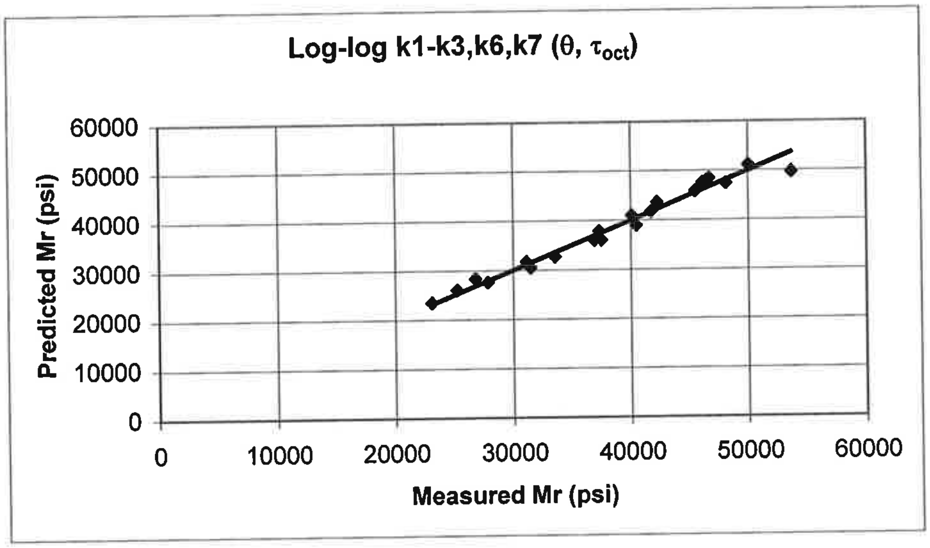

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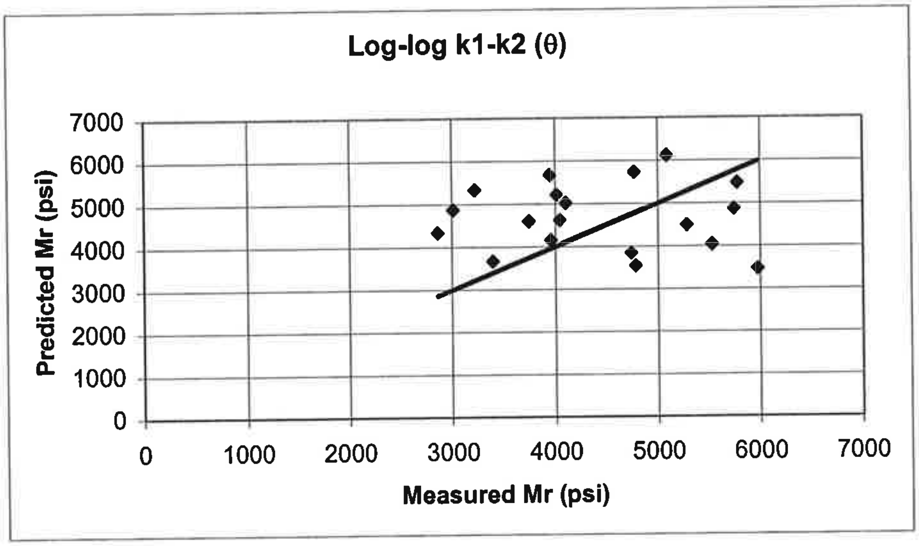

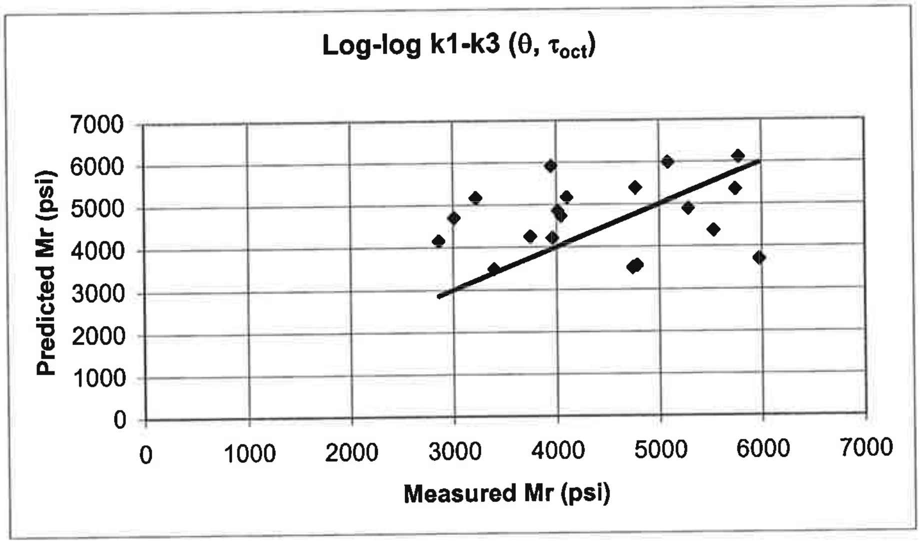

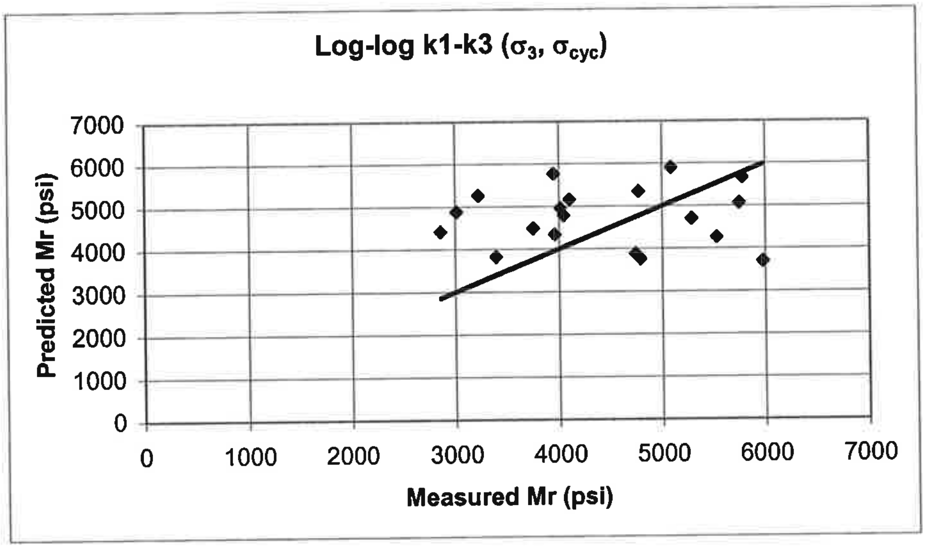

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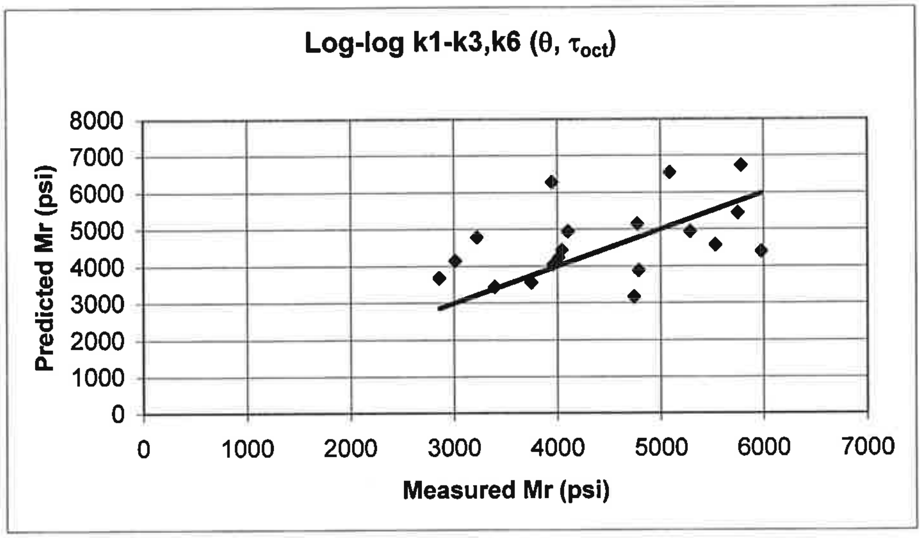

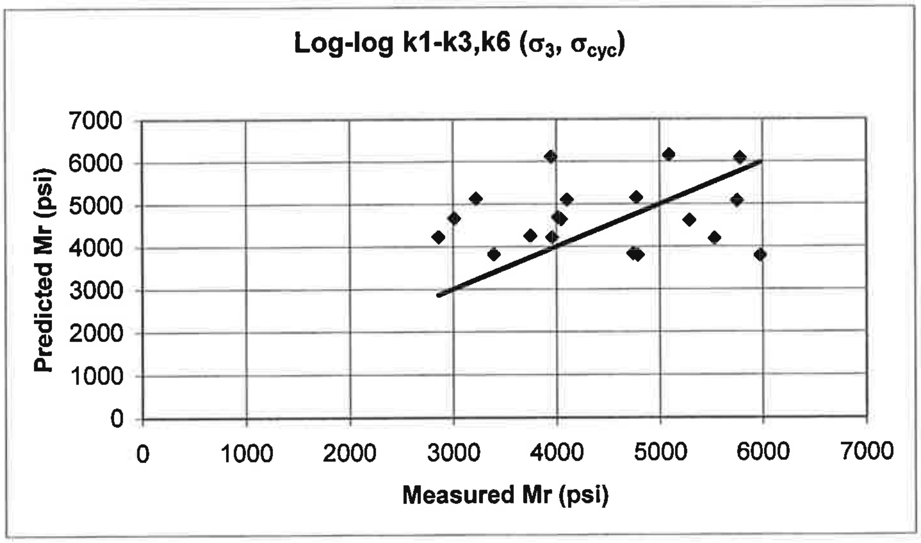

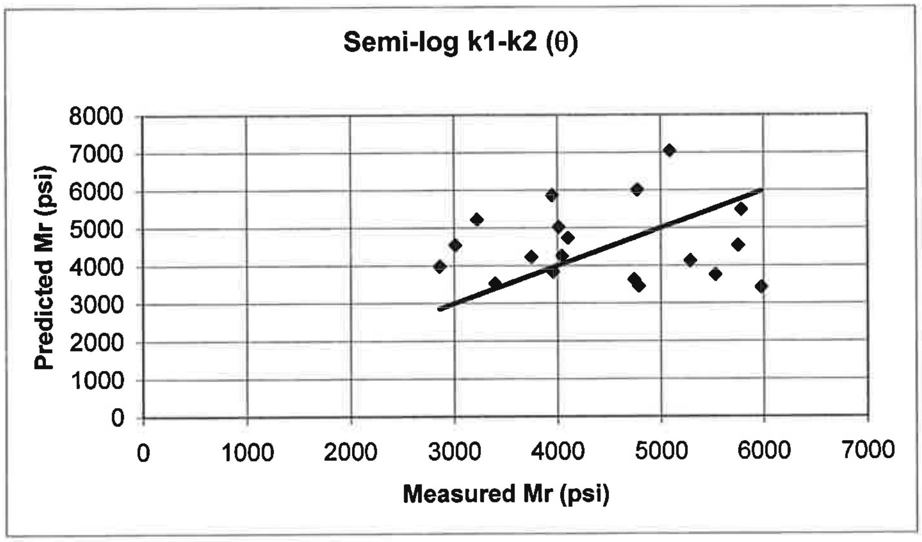

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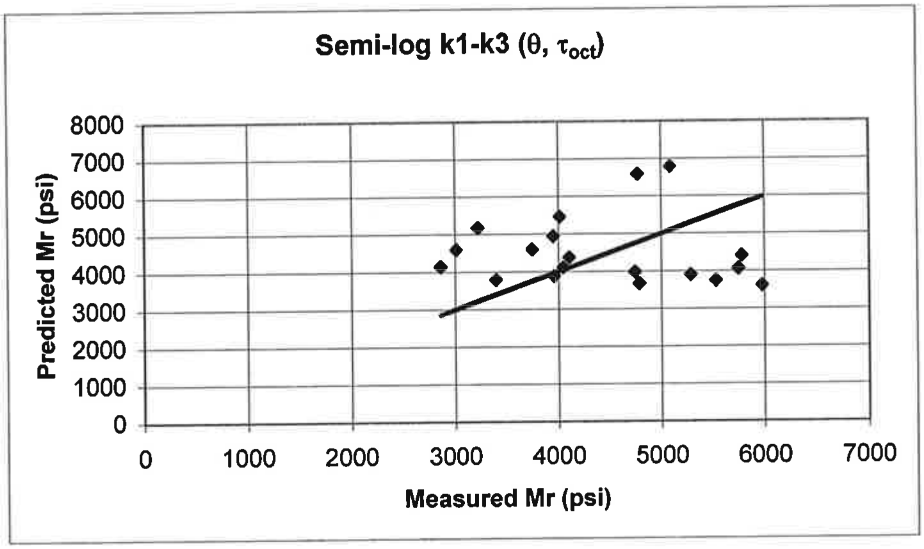

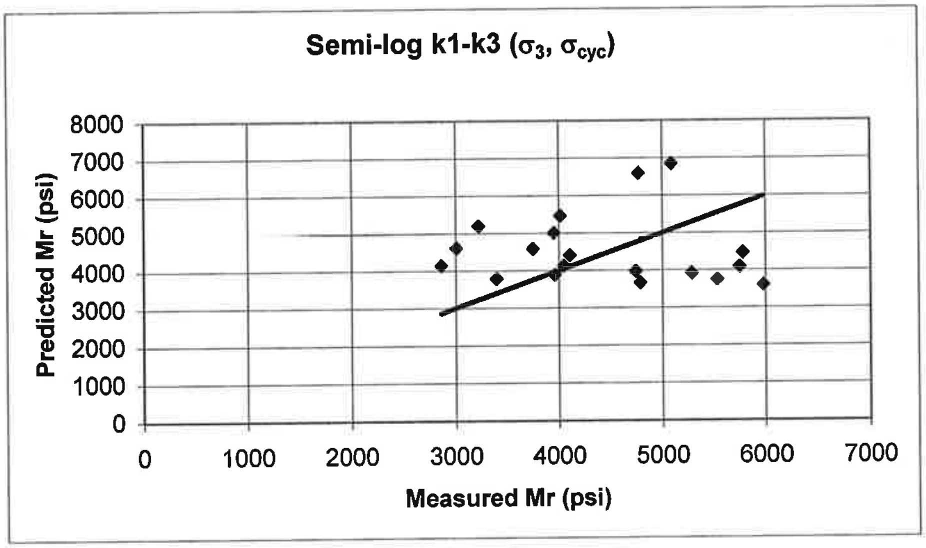

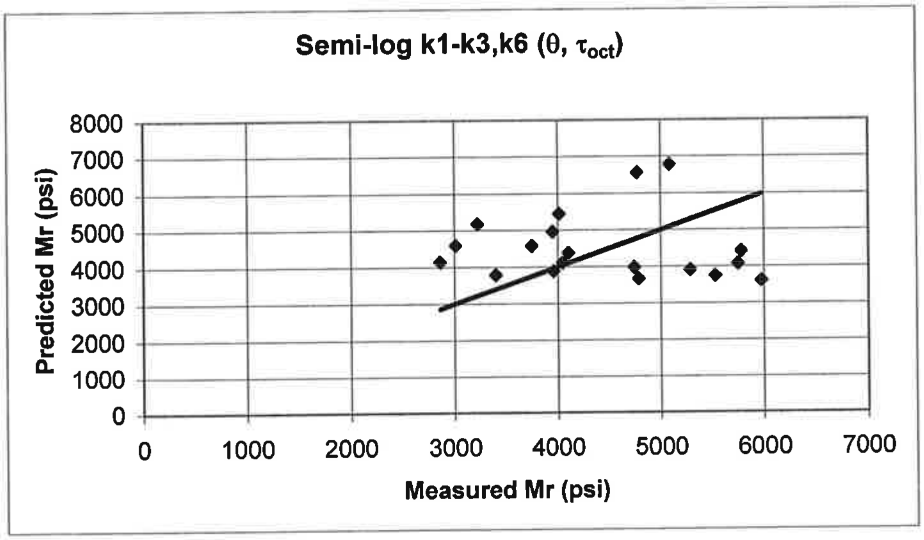

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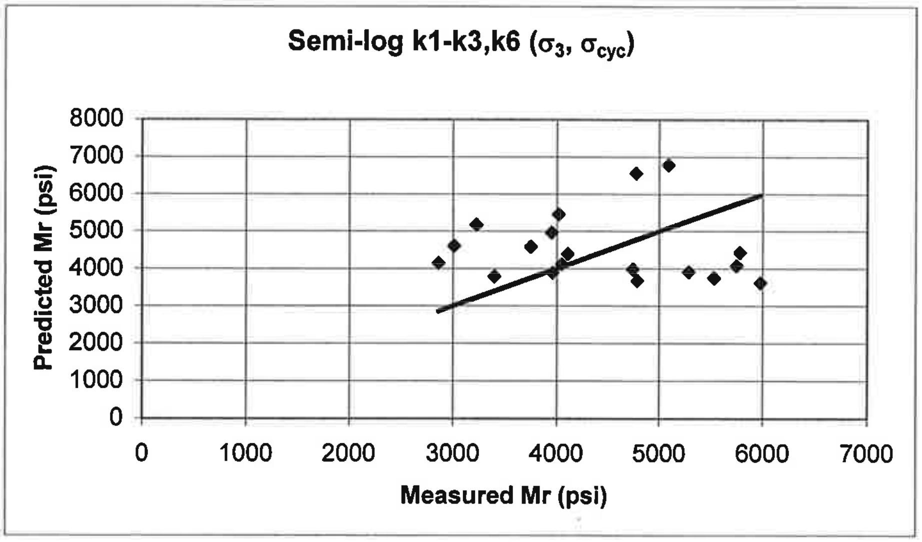

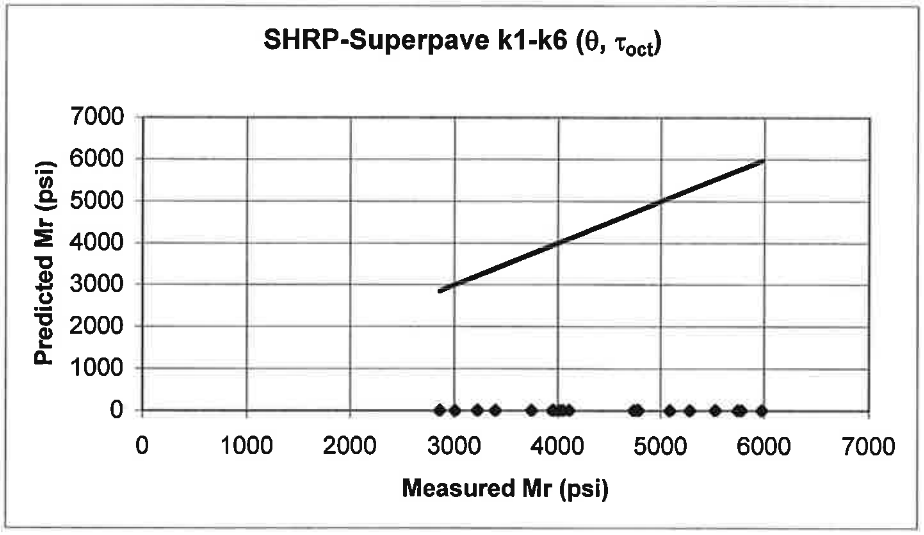

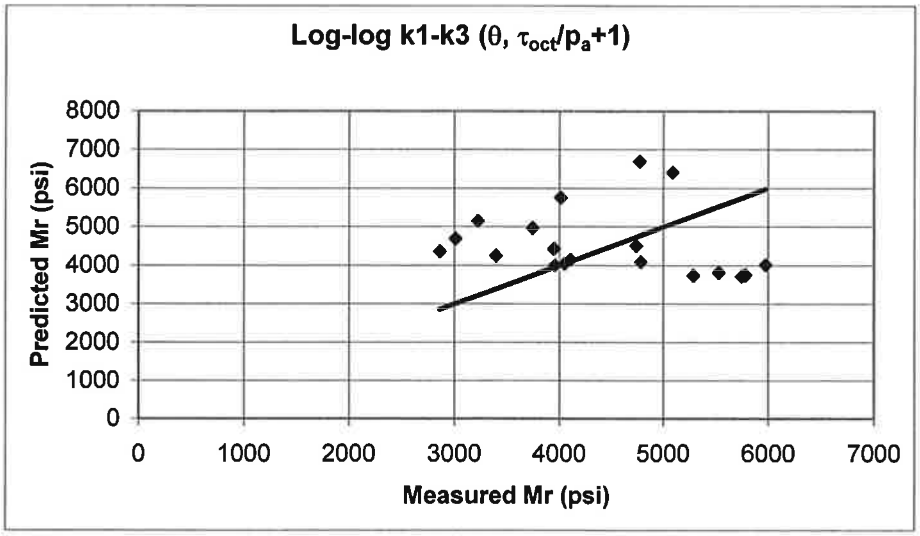

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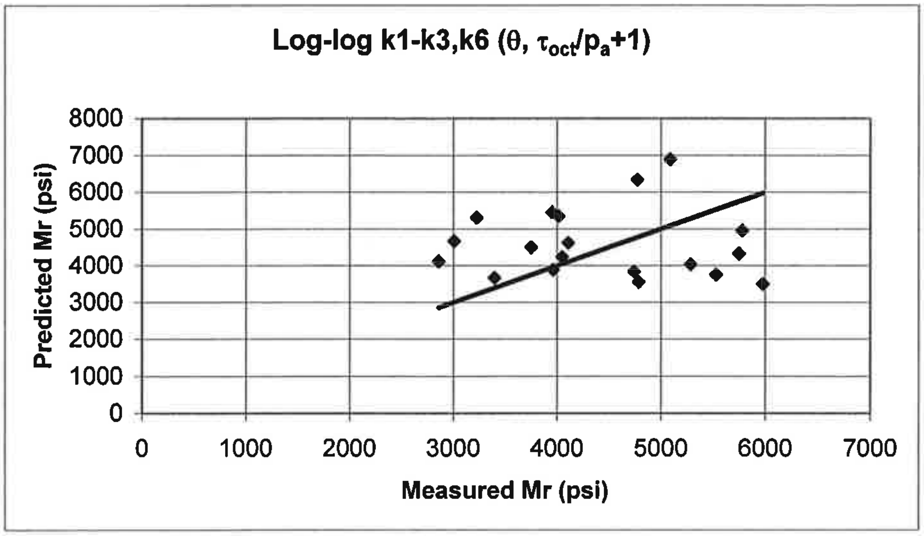
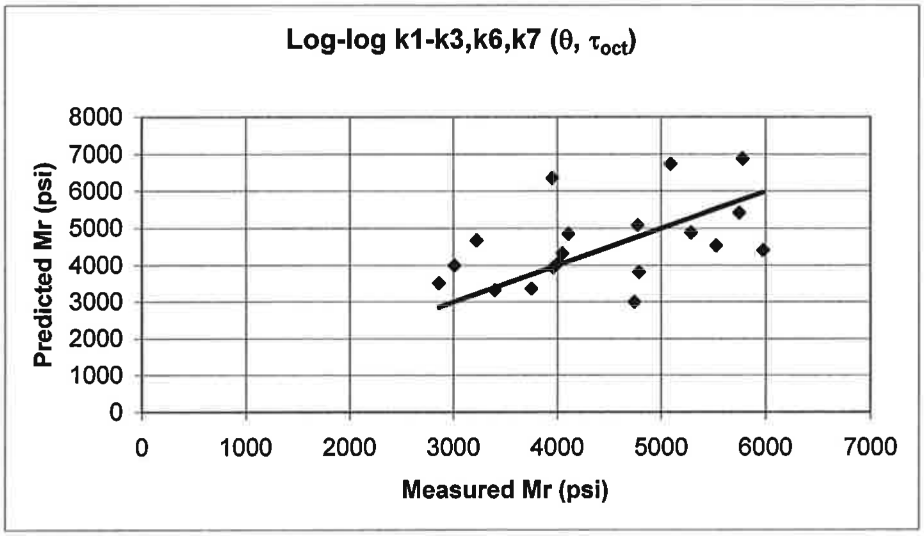




Measured Vs. Predicted M_R for Test S13_wet

NCHRP Note:

Tables & figures for insertion at blank, numbered pages within report

TABLE 2-1 COMPARISON BETWEEN EXISTING PROTOCOLS

	AASHTO T 292-91	AASHTO T 294-92 (SHRP P46)	AASHTO T P46-94	NCHRP 1-28
TESTING SYSTEM				
Loading Device	Any device capable of providing varying repeated loads in fixed cycles of load and release.	Closed loop electro-hydraulic.	Top-loading closed loop electro-hydraulic testing machine with a function generator capable of applying repeated cycles of haversine shaped load pulse (0.1 sec loading time / 0.9 sec rest time).	Same as AASHTO T P46-94
Triaxial Chamber	Fluid: air	Same as AASHTO T 292-91	- Fluid: air; - Triaxial chamber made of see-through material.	- Fluid: air; - Triaxial chamber made of see-through material; - Triaxial chamber used only for cohesionless materials.
Data Acquisition	- Strip chart or computer; - Simultaneous recording of axial load and deformation; - Do not use filters that attenuate signals.	- LVDT's monitored separately; - Simultaneous recording of axial load and deformation; - Filters should have a frequency that cannot attenuate the signal.	- Simultaneous recording of axial load and deformation; - Filters should have a frequency which cannot attenuate the signal; - Minimum 200 data points for each of the two LVDT's per load cycle; - The sensors shall be wired so that each transducer is read and the results are reviewed independently.	- Analog to digital data acquisition system required; - Automatic data reduction; - 25 ms A/D conversion time; - 12 bit resolution; - Minimum 200 data points for each of the two LVDT's per load cycle; - The sensors shall be wired so that each transducer is read and the results are reviewed independently.

TABLE 2-1 COMPARISON BETWEEN EXISTING PROTOCOLS

	AASHTO T 292-91	AASHTO T 294-92	AASHTO T P46-94	NCHRP 1-28
		MATERIAL PREPARATION		
Types of Materials	**Granular** - A-1, A-2-4, A-2-5, A-3; - For PI<6: A-4, A-5. - Scalp off material greater than 1.5 in.	**Material Type 1:** - All unbound granular base/subbase material; - All untreated subgrade material for which less than 70% passes the No. 10 sieve and less than 20% passes the No. 200 sieve; - A-1-a; - May include: A-1-b, A-2, A-3; - If more than 5% of a sample is retained on the 1.25 in sieve, the specimen shall not be tested; ELSE, remove all material greater than 1.25 in.	**Material Type 1:** - All untreated granular base/subbase materials and all untreated subgrade soils which meet the criteria of less than 70% passing the 2.00 mm (No. 10) sieve and less than 20% passing the 75µm (No. 200) sieve and which have PI < 10; - Due to edge effects, all material greater than 37.5 mm (1.5 in) shall be scalped off prior to testing.	**Material Type 1** - All unbound granular base and subbase material and all untreated subgrade soils which meet the criteria of less than 70% passing the 2.00 mm (No. 10) sieve and less than 20% passing the 75µm (No. 200) sieve and which have PI < 10; - **Type 1a** material shall have 100% passing the 37.5 mm (1.5 in) sieve; - **Type 1b** material shall have 100% passing the 25.4 mm (1.0 in) sieve; - If 10% or less of a Type 1a sample is retained on the 37.5 mm (1.5 in) sieve, the material greater than 37.5 mm (1.5 in) shall be scalped off and replaced by 25.4 to 37.5 mm (1.0-1.5 in) material prior to testing.
	Cohesive - A-2-6, A-2-7, A-6, A-7; - For PI>6: A-4, A-5.	**Material Type 2** - All untreated subgrade materials not meeting the above criteria; - Thin walled tube samples of untreated subgrades; - A-4, A-5, A-6, A-7; - May include A-1-b, A-2, A-3.	**Material Type 2** - All untreated granular base/subbase materials and all untreated subgrade soils not meeting the criteria for material Type 1; - Due to edge effects, all material greater than 12.5 mm (0.5 in) shall be scalped off prior to testing.	**Material Type 2** - All unbound granular base/subbase and untreated subgrade soils not meeting the criteria for material Type 1; - If 10% or less of a Type 2 sample is retained on the 12.5 mm (0.5 in) sieve, the material greater than 12.5 mm (0.5 in) shall be scalped off and replaced by 9.5 to 12.5 mm (0.375 – 0.5 in) material prior to testing.

TABLE 2-1 COMPARISON BETWEEN EXISTING PROTOCOLS

	AASHTO T 292-91	AASHTO T 294-92	AASHTO T P46-94	NCHRP 1-28
Specimen Preparation	- Minimum specimen diameter is 2.8 in; - For compaction select the method that best simulates field conditions (impact, kneading, static, vibratory).	- Minimum specimen diameter is 2.8 in or five times the nominal particle size; - Use the 2.8 in diameter undisturbed specimen from the thin walled tube samples for cohesive subgrade soils (Material Type 2); - 2.8 in diameter mold will be used to reconstitute Type 2 test specimens; - Use 4 in diameter split molds to reconstitute specimens for all Type 1 soils when the nominal particle size does not exceed ¾ in; - Use 6 in diameter split molds to prepare specimens for all Type 1 materials with nominal particle sizes between ¾ and 1 ¼ in without removing any coarse aggregate; - Type 1 soils will be recompacted by vibratory compaction; - Cohesionless soils are compacted readily by use of a split mold mounted on the base of the triaxial cell; compaction by small hand-held air hammer; - Type 2 soils are compacted by static loading.	- Soils classified as Type 1 will be molded in 150 mm (6 in) diameter mold; - Remolded Type 2 specimens will be compacted in a 71 mm (2.8 in) diameter mold; static compaction; - Type 1 materials will be recompacted using split molds and vibratory compaction; - Cohesionless soils shall be compacted in 6 lifts in a split mold mounted on the base of the triaxial cell; vibratory impact hammer without kneading action.	- **Materials** classified as Type 1a should be molded in a 152 mm (6 in) diameter mold; - Materials classified as Type 1b can be molded in either 102 mm (4 in) or 152 mm (6 in) diameter mold; - Use 102 mm (4 in) diameter molds for maximum particle size less than 25.4 mm (1 in); - Type 1 materials will be recompacted using split molds and vibratory compaction; - Cohesionless soils shall be compacted in six lifts in a split mold mounted on the base of the triaxial cell; vibratory impact hammer without kneading action; - Remolded Type 2 specimens can be compacted in either 71 mm (2.8 in) or 102 mm (4 in) diameter mold. The compaction method should simulate the filed conditions.

TABLE 2-1 COMPARISON BETWEEN EXISTING PROTOCOLS

	AASHTO T 292-91	AASHTO T 294-92	AASHTO T P46-94	NCHRP 1-28
		SENSORS		
Axial Load	Electronic load cell located inside the triaxial cell (on top of specimen cap).	Electronic load cell located inside the triaxial cell.	Electronic load cell located between the actuator and the chamber piston rod (outside triaxial cell).	Electronic load cell located inside the triaxial cell; non-fatigue rated cell recommended.
Axial Deformation	- Clamps (internally) mounted LVTD's; - Clamps mounted in the ¼ position; - Use spring-loaded LVDT's; - If the specimen is soft enough to be damaged by clamps or slippage of clamps is suspected, use externally mounted LVDT's (on the loading piston).	- Externally mounted LVDT's.	- Externally mounted spring loaded LVDT's; - An acceptable displacement ratio is defined as R = Ymax/Ymin (Ymax equals the larger of the two measured values and Ymin the smaller).	- Optical extensometer; - Non-contact sensors; - Clamps (internally) mounted LVDT's; - Clamps mounted in the ¼ position; - Use spring loaded LVDT's; - If the specimen is soft enough to be damaged by clamps or slippage of clamps is suspected use top-bottom platen measurements; - An acceptable displacement ratio is defined as R = Ymax/Ymin (Ymax equals the larger of the two measured values and Ymin the smaller).

TABLE 2-1 COMPARISON BETWEEN EXISTING PROTOCOLS

	AASHTO T 292-91	AASHTO T 294-92	AASHTO T P46-94	NCHRP 1-28
	TEST PROCEDURE			
Load Pulse	- Fixed load duration 0.1, 0.15, 1.0, 0.5 seconds; haversine, rectangular or triangular shapes may be used.	Haversine shaped 0.1 second load pulse followed by a 0.9 second rest period.	Same as AASHTO T 294-92	Same as AASHTO T 294-92
Stress Sequence 1	**<u>Cohesive soils:</u>** - Triaxial test; Conditioning: 3/3/1000 (Confining Stress / Deviatoric Stress / Number of Repetitions) Test: 3/3, 5, 7, 10, 15/50x5 - Stress ranges should be selected to cover the expected in-service range; - To determine the number of repetitions necessary, compare the recoverable axial deformations at the 20th and the 50th repetitions. If the difference is greater than 5% apply an additional 50 repetitions at this stress state.	**<u>Type 2 soils:</u>** - Triaxial test; Conditioning: 6/4/1000 (Confining Stress / Deviatoric Stress / Number of Repetitions) Test: 6/2, 4, 6, 8, 10/100x5 3/2, 4, 6, 8, 10/100x5 0/2, 4, 6, 8, 10/100x5 - If at any time the permanent strain of the sample exceeds 10%, stop the test and report the result on an appropriate worksheet.	**<u>Subgrade soils:</u>** - Includes undisturbed laboratory compacted specimens of subgrade soils; - Triaxial test; Conditioning: 6/4/500 (Confining Stress / Deviatoric Stress / Number of Repetitions) - If the sample is still decreasing in height at the end of the conditioning process, stress cycling should be continued up to 1000 repetitions prior to testing; - If the vertical permanent strain reaches 5% during conditioning then the conditioning process shall be terminated (inadequate compaction); Test: 6/2, 4, 6, 8, 10/100x5 3/2, 4, 6, 8, 10/100x5 0/2, 4, 6, 8, 10/100x5 - If at any time the permanent strain of the sample exceeds 5%, stop the test and report the result on an appropriate worksheet; - After the completion of the test, if the total vertical permanent strain did not exceed 5%, continue with the quick shear test procedure.	**<u>Unconfined test for cohesive subgrade soils:</u>** - Includes all undisturbed or laboratory compacted specimens of cohesive subgrade soils (PI>10; hold together during the test); - Soil should exhibit stress softening characteristics; - Unconfined test; - For stiff to very stiff specimens (Su>750 psf) axial deformation should preferably be measured either directly on the specimen or else between the solid end platens using grouted specimen ends; - For soft specimens do not use clamps; grouting is not needed if the measured resilient modulus is less than 10,000 psi; Conditioning: 0/5/200 (Confining Stress / Deviatoric Stress / Number of Repetitions) - If the vertical permanent strain reaches 5% during conditioning then the conditioning process shall be terminated (inadequate compaction); Test: 0/3, 5, 7, 9, 11/50x5 - After the completion of the test, perform the rapid shear test with no confining pressure.

TABLE 2-1 COMPARISON BETWEEN EXISTING PROTOCOLS

	AASHTO T 292-91	AASHTO T 294-92	AASHTO T P46-94	NCHRP 1-28
Stress Sequence 2	Granular subgrades: - Triaxial test; Conditioning: 15/12/1000 (Confining Stress / Deviatoric Stress / Number of Repetitions) Test: 15/7, 10, 15/50x3 10/5, 7, 10, 15/50x4 5/3, 5, 7, 10/50x4 2/3, 5, 7/50x3 - Stress ranges should be selected to cover the expected in-service range; - To determine the number of repetitions necessary, compare the recoverable axial deformations at the 20th and the 50th repetitions. If the difference is greater than 5% apply an additional 50 repetitions at this stress state.			Granular and low cohesion subgrade soils: - Includes all Type 1 subgrade materials and Type 2 materials having a PI < 10; - Triaxial test; Conditioning: 6/9.2/500 (Confining Stress / Deviatoric Stress / Number of Repetitions) - If the sample is still decreasing in height at the end of the conditioning process, stress cycling should be continued up to 1000 repetitions prior to testing; - If the vertical permanent strain reaches 5% during conditioning then the conditioning process shall be terminated (inadequate compaction); Test: 2/2.4, 3.4, 4.4/100x3 3/3.6, 4.4, 6.6/100x3 4/4.8, 6.8, 8.8/100x3 6/5.2, 7.2, 9.2/100x3 8/7.6, 9.6, 11.6/100x3 - If at any time the permanent strain of the sample exceeds 5%, stop the test and report the result on an appropriate worksheet; - After the completion of the test, if the total vertical permanent strain did not exceed 5%, continue with the quick shear test procedure.

TABLE 2-1 COMPARISON BETWEEN EXISTING PROTOCOLS

	AASHTO T 292-91	AASHTO T 294-92	AASHTO T P46-94	NCHRP 1-28
Stress Sequence 3	Granular base/subbase materials: - Triaxial test; Conditioning: 20/15/1000 (Confining Stress / Deviatoric Stress / Number of Repetitions) Test: 20/10, 20, 30, 40/50x4 15/10, 20, 30, 40/50x4 10/5, 10, 20, 30/50x4 5/5, 10, 15/50x3 3/5, 7, 9/50x3 - Stress ranges should be selected to cover the expected in-service range; - To determine the number of repetitions necessary, compare the recoverable axial deformations at the 20th and the 50th repetitions. If the difference is greater than 5% apply an additional 50 repetitions at this stress state.	Type 1 soils: - Triaxial test; Conditioning: 15/15/1000 (Confining Stress / Deviatoric Stress / Number of Repetitions) Test: 3/3, 6, 9/100x3 5/5, 10, 15/100x3 10/10, 20, 30/100x3 15/10, 15, 30/100x3 20/15, 20, 40.8/100x3 - If at any time the permanent strain of the sample exceeds 10%, stop the test and report the result on an appropriate worksheet.	Base/subbase materials: - Includes all unbound granular base and subbase materials; - Triaxial test; Conditioning: 15/15/500 (Confining Stress / Deviatoric Stress / Number of Repetitions) - If the sample is still decreasing in height at the end of the conditioning process, stress cycling should be continued up to 1000 repetitions prior to testing; - If the vertical permanent strain reaches 5% during conditioning then the conditioning process shall be terminated (inadequate compaction); Test: 3/3, 6, 9/100x3 5/5, 10, 15/100x3 10/10, 20, 30/100x3 15/10, 15, 30/100x3 20/15, 20, 40.8/100x3 - If at any time the permanent strain of the sample exceeds 5%, stop the test and report the result on an appropriate worksheet; - After the completion of the test, if the total vertical permanent strain did not exceed 5%, continue with the quick shear test procedure or permanent deformation test.	Base/subbase materials: - Includes all base and subbase materials; - Triaxial test; Conditioning: 15/18/200 (Confining Stress / Deviatoric Stress / Number of Repetitions) - If the sample is still decreasing in height at the end of the conditioning process, stress cycling should be continued up to 1000 repetitions prior to testing; - If the vertical permanent strain reaches 5% during conditioning then the conditioning process shall be terminated (inadequate compaction); Test: 3/3.6, 6.6, 9.6/50x3 4.5/5.4, 9.4, 14.4/50x3 6/7.2, 13.2, 19.2/50x3 9/10.8, 19.8, 28.8/50x3 14/11.8, 16.8, 30.8/50x3 - If at any time the permanent strain of the sample exceeds 5%, stop the test and report the result on an appropriate worksheet; - After the completion of the test, if the total vertical permanent strain did not exceed 5%, continue with the quick shear test procedure or permanent deformation test.

TABLE 2-1 COMPARISON BETWEEN EXISTING PROTOCOLS

	AASHTO T 292-91	AASHTO T 294-92	AASHTO T P46-94	NCHRP 1-28
PREDICTIVE EQUATIONS				
Predictive Equation	Cohesive: $Mr = k_1(\sigma_d)^{k2}$ Granular: $Mr = k_1(\theta)^{k2}$ σ_d = deviatoric stress θ = bulk stress k_1, k_2 = regression constants	Cohesive: $Mr = k_1(\sigma_d)^{k2}$ Granular: $Mr = k_1(\theta)^{k2}$ σ_d = deviatoric stress θ = bulk stress k_1, k_2 = regression constants	None	$\varepsilon_r = k_1(\sigma_{cyclic})^{k2}(\sigma_3)^{k3}$ $Mr = (\sigma_{cyclic})/\varepsilon_r$ σ_{cyclic} = cyclic stress σ_3 = confining pressure k_1, k_2, k_3 = regression constants ε_r = resilient strain

TABLE 3-1 COMPARISON OF NCHRP 1-28 APPENDIX E AND HARMONIZED METHOD

	NCHRP 1-28 Appendix E	NCHRP 1-28 A
TESTING SYSTEM		
Loading Device	Top-loading closed loop electro-hydraulic testing machine with a function generator capable of applying repeated cycles of haversine shaped load pulse (0.1 sec loading time / 0.9 sec rest time).	Same as NCHRP 1-28
Triaxial Chamber	- Fluid: air; - Triaxial chamber made of see-through material; - Triaxial chamber used only for cohesionless materials.	- Fluid: air; - Triaxial chamber made of see-through material;
Data Acquisition	- Analog to digital data acquisition system required; - Automatic data reduction; - 25 ms A/D conversion time; - 12 bit resolution; - Minimum 200 data points for each of the two LVDT's per load cycle; - The sensors shall be wired so that each transducer is read and the results are reviewed independently.	Same as NCHRP 1-28

TABLE 3-1 COMPARISON OF NCHRP 1-28 APPENDIX E AND HARMONIZED METHOD

	NCHRP 1-28 Appendix E	NCHRP 1-28 A
MATERIAL PREPARATION		
Types of Materials	Material Type 1 - All unbound granular base and subbase material and all untreated subgrade soils which meet the criteria of less than 70% passing the 2.00 mm (No. 10) sieve and less than 20% passing the 75μm (No. 200) sieve and which have PI < 10; - Type 1a material shall have 100% passing the 37.5 mm (1.5 in) sieve; - Type 1b material shall have 100% passing the 25.4 mm (1.0 in) sieve; - If 10% or less of a Type 1a sample is retained on the 37.5 mm (1.5 in) sieve, the material greater than 37.5 mm (1.5 in) shall be scalped off and replaced by 25.4 to 37.5 mm (1.0-1.5 in) material prior to testing.	Material Type 1 - Includes all unbound granular base and subbase materials and all untreated subgrade soils with maximum particle sizes greater than 9.5 mm (0.375 in). All material greater than 25.4 mm (1.0 in) shall be scalped off prior to testing
		Material Type 2 - Includes all unbound granular base and subbase materials and all untreated subgrade soils which have a maximum particle size less than 9.5 mm (0.375 in) and which meet the criteria of less than 10% passing the 75mm (No. 200) sieve.
	Material Type 2 - All unbound granular base/subbase and untreated subgrade soils not meeting the criteria for material Type 1; - If 10% or less of a Type 2 sample is retained on the 12.5 mm (0.5 in) sieve, the material greater than 12.5 mm (0.5 in) shall be scalped off and replaced by 9.5 to 12.5 mm (0.375 – 0.5 in) material prior to testing.	Material Type 3 - Includes all unbound granular base and subbase materials and all untreated subgrade soils which have a maximum particle size less than 9.5 mm (0.375 in) and which meet the criteria of more than 10% passing the 75mm (No. 200) sieve.
		Material Type 4 - Includes thin-walled tube samples of untreated subgrade soils.

TABLE 3-1 COMPARISON OF NCHRP 1-28 APPENDIX E AND HARMONIZED METHOD

	NCHRP 1-28 Appendix E	NCHRP 1-28 A
Specimen Preparation	- Materials classified as Type 1a should be molded in a 152 mm (6 in) diameter mold; - Materials classified as Type 1b can be molded in either 102 mm (4 in) or 152 mm (6 in) diameter mold; - Use 102 mm (4 in) diameter molds for maximum particle size less than 25.4 mm (1 in); - Type 1 materials will be recompacted using split molds and vibratory compaction; - Cohesionless soils shall be compacted in six lifts in a split mold mounted on the base of the triaxial cell; vibratory impact hammer without kneading action; - Remolded Type 2 specimens can be compacted in either 71 mm (2.8 in) or 102 mm (4 in) diameter mold. The compaction method should simulate the filed conditions.	- Materials classified as Type 1 shall be molded in either a 152 mm (6 in) diameter mold or a 102 mm (4 in) diameter mold. Materials classified as Type 1 shall be compacted by impact or vibratory compaction. - Materials classified as Type 2 shall be molded in a 102 mm (4 in) diameter mold and compacted by vibratory compaction. - Materials classified as Type 3 shall be molded in a 102 mm (4 in) diameter mold and compacted by impact or kneading compaction. - Materials Type 4 represent undisturbed samples of subgrade soils, tested as 71 mm (2.8 in) diameter specimens.

TABLE 3-1 COMPARISON OF NCHRP 1-28 APPENDIX E AND HARMONIZED METHOD

	NCHRP 1-28 Appendix E	NCHRP 1-28 A
	SENSORS	
Axial Load	Electronic load cell located inside the triaxial cell; non-fatigue rated cell recommended.	Same as NCHRP 1-28
Axial Deformation	- Optical extensometer; - Non-contact sensors; - Clamps (internally) mounted LVDT's; - Clamps mounted in the ¼ position; - Use spring loaded LVDT's; - If the specimen is soft enough to be damaged by clamps or slippage of clamps is suspected use top-bottom platen measurements; - An acceptable displacement ratio is defined as R = Ymax/Ymin (Ymax equals the larger of the two measured values and Ymin the smaller).	Same as NCHRP 1-28

TABLE 3-1 COMPARISON OF NCHRP 1-28 APPENDIX E AND HARMONIZED METHOD

	NCHRP 1-28 Appendix E	NCHRP 1-28 A
TEST PROCEDURE		
Load Pulse	Haversine shaped 0.1 second load pulse followed by a 0.9 second rest period.	Same as NCHRP 1-28
Stress Sequence 1	Unconfined test for cohesive subgrade soils: - Includes all undisturbed or laboratory compacted specimens of cohesive subgrade soils (PI>10; hold together during the test); - Soil should exhibit stress softening characteristics; - Unconfined test; - For stiff to very stiff specimens (Su>750 psf) axial deformation should preferably be measured either directly on the specimen or else between the solid end platens using grouted specimen ends; - For soft specimens do not use clamps; grouting is not needed if the measured resilient modulus is less than 10,000 psi; Conditioning: 0/5/200 (Confining Stress / Deviatoric Stress / Number of Repetitions) - If the vertical permanent strain reaches 5% during conditioning then the conditioning process shall be terminated (inadequate compaction); Test: - Unconfined test, the cyclic stress is increased at zero confining pressure; See Appendix A, Table A-3. - After the completion of the test, perform the rapid shear test with no confining pressure.	Procedure II - for fine-grained subgrade soils: - Includes all untreated subgrade soils which meet the criteria of more than 25% passing the 75μm (No. 200) sieve. - For stiff to very stiff specimens (Su>750 psf) axial deformation should preferably be measured either directly on the specimen or else between the solid end platens using grouted specimen ends; - For soft specimens do not use clamps; grouting is not needed if the measured resilient modulus is less than 10,000 psi; Conditioning: 4/7/1000 (Confining Stress / Deviatoric Stress / Number of Repetitions) - If the vertical permanent strain reaches 5% during conditioning then the conditioning process shall be terminated (inadequate compaction); Test: - Confined test, both cyclic and confining stresses are decreased at constant deviatoric stress; the deviatoric stress is then increased; See Appendix A, Table A-3.

TABLE 3-1 COMPARISON OF NCHRP 1-28 APPENDIX E AND HARMONIZED METHOD

	NCHRP 1-28 Appendix E	NCHRP 1-28 A
Stress Sequence 2	Granular and low cohesion subgrade soils: - Includes all Type 1 subgrade materials and Type 2 materials having a PI < 10; - Triaxial test; Conditioning: 6/9.2/500 (Confining Stress / Deviatoric Stress / Number of Repetitions) - If the sample is still decreasing in height at the end of the conditioning process, stress cycling should be continued up to 1000 repetitions prior to testing; - If the vertical permanent strain reaches 5% during conditioning then the conditioning process shall be terminated (inadequate compaction); Test: See Appendix A, Table A-3. - If at any time the permanent strain of the sample exceeds 5%, stop the test and report the result on an appropriate worksheet; - After the completion of the test, if the total vertical permanent strain did not exceed 5%, continue with the quick shear test procedure.	Procedure Ib – for granular and low cohesion subgrade soils: - Includes all untreated subgrade soils which meet the criteria of less than 25% passing the 75µm (No. 200) sieve. - - Triaxial test; Conditioning: 6/9.2/500 (Confining Stress / Deviatoric Stress / Number of Repetitions) - If the sample is still decreasing in height at the end of the conditioning process, stress cycling should be continued up to 1000 repetitions prior to testing; - If the vertical permanent strain reaches 5% during conditioning then the conditioning process shall be terminated (inadequate compaction); Test: - Confined test, both cyclic and confining stresses are increased at constant stress ratio; the stress ratio is then increased; See Appendix A, Table A-3.

TABLE 3-1 COMPARISON OF NCHRP 1-28 APPENDIX E AND HARMONIZED METHOD

	NCHRP 1-28 Appendix E	NCHRP 1-28 A
Stress Sequence 3	Base/subbase materials: - Includes all base and subbase materials; - Triaxial test; Conditioning: 15/18/200 (Confining Stress / Deviatoric Stress / Number of Repetitions) - If the sample is still decreasing in height at the end of the conditioning process, stress cycling should be continued up to 1000 repetitions prior to testing; - If the vertical permanent strain reaches 5% during conditioning then the conditioning process shall be terminated (inadequate compaction); Test: See Appendix A, Table A-3. - If at any time the permanent strain of the sample exceeds 5%, stop the test and report the result on an appropriate worksheet; - After the completion of the test, if the total vertical permanent strain did not exceed 5%, continue with the quick shear test procedure or permanent deformation test.	Base/subbase materials: - Includes all base and subbase materials; - Triaxial test; Conditioning: 15/18/200 (Confining Stress / Deviatoric Stress / Number of Repetitions) - If the sample is still decreasing in height at the end of the conditioning process, stress cycling should be continued up to 1000 repetitions prior to testing; - If the vertical permanent strain reaches 5% during conditioning then the conditioning process shall be terminated (inadequate compaction); Test: - Confined test, both cyclic and confining stresses are increased at constant stress ratio; the stress ratio is then increased; See Appendix A, Table A-3.
Predictive Equation	$\varepsilon_r = k_1(\sigma_{cyclic})^{k2}(\sigma_3)^{k3}$ $Mr = (\sigma_{cyclic})/\varepsilon_r$ σ_{cyclic} = cyclic stress σ_3 = confining pressure k_1, k_2, k_3 = regression constants ε_r = resilient strain	Log-log k_1, k_2, k_3, k_6, k_7 (θ, τ_{oct}) normalized by p_a k_1, k_2, k_3, k_6, k_7 = regression constants See chapter 6

TABLE 4-1
COMPARISON OF STRESS SEQUENCES FOR BASE/SUBBASE MATERIALS

Sequence	S3 (psi)		Scon		Scyc		Ratio		Smax		S1		Nrep	
	1-28	1-28A	1-28	1-28A	1-28	1-28A	1-28	1-28A	1-28	1-28A	1-28	1-28A	1-28	1-28A
0	15.0	15.0	3.0	3.0	15.0	30.0	2.2	3.0	18.0	33.0	33.0	48.0	200	1000
1	3.0	3.0	0.6	0.6	3.0	1.5	2.2	1.5	3.6	2.1	6.6	5.1	50	100
2	3.0	6.0	0.6	1.2	6.0	3.0	3.2	1.5	6.6	4.2	9.6	10.2	50	100
3	3.0	10.0	0.6	2.0	9.0	5.0	4.2	1.5	9.6	7.0	12.6	17.0	50	100
4	4.5	15.0	0.9	3.0	4.5	7.5	2.2	1.5	5.4	10.5	9.9	25.5	50	100
5	4.5	20.0	0.9	4.0	9.0	10.0	3.2	1.5	9.9	14.0	14.4	34.0	50	100
6	4.5	3.0	0.9	0.6	13.5	3.0	4.2	2.0	14.4	3.6	18.9	6.6	50	100
7	6.0	6.0	1.2	1.2	6.0	6.0	2.2	2.0	7.2	7.2	13.2	13.2	50	100
8	6.0	10.0	1.2	2.0	12.0	10.0	3.2	2.0	13.2	12.0	19.2	22.0	50	100
9	6.0	15.0	1.2	3.0	18.0	15.0	4.2	2.0	19.2	18.0	25.2	33.0	50	100
10	9.0	20.0	1.8	4.0	9.0	20.0	2.2	2.0	10.8	24.0	19.8	44.0	50	100
11	9.0	3.0	1.8	0.6	18.0	6.0	3.2	3.0	19.8	6.6	28.8	9.6	50	100
12	9.0	6.0	1.8	1.2	27.0	12.0	4.2	3.0	28.8	13.2	37.8	19.2	50	100
13	14.0	10.0	2.8	2.0	9.0	20.0	1.8	3.0	11.8	22.0	25.8	32.0	50	100
14	14.0	15.0	2.8	3.0	14.0	30.0	2.2	3.0	16.8	33.0	30.8	48.0	50	100
15	14.0	20.0	2.8	4.0	28.0	40.0	3.2	3.0	30.8	44.0	44.8	64.0	50	100
16		3.0		0.6		9.0		4.0		9.6		12.6		100
17		6.0		1.2		18.0		4.0		19.2		25.2		100
18		10.0		2.0		30.0		4.0		32.0		42.0		100
19		15.0		3.0		45.0		4.0		48.0		63.0		100
20		20.0		4.0		60.0		4.0		64.0		84.0		100
21		3.0		0.6		15.0		6.0		15.6		18.6		100
22		6.0		1.2		30.0		6.0		31.2		37.2		100
23		10.0		2.0		50.0		6.0		52.0		62.0		100
24		15.0		3.0		75.0		6.0		78.0		93.0		100
25		20.0		4.0		100.0		6.0		104.0		124.0		100
26		3.0		0.6		21.0		8.0		21.6		24.6		100
27		6.0		1.2		42.0		8.0		43.2		49.2		100
28		10.0		2.0		70.0		8.0		72.0		82.0		100
29		15.0		3.0		105.0		8.0		108.0		123.0		100
30		20.0		4.0		140.0		8.0		144.0		164.0		100

TABLE 4-2
COMPARISON OF STRESS SEQUENCES FOR COARSE-GRAINED SUBGRADES

Sequence	S3 (psi)		Scon		Scyc		Ratio		Smax		S1		Nrep	
	1-28	1-28A	1-28	1-28A	1-28	1-28A	1-28	1-28A	1-28	1-28A	1-28	1-28A	1-28	1-28A
0	6.0	4.0	1.2	0.8	8.0	8.0	2.5	3.0	9.2	8.8	15.2	12.8	500	1000
1	2.0	2.0	0.4	0.4	2.0	1.0	2.2	1.5	2.4	1.4	4.4	3.4	100	100
2	2.0	4.0	0.4	0.8	3.0	2.0	2.7	1.5	3.4	2.8	5.4	6.8	100	100
3	2.0	6.0	0.4	1.2	4.0	3.0	3.2	1.5	4.4	4.2	6.4	10.2	100	100
4	3.0	8.0	0.6	1.6	3.0	4.0	2.2	1.5	3.6	5.6	6.6	13.6	100	100
5	3.0	12.0	0.6	2.4	3.8	6.0	2.5	1.5	4.4	8.4	7.4	20.4	100	100
6	3.0	2.0	0.6	0.4	6.0	2.0	3.2	2.0	6.6	2.4	9.6	4.4	100	100
7	4.0	4.0	0.8	0.8	4.0	4.0	2.2	2.0	4.8	4.8	8.8	8.8	100	100
8	4.0	6.0	0.8	1.2	6.0	6.0	2.7	2.0	6.8	7.2	10.8	13.2	100	100
9	4.0	8.0	0.8	1.6	8.0	8.0	3.2	2.0	8.8	9.6	12.8	17.6	100	100
10	6.0	12.0	1.2	2.4	4.0	12.0	1.9	2.0	5.2	14.4	11.2	26.4	100	100
11	6.0	2.0	1.2	0.4	6.0	4.0	2.2	3.0	7.2	4.4	13.2	6.4	100	100
12	6.0	4.0	1.2	0.8	8.0	8.0	2.5	3.0	9.2	8.8	15.2	12.8	100	100
13	8.0	6.0	1.6	1.2	6.0	12.0	2.0	3.0	7.6	13.2	15.6	19.2	100	100
14	8.0	8.0	1.6	1.6	8.0	16.0	2.2	3.0	9.6	17.6	17.6	25.6	100	100
15	8.0	12.0	1.6	2.4	10.0	24.0	2.5	3.0	11.6	26.4	19.6	38.4	100	100
16		2.0		0.4		6.0		4.0		6.4		8.4		100
17		4.0		0.8		12.0		4.0		12.8		16.8		100
18		6.0		1.2		18.0		4.0		19.2		25.2		100
19		8.0		1.6		24.0		4.0		25.6		33.6		100
20		12.0		2.4		36.0		4.0		38.4		50.4		100

TABLE 4-3
COMPARISON OF STRESS SEQUENCES FOR FINE-GRAINED SUBGRADES

Sequence	S3 (psi)		Scon		Scyc		Ratio		Smax		S1		Nrep	
	1-28	1-28A	1-28	1-28A	1-28	1-28A	1-28	1-28A	1-28	1-28A	1-28	1-28A	1-28	1-28A
0	0	4.0	1.0	0.8	4.0	7.0	N/A	2.8	5.0	7.8	5.0	11.8	200	1000
1	0	8.0	0.6	1.6	2.4	4.0	N/A	1.5	3.0	5.6	3.0	13.6	50	100
2	0	6.0	1.0	1.2	4.0	4.0	N/A	1.7	5.0	5.2	5.0	11.2	50	100
3	0	4.0	1.4	0.8	5.6	4.0	N/A	2.0	7.0	4.8	7.0	8.8	50	100
4	0	2.0	1.8	0.4	7.2	4.0	N/A	3.0	9.0	4.4	9.0	6.4	50	100
5	0	8.0	2.2	1.6	8.8	7.0	N/A	1.9	11.0	8.6	11.0	16.6	50	100
6		6.0		1.2		7.0		2.2		8.2		14.2		100
7		4.0		0.8		7.0		2.8		7.8		11.8		100
8		2.0		0.4		7.0		4.5		7.4		9.4		100
9		8.0		1.6		10.0		2.3		11.6		19.6		100
10		6.0		1.2		10.0		2.7		11.2		17.2		100
11		4.0		0.8		10.0		3.5		10.8		14.8		100
12		2.0		0.4		10.0		6.0		10.4		12.4		100
13		8.0		1.6		14.0		2.8		15.6		23.6		100
14		6.0		1.2		14.0		3.3		15.2		21.2		100
15		4.0		0.8		14.0		4.5		14.8		18.8		100
16		2.0		0.4		14.0		8.0		14.4		16.4		100

TABLE 6-1
COMPARISON OF Se/Sy AVERAGE VALUES FOR DIFFERENT MATERIALS (S12, S1 AND S3) AND STRESS SEQUENCES (HARMONIZED/NCHRP 1-28 APPENDIX E)

Models		Se/Sy									
		Harmonized Stress Sequence					NCHRP Appendix** E Stress Sequence				
ID	Name	S12	S1	S3	Average	Rank	S12	S1	S3	Average	Rank
1	log-log k1, k2 (θ or τ_{oct})	0.388	1.009	0.864	0.754	12	0.362	0.971	0.871	0.735	12
2	log-log k1, k2, k3 (θ, τ_{oct})	0.240	0.441	0.310	0.330	6	0.199	0.809		0.504	4
3	log-log k1, k2, k3 (σ_3, σ_{cyc})	0.198	0.434	0.305	0.312	3	0.199	0.806	0.907	0.637	10
4	log-log k1, k2, k3, k6 (θ, τ_{oct})	0.241	0.428	0.313	0.327	4	0.195	0.775		0.485	2
5	log-log k1, k2, k3, k6 (σ_3, σ_{cyc})	0.198	0.420	0.303	0.307	2	0.194	0.784		0.489	3
6	semi-log k1, k2 (θ or τ_{oct})	0.499	1.009	0.863	0.791	13	0.369	0.992	0.858	0.740	13
7	semi-log k1, k2,k3 (θ, τ_{oct})	0.275	0.558	0.258	0.364	9	0.225	0.852		0.539	6
8	semi-log k1, k2, k3 (σ_3, σ_{cyc})	0.276	0.557	0.256	0.363	8	0.224	0.853	0.893	0.657	11
9	semi-log k1, k2, k3, k6 (θ, τ_{oct})	0.277	0.563	0.260	0.367	11	0.227	0.863		0.545	8
10	semi-log k1, k2, k3, k6 (σ_3, σ_{cyc})	0.277	0.563	0.259	0.366	10	0.226	0.863		0.545	7
11	SHRP-Superpave* k1-k6					14					14
12	log-log k1, k2, k3 (θ, τ_{oct}/p_a+1)	0.206	0.578	0.263	0.349	7	0.220	0.885		0.552	9
13	log-log k1, k2, k3, k6 (θ, τ_{oct}/p_a+1)	0.191	0.531	0.263	0.329	5	0.201	0.855		0.528	5
14	log-log k1, k2, k3, k6, k7 (θ, τ_{oct})	0.174	0.426	0.263	0.288	1	0.198	0.758		0.478	1

*The SHRP-Superpave model (11) could not be calibrated for all tests, therefore no Se/Sy value is reported.

**Material S3 falls into a group of materials for which the NCHRP1-28 Appendix E procedure recommends an unconfined test.Therefore σ_3=0and only models 1, 3, 6 and 8 may be used.

TABLE 6-2
Se/Sy AVERAGE VALUES FOR ALL TESTS USING THE HARMONIZED PROCEDURE

Models		Se/Sy	
ID	Name	Average	Rank
1	log-log k1, k2 (θ or τ_{oct})	0.679	12
2	log-log k1, k2, k3 (θ, τ_{oct})	0.368	5
3	log-log k1, k2, k3 (σ_3, σ_{cyc})	0.368	4
4	log-log k1, k2, k3, k6 (θ, τ_{oct})	0.315	2
5	log-log k1, k2, k3, k6 (σ_3, σ_{cyc})	0.363	3
6	semi-log k1, k2 (θ or τ_{oct})	0.717	13
7	semi-log k1, k2,k3 (θ, τ_{oct})	0.474	8
8	semi-log k1, k2, k3 (σ_3, σ_{cyc})	0.474	9
9	semi-log k1, k2, k3, k6 (θ, τ_{oct})	0.489	10
10	semi-log k1, k2, k3, k6 (σ_3, σ_{cyc})	0.489	11
11	SHRP-Superpave k1-k6		14
12	log-log k1, k2, k3 (θ, τ_{oct}/p_a+1)	0.414	7
13	log-log k1, k2, k3, k6 (θ, τ_{oct}/p_a+1)	0.395	6
14	log-log k1, k2, k3, k6, k7 (θ, τ_{oct})	0.267	1

TABLE 6-3
RANKING OF THE MODELS FOR ALL TESTS USING THE HARMONIZED PROCEDURE

Models		Se/Sy	
ID	Name	Average	Rank
14	log-log k1, k2, k3, k6, k7 (θ, τ_{oct})	0.267	1
4	log-log k1, k2, k3, k6 (θ, τ_{oct})	0.315	2
5	log-log k1, k2, k3, k6 (σ_3, σ_{cyc})	0.363	3
3	log-log k1, k2, k3 (σ_3, σ_{cyc})	0.368	4
2	log-log k1, k2, k3 (θ, τ_{oct})	0.368	5
13	log-log k1, k2, k3, k6 (θ, τ_{oct}/p_a+1)	0.395	6
12	log-log k1, k2, k3 (θ, τ_{oct}/p_a+1)	0.414	7
7	semi-log k1, k2,k3 (θ, τ_{oct})	0.474	8
8	semi-log k1, k2, k3 (σ_3, σ_{cyc})	0.474	9
9	semi-log k1, k2, k3, k6 (θ, τ_{oct})	0.489	10
10	semi-log k1, k2, k3, k6 (σ_3, σ_{cyc})	0.489	11
1	log-log k1, k2 (θ or τ_{oct})	0.679	12
6	semi-log k1, k2 (θ or τ_{oct})	0.717	13
11	SHRP-Superpave k1-k6		14

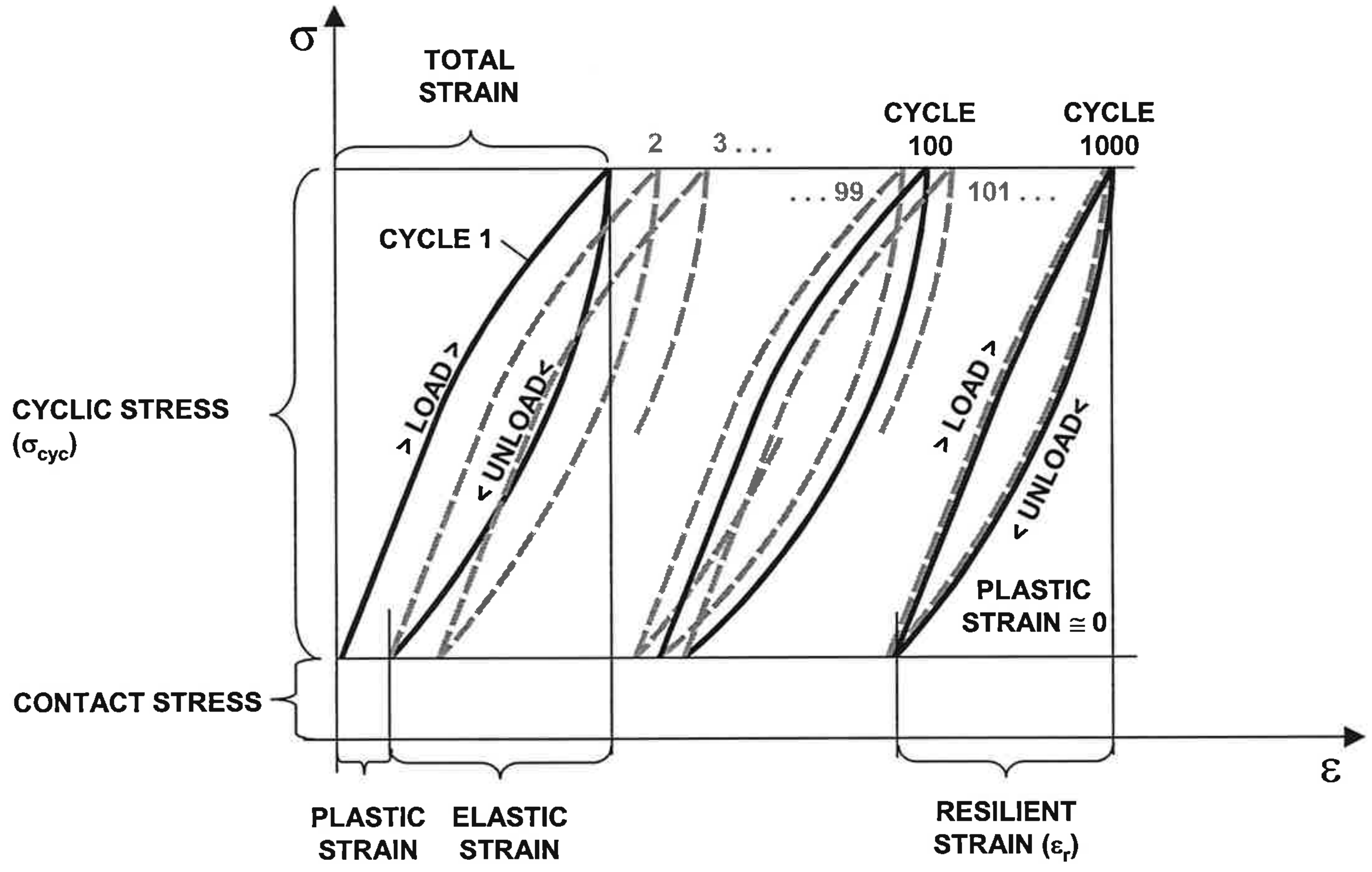


Figure 1-1. Resilient Behavior of Unbound Materials Under Repeated Loads

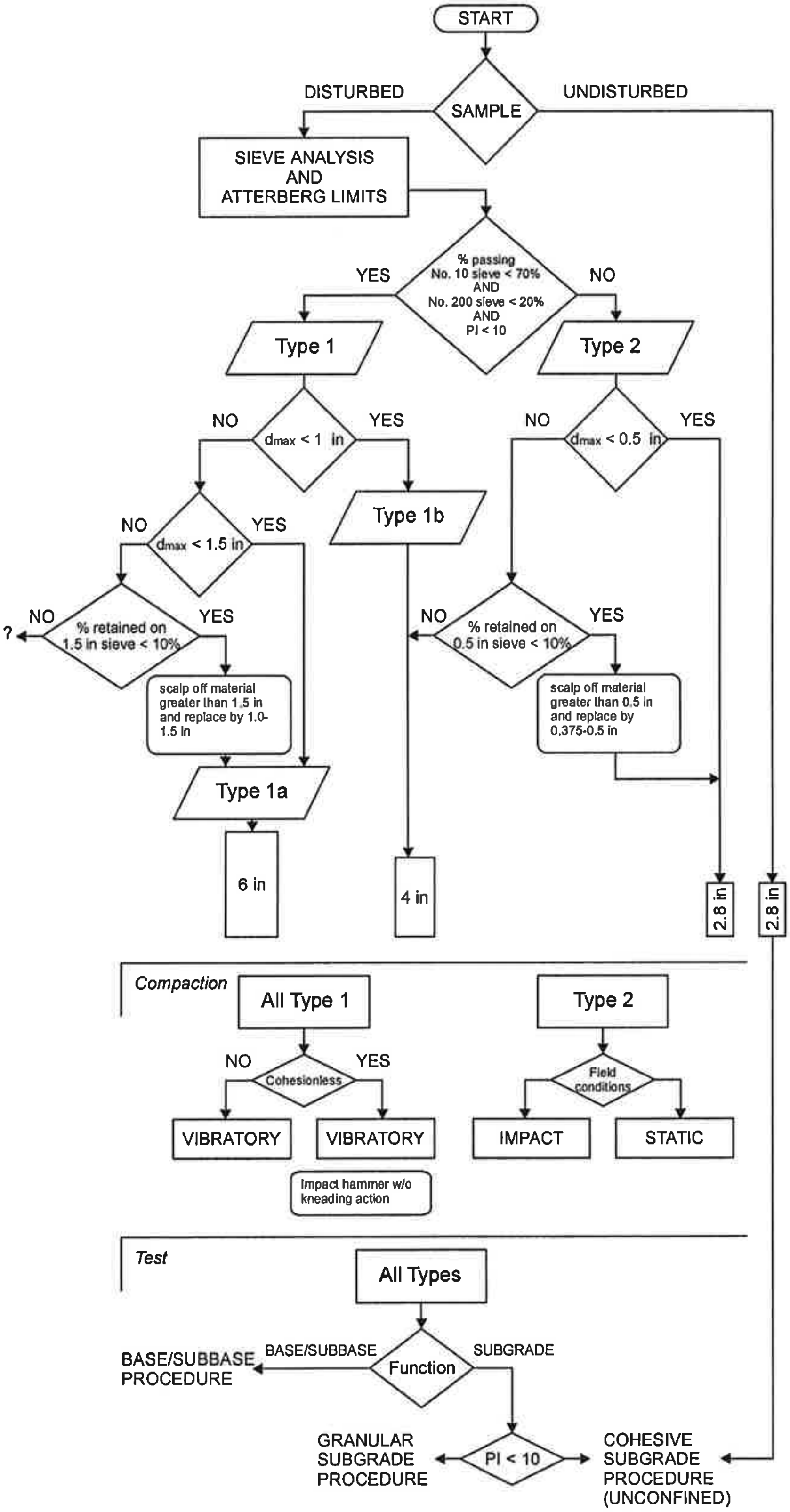


Figure 4-1. NCHRP 1-28 Appendix E Flowchart

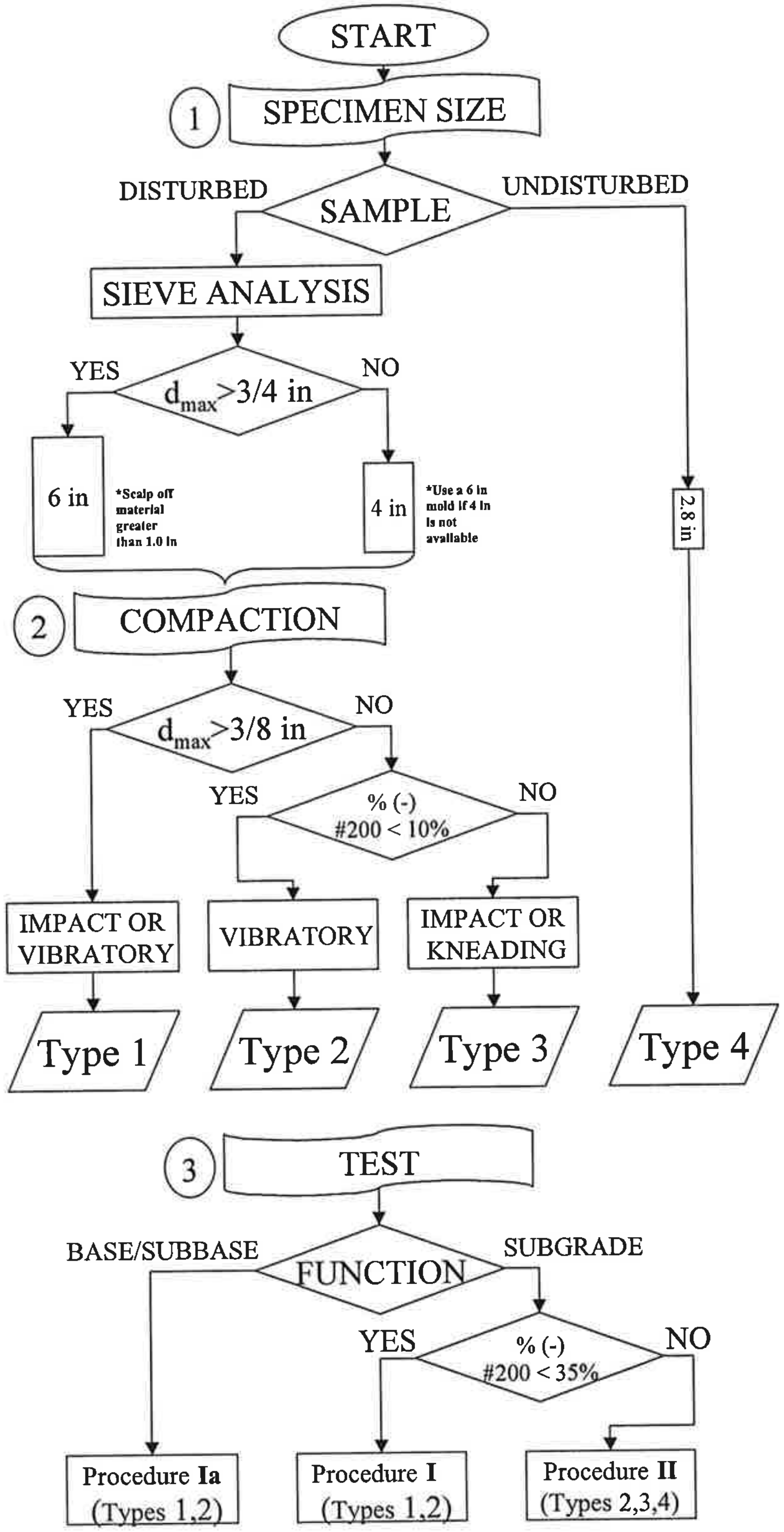


Figure 4-2. Harmonized Protocol Flowchart

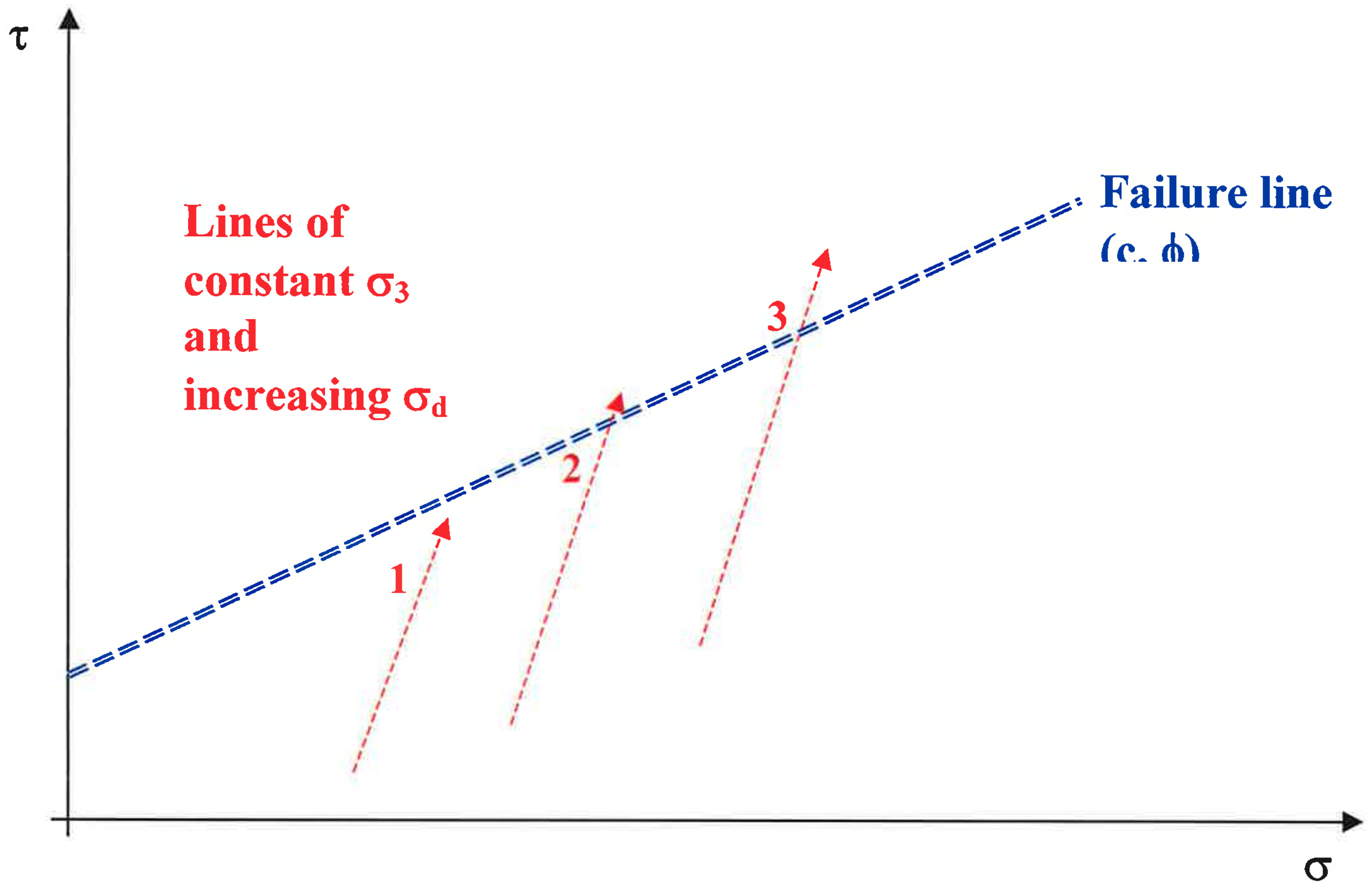


Figure 4-3. Variation of the State of Stress During the Test

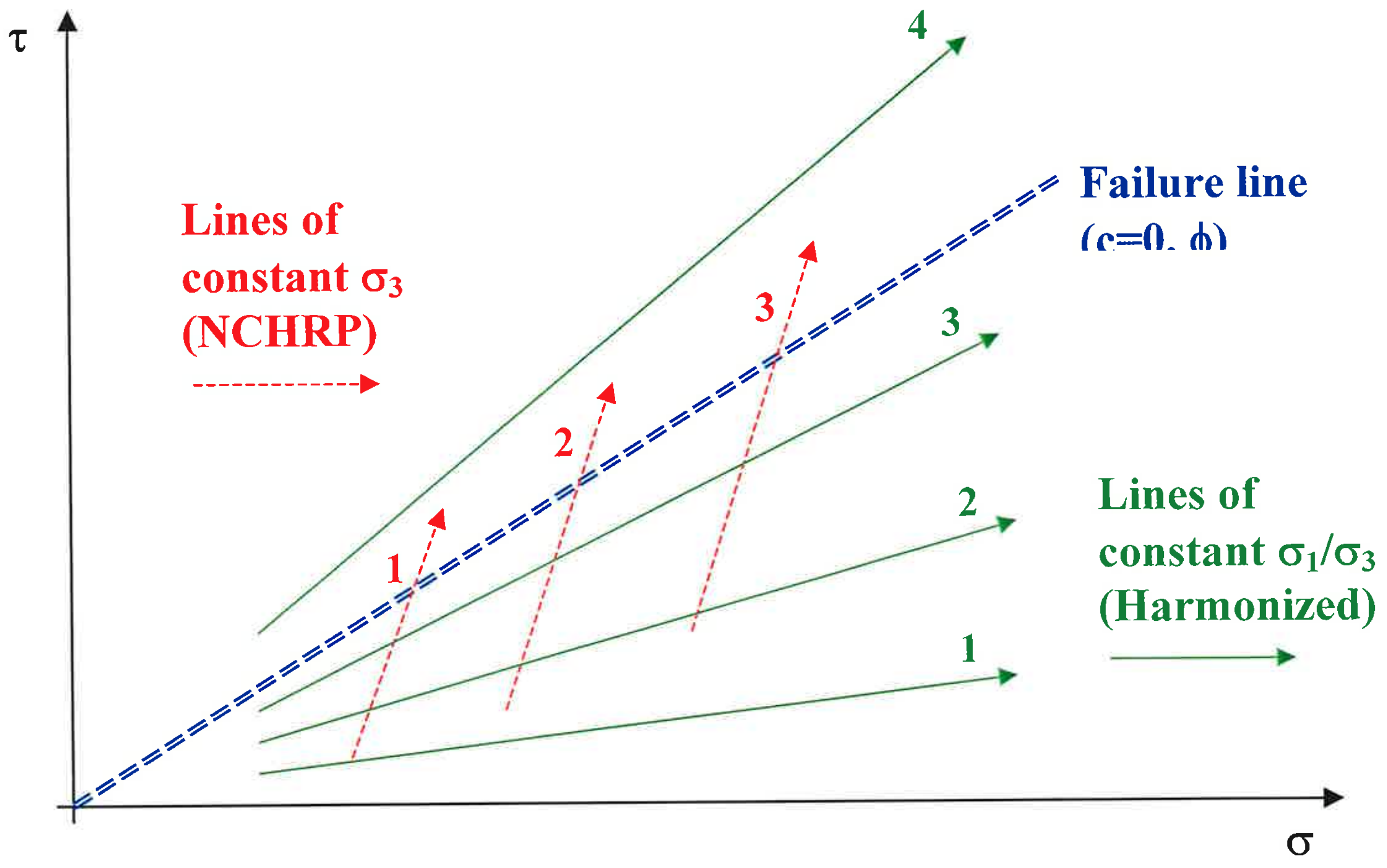


Figure 4-4. The Two Methods Compared, for a Pure Granular Material

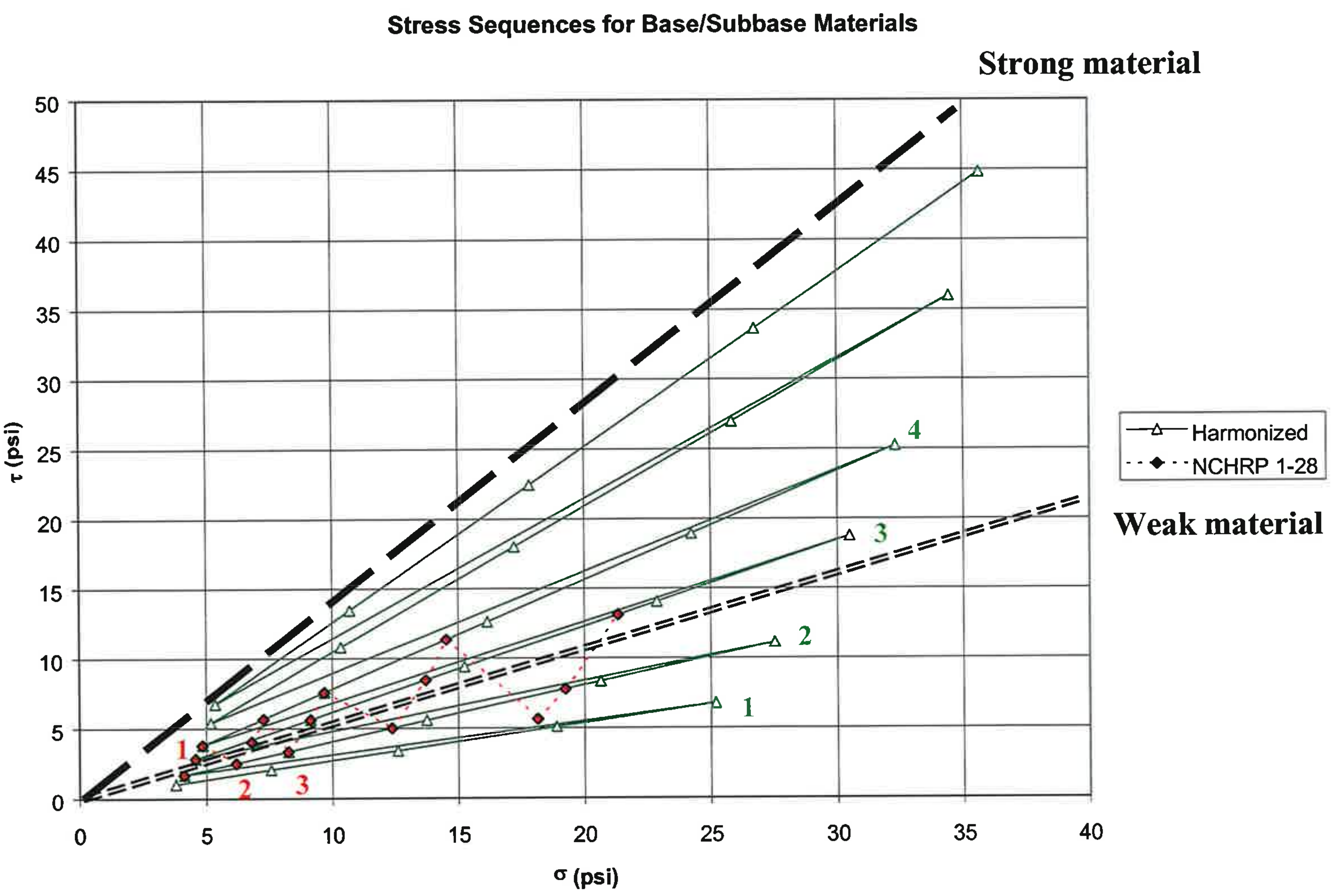


Figure 4-5. Actual Stress Combinations in the σ-τ Space, for Base/Subbase Materials

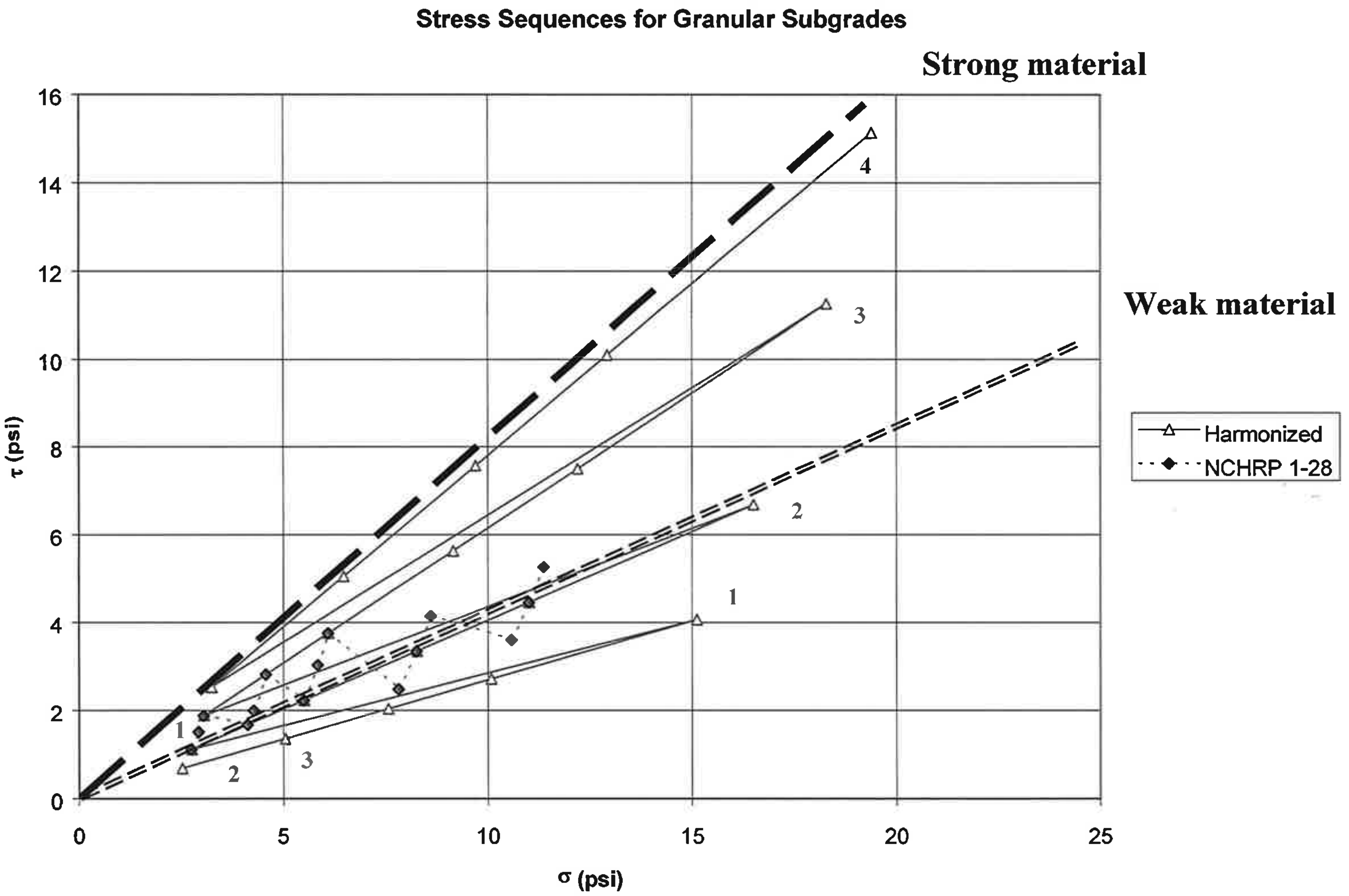


Figure 4-6. Actual Stress Combinations in the σ-τ Space, for Coarse-Grained Subgrades

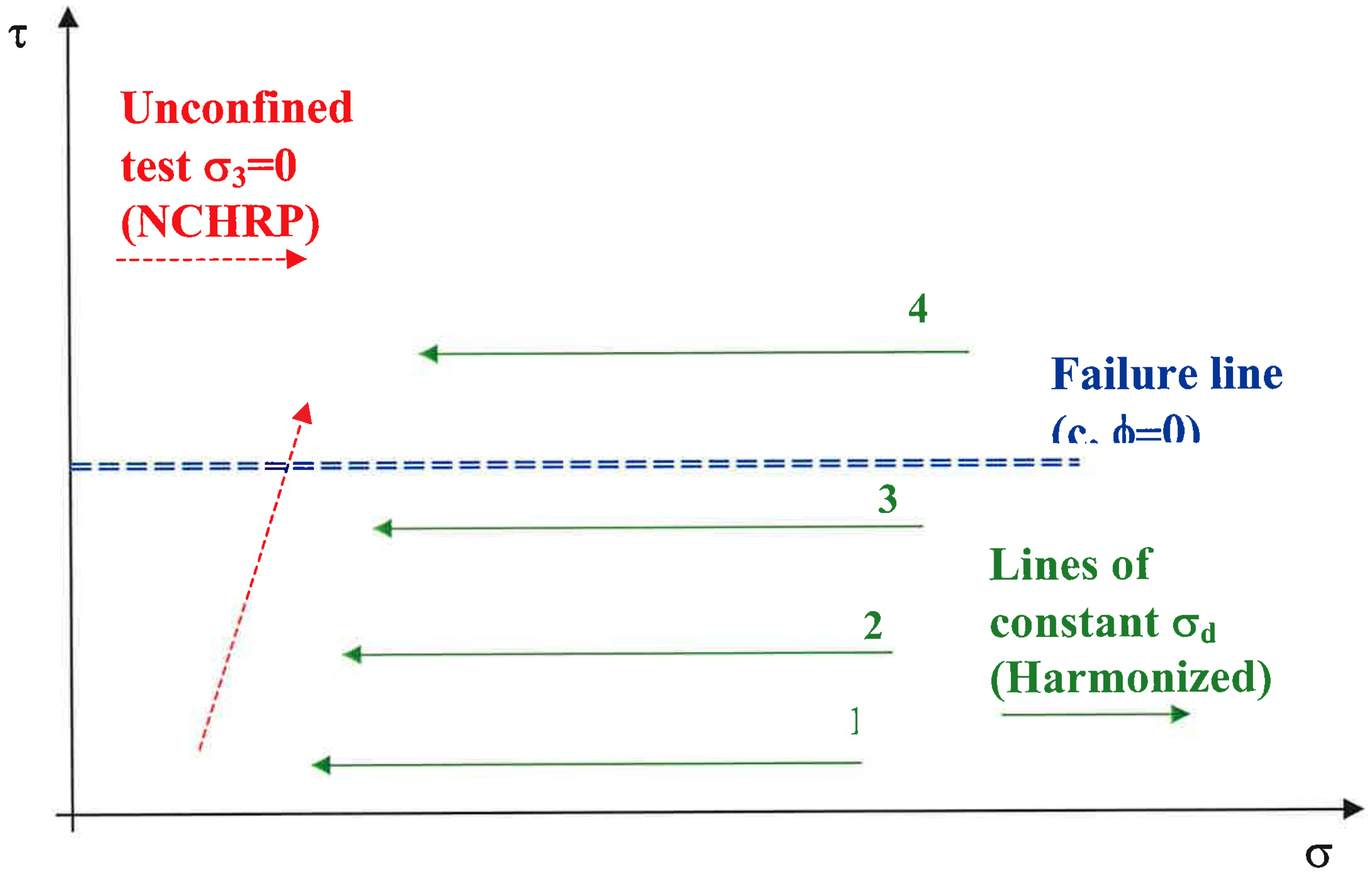


Figure 4-7. The Two Methods Compared, for a Pure Cohesive Material

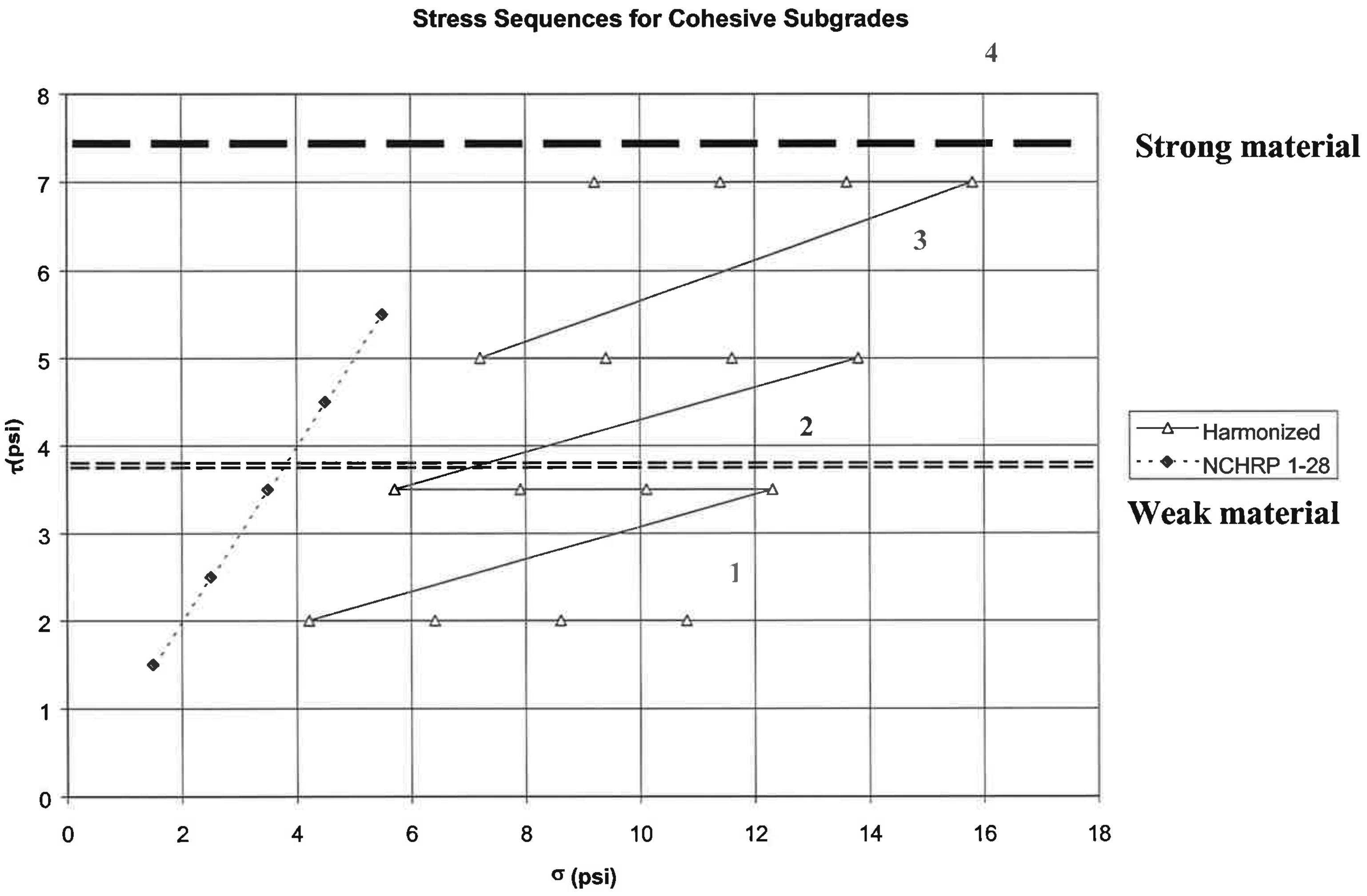


Figure 4-8. Actual Stress Combinations in the σ-τ Space, for Fine Grained Subgrades

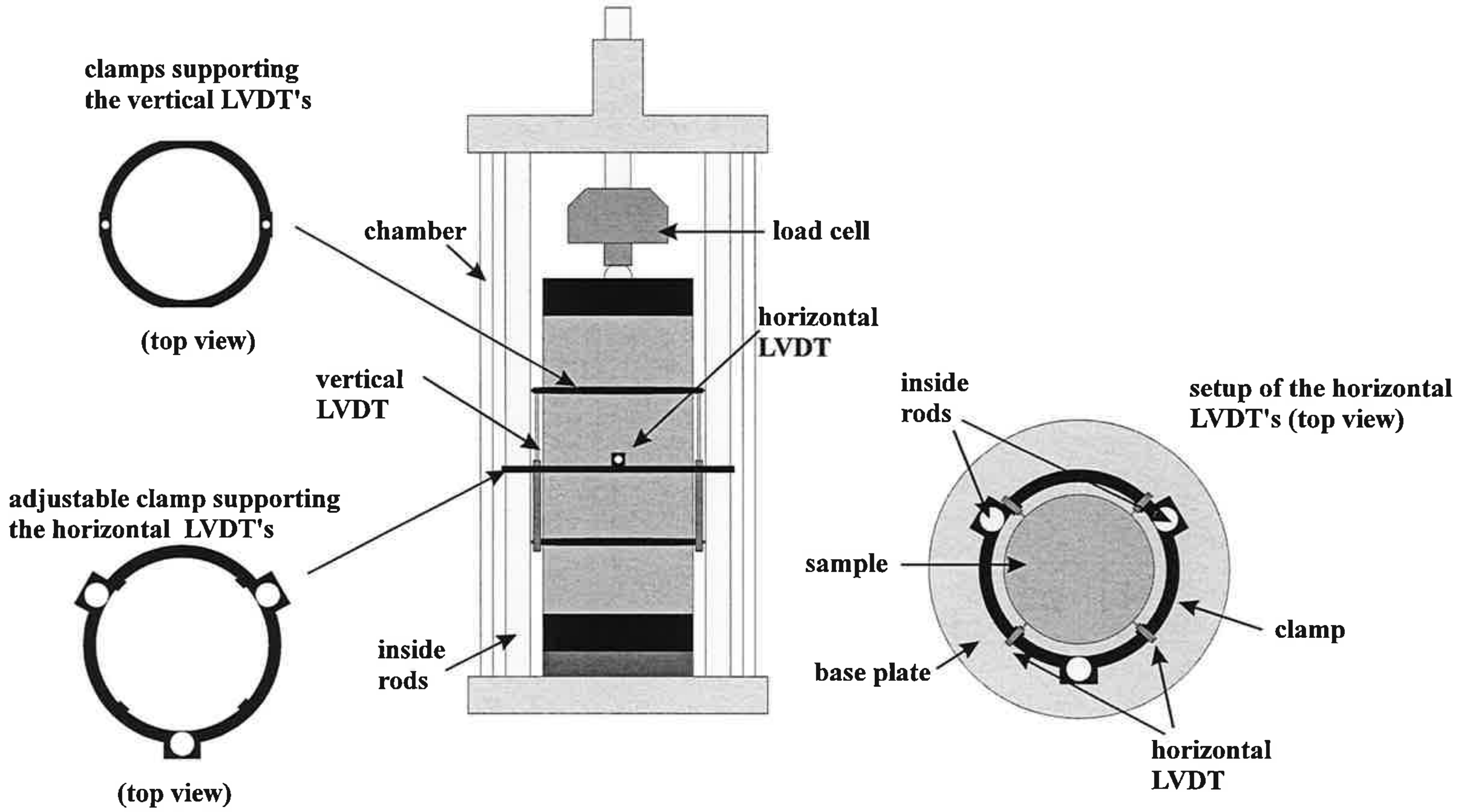


Figure 5-1.Triaxial Cell Set-Up

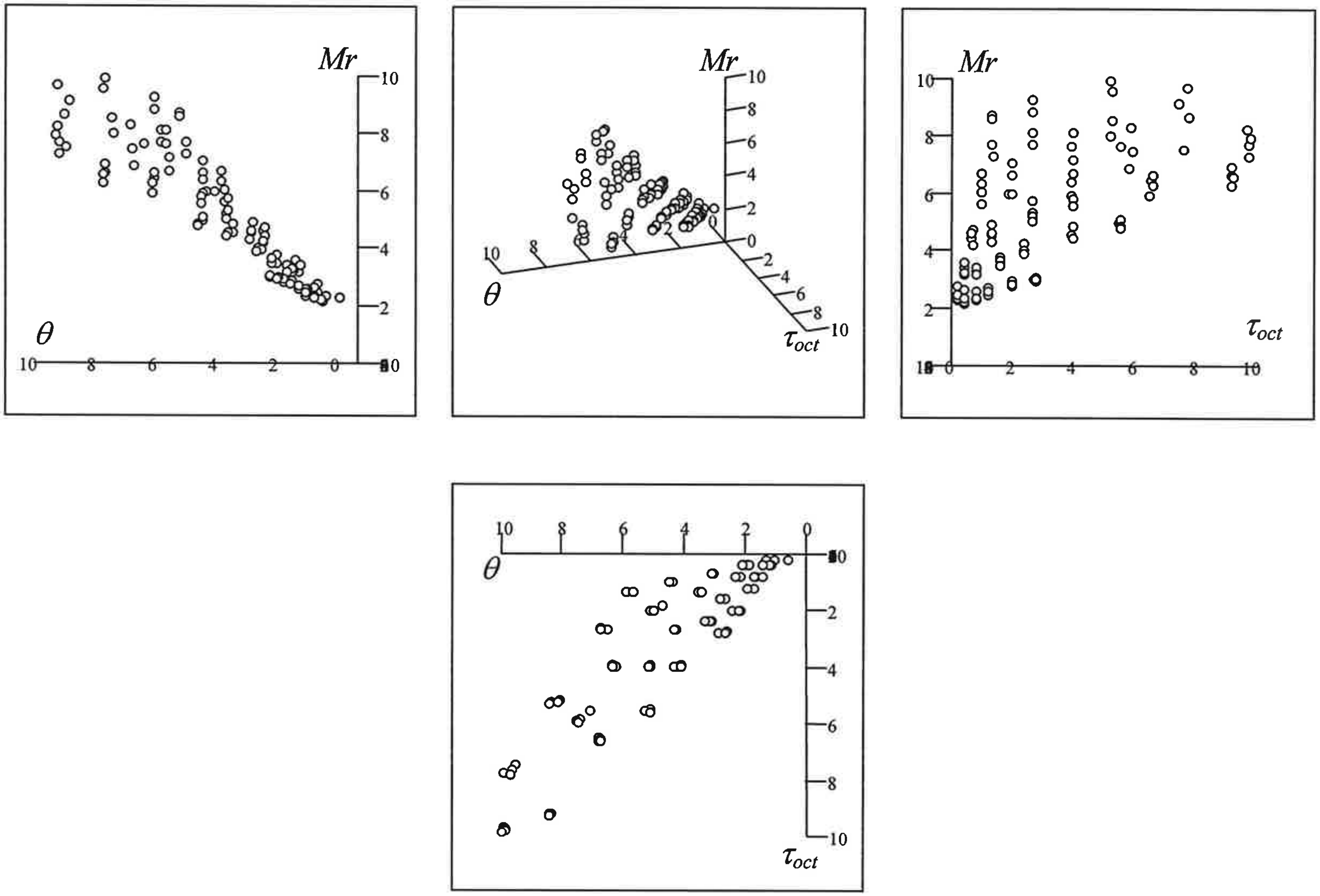


Figure 5-2. Test Results for Base/Subbase Materials, Procedure Ia (Harmonized Protocol)

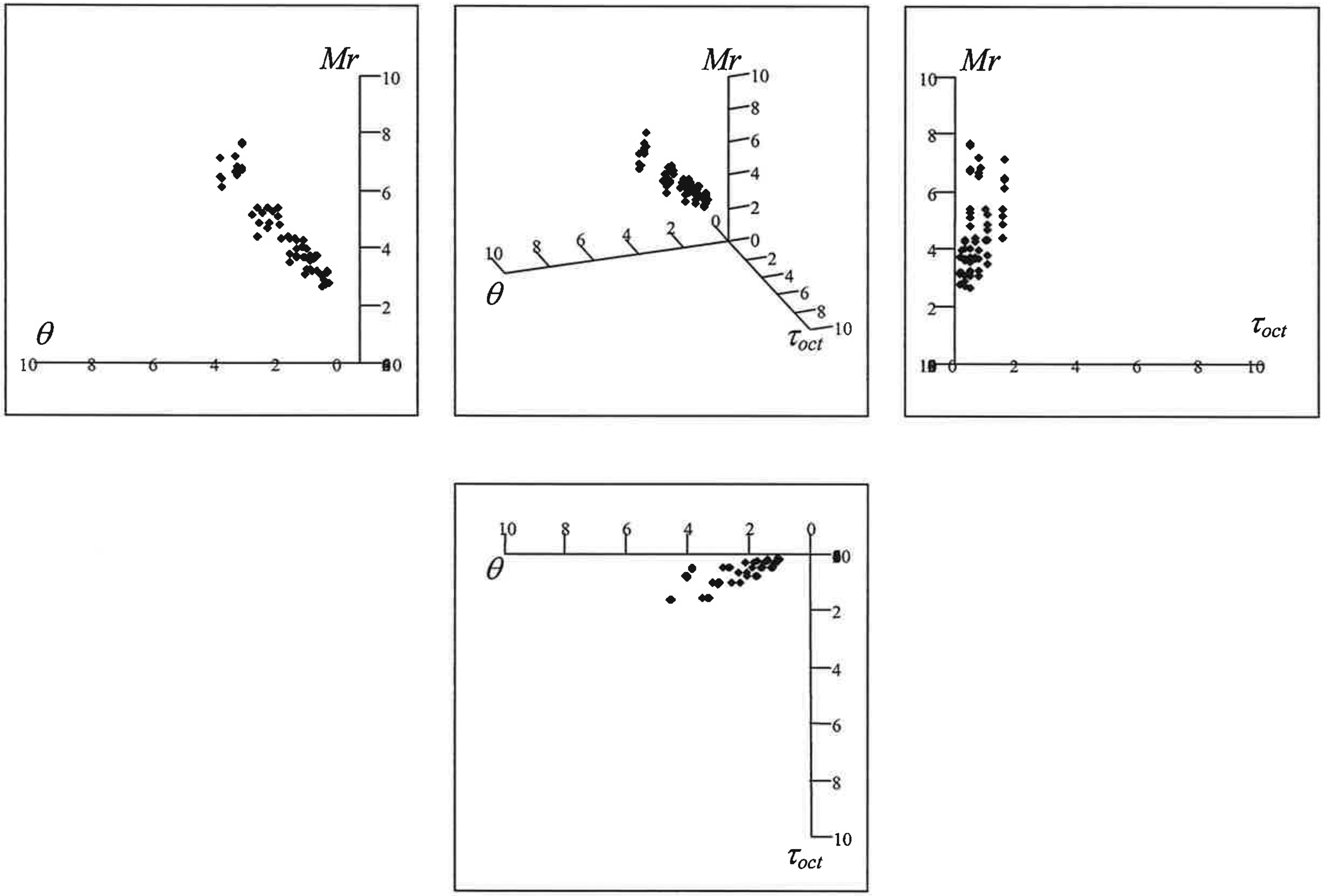


Figure 5-3. Test Results for Base/Subbase Materials, NCHRP 1-28 Procedure

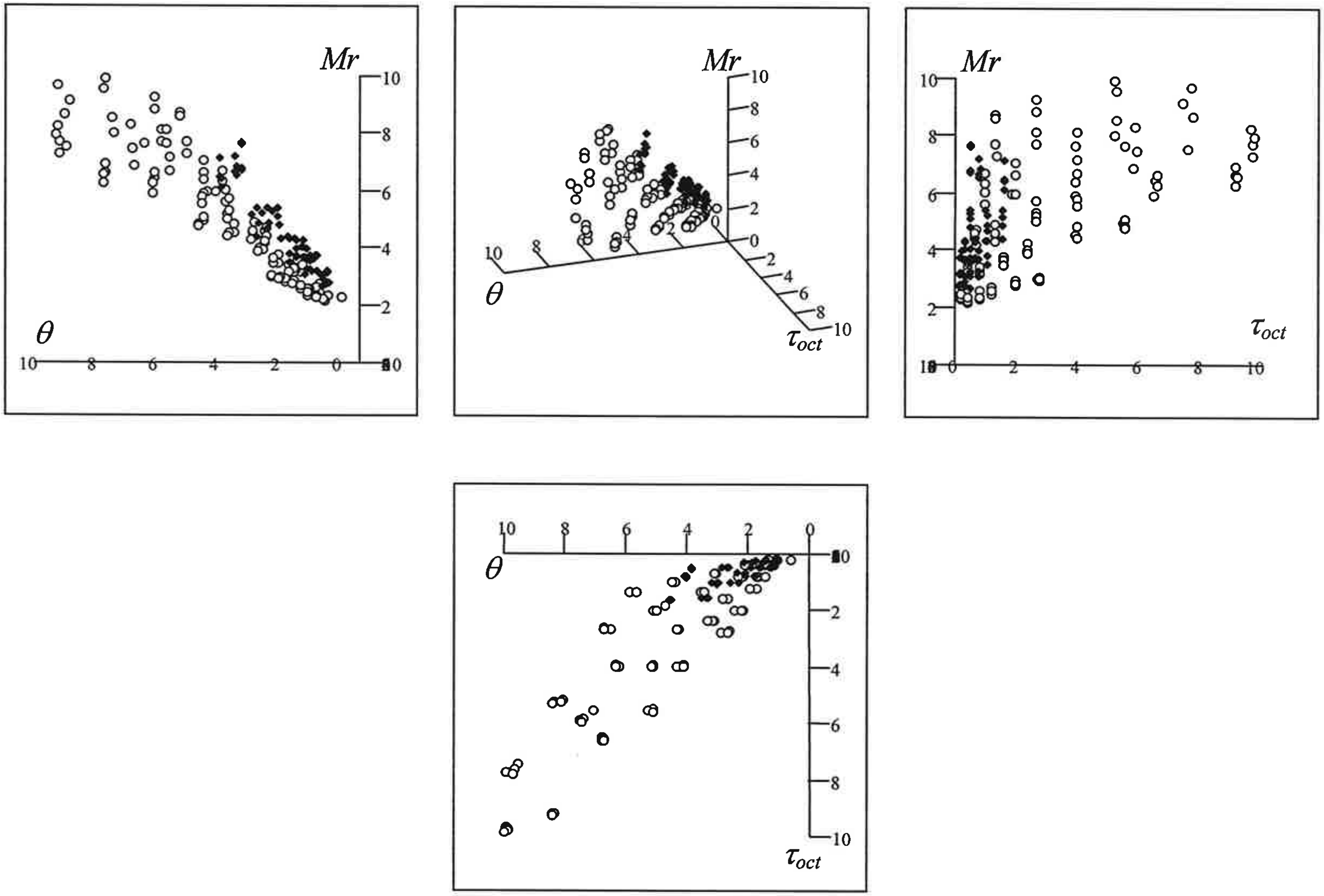


Figure 5-4. Superposition of Test Results for Base/Subbase Materials (NCHRP - Black Diamonds, Harmonized - White Circles)

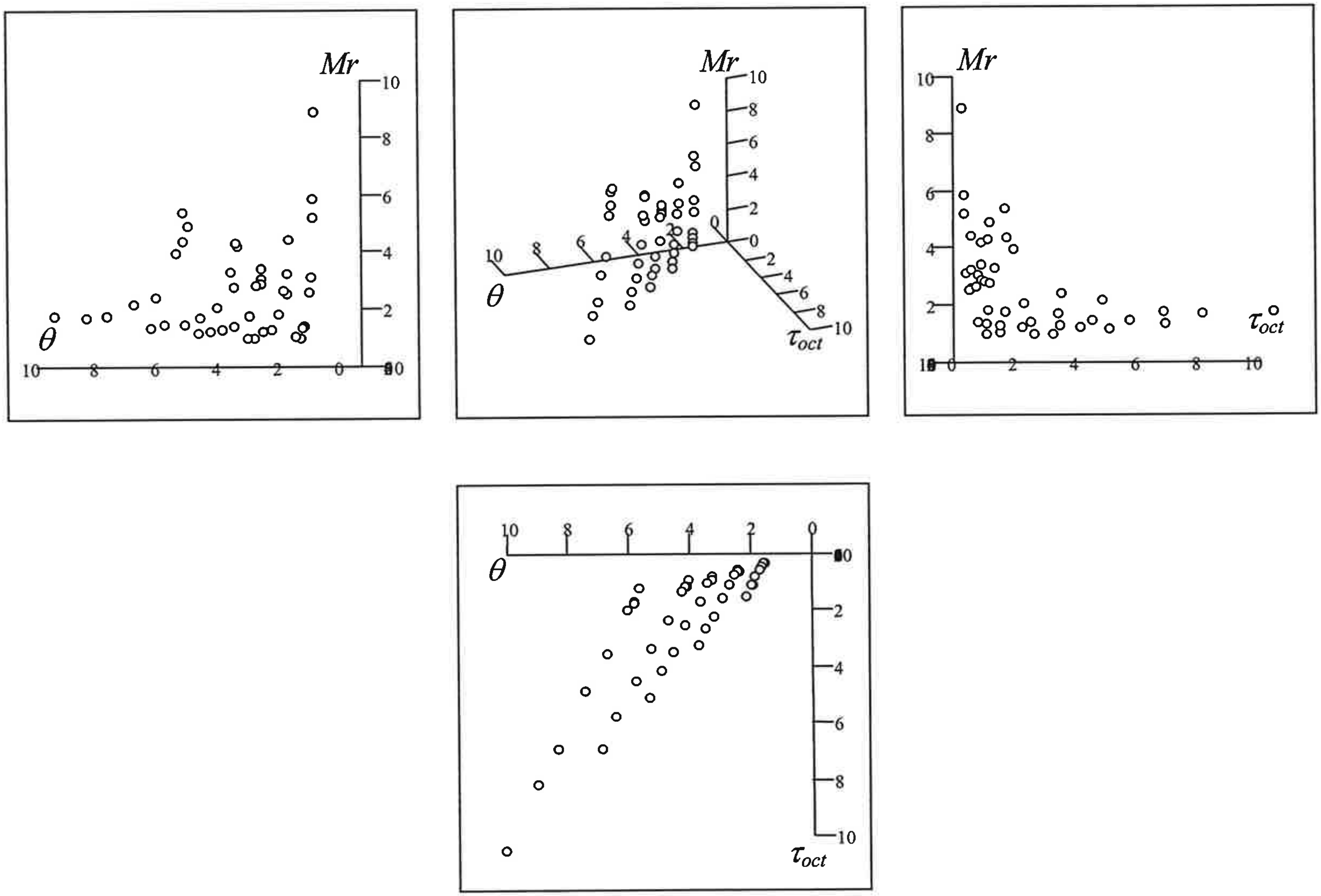


Figure 5-5. Test Results for Coarse Grained Subgrades, Procedure Ib (Harmonized Protocol)

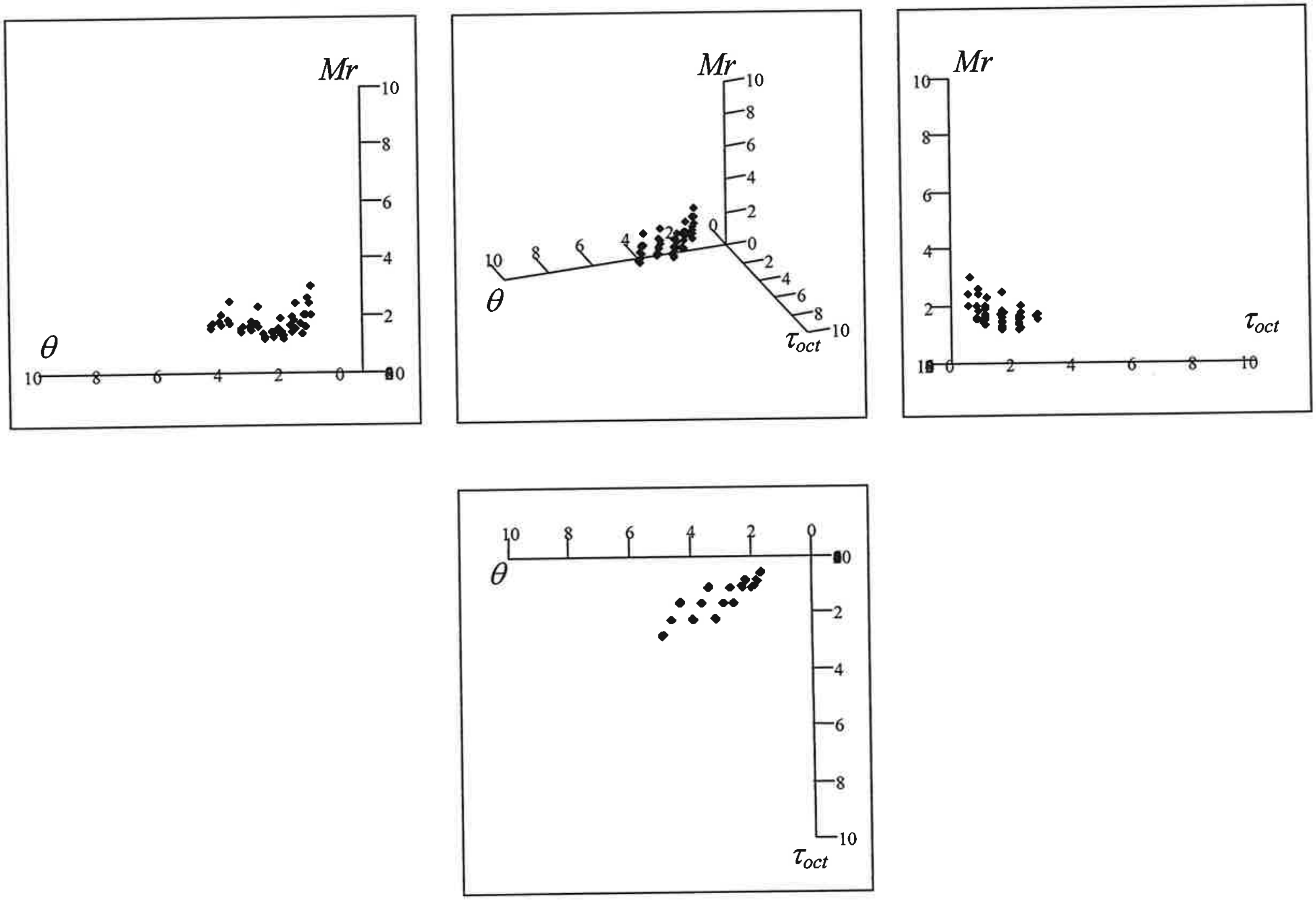


Figure 5-6. Test Results for Coarse Grained Subgrades, NCHRP 1-28 Procedure

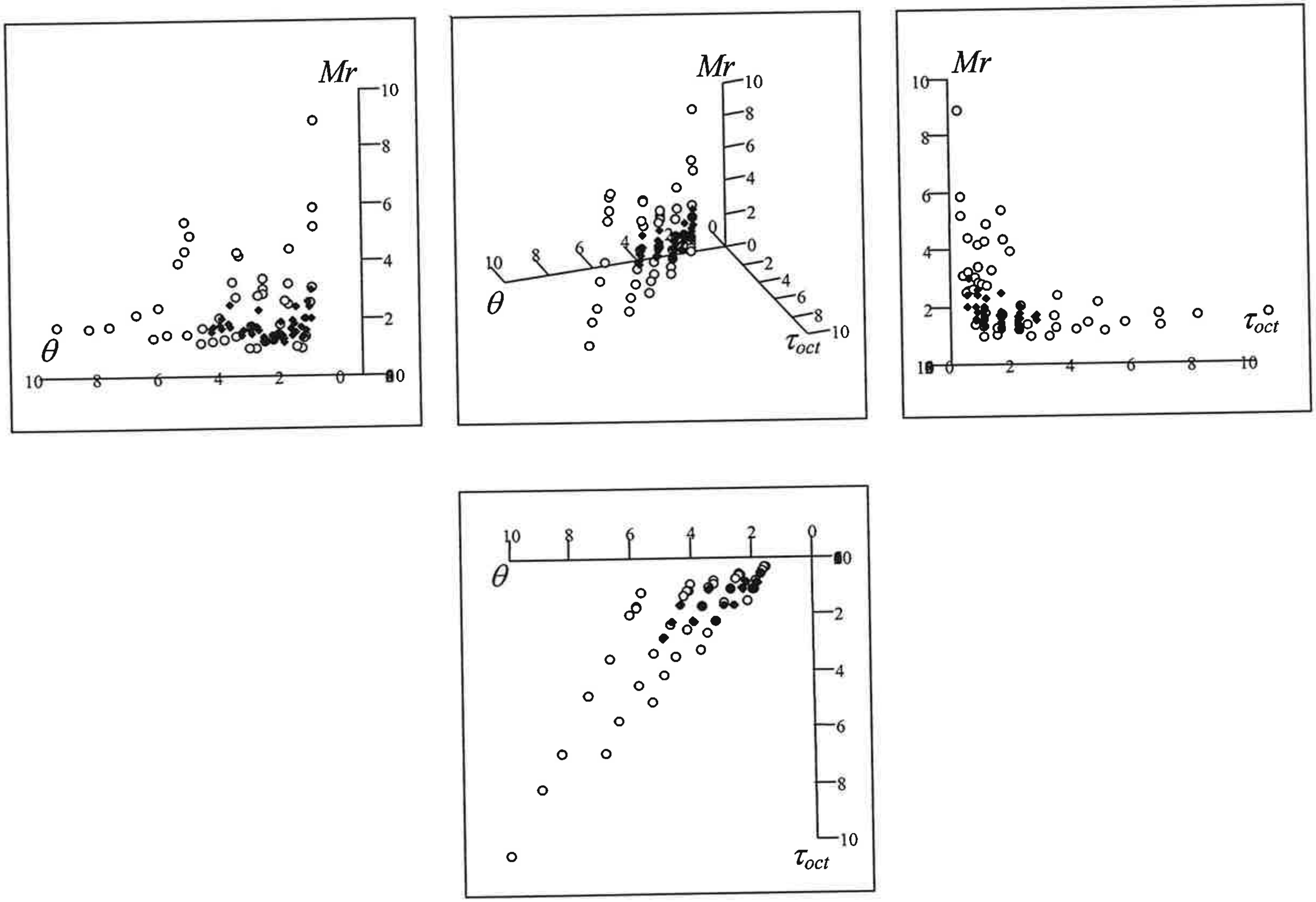


Figure 5-7. Superposition of Test Results for Coarse Grained Subgrades (NCHRP- Black Diamonds, Harmonized - White Circles)

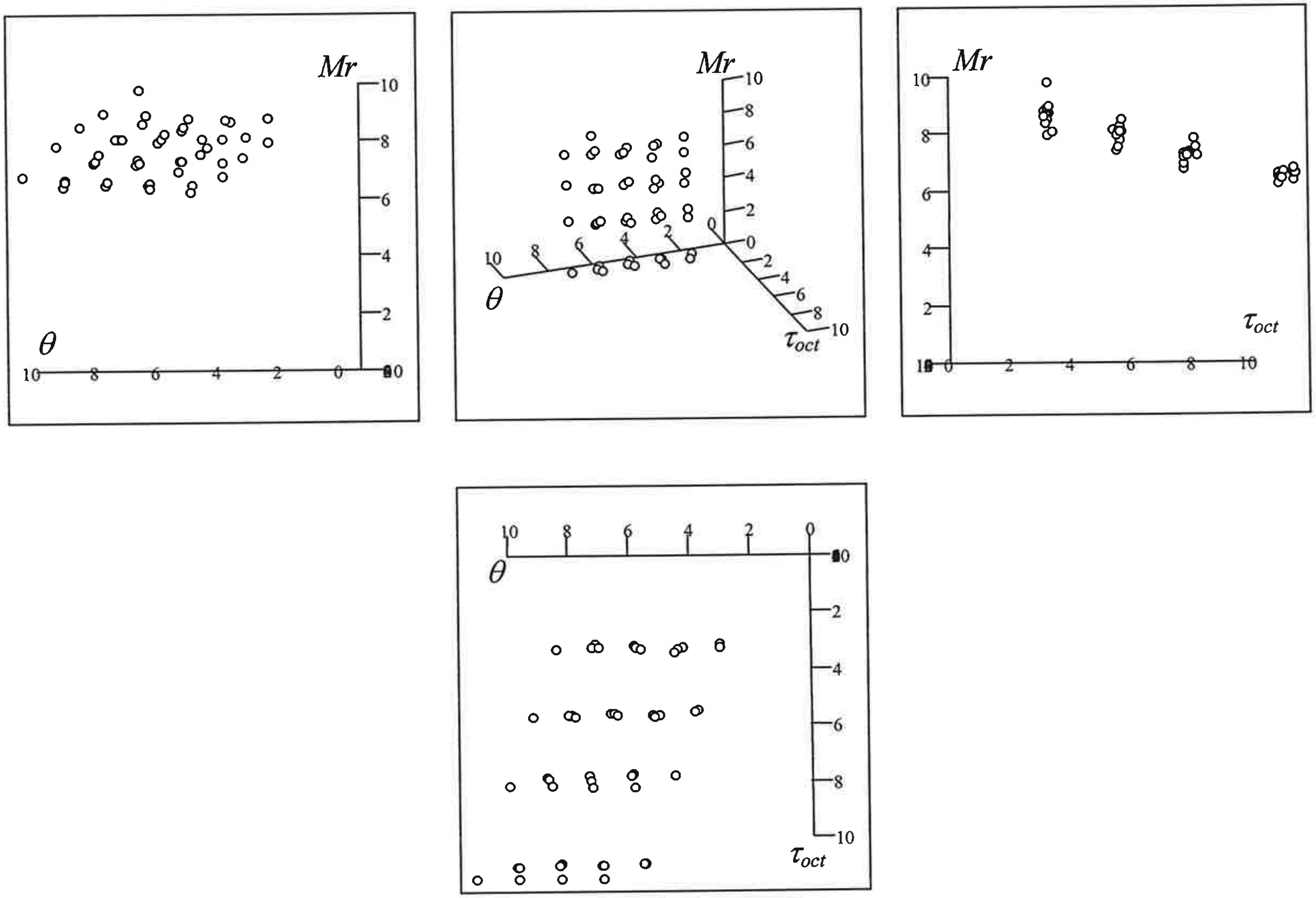


Figure 5-8. Test Results for Fine Grained Subgrades, Procedure II (Harmonized Protocol)

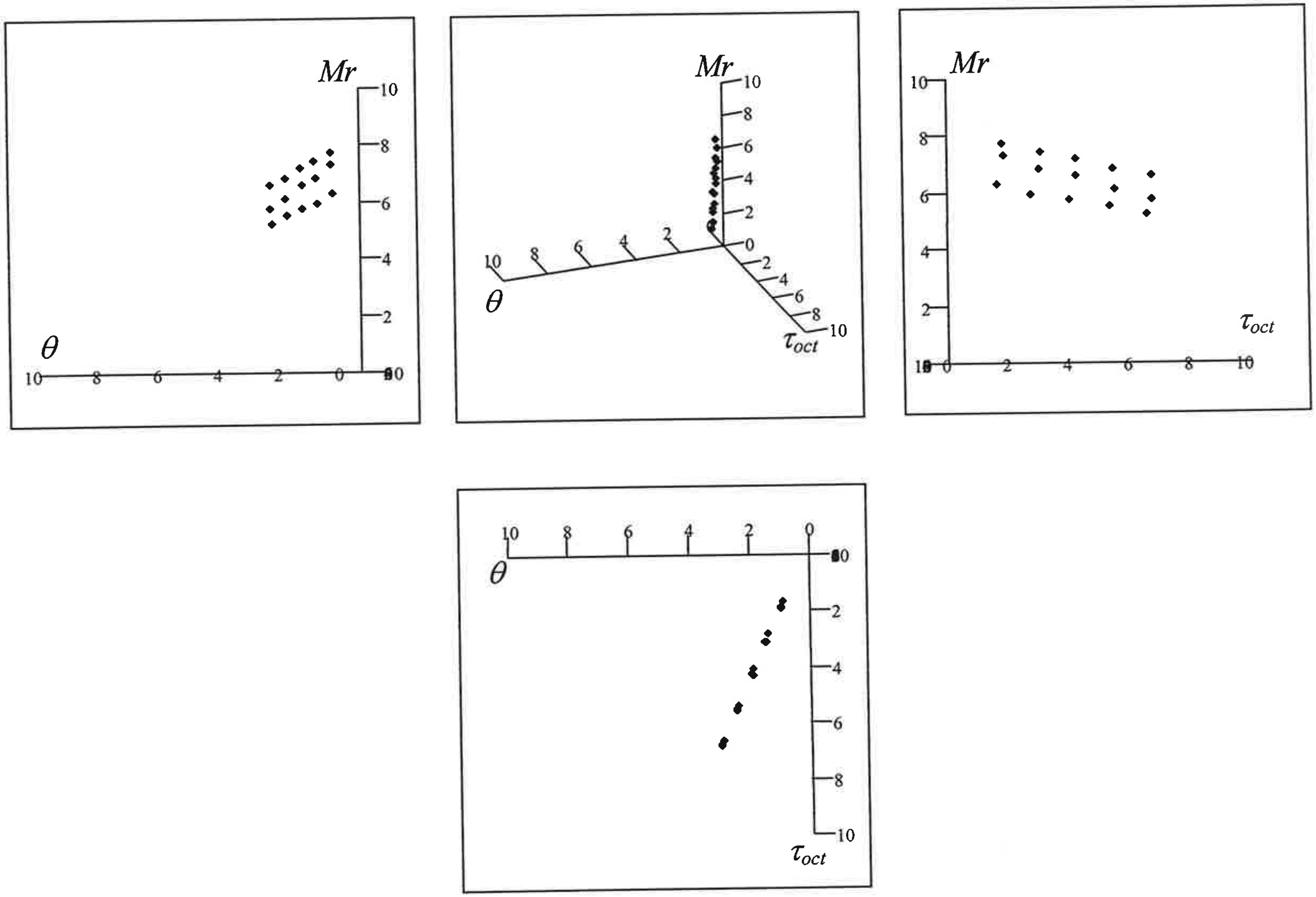


Figure 5-9. Test Results for Fine Grained Subgrades, NCHRP 1-28 Procedure

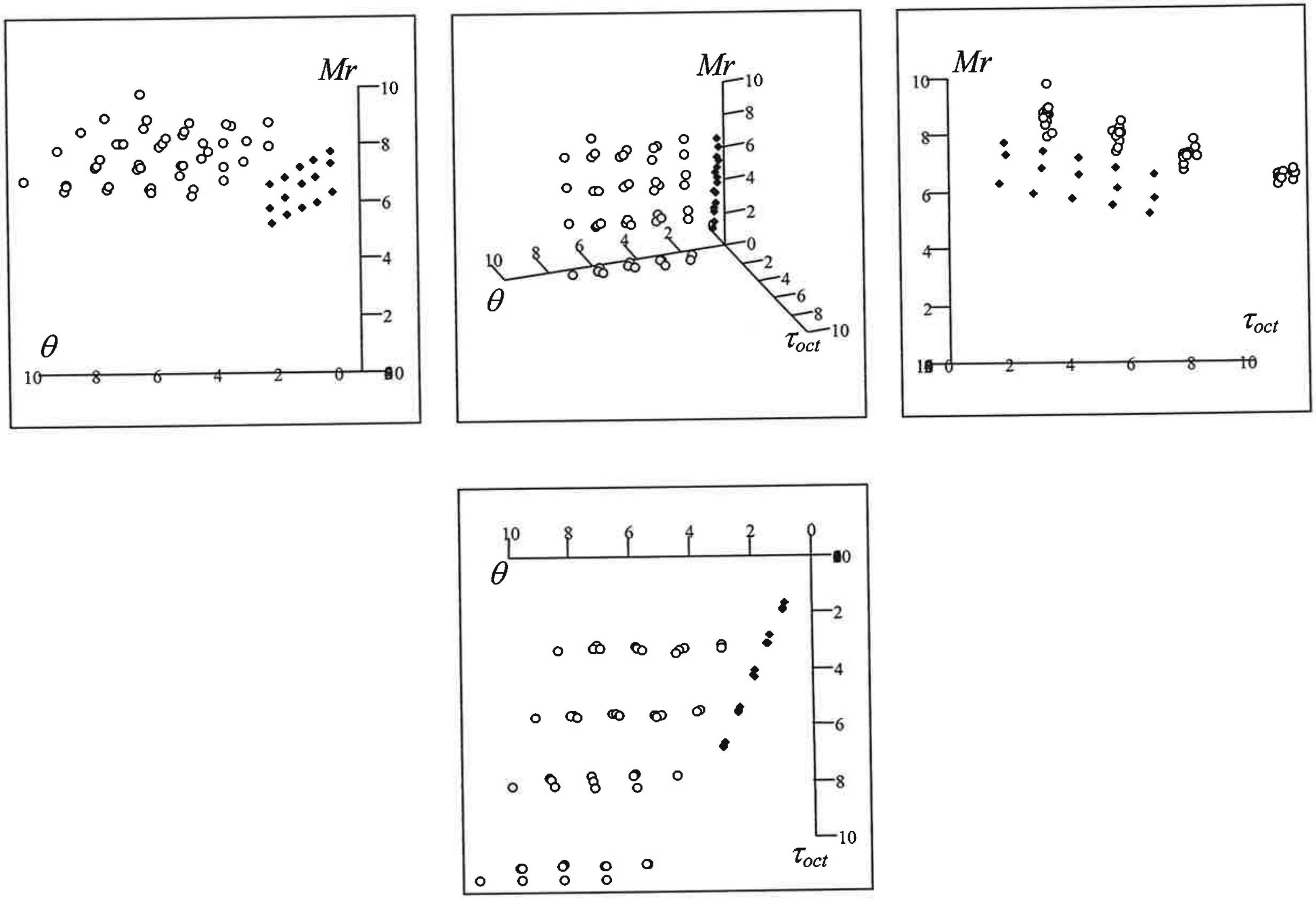


Figure 5-10. Superposition of Test Results for Fine Grained Subgrades (NCHRP - Black Diamonds, Harmonized - White Circles)

Resilient Modulus Model:

$$M_R = k_1 p_a \left(\frac{(\theta - k_6)}{p_a} \right)^{k_2} \left(\frac{\tau_{oct}}{p_a} \right)^{k_3}$$

Poisson's Ratio Model:

$$v(x, y, k_2, k_3, k_4, k_5, k_6) := (x - 3 \cdot k_6)^{k_2} \cdot y^{\frac{k_3}{2}} \cdot \left[k_4 \cdot \left[-\left[3 \cdot y - (x - 3 \cdot k_6)^2 \right] \right]^{k_5} + \frac{3^{\frac{k_3}{2}}}{2 \cdot \left[(x - 3 \cdot k_6)^2 - 3 \cdot y \right]^{\frac{k_2 + k_3}{2}}} \cdot \left[-k_2 \cdot B \left[\frac{k_2 + k_3}{2}, \frac{-k_3}{2} + 1, 1 - \frac{3 \cdot y}{(x - 3 \cdot k_6)^2} \right] \frac{k_3}{2} \cdot B \left[\frac{k_2 + k_3}{2}, \frac{-k_3}{2}, 1 - \frac{3 \cdot y}{(x - 3 \cdot k_6)^2} \right] \right] \right]$$

(Equation 6-11)

Where:

$x = \theta$

$y = 2/3(\tau_{oct})^2$

B(a,b,c) = The Incomplete Beta Function

Figure 6-1. SHRP-Superpave k1-k6 Model Formulation

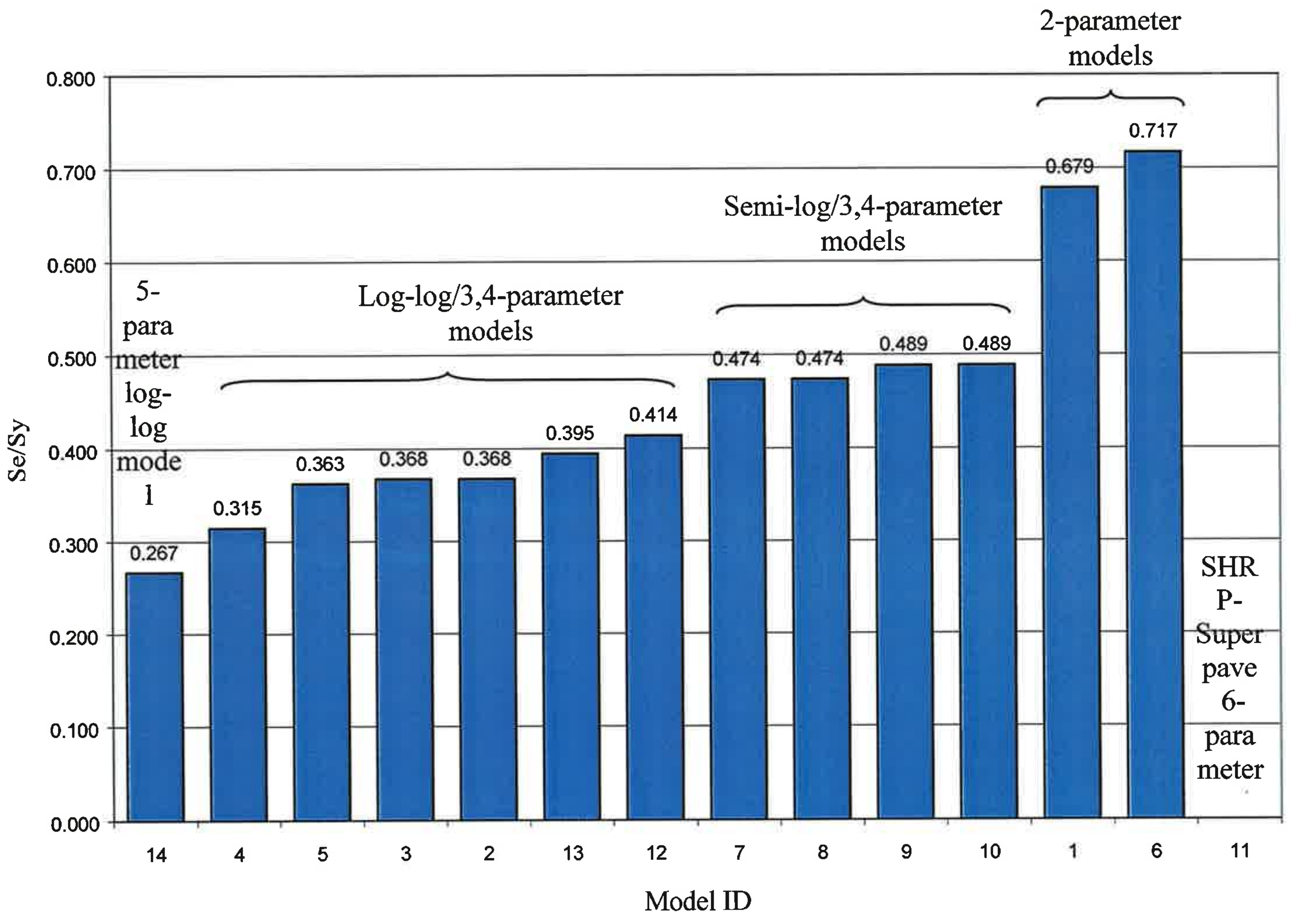
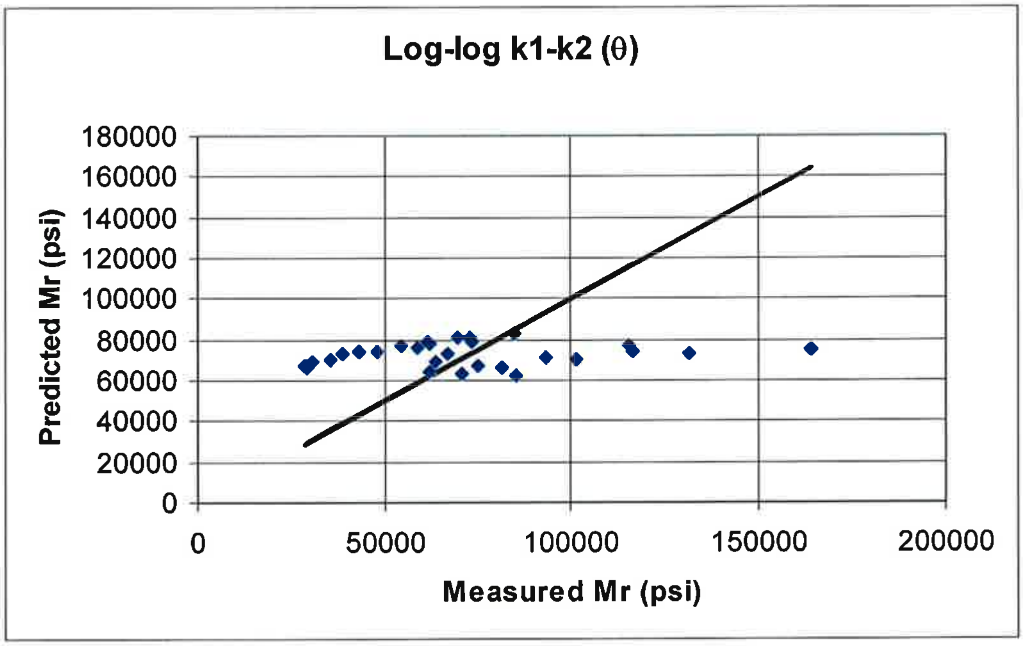


Figure 6-2. Average Se/Sy Ratios for All Models (Harmonized Data)



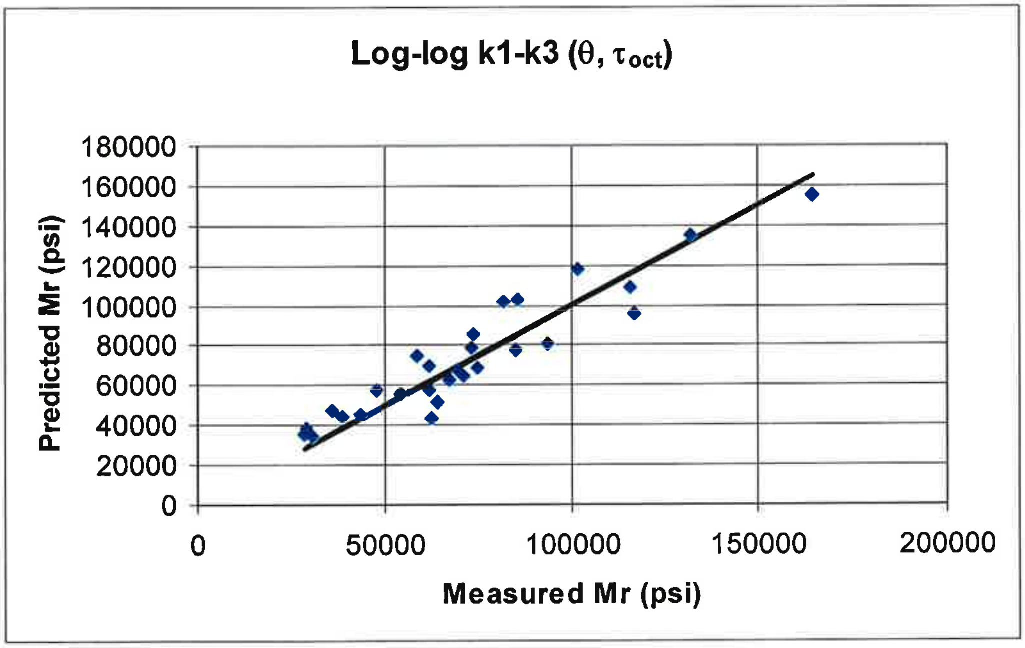
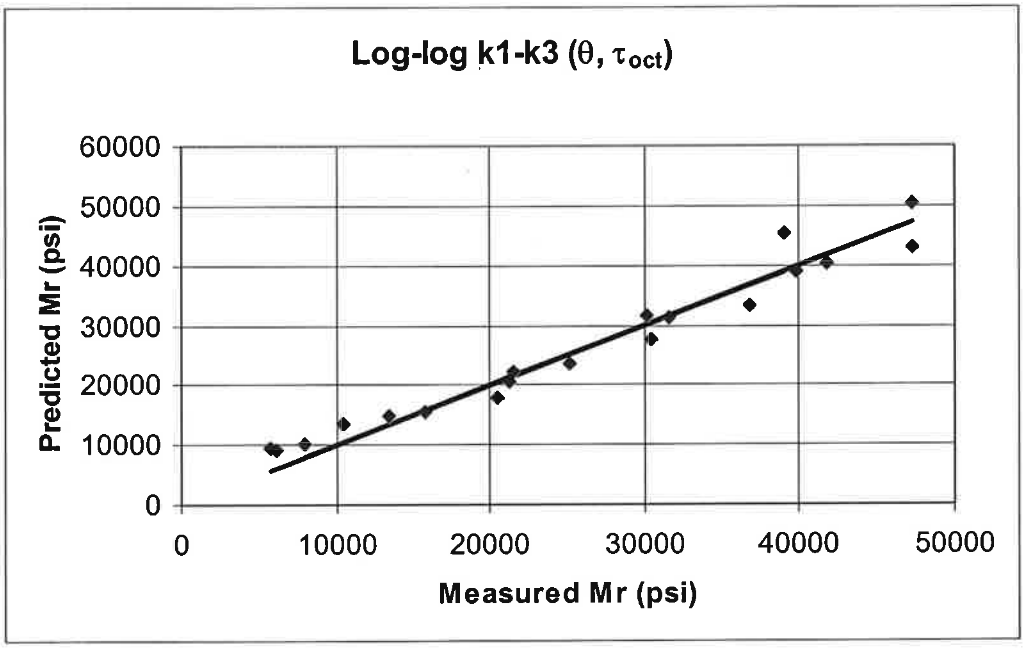


Figure 6-3. One Predictor Variable Vs. Two Predictor Variables (S12)



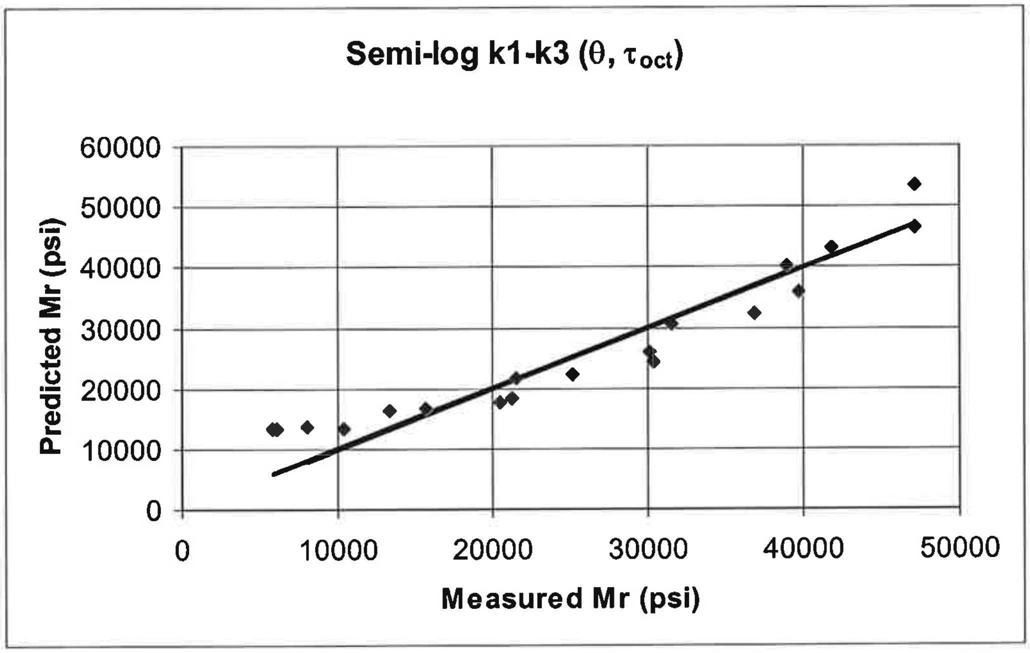
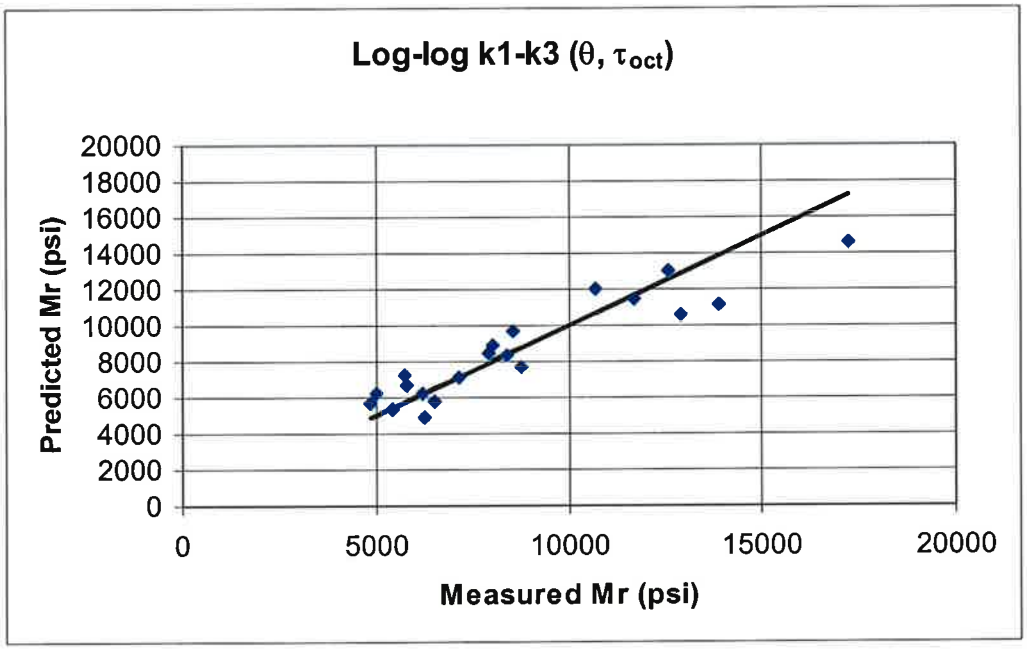


Figure 6-4. Log-log Vs. Semi-log Model Form (S12). Note Local Bias in Predictions for Semi-log Model



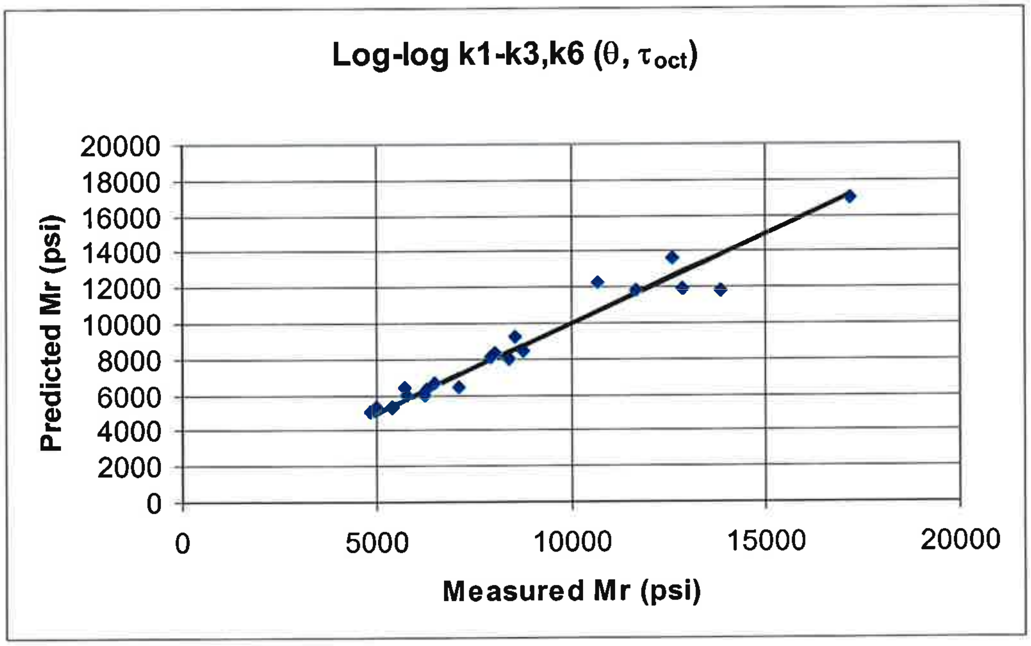
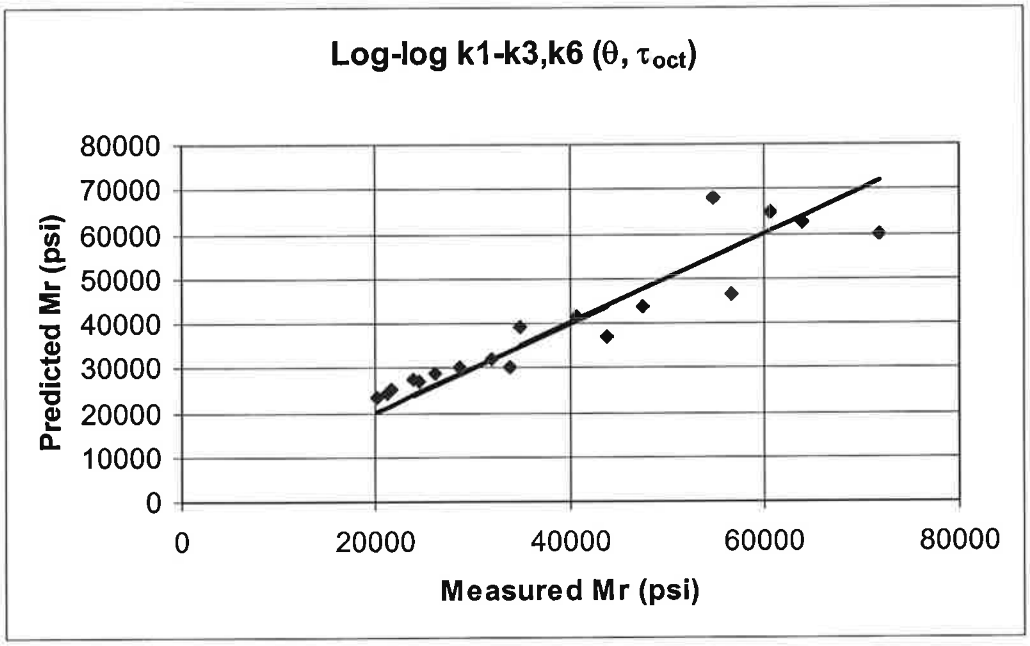


Figure 6-5. Effect of k_6 (S7)



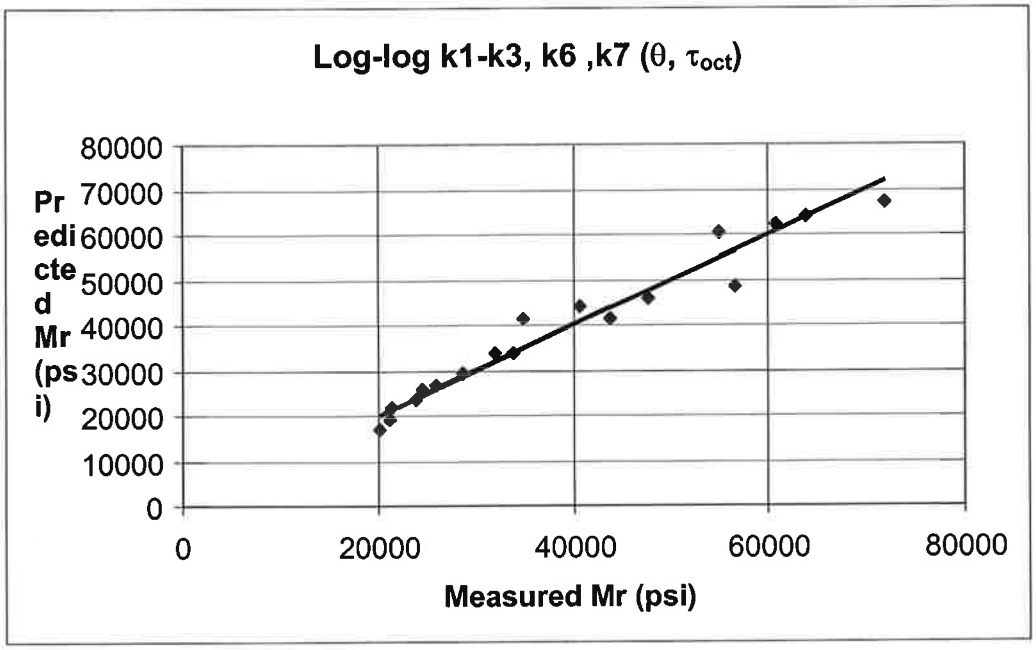


Figure 6-6. Effect of k_7 (S13)

TABLE A-1
SPECIFICATIONS FOR AXIAL LVDT'S AND NON-CONTACT PROXIMITY DEFORMATION MEASUREMENT INSTRUMENTATION

MATERIAL/SPECIMEN SIZE	MIN. RANGE (IN.) (+/-)	APPROX. RESILIENT SPECIMEN DISP. (IN.)	MINIMUM A.C. OUTPUT (MV)	TYPICAL LVDT MIN. SENSITIVITY @ 3V, MV/V/0.001 IN.	TYPICAL PROXIMITY GAUGE MIN. SENSITIVITY (MV/V/0.001 IN.)
AGGREGATE BASE					
6 IN DIA. SPECIMEN	0.25	0.001	6	2.1	-
4 IN DIA. SPECIMEN	0.1	0.00065	5	2.8	5
SUBGRADE SOIL – SAND					
4 IN DIA. SPECIMEN	.25	0.0014	8	2.1	-
2.8 IN DIA. SPECIMEN	.25	0.001	6	2.1	-
SUBGRADE SOIL – COHESIVE, 2.8 IN					
SOFT (NOTE 2)	0.1	0.008	20	1.8	2 – 5.0
FIRM	0.1	0.002	10	2.1	5
STIFF – VERY STIFF (NOTE 3)	0.1	0.0004	3.5	2.8 (NOTE 4)	5

NOTES:

1. MINIMUM RESILIENT DISPLACEMENTS, EXEPT AS NOTED, ARE MEASURED OVER THE CENTRAL ONE-HALF OF A SPECIMEN HAVING A HEIGHT TWICE ITS DIAMETER. CORRECT THIS DISPLACEMENT IF ANOTHER GAUGE LENGTH IS USED. MINIMUM RESILIENT MODULUS DISPLACEMENT IS APPROXIMATE AND VARIES WITH THE MATERIALS TESTED.

2. RESILIENT DISPLACEMENT MEASURED OVER ENTIRE SPECIMEN HEIGHT.

3. CONSIDER USING GROUTED ENDS AND TOP TO BOTTOM LVDT'S OR 4.0 IN DIAMETER SPECIMENS BECAUSE OF POTENTIALLY VERY SMALL DISPLACEMENT AT SMALL DEVIATOR STRESSES.

4. PUSH MEASUREMENT SYSTEM TO MAXIMUM OUTPUT: CONSIDER EXCEEDING RECOMMENDED VOLTAGE.

TABLE A-2
PROCEDURE Ib - TEST SEQUENCE FOR GRANULAR SUBGRADES

Procedure Ib (Granular Subgrades)									
Sequence	**Confining Pressure**		**Contact Stress**		**Cyclic Stress**		**Maximum Stress**		**Nrep**
	kPa	**psi**	**kPa**	**psi**	**kPa**	**psi**	**kPa**	**psi**	
0	27.6	4.0	5.5	0.8	55.2	8.0	60.7	8.8	1000
1	13.8	2.0	2.8	0.4	6.9	1.0	9.7	1.4	100
2	27.6	4.0	5.5	0.8	13.8	2.0	19.3	2.8	100
3	41.4	6.0	8.3	1.2	20.7	3.0	29.0	4.2	100
4	55.2	8.0	11.0	1.6	27.6	4.0	38.6	5.6	100
5	82.8	12.0	16.6	2.4	41.4	6.0	58.0	8.4	100
6	13.8	2.0	2.8	0.4	13.8	2.0	16.6	2.4	100
7	27.6	4.0	5.5	0.8	27.6	4.0	33.1	4.8	100
8	41.4	6.0	8.3	1.2	41.4	6.0	49.7	7.2	100
9	55.2	8.0	11.0	1.6	55.2	8.0	66.2	9.6	100
10	82.8	12.0	16.6	2.4	82.8	12.0	99.4	14.4	100
11	13.8	2.0	2.8	0.4	27.6	4.0	30.4	4.4	100
12	27.6	4.0	5.5	0.8	55.2	8.0	60.7	8.8	100
13	41.4	6.0	8.3	1.2	82.8	12.0	91.1	13.2	100
14	55.2	8.0	11.0	1.6	110.4	16.0	121.4	17.6	100
15	82.8	12.0	16.6	2.4	165.6	24.0	182.2	26.4	100
16	13.8	2.0	2.8	0.4	41.4	6.0	44.2	6.4	100
17	27.6	4.0	5.5	0.8	82.8	12.0	88.3	12.8	100
18	41.4	6.0	8.3	1.2	124.2	18.0	132.5	19.2	100
19	55.2	8.0	11.0	1.6	165.6	24.0	176.6	25.6	100
20	82.8	12.0	16.6	2.4	248.4	36.0	265.0	38.4	100

TABLE A-3
PROCEDURE II - TEST SEQUENCE FOR FINE-GRAINED SUBGRADES

Procedure II (Cohesive Subgrades)									
Sequence	**Confining Pressure**		**Contact Stress**		**Cyclic Stress**		**Maximum Stress**		**Nrep**
	kPa	**psi**	**kPa**	**psi**	**kPa**	**psi**	**kPa**	**psi**	
0	27.6	4.0	5.5	0.8	48.3	7.0	53.8	7.8	1000
1	55.2	8.0	11.0	1.6	27.6	4.0	38.6	5.6	100
2	41.4	6.0	8.3	1.2	27.6	4.0	35.9	5.2	100
3	27.6	4.0	5.5	0.8	27.6	4.0	33.1	4.8	100
4	13.8	2.0	2.8	0.4	27.6	4.0	30.4	4.4	100
5	55.2	8.0	11.0	1.6	48.3	7.0	59.3	8.6	100
6	41.4	6.0	8.3	1.2	48.3	7.0	56.6	8.2	100
7	27.6	4.0	5.5	0.8	48.3	7.0	53.8	7.8	100
8	13.8	2.0	2.8	0.4	48.3	7.0	51.1	7.4	100
9	55.2	8.0	11.0	1.6	69.0	10.0	80.0	11.6	100
10	41.4	6.0	8.3	1.2	69.0	10.0	77.3	11.2	100
11	27.6	4.0	5.5	0.8	69.0	10.0	74.5	10.8	100
12	13.8	2.0	2.8	0.4	69.0	10.0	71.8	10.4	100
13	55.2	8.0	11.0	1.6	96.6	14.0	107.6	15.6	100
14	41.4	6.0	8.3	1.2	96.6	14.0	104.9	15.2	100
15	27.6	4.0	5.5	0.8	96.6	14.0	102.1	14.8	100
16	13.8	2.0	2.8	0.4	96.6	14.0	99.4	14.4	100

TABLE A-4
PROCEDURE Ia - TEST SEQUENCE FOR BASE/SUBBASE MATERIALS

Procedure Ia (Base/Subbase Materials)									
Sequence	Confining Pressure		Contact Stress		Cyclic Stress		Maximum Stress		Nrep
	kPa	psi	kPa	psi	kPa	psi	kPa	psi	
0	103.5	15.0	20.7	3.0	207.0	30.0	227.7	33.0	1000
1	20.7	3.0	4.1	0.6	10.4	1.5	14.5	2.1	100
2	41.4	6.0	8.3	1.2	20.7	3.0	29.0	4.2	100
3	69.0	10.0	13.8	2.0	34.5	5.0	48.3	7.0	100
4	103.5	15.0	20.7	3.0	51.8	7.5	72.5	10.5	100
5	138.0	20.0	27.6	4.0	69.0	10.0	96.6	14.0	100
6	20.7	3.0	4.1	0.6	20.7	3.0	24.8	3.6	100
7	41.4	6.0	8.3	1.2	41.4	6.0	49.7	7.2	100
8	69.0	10.0	13.8	2.0	69.0	10.0	82.8	12.0	100
9	103.5	15.0	20.7	3.0	103.5	15.0	124.2	18.0	100
10	138.0	20.0	27.6	4.0	138.0	20.0	165.6	24.0	100
11	20.7	3.0	4.1	0.6	41.4	6.0	45.5	6.6	100
12	41.4	6.0	8.3	1.2	82.8	12.0	91.1	13.2	100
13	69.0	10.0	13.8	2.0	138.0	20.0	151.8	22.0	100
14	103.5	15.0	20.7	3.0	207.0	30.0	227.7	33.0	100
15	138.0	20.0	27.6	4.0	276.0	40.0	303.6	44.0	100
16	20.7	3.0	4.1	0.6	62.1	9.0	66.2	9.6	100
17	41.4	6.0	8.3	1.2	124.2	18.0	132.5	19.2	100
18	69.0	10.0	13.8	2.0	207.0	30.0	220.8	32.0	100
19	103.5	15.0	20.7	3.0	310.5	45.0	331.2	48.0	100
20	138.0	20.0	27.6	4.0	414.0	60.0	441.6	64.0	100
21	20.7	3.0	4.1	0.6	103.5	15.0	107.6	15.6	100
22	41.4	6.0	8.3	1.2	207.0	30.0	215.3	31.2	100
23	69.0	10.0	13.8	2.0	345.0	50.0	358.8	52.0	100
24	103.5	15.0	20.7	3.0	517.5	75.0	538.2	78.0	100
25	138.0	20.0	27.6	4.0	690.0	100.0	717.6	104.0	100
26	20.7	3.0	4.1	0.6	144.9	21.0	149.0	21.6	100
27	41.4	6.0	8.3	1.2	289.8	42.0	298.1	43.2	100
28	69.0	10.0	13.8	2.0	483.0	70.0	496.8	72.0	100
29	103.5	15.0	20.7	3.0	724.5	105.0	745.2	108.0	100
30	138.0	20.0	27.6	4.0	966.0	140.0	993.6	144.0	100

TABLE B-1
TEST PARAMETERS

Type	Test ID	Soil ID (Table B-4)	Specimen Size (inXin)	Compactive effort	γ_{dry} (pcf)	% γ_{opt}	w (%)	% w_{opt}	Procedure ID (Table B-3)
replicate	S12_1	S12	6X12	modified	139.76	96.72	4.07	92.61	UMd-Ia
replicate	S12_2	S12	6X12	modified	138.64	95.94	4.51	102.40	UMd-Ia
replicate	S12_5	S12	6X12	modified	147.23	101.89	4.37	99.40	UMd-Ia
replicate	S12_6	S12	6X12	modified	143.60	99.38	4.36	99.19	UMd-Ia
average	S12_1,2,5,6	S12	6X12	modified	142.31	98.48	4.33	98.40	UMd-Ia
replicate	NS12_2	S12	6X12	modified	142.16	98.38	4.33	98.39	NCHRP-Ia
replicate	NS12_3	S12	6X12	modified	144.64	100.09	3.89	88.41	NCHRP-Ia
replicate	NS12_4	S12	6X12	modified	140.10	96.96	3.81	86.54	NCHRP-Ia
replicate	NS12_5	S12	6X12	modified	143.16	99.07	4.83	109.84	NCHRP-Ia
average	NS12_2,3,4,5	S12	6X12	modified	142.51	98.63	4.21	95.79	NCHRP-Ia
replicate	S1_1	S1	4X8	modified	131.40	102.26	8.59	104.73	UMd-Ib
replicate	S1_2	S1	4X8	modified	129.71	100.94	8.59	104.73	UMd-Ib
replicate	S1_3	S1	4X8	modified	131.29	102.17	7.51	91.58	UMd-Ib
average	S1_1,2,3	S1	4X8	modified	130.80	101.79	8.23	100.35	UMd-Ib
replicate	NS1_1	S1	4X8	modified	131.54	102.37	8.77	106.97	NCHRP-Ib
replicate	NS1_2	S1	4X8	modified	128.52	100.01	8.44	102.95	NCHRP-Ib
replicate	NS1_3	S1	4X8	modified	129.53	100.80	8.02	97.81	NCHRP-Ib
average	NS1_1,2,3	S1	4X8	modified	129.86	101.06	8.41	102.58	NCHRP-Ib
replicate	S3_1	S3	4X8	modified	106.77	94.49	16.70	102.47	UMd-II
replicate	S3_2	S3	4X8	modified	106.75	94.47	16.65	102.15	UMd-II
replicate	S3_3	S3	4X8	modified	105.90	93.72	17.26	105.87	UMd-II
average	S3_1,2,3	S3	4X8	modified	106.47	94.22	16.87	103.50	UMd-II
replicate	NS3_1	S3	4X8	modified	107.62	95.24	15.93	97.73	NCHRP-II
replicate	NS3_3	S3	4X8	modified	106.94	94.64	16.49	101.14	NCHRP-II
replicate	NS3_4	S3	4X8	modified	106.10	93.89	16.63	102.02	NCHRP-II
average	NS3_1,3,4	S3	4X8	modified	106.89	94.59	16.35	100.29	NCHRP-II

TABLE B-2
TEST PARAMETERS FOR 15 ADDITIONAL TESTS

Type	Test ID	Soil ID (Table B-4)	Specimen Size (inXin)	Compactive effort	γ_{dry} (pcf)	% γ_{opt}	w (%)	% w_{opt}	Procedure ID (Table B-3)
replicate	S11_high	S11	4X8	modified	137.90	103.68	7.08	86.34	UMd-Ia
replicate	S11_dry	S11	4X8	modified	135.82	102.12	6.45	78.66	UMd-Ia
replicate	S11_mid	S11	4X8	modified	135.51	101.89	7.85	95.73	UMd-Ia
replicate	S11_wet	S11	4X8	modified	132.81	99.86	10.07	122.80	UMd-Ia
replicate	S11_low	S11	4X8	modified	135.29	101.72	7.49	91.34	UMd-Ia
replicate	S7_high	S7	4X8	modified	115.29	94.11	16.28	125.23	UMd-Ib
replicate	S7_dry	S7	4X8	modified	118.74	96.93	12.18	93.69	UMd-Ib
replicate	S7_mid	S7	4X8	modified	113.69	92.81	15.28	117.54	UMd-Ib
replicate	S7_wet	S7	4X8	modified	107.39	87.67	13.58	104.46	UMd-Ib
replicate	S7_low	S7	4X8	modified	103.48	84.47	19.79	152.23	UMd-Ib
replicate	S13_high	S13	4X8	standard	110.88	99.44	13.14	96.62	UMd-Ib
replicate	S13_dry	S13	4X8	standard	104.18	93.43	10.84	79.71	UMd-Ib
replicate	S13_mid	S13	4X8	standard	104.61	93.82	13.13	96.54	UMd-Ib
replicate	S13_wet	S13	4X8	standard	110.15	98.79	17.17	126.25	UMd-Ib
replicate	S13_low	S13	4X8	standard	102.80	92.20	13.03	95.81	UMd-Ib

TABLE B-3
STRESS SEQUENCES

Sequence	Confining Pressure (psi)	Contact Stress (psi)	Cyclic Stress (psi)	Principal Stresses Ratio	Maximum Stress (psi)	σ_1 (psi)	Nrep
Harmonized Ia - Test Sequence for Base/Subbase Materials							
Conditioning	15.0	3.0	30.0	3.0	33.0	48.0	1000
1	3.0	0.6	1.5	1.5	2.1	5.1	100
2	6.0	1.2	3.0	1.5	4.2	10.2	100
3	10.0	2.0	5.0	1.5	7.0	17.0	100
4	15.0	3.0	7.5	1.5	10.5	25.5	100
5	20.0	4.0	10.0	1.5	14.0	34.0	100
6	3.0	0.6	3.0	2.0	3.6	6.6	100
7	6.0	1.2	6.0	2.0	7.2	13.2	100
8	10.0	2.0	10.0	2.0	12.0	22.0	100
9	15.0	3.0	15.0	2.0	18.0	33.0	100
10	20.0	4.0	20.0	2.0	24.0	44.0	100
11	3.0	0.6	6.0	3.0	6.6	9.6	100
12	6.0	1.2	12.0	3.0	13.2	19.2	100
13	10.0	2.0	20.0	3.0	22.0	32.0	100
14	15.0	3.0	30.0	3.0	33.0	48.0	100
15	20.0	4.0	40.0	3.0	44.0	64.0	100
16	3.0	0.6	9.0	4.0	9.6	12.6	100
17	6.0	1.2	18.0	4.0	19.2	25.2	100
18	10.0	2.0	30.0	4.0	32.0	42.0	100
19	15.0	3.0	45.0	4.0	48.0	63.0	100
20	20.0	4.0	60.0	4.0	64.0	84.0	100
21	3.0	0.6	15.0	6.0	15.6	18.6	100
22	6.0	1.2	30.0	6.0	31.2	37.2	100
23	10.0	2.0	50.0	6.0	52.0	62.0	100
24	15.0	3.0	75.0	6.0	78.0	93.0	100
25	20.0	4.0	100.0	6.0	104.0	124.0	100
26	3.0	0.6	21.0	8.0	21.6	24.6	100
27	6.0	1.2	42.0	8.0	43.2	49.2	100
28	10.0	2.0	70.0	8.0	72.0	82.0	100
29	15.0	3.0	105.0	8.0	108.0	123.0	100
30	20.0	4.0	140.0	8.0	144.0	164.0	100
NCHRP 1-28 Appendix E - Test Sequence for Base/Subbase Materials							
Conditioning	15.0	3.0	15.0	2.2	18.0	33.0	200
1	3.0	0.6	3.0	2.2	3.6	6.6	50
2	3.0	0.6	6.0	3.2	6.6	9.6	50
3	3.0	0.6	9.0	4.2	9.6	12.6	50
4	4.5	0.9	4.5	2.2	5.4	9.9	50
5	4.5	0.9	9.0	3.2	9.9	14.4	50
6	4.5	0.9	13.5	4.2	14.4	18.9	50
7	6.0	1.2	6.0	2.2	7.2	13.2	50
8	6.0	1.2	12.0	3.2	13.2	19.2	50
9	6.0	1.2	18.0	4.2	19.2	25.2	50
10	9.0	1.8	9.0	2.2	10.8	19.8	50
11	9.0	1.8	18.0	3.2	19.8	28.8	50
12	9.0	1.8	27.0	4.2	28.8	37.8	50
13	14.0	2.8	9.0	1.8	11.8	25.8	50
14	14.0	2.8	14.0	2.2	16.8	30.8	50
15	14.0	2.8	28.0	3.2	30.8	44.8	50

TABLE B-3
STRESS SEQUENCES

Sequence	Confining Pressure (psi)	Contact Stress (psi)	Cyclic Stress (psi)	Principal Stresses Ratio	Maximum Stress (psi)	σ_1 (psi)	Nrep
Harmonized Ib - Test Sequence for Granular Subgrades							
Conditioning	4.0	0.8	8.0	3.0	8.8	12.8	1000
1	2.0	0.4	1.0	1.5	1.4	3.4	100
2	4.0	0.8	2.0	1.5	2.8	6.8	100
3	6.0	1.2	3.0	1.5	4.2	10.2	100
4	8.0	1.6	4.0	1.5	5.6	13.6	100
5	12.0	2.4	6.0	1.5	8.4	20.4	100
6	2.0	0.4	2.0	2.0	2.4	4.4	100
7	4.0	0.8	4.0	2.0	4.8	8.8	100
8	6.0	1.2	6.0	2.0	7.2	13.2	100
9	8.0	1.6	8.0	2.0	9.6	17.6	100
10	12.0	2.4	12.0	2.0	14.4	26.4	100
11	2.0	0.4	4.0	3.0	4.4	6.4	100
12	4.0	0.8	8.0	3.0	8.8	12.8	100
13	6.0	1.2	12.0	3.0	13.2	19.2	100
14	8.0	1.6	16.0	3.0	17.6	25.6	100
15	12.0	2.4	24.0	3.0	26.4	38.4	100
16	2.0	0.4	6.0	4.0	6.4	8.4	100
17	4.0	0.8	12.0	4.0	12.8	16.8	100
18	6.0	1.2	18.0	4.0	19.2	25.2	100
19	8.0	1.6	24.0	4.0	25.6	33.6	100
20	12.0	2.4	36.0	4.0	38.4	50.4	100
NCHRP 1-28 Appendix E - Test Sequence for Granular Subgrades							
Conditioning	6.0	1.2	8.0	2.5	9.2	15.2	500
1	2.0	0.4	2.0	2.2	2.4	4.4	100
2	2.0	0.4	3.0	2.7	3.4	5.4	100
3	2.0	0.4	4.0	3.2	4.4	6.4	100
4	3.0	0.6	3.0	2.2	3.6	6.6	100
5	3.0	0.6	3.8	2.5	4.4	7.4	100
6	3.0	0.6	6.0	3.2	6.6	9.6	100
7	4.0	0.8	4.0	2.2	4.8	8.8	100
8	4.0	0.8	6.0	2.7	6.8	10.8	100
9	4.0	0.8	8.0	3.2	8.8	12.8	100
10	6.0	1.2	4.0	1.9	5.2	11.2	100
11	6.0	1.2	6.0	2.2	7.2	13.2	100
12	6.0	1.2	8.0	2.5	9.2	15.2	100
13	8.0	1.6	6.0	2.0	7.6	15.6	100
14	8.0	1.6	8.0	2.2	9.6	17.6	100
15	8.0	1.6	10.0	2.5	11.6	19.6	100

TABLE B-3
STRESS SEQUENCES

Sequence	Confining Pressure (psi)	Contact Stress (psi)	Cyclic Stress (psi)	Principal Stresses Ratio	Maximum Stress (psi)	σ_1 (psi)	Nrep
Harmonized II - Test Sequence for Fine-Grained Subgrades							
Conditioning	4.0	0.8	7.0	2.8	7.8	11.8	1000
1	8.0	1.6	4.0	1.5	5.6	13.6	100
2	6.0	1.2	4.0	1.7	5.2	11.2	100
3	4.0	0.8	4.0	2.0	4.8	8.8	100
4	2.0	0.4	4.0	3.0	4.4	6.4	100
5	8.0	1.6	7.0	1.9	8.6	16.6	100
6	6.0	1.2	7.0	2.2	8.2	14.2	100
7	4.0	0.8	7.0	2.8	7.8	11.8	100
8	2.0	0.4	7.0	4.5	7.4	9.4	100
9	8.0	1.6	10.0	2.3	11.6	19.6	100
10	6.0	1.2	10.0	2.7	11.2	17.2	100
11	4.0	0.8	10.0	3.5	10.8	14.8	100
12	2.0	0.4	10.0	6.0	10.4	12.4	100
13	8.0	1.6	14.0	2.8	15.6	23.6	100
14	6.0	1.2	14.0	3.3	15.2	21.2	100
15	4.0	0.8	14.0	4.5	14.8	18.8	100
16	2.0	0.4	14.0	8.0	14.4	16.4	100
NCHRP 1-28 Appendix E - Test Sequence for Cohesive Subgrades							
Conditioning	0	1.0	4.0		5.0	5.0	200
1	0	0.6	2.4		3.0	3.0	50
2	0	1.0	4.0		5.0	5.0	50
3	0	1.4	5.6		7.0	7.0	50
4	0	1.8	7.2		9.0	9.0	50
5	0	2.2	8.8		11.0	11.0	50

TABLE B-4
DESCRIPTION OF MATERIALS

Soil ID	Project/Study	Description	AASHTO classification	Unified classification
S12	MnRoad	Class 6 base	A-1-a	SW-SM
S1	USACE-CRREL	Silty sand from Moulton Pit	A-4(1)	SM
S3	USACE-CRREL	Clay from St. Albans	A-6(9)	CL
S11	MnRoad	Class 3 subbase	A-1-b	SM
S7	ALF-FHWA	ALF subgrade	A-4(3)	SM
S13	MnRoad	Silty sand subgrade	A-6(7)	CL

TABLE B-5
SIEVE ANALYSIS

Sieve US	Opening (mm)	S12 % finer	S1 % finer	S3 % finer	S11 % finer	S7 % finer	S13 % finer
1.5 in	38.100	100.0	100.0	100.0	100.0	100.0	100.0
1 in	25.400	100.0	100.0	100.0	100.0	100.0	100.0
0.75 in	19.050	100.0	100.0	100.0	100.0	100.0	100.0
0.5 in	12.700	86.2	98.0	100.0	99.9	98.9	100.0
0.38 in	9.525	75.9	95.3	100.0	98.9	97.4	99.8
No. 4	4.750	57.4	86.7	99.7	94.1	95.7	98.6
No. 10	2.000	40.8	79.0	98.9	84.0	93.0	95.8
No. 20	0.850	29.5	68.3	94.7	66.9	86.7	91.9
No. 40	0.425	23.2	54.3	97.1	44.2	79.6	87.3
No. 60	0.250	19.1	45.1	96.1	29.8	70.9	80.8
No. 100	0.150	15.3	42.6	95.3	20.9	61.4	73.0
No. 200	0.075	9.2	41.6	94.7	15.4	49.9	63.8

TABLE B-6
TEST DATA

Test ID (Table B-1)	Sequence	Vertical Strain	Horizontal Strain	Contact Stress (psi)	Confining Pressure (psi)	Cyclic Stress (psi)	θ (psi)	τ_{oct} (psi)	σ_1 (psi)	Mr (psi)	ν
S12_1	1	7.E-05	8.E-06	0.60	3.90	1.54	8.00	0.73	6.04	22885	0.121
	2	1.E-04	1.E-05	1.22	6.77	3.07	24.58	1.45	11.05	31999	0.133
	3	1.E-04	2.E-05	2.01	10.58	5.23	38.97	2.46	17.82	44061	0.137
	4	1.E-04	2.E-05	3.02	15.35	7.84	56.91	3.70	26.21	63599	0.132
	5	1.E-04	2.E-05	3.99	20.14	10.39	74.80	4.90	34.52	85868	0.139
	6	1.E-04	2.E-05	0.60	3.90	3.13	15.43	1.48	7.63	22195	0.152
	7	2.E-04	3.E-05	1.21	6.76	6.22	27.71	2.93	14.18	31902	0.167
	8	2.E-04	4.E-05	2.04	10.59	10.31	44.12	4.86	22.94	45538	0.161
	9	2.E-04	4.E-05	3.01	15.36	15.51	64.61	7.31	33.88	66575	0.159
	10	2.E-04	4.E-05	4.01	20.16	20.53	85.00	9.68	44.69	88429	0.156
	11	3.E-04	5.E-05	0.60	3.93	6.19	18.57	2.92	10.72	22994	0.188
	12	4.E-04	7.E-05	1.21	6.79	12.35	33.92	5.82	20.35	34867	0.193
	13	4.E-04	7.E-05	2.05	10.60	20.57	54.43	9.70	33.23	53226	0.192
	14	4.E-04	8.E-05	3.03	15.38	30.76	79.93	14.50	49.17	76364	0.190
	15	4.E-04	8.E-05	4.02	20.16	41.30	105.79	19.47	65.48	95819	0.184
	16	4.E-04	8.E-05	0.61	3.93	9.45	21.85	4.46	13.99	24855	0.205
	17	5.E-04	1.E-04	1.23	6.79	18.53	40.14	8.73	26.55	39424	0.216
	18	5.E-04	1.E-04	2.04	10.61	30.79	64.66	14.51	43.44	59392	0.215
	19	6.E-04	1.E-04	2.85	14.43	43.19	89.32	20.36	60.47	76344	0.215
	20	6.E-04	1.E-04	3.84	19.20	58.38	119.83	27.52	81.43	91184	0.214
	21	6.E-04	1.E-04	0.60	3.94	15.68	28.10	7.39	20.22	27791	0.245
	22	7.E-04	2.E-04	1.23	6.80	30.53	52.15	14.39	38.56	45683	0.260
	23	8.E-04	2.E-04	2.08	10.60	51.37	85.24	24.21	64.05	64834	0.274
	24	1.E-03	3.E-04	3.08	15.38	76.70	125.92	36.16	95.16	79583	0.269
	25	7.E-04	2.E-04	0.63	3.92	21.60	33.99	10.18	26.15	29706	0.292
	29	9.E-04	3.E-04	1.27	6.78	42.88	64.48	20.21	50.92	49478	0.314
	30	1.E-03	4.E-04	2.08	10.60	71.79	105.66	33.84	84.47	66584	0.330
S12_2	1	7.E-05	9.E-06	0.59	3.86	1.61	13.79	0.76	6.07	23806	0.140
	2	9.E-05	1.E-05	1.20	6.72	3.07	24.44	1.45	11.00	33991	0.138
	3	1.E-04	1.E-05	2.02	10.54	5.25	38.90	2.48	17.81	47471	0.128
	4	1.E-04	1.E-05	3.01	15.31	7.79	56.73	3.67	26.11	67040	0.125
	5	1.E-04	1.E-05	4.00	20.10	10.34	74.63	4.87	34.43	87026	0.125
	6	1.E-04	2.E-05	0.61	3.87	3.05	15.28	1.44	7.53	21996	0.157
	7	2.E-04	3.E-05	1.21	6.72	6.31	27.69	2.97	14.24	33101	0.154
	8	2.E-04	3.E-05	2.00	10.54	10.45	44.05	4.92	22.98	49125	0.148
	9	2.E-04	3.E-05	3.01	15.32	15.52	64.49	7.32	33.85	70636	0.139
	10	2.E-04	3.E-05	4.01	20.10	20.76	85.08	9.79	44.87	92572	0.134
	11	3.E-04	5.E-05	0.61	3.86	6.18	18.37	2.91	10.65	23355	0.188
	12	3.E-04	6.E-05	1.22	6.74	12.43	33.87	5.86	20.39	38005	0.187
	13	4.E-04	6.E-05	2.06	10.55	20.63	54.33	9.72	33.24	57679	0.174
	14	4.E-04	6.E-05	3.02	15.32	31.06	80.05	14.64	49.40	81184	0.160
	15	4.E-04	6.E-05	4.02	20.10	40.87	105.20	19.27	65.00	98919	0.151
	16	4.E-04	7.E-05	0.62	3.88	9.44	21.71	4.45	13.95	25889	0.197
	17	4.E-04	8.E-05	1.22	6.73	18.43	39.86	8.69	26.39	42499	0.194
	18	5.E-04	9.E-05	2.06	10.54	30.93	64.62	14.58	43.53	64149	0.188
	19	6.E-04	1.E-04	3.04	15.32	46.08	95.08	21.72	64.44	83184	0.181
	20	6.E-04	1.E-04	4.04	20.11	60.45	124.82	28.50	84.60	96965	0.170
	21	5.E-04	1.E-04	0.61	3.89	15.49	27.76	7.30	19.99	28755	0.234
	22	6.E-04	2.E-04	1.23	6.73	30.99	52.42	14.61	38.95	48406	0.238

TABLE B-6
TEST DATA

Test ID (Table B-1)	Sequence	Vertical Strain	Horizontal Strain	Contact Stress (psi)	Confining Pressure (psi)	Cyclic Stress (psi)	θ (psi)	τ_{oct} (psi)	σ_1 (psi)	Mr (psi)	ν
	23	8.E-04	2.E-04	2.08	10.54	51.55	85.27	24.30	64.18	66601	0.247
	24	9.E-04	2.E-04	3.04	15.32	75.65	124.66	35.66	94.01	82618	0.239
	25	7.E-04	2.E-04	0.64	3.88	21.28	33.56	10.03	25.80	30132	0.281
	29	9.E-04	3.E-04	1.25	6.74	43.50	64.97	20.50	51.49	51171	0.297
	30	1.E-03	3.E-04	2.07	10.55	71.66	105.39	33.78	84.28	69354	0.313
S12_5	1	6.E-05	8.E-06	0.60	4.96	1.53	17.01	0.72	7.09	24766	0.133
	2	1.E-04	1.E-05	1.20	7.47	3.09	26.69	1.46	11.76	32296	0.141
	3	1.E-04	2.E-05	2.01	10.80	5.26	39.66	2.48	18.07	42044	0.133
	4	1.E-04	2.E-05	3.03	14.98	7.84	55.80	3.70	25.85	56234	0.136
	5	1.E-04	2.E-05	3.95	19.17	10.56	72.03	4.98	33.68	72889	0.139
	6	1.E-04	2.E-05	0.62	4.98	3.16	18.71	1.49	8.75	23665	0.160
	7	2.E-04	3.E-05	1.18	7.47	6.31	29.90	2.97	14.96	31967	0.169
	8	2.E-04	4.E-05	2.00	10.81	10.45	44.88	4.92	23.26	43097	0.170
	9	3.E-04	4.E-05	3.04	14.99	15.53	63.53	7.32	33.56	59710	0.165
	10	3.E-04	4.E-05	4.03	19.17	20.75	82.28	9.78	43.94	76832	0.162
	11	3.E-04	5.E-05	0.58	4.98	6.19	21.70	2.92	11.75	23655	0.184
	12	4.E-04	7.E-05	1.20	7.48	12.48	36.12	5.89	21.16	34801	0.198
	13	4.E-04	8.E-05	2.04	10.83	20.76	55.28	9.79	33.62	50448	0.200
	14	5.E-04	9.E-05	3.01	14.99	30.97	78.97	14.60	48.98	67205	0.196
	15	5.E-04	9.E-05	4.02	19.17	40.58	102.12	19.13	63.77	80259	0.185
	16	4.E-04	8.E-05	0.61	4.99	9.40	24.98	4.43	15.01	25647	0.210
	17	5.E-04	1.E-04	1.23	7.49	18.58	42.28	8.76	27.30	39186	0.219
	18	6.E-04	1.E-04	2.05	10.83	31.07	65.62	14.64	43.95	55364	0.221
	19	7.E-04	1.E-04	3.05	15.00	45.38	93.42	21.39	63.42	68640	0.216
	20	8.E-04	2.E-04	4.07	19.18	59.61	121.21	28.10	82.85	75018	0.221
	21	5.E-04	1.E-04	0.60	4.99	15.44	31.01	7.28	21.03	28075	0.244
	22	7.E-04	2.E-04	1.25	7.49	30.99	54.71	14.61	39.72	44283	0.262
	23	9.E-04	2.E-04	2.05	10.83	50.90	85.43	23.99	63.78	59229	0.275
	24	1.E-03	3.E-04	3.06	15.00	76.07	124.13	35.86	94.13	72823	0.289
	25	7.E-04	2.E-04	0.63	4.99	21.51	37.10	10.14	27.12	30246	0.286
	29	9.E-04	3.E-04	1.15	7.48	43.43	67.02	20.47	52.06	48055	0.307
	30	1.E-03	4.E-04	2.06	10.80	71.56	106.03	33.73	84.43	62900	0.339
S12_6	1	6.E-05	2.E-06	0.60	4.90	1.60	16.90	0.75	7.10	27877	0.043
	2	9.E-05	6.E-06	1.20	7.40	3.06	26.47	1.44	11.67	36036	0.075
	3	1.E-04	1.E-05	2.02	10.74	5.22	39.47	2.46	17.99	46239	0.093
	4	1.E-04	1.E-05	3.00	14.92	7.78	55.56	3.67	25.71	60257	0.097
	5	1.E-04	1.E-05	4.00	19.12	10.42	71.76	4.91	33.53	77233	0.099
	6	1.E-04	9.E-06	0.61	4.91	3.07	18.40	1.45	8.59	26288	0.081
	7	2.E-04	2.E-05	1.21	7.41	6.23	29.68	2.94	14.85	34497	0.101
	8	2.E-04	3.E-05	2.03	10.75	10.43	44.72	4.92	23.21	46426	0.118
	9	2.E-04	3.E-05	2.82	14.10	14.47	59.58	6.82	31.39	60062	0.117
	10	3.E-04	3.E-05	4.03	19.12	20.67	82.06	9.74	43.82	81270	0.111
	11	2.E-04	3.E-05	0.62	4.91	6.15	21.49	2.90	11.68	25924	0.107
	12	3.E-04	4.E-05	1.22	7.41	12.52	35.98	5.90	21.15	36881	0.125
	13	4.E-04	5.E-05	2.04	10.75	20.57	54.87	9.70	33.37	52310	0.134
	14	4.E-04	6.E-05	3.02	14.93	31.05	78.87	14.64	49.01	71778	0.128
	15	5.E-04	6.E-05	4.02	19.12	41.06	102.43	19.36	64.20	85696	0.132
	16	4.E-04	4.E-05	0.62	4.91	9.46	24.79	4.46	14.98	26970	0.123
	17	5.E-04	6.E-05	1.22	7.42	18.50	41.96	8.72	27.13	40228	0.138

TABLE B-6
TEST DATA

Test ID (Table B-1)	Sequence	Vertical Strain	Horizontal Strain	Contact Stress (psi)	Confining Pressure (psi)	Cyclic Stress (psi)	θ (psi)	τ_{oct} (psi)	σ_1 (psi)	Mr (psi)	ν
	18	5.E-04	8.E-05	2.03	10.75	31.00	65.27	14.61	43.78	58057	0.150
	19	6.E-04	1.E-04	3.03	14.94	46.30	94.13	21.82	64.26	74616	0.161
	20	7.E-04	1.E-04	4.05	19.12	60.93	122.35	28.72	84.10	86729	0.160
	21	5.E-04	8.E-05	0.60	4.91	15.58	30.92	7.35	21.09	29287	0.155
	22	7.E-04	1.E-04	1.25	7.41	30.90	54.38	14.57	39.56	45756	0.179
	23	8.E-04	2.E-04	2.04	10.75	51.49	85.78	24.27	64.28	62717	0.196
	24	1.E-03	2.E-04	3.06	14.93	76.18	124.03	35.91	94.17	77036	0.214
	25	7.E-04	1.E-04	0.61	4.91	21.55	36.88	10.16	27.07	30736	0.206
	29	9.E-04	2.E-04	1.26	7.41	43.39	66.88	20.46	52.06	48804	0.226
	30	1.E-03	3.E-04	2.07	10.75	71.95	106.28	33.92	84.77	65543	0.258
NS12_2	1	5.E-05	1.E-05	0.29	3.89	1.49	13.46	0.70	5.67	31437	0.221
	2	9.E-05	2.E-05	0.29	3.89	2.74	14.72	1.29	6.93	28867	0.257
	3	2.E-04	4.E-05	0.30	3.89	4.10	16.06	1.93	8.29	26544	0.272
	4	6.E-05	1.E-05	0.39	5.32	2.17	18.53	1.02	7.88	37495	0.251
	5	1.E-04	3.E-05	0.40	5.32	4.09	20.45	1.93	9.81	32417	0.252
	6	2.E-04	6.E-05	0.39	5.32	6.19	22.52	2.92	11.89	30483	0.272
	7	7.E-05	2.E-05	0.52	6.75	2.80	23.58	1.32	10.08	40123	0.241
	8	2.E-04	4.E-05	0.55	6.75	5.49	26.27	2.59	12.78	36487	0.255
	9	2.E-04	7.E-05	0.54	6.74	8.39	29.17	3.96	15.68	34756	0.276
	10	8.E-05	2.E-05	0.80	9.61	4.13	33.76	1.95	14.54	50749	0.241
	11	2.E-04	5.E-05	0.82	9.61	8.45	38.11	3.98	18.88	46760	0.253
	12	3.E-04	8.E-05	0.82	9.61	12.49	42.14	5.89	22.92	43897	0.268
	13	5.E-05	1.E-05	1.24	14.39	4.16	48.57	1.96	19.79	76288	0.253
	14	1.E-04	2.E-05	1.23	14.40	6.57	51.00	3.10	22.20	68299	0.237
	15	2.E-04	5.E-05	1.25	14.40	12.84	57.28	6.06	28.49	61079	0.240
NS12_3	1	4.E-05	7.E-06	0.29	3.98	1.40	13.63	0.66	5.67	32084	0.162
	2	9.E-05	2.E-05	0.30	3.97	2.67	14.88	1.26	6.94	30676	0.181
	3	1.E-04	3.E-05	0.29	3.97	4.13	16.33	1.95	8.39	30549	0.193
	4	6.E-05	9.E-06	0.38	5.40	2.11	18.67	0.99	7.88	37117	0.155
	5	1.E-04	2.E-05	0.42	5.40	4.09	20.70	1.93	9.90	37010	0.181
	6	2.E-04	3.E-05	0.39	5.39	6.18	22.73	2.91	11.96	36715	0.195
	7	6.E-05	1.E-05	0.53	6.83	2.71	23.73	1.28	10.07	42675	0.153
	8	1.E-04	2.E-05	0.53	6.82	5.49	26.49	2.59	12.85	42447	0.180
	9	2.E-04	4.E-05	0.53	6.83	8.34	29.36	3.93	15.70	42929	0.192
	10	8.E-05	1.E-05	0.82	9.68	4.10	33.97	1.93	14.61	53643	0.155
	11	2.E-04	3.E-05	0.82	9.69	8.24	38.12	3.89	18.75	53767	0.176
	12	2.E-04	4.E-05	0.84	9.68	12.30	42.17	5.80	22.81	53992	0.190
	13	6.E-05	8.E-06	1.23	14.45	4.20	48.80	1.98	19.89	76034	0.140
	14	9.E-05	1.E-05	1.24	14.46	6.52	51.12	3.07	22.21	72017	0.157
	15	2.E-04	3.E-05	1.25	14.46	12.81	57.45	6.04	28.53	70989	0.173
NS12_4	1	5.E-05	6.E-06	0.31	3.81	1.42	13.17	0.67	5.55	27746	0.120
	2	1.E-04	1.E-05	0.31	3.80	2.71	14.43	1.28	6.83	26856	0.141
	3	2.E-04	2.E-05	0.28	3.80	4.06	15.74	1.91	8.14	26729	0.159
	4	7.E-05	8.E-06	0.38	5.23	2.10	18.16	0.99	7.71	31618	0.128
	5	1.E-04	2.E-05	0.37	5.22	4.09	20.14	1.93	9.69	31830	0.148
	6	2.E-04	3.E-05	0.39	5.22	6.19	22.23	2.92	11.80	32209	0.163
	7	7.E-05	1.E-05	0.53	6.67	2.72	23.26	1.28	9.92	36425	0.146
	8	1.E-04	2.E-05	0.55	6.67	5.50	26.07	2.59	12.73	37364	0.160
	9	2.E-04	4.E-05	0.53	6.68	8.35	28.91	3.94	15.55	37903	0.165

TABLE B-6
TEST DATA

Test ID (Table B-1)	Sequence	Vertical Strain	Horizontal Strain	Contact Stress (psi)	Confining Pressure (psi)	Cyclic Stress (psi)	θ (psi)	τ_{oct} (psi)	σ_1 (psi)	Mr (psi)	ν
	10	8.E-05	1.E-05	0.81	9.53	4.07	33.47	1.92	14.41	48094	0.139
	11	2.E-04	2.E-05	0.84	9.53	8.33	37.76	3.93	18.70	48455	0.145
	12	3.E-04	4.E-05	0.84	9.53	12.35	41.79	5.82	22.72	48268	0.159
	13	6.E-05	8.E-06	1.23	14.30	4.21	48.33	1.99	19.74	67337	0.124
	14	1.E-04	1.E-05	1.25	14.30	6.47	50.62	3.05	22.02	64924	0.125
	15	2.E-04	3.E-05	1.23	14.30	12.79	56.93	6.03	28.32	63887	0.134
NS12_5	1	4.E-05	5.E-06	0.28	5.36	1.40	17.78	0.66	7.05	37149	0.129
	2	8.E-05	1.E-05	0.27	5.37	2.78	19.15	1.31	8.42	36066	0.127
	3	1.E-04	2.E-05	0.29	5.37	4.03	20.43	1.90	9.69	35415	0.135
	4	5.E-05	5.E-06	0.38	6.61	2.09	22.30	0.98	9.08	39833	0.102
	5	1.E-04	1.E-05	0.39	6.61	4.04	24.27	1.91	11.04	40329	0.127
	6	2.E-04	2.E-05	0.44	6.62	6.14	26.43	2.90	13.20	39647	0.138
	7	6.E-05	7.E-06	0.53	7.86	2.73	26.83	1.29	11.12	43059	0.106
	8	1.E-04	2.E-05	0.55	7.86	5.41	29.53	2.55	13.81	43742	0.134
	9	2.E-04	3.E-05	0.54	7.86	8.25	32.38	3.89	16.65	43373	0.147
	10	8.E-05	9.E-06	0.81	10.35	4.06	35.94	1.92	15.23	52712	0.121
	11	2.E-04	2.E-05	0.82	10.35	8.32	40.20	3.92	19.49	52260	0.138
	12	2.E-04	3.E-05	0.82	10.35	12.31	44.19	5.80	23.49	51724	0.145
	13	6.E-05	6.E-06	1.24	14.51	4.12	48.88	1.94	19.87	67085	0.103
	14	1.E-04	1.E-05	1.24	14.50	6.47	51.21	3.05	22.20	66301	0.119
	15	2.E-04	3.E-05	1.25	14.50	12.79	57.55	6.03	28.54	64799	0.131
S1_1	1	8.E-06	9.E-07	0.37	3.62	1.23	12.46	0.58	5.22	145835	0.104
	2	3.E-05	1.E-06	0.78	5.27	1.96	18.56	0.92	8.01	63879	0.044
	3	4.E-05	2.E-06	1.18	6.93	2.81	24.79	1.32	10.92	76703	0.049
	4	3.E-05	4.E-06	1.58	8.60	3.30	30.68	1.56	13.48	104833	0.122
	5	4.E-05	2.E-06	2.41	11.95	4.32	42.57	2.04	18.68	123069	0.057
	6	2.E-05	9.E-07	0.35	3.66	1.53	12.86	0.72	5.54	77889	0.047
	7	4.E-05	2.E-06	0.77	5.31	2.63	19.33	1.24	8.71	65926	0.040
	8	5.E-05	2.E-06	1.19	6.97	3.77	25.86	1.77	11.92	70634	0.039
	9	6.E-05	2.E-06	1.63	8.62	4.93	32.43	2.32	15.18	81887	0.027
	10	7.E-05	1.E-05	2.49	11.95	7.19	45.52	3.39	21.63	98279	0.147
	11	8.E-05	9.E-06	0.40	3.68	2.85	14.29	1.34	6.93	34817	0.114
	12	2.E-04	2.E-05	0.86	5.32	5.59	22.42	2.63	11.77	32387	0.089
	13	3.E-04	3.E-05	1.30	6.99	9.14	31.40	4.31	17.43	35471	0.116
	14	3.E-04	4.E-05	1.73	8.64	12.23	39.89	5.76	22.60	42247	0.141
	15	3.E-04	4.E-05	2.61	11.95	17.47	55.94	8.23	32.03	54297	0.119
	16	2.E-04	2.E-05	0.44	3.68	3.94	15.41	1.86	8.05	25266	0.129
	17	4.E-04	5.E-05	0.89	5.34	9.49	26.40	4.47	15.72	23909	0.115
	18	5.E-04	5.E-05	1.33	6.99	15.00	37.29	7.07	23.31	31109	0.112
	19	6.E-04	6.E-05	1.77	8.65	20.78	48.51	9.80	31.20	36270	0.111
	20	7.E-04	7.E-05	2.69	11.96	29.26	67.84	13.79	43.91	42429	0.108
S1_2	1	9.E-06	5.E-07	0.38	3.52	1.23	12.15	0.58	5.12	129976	0.056
	2	3.E-05	8.E-07	0.78	5.18	2.18	18.49	1.03	8.14	81287	0.031
	3	4.E-05	3.E-06	1.21	6.84	3.26	24.98	1.54	11.30	72494	0.070
	4	6.E-05	5.E-06	1.61	8.49	4.23	31.31	1.99	14.33	69912	0.088
	5	6.E-05	7.E-06	2.43	11.81	6.23	44.09	2.94	20.47	109959	0.115
	6	3.E-05	6.E-07	0.42	3.52	2.09	13.07	0.99	6.03	64116	0.017
	7	9.E-05	4.E-06	0.81	5.19	4.04	20.42	1.90	10.04	45604	0.048
	8	1.E-04	1.E-05	1.19	6.85	6.11	27.83	2.88	14.14	44182	0.075

TABLE B-6
TEST DATA

Test ID (Table B-1)	Sequence	Vertical Strain	Horizontal Strain	Contact Stress (psi)	Confining Pressure (psi)	Cyclic Stress (psi)	θ (psi)	τ_{oct} (psi)	σ_1 (psi)	Mr (psi)	ν
	9	2.E-04	2.E-05	1.61	8.50	8.38	35.48	3.95	18.48	51720	0.095
	10	2.E-04	2.E-05	2.42	11.82	12.72	50.61	6.00	26.96	60094	0.099
	11	1.E-04	2.E-06	0.41	3.54	3.89	14.92	1.83	7.84	33603	0.021
	12	3.E-04	2.E-05	0.79	5.20	8.12	24.51	3.83	14.11	30941	0.072
	13	4.E-04	4.E-05	1.19	6.85	12.50	34.24	5.89	20.54	31703	0.094
	14	4.E-04	5.E-05	1.65	8.50	16.23	43.39	7.65	26.39	36489	0.106
	15	6.E-04	6.E-05	2.41	11.81	24.81	62.65	11.70	39.03	43554	0.103
	16	2.E-04	5.E-06	0.40	3.53	5.55	16.53	2.62	9.48	25889	0.025
	17	5.E-04	4.E-05	0.83	5.20	11.73	28.14	5.53	17.75	24478	0.083
	18	6.E-04	7.E-05	1.22	6.85	18.37	40.13	8.66	26.44	28866	0.108
	19	8.E-04	1.E-04	1.61	8.50	24.85	51.95	11.71	34.95	32998	0.131
	20	8.E-04	1.E-04	2.45	11.83	37.75	75.69	17.79	52.03	44488	0.160
S1_3	1	5.E-06	6.E-07	0.39	3.46	1.14	11.89	0.54	4.98	222864	0.118
	2	2.E-05	3.E-06	0.80	5.12	2.16	18.32	1.02	8.08	110291	0.130
	3	4.E-05	6.E-06	1.18	6.78	3.22	24.73	1.52	11.18	85100	0.164
	4	4.E-05	1.E-05	1.59	8.44	4.15	31.07	1.96	14.19	107363	0.265
	5	5.E-05	9.E-06	2.38	11.78	6.08	43.79	2.86	20.24	134918	0.194
	6	1.E-05	8.E-07	0.38	3.49	2.11	12.95	1.00	5.98	146131	0.056
	7	5.E-05	5.E-06	0.81	5.14	4.10	20.34	1.93	10.05	78996	0.104
	8	9.E-05	1.E-05	1.19	6.81	6.14	27.76	2.89	14.13	66148	0.109
	9	1.E-04	2.E-05	1.61	8.47	8.29	35.31	3.91	18.37	70342	0.136
	10	1.E-04	2.E-05	2.37	11.78	12.51	50.23	5.90	26.67	84060	0.144
	11	6.E-05	5.E-06	0.41	3.49	3.91	14.79	1.85	7.81	66327	0.082
	12	2.E-04	2.E-05	0.80	5.14	8.08	24.31	3.81	14.02	36456	0.093
	13	3.E-04	3.E-05	1.20	6.80	12.27	33.86	5.78	20.27	38529	0.105
	14	4.E-04	4.E-05	1.61	8.47	16.43	43.46	7.75	26.52	41564	0.096
	15	5.E-04	5.E-05	2.46	11.79	24.74	62.58	11.66	38.99	50052	0.103
	16	2.E-04	1.E-05	0.39	3.51	5.86	16.78	2.76	9.76	25953	0.051
	17	4.E-04	4.E-05	0.80	5.16	12.12	28.41	5.71	18.08	29258	0.086
	18	5.E-04	5.E-05	1.22	6.84	18.57	40.30	8.75	26.63	35041	0.103
	19	6.E-04	7.E-05	1.61	8.49	24.95	52.05	11.76	35.06	42276	0.115
	20	7.E-04	9.E-05	2.43	11.82	36.56	74.44	17.23	50.81	54012	0.127
NS1_1	1	3.E-05	1.E-06	0.42	3.35	2.22	12.70	1.05	6.00	74895	0.047
	2	5.E-05	2.E-06	0.38	3.35	3.28	13.71	1.55	7.01	65390	0.038
	3	8.E-05	3.E-06	0.40	3.34	4.06	14.48	1.91	7.80	49150	0.042
	4	5.E-05	2.E-06	0.63	4.17	3.32	16.46	1.56	8.12	60838	0.037
	5	9.E-05	3.E-06	0.64	4.17	4.08	17.24	1.92	8.89	47737	0.035
	6	2.E-04	7.E-06	0.64	4.18	6.17	19.35	2.91	10.99	31957	0.035
	7	9.E-05	3.E-06	0.85	5.00	4.14	20.00	1.95	10.00	46397	0.038
	8	2.E-04	7.E-06	0.80	5.01	6.16	21.99	2.91	11.97	34989	0.037
	9	3.E-04	1.E-05	0.85	5.01	8.29	24.15	3.91	14.14	30812	0.040
	10	7.E-05	3.E-06	1.23	6.67	4.26	25.51	2.01	12.16	57913	0.041
	11	1.E-04	5.E-06	1.15	6.68	6.22	27.40	2.93	14.05	43357	0.037
	12	2.E-04	9.E-06	1.17	6.67	8.32	29.50	3.92	16.16	39070	0.043
	13	1.E-04	5.E-06	1.61	8.33	6.17	32.77	2.91	16.11	61986	0.045
	14	2.E-04	7.E-06	1.60	8.34	8.27	34.87	3.90	18.20	50370	0.041
	15	2.E-04	1.E-05	1.64	8.34	10.29	36.93	4.85	20.26	42880	0.043
NS1_2	1	4.E-05	1.E-06	0.39	3.42	2.11	12.75	1.00	5.92	49155	0.024
	2	8.E-05	6.E-07	0.39	3.40	3.18	13.79	1.50	6.98	39788	0.008

TABLE B-6
TEST DATA

Test ID (Table B-1)	Sequence	Vertical Strain	Horizontal Strain	Contact Stress (psi)	Confining Pressure (psi)	Cyclic Stress (psi)	θ (psi)	τ_{oct} (psi)	σ_1 (psi)	Mr (psi)	ν
	3	1.E-04	1.E-06	0.41	3.40	4.04	14.66	1.90	7.86	34076	0.013
	4	8.E-05	1.E-06	0.64	4.23	3.14	16.47	1.48	8.00	38219	0.014
	5	1.E-04	1.E-06	0.64	4.23	3.89	17.21	1.83	8.76	34970	0.012
	6	2.E-04	3.E-06	0.65	4.23	6.04	19.39	2.85	10.92	29634	0.016
	7	1.E-04	2.E-06	0.81	5.06	4.09	20.08	1.93	9.96	33406	0.020
	8	2.E-04	5.E-06	0.80	5.05	6.06	22.03	2.86	11.92	31025	0.023
	9	3.E-04	8.E-06	0.81	5.05	8.14	24.10	3.84	14.00	29360	0.028
	10	1.E-04	3.E-06	1.19	6.73	4.07	25.45	1.92	11.99	39089	0.033
	11	2.E-04	6.E-06	1.21	6.72	6.06	27.44	2.86	13.99	36262	0.037
	12	2.E-04	9.E-06	1.20	6.73	8.19	29.59	3.86	16.12	34963	0.037
	13	1.E-04	6.E-06	1.60	8.39	6.00	32.75	2.83	15.98	42990	0.046
	14	2.E-04	9.E-06	1.61	8.39	8.20	34.99	3.86	18.20	41553	0.043
	15	3.E-04	1.E-05	1.60	8.40	10.33	37.12	4.87	20.33	38581	0.040
NS1_3	1	4.E-05	3.E-06	0.40	3.51	2.19	13.13	1.03	6.11	60185	0.077
	2	6.E-05	4.E-06	0.41	3.51	3.17	14.11	1.49	7.09	49938	0.059
	3	1.E-04	5.E-06	0.42	3.52	4.10	15.08	1.93	8.04	41801	0.053
	4	7.E-05	3.E-06	0.63	4.37	3.21	16.94	1.51	8.21	44672	0.048
	5	1.E-04	4.E-06	0.64	4.34	4.05	17.70	1.91	9.03	41482	0.044
	6	2.E-04	7.E-06	0.65	4.35	6.14	19.85	2.90	11.14	34554	0.042
	7	1.E-04	5.E-06	0.78	5.17	4.19	20.48	1.97	10.14	38444	0.046
	8	2.E-04	8.E-06	0.83	5.17	6.14	22.48	2.90	12.14	35296	0.045
	9	2.E-04	1.E-05	0.81	5.17	8.15	24.48	3.84	14.13	33015	0.045
	10	1.E-04	5.E-06	1.23	6.84	4.15	25.90	1.96	12.23	42627	0.051
	11	2.E-04	8.E-06	1.25	6.84	6.06	27.82	2.86	14.15	39897	0.052
	12	2.E-04	1.E-05	1.22	6.84	8.11	29.86	3.82	16.18	37879	0.052
	13	1.E-04	8.E-06	1.60	8.50	6.18	33.27	2.91	16.28	45948	0.062
	14	2.E-04	1.E-05	1.60	8.49	8.22	35.31	3.88	18.32	44442	0.055
	15	3.E-04	1.E-05	1.59	8.50	10.20	37.29	4.81	20.29	40792	0.053
S3_1	1	9.E-05	1.E-05	1.59	9.03	4.20	32.87	1.98	14.82	44696	0.110
	2	9.E-05	1.E-05	1.19	7.35	4.16	27.39	1.96	12.70	44542	0.112
	3	1.E-04	1.E-05	0.80	5.69	4.17	22.02	1.96	10.65	43814	0.118
	4	1.E-04	1.E-05	0.40	4.01	4.15	16.59	1.96	8.57	43389	0.116
	5	2.E-04	1.E-05	1.59	9.02	7.24	35.89	3.41	17.85	42425	0.077
	6	2.E-04	1.E-05	1.19	7.36	7.25	30.50	3.42	15.79	40324	0.079
	7	2.E-04	2.E-05	0.82	5.68	7.19	25.04	3.39	13.69	41083	0.089
	8	2.E-04	2.E-05	0.40	4.00	7.19	19.61	3.39	11.60	38875	0.091
	9	3.E-04	2.E-05	1.61	9.02	10.30	38.98	4.86	20.93	39083	0.072
	10	3.E-04	2.E-05	1.20	7.35	10.34	33.58	4.87	18.89	37731	0.072
	11	3.E-04	2.E-05	0.81	5.67	10.40	28.22	4.90	16.88	36217	0.074
	12	3.E-04	2.E-05	0.41	4.00	10.38	22.81	4.89	14.80	36486	0.073
	13	4.E-04	2.E-05	1.61	9.02	14.47	43.13	6.82	25.10	33732	0.046
	14	4.E-04	2.E-05	1.21	7.34	14.52	37.76	6.85	23.08	32835	0.048
	15	4.E-04	2.E-05	0.80	5.67	14.48	32.30	6.83	20.95	32844	0.047
	16	5.E-04	2.E-05	0.42	4.00	14.47	26.89	6.82	18.89	31834	0.046
S3_2	1	8.E-05	5.E-06	1.57	7.50	4.16	28.21	1.96	13.22	49081	0.060
	2	1.E-04	5.E-06	1.28	5.84	4.05	22.86	1.91	11.17	41786	0.053
	3	1.E-04	5.E-06	0.75	4.17	4.32	17.58	2.04	9.24	40312	0.051
	4	1.E-04	5.E-06	0.28	2.49	4.14	11.89	1.95	6.91	39867	0.051
	5	2.E-04	9.E-06	1.59	7.49	7.16	31.22	3.37	16.24	40189	0.048

TABLE B-6
TEST DATA

Test ID (Table B-1)	Sequence	Vertical Strain	Horizontal Strain	Contact Stress (psi)	Confining Pressure (psi)	Cyclic Stress (psi)	θ (psi)	τ_{oct} (psi)	σ_1 (psi)	Mr (psi)	ν
	6	2.E-04	9.E-06	1.21	5.84	7.07	25.80	3.33	14.12	39846	0.049
	7	2.E-04	8.E-06	0.74	4.17	7.13	20.38	3.36	12.04	37703	0.045
	8	2.E-04	8.E-06	0.45	2.50	7.01	14.95	3.30	9.95	37166	0.044
	9	3.E-04	2.E-05	1.60	7.50	9.97	34.06	4.70	19.07	36283	0.056
	10	3.E-04	2.E-05	1.22	5.84	9.90	28.65	4.66	16.96	35717	0.055
	11	3.E-04	1.E-05	0.84	4.17	9.87	23.23	4.66	14.89	34696	0.049
	12	3.E-04	1.E-05	0.40	2.50	9.86	17.76	4.65	12.76	33731	0.045
	13	4.E-04	2.E-05	1.64	7.50	13.98	38.12	6.59	23.12	32068	0.040
	14	4.E-04	2.E-05	1.22	5.84	13.88	32.63	6.54	20.94	32412	0.041
	15	4.E-04	2.E-05	0.80	4.17	13.89	27.21	6.55	18.87	32219	0.042
	16	4.E-04	2.E-05	0.41	2.50	13.83	21.75	6.52	16.74	31054	0.043
S3_3	1	9.E-05	8.E-07	1.66	7.41	4.01	27.90	1.89	13.08	42911	0.009
	2	1.E-04	1.E-07	1.18	5.75	4.13	22.55	1.95	11.05	42497	0.001
	3	1.E-04	6.E-07	0.76	4.10	4.21	17.27	1.98	9.07	43579	0.006
	4	9.E-05	2.E-06	0.43	2.44	4.00	11.76	1.89	6.87	43908	0.020
	5	2.E-04	1.E-06	1.57	7.41	7.15	30.94	3.37	16.12	40310	0.007
	6	2.E-04	2.E-06	1.19	5.76	7.08	25.54	3.34	14.03	40324	0.010
	7	2.E-04	1.E-07	0.73	4.10	7.25	20.27	3.42	12.08	40256	0.001
	8	2.E-04	1.E-07	0.41	2.45	6.92	14.67	3.26	9.77	40492	0.001
	9	3.E-04	-4.E-07	1.59	7.42	10.01	33.88	4.72	19.03	36525	-0.001
	10	3.E-04	-2.E-07	1.19	5.76	10.08	28.56	4.75	17.04	36884	-0.001
	11	3.E-04	-2.E-07	0.84	4.11	9.83	23.01	4.64	14.79	36403	-0.001
	12	3.E-04	2.E-07	0.41	2.45	9.86	17.61	4.65	12.72	36242	0.001
	13	4.E-04	2.E-07	1.59	7.43	14.00	37.88	6.60	23.02	33075	0.001
	14	4.E-04	2.E-06	1.18	5.77	13.84	32.34	6.53	20.80	32941	0.005
	15	4.E-04	5.E-06	0.78	4.11	13.91	27.02	6.56	18.80	32544	0.011
	16	4.E-04	6.E-06	0.42	2.46	13.81	21.59	6.51	16.68	32178	0.014
NS3_1	1	7.E-05	3.E-06	0.66	0.00	2.17	3.59	1.02	3.08	31361	0.050
	2	1.E-04	6.E-06	1.10	0.00	3.60	5.48	1.70	4.97	29730	0.052
	3	2.E-04	9.E-06	1.47	0.00	5.18	7.40	2.44	6.90	28739	0.050
	4	3.E-04	1.E-05	1.88	0.00	6.87	9.50	3.24	9.00	27392	0.048
	5	3.E-04	2.E-05	2.31	0.00	8.42	11.47	3.97	10.97	26141	0.051
NS3_3	1	6.E-05	7.E-07	0.71	0.00	2.37	3.85	1.12	3.34	38615	0.012
	2	1.E-04	9.E-07	1.14	0.00	3.99	5.88	1.88	5.38	37104	0.008
	3	2.E-04	9.E-07	1.50	0.00	5.45	7.70	2.57	7.20	35823	0.006
	4	2.E-04	7.E-07	1.86	0.00	7.01	9.60	3.30	9.11	34176	0.004
	5	3.E-04	2.E-06	2.21	0.00	8.64	11.63	4.07	11.11	32763	0.007
NS3_4	1	7.E-05	4.E-06	0.64	0.00	2.43	3.72	1.14	3.29	36411	0.060
	2	1.E-04	6.E-06	1.03	0.00	3.95	5.64	1.86	5.20	33949	0.049
	3	2.E-04	8.E-06	1.40	0.00	5.48	7.55	2.58	7.11	32995	0.047
	4	2.E-04	1.E-05	1.83	0.00	7.09	9.54	3.34	9.12	30400	0.048
	5	3.E-04	2.E-05	2.29	0.00	8.63	11.58	4.07	11.14	28715	0.056

TABLE B-7
TEST DATA FOR ADDITIONAL TESTS

Test ID (Table B-2)	Sequence	Vertical Strain	Horizontal Strain	Contact Stress (psi)	Confining Pressure (psi)	Cyclic Stress (psi)	θ (psi)	τ_{oct} (psi)	σ_1 (psi)	Mr (psi)	ν
S11_dry	1	2.E-05	4.E-06	0.64	4.27	1.68	15.13	0.79	6.59	85664	0.209
	2	4.E-05	4.E-06	1.20	6.89	3.17	25.05	1.50	11.26	81767	0.094
	3	5.E-05	5.E-06	2.00	10.38	5.20	38.36	2.45	17.59	101717	0.099
	4	6.E-05	6.E-06	3.05	14.76	7.73	55.08	3.65	25.55	132059	0.095
	5	6.E-05	7.E-06	3.99	19.15	10.45	71.89	4.93	33.59	164573	0.116
	6	4.E-05	7.E-06	0.63	4.27	3.17	16.60	1.49	8.07	71034	0.161
	7	8.E-05	1.E-05	1.21	6.89	6.08	27.97	2.87	14.19	74977	0.126
	8	1.E-04	2.E-05	2.00	10.38	10.29	43.45	4.85	22.68	93692	0.159
	9	1.E-04	2.E-05	3.02	14.76	15.65	62.95	7.38	33.43	116912	0.156
	10	2.E-04	2.E-05	4.00	19.15	20.77	82.21	9.79	43.92	115929	0.123
	11	1.E-04	2.E-05	0.64	4.27	6.14	19.60	2.90	11.06	62284	0.161
	12	2.E-04	3.E-05	1.22	6.89	12.43	34.30	5.86	20.53	63958	0.178
	13	3.E-04	5.E-05	2.01	10.38	20.92	54.05	9.86	33.30	67133	0.154
	14	5.E-04	5.E-05	3.04	14.76	30.87	78.20	14.55	48.67	58923	0.100
	15	6.E-04	5.E-05	4.03	19.14	41.47	102.92	19.55	64.64	73750	0.098
	16	3.E-04	3.E-05	0.67	4.27	9.19	22.65	4.33	14.12	29060	0.100
	17	5.E-04	6.E-05	1.22	6.88	18.92	40.79	8.92	27.02	35937	0.115
	18	6.E-04	8.E-05	2.01	10.38	31.03	64.19	14.63	43.43	48184	0.121
	19	8.E-04	9.E-05	3.07	14.75	46.66	93.98	21.99	64.48	62141	0.117
	20	8.E-04	1.E-04	4.04	19.14	61.83	123.30	29.15	85.01	73164	0.123
	21	5.E-04	7.E-05	0.66	4.26	15.58	29.02	7.35	20.50	28544	0.130
	22	8.E-04	1.E-04	1.23	6.89	30.99	52.89	14.61	39.11	38931	0.141
	23	9.E-04	1.E-04	2.04	10.39	51.67	84.88	24.36	64.10	54571	0.156
	24	1.E-03	2.E-04	3.10	14.75	77.32	124.68	36.45	95.18	69625	0.180
	25	1.E-03	2.E-04	4.10	19.13	102.67	164.17	48.40	125.90	84918	0.198
	26	7.E-04	1.E-04	0.67	4.26	21.79	35.24	10.27	26.72	30667	0.167
	27	1.E-03	2.E-04	1.25	6.87	43.19	65.06	20.36	51.32	43433	0.197
	28	1.E-03	2.E-04	2.08	10.37	71.42	104.62	33.67	83.87	61861	0.217
	29	1.E-03	6.E-04	3.18	10.38	107.39	141.70	50.62	120.95	75723	0.396
	30	9.E-03	4.E-04	4.95	10.40	95.09	131.25	44.83	110.45	10364	0.039
S11_high	1	2.E-04	3.E-05	0.70	4.29	1.24	14.81	0.59	6.23	5665	0.155
	2	2.E-04	6.E-05	1.19	6.90	3.02	24.92	1.43	11.11	13277	0.247
	3	2.E-04	6.E-05	1.97	10.39	5.16	38.29	2.43	17.51	24454	0.263
	4	2.E-04	4.E-05	3.04	14.75	8.06	55.35	3.80	25.85	38296	0.213
	5	2.E-04	4.E-05	3.97	19.13	10.42	71.78	4.91	33.52	51017	0.184
	6	4.E-04	7.E-05	0.73	4.30	2.66	16.28	1.25	7.69	6580	0.166
	7	4.E-04	1.E-04	1.23	6.91	6.14	28.10	2.89	14.28	16218	0.266
	8	4.E-04	1.E-04	2.01	10.39	10.45	43.63	4.92	22.84	28148	0.277
	9	4.E-04	9.E-05	3.06	14.76	15.63	62.97	7.37	33.45	42277	0.235
	10	4.E-04	8.E-05	3.99	19.14	20.59	82.01	9.71	43.73	54349	0.199
	11	6.E-04	1.E-04	0.68	4.30	5.93	19.51	2.80	10.91	9126	0.181
	12	6.E-04	2.E-04	1.22	6.91	12.63	34.59	5.95	20.76	21476	0.284
	13	6.E-04	2.E-04	2.01	10.40	20.66	53.88	9.74	33.07	35231	0.307
	14	6.E-04	2.E-04	3.05	14.77	30.84	78.20	14.54	48.66	48192	0.291
	15	7.E-04	2.E-04	4.04	19.14	41.19	102.65	19.42	64.37	57999	0.258
	16	8.E-04	2.E-04	0.67	4.30	9.48	23.06	4.47	14.46	11779	0.204
	17	7.E-04	2.E-04	1.23	6.92	18.57	40.55	8.75	26.71	24947	0.305
	18	8.E-04	3.E-04	2.01	10.41	30.72	63.96	14.48	43.15	38634	0.341
	19	9.E-04	3.E-04	3.06	14.77	46.11	93.47	21.74	63.94	49412	0.340

TABLE B-7
TEST DATA FOR ADDITIONAL TESTS

Test ID (Table B-2)	Sequence	Vertical Strain	Horizontal Strain	Contact Stress (psi)	Confining Pressure (psi)	Cyclic Stress (psi)	θ (psi)	τ_{oct} (psi)	σ_1 (psi)	Mr (psi)	ν
	20	1.E-03	4.E-04	4.04	19.15	61.73	123.21	29.10	84.92	56026	0.338
	21	1.E-03	3.E-04	0.67	4.31	15.77	29.38	7.44	20.76	15857	0.259
	22	1.E-03	4.E-04	1.22	6.92	30.54	52.52	14.40	38.68	30226	0.360
	23	1.E-03	5.E-04	2.05	10.41	51.29	84.57	24.18	63.76	43508	0.435
	24	1.E-03	7.E-04	3.09	14.78	77.04	124.47	36.32	94.91	53773	0.469
	25	2.E-03	8.E-04	4.07	19.15	102.36	163.89	48.25	125.59	62776	0.515
	26	1.E-03	4.E-04	0.67	4.31	21.97	35.58	10.35	26.95	19387	0.391
	27	1.E-03	6.E-04	1.23	6.93	42.49	64.52	20.03	50.65	34078	0.463
	28	1.E-03	8.E-04	2.06	10.42	72.15	105.47	34.01	84.63	49536	0.538
	29	2.E-03	2.E-03	3.11	10.41	106.03	140.38	49.98	119.55	57263	1.080
	30	2.E-06	3.E-07	9.06	10.41	12.15	52.44	5.73	31.62	4989264	0.115
S11_low	1	1.E-04	3.E-05	0.59	4.07	1.38	14.19	0.65	6.04	14207	0.285
	2	1.E-04	3.E-05	1.19	6.70	2.84	24.14	1.34	10.73	24070	0.246
	3	1.E-04	3.E-05	2.06	10.22	4.86	37.58	2.29	17.14	35779	0.205
	4	1.E-04	3.E-05	3.00	14.60	7.59	54.40	3.58	25.20	51287	0.181
	5	2.E-04	3.E-05	3.95	18.99	10.52	71.43	4.96	33.45	65406	0.174
	6	2.E-04	6.E-05	0.61	4.09	2.71	15.58	1.28	7.40	13251	0.312
	7	2.E-04	7.E-05	1.16	6.72	5.67	26.98	2.67	13.55	23966	0.291
	8	3.E-04	7.E-05	1.98	10.22	10.00	42.65	4.72	22.21	36995	0.248
	9	3.E-04	6.E-05	3.00	14.62	15.61	62.47	7.36	33.23	53853	0.218
	10	3.E-04	6.E-05	3.97	19.00	21.02	81.97	9.91	43.98	68912	0.202
	11	3.E-04	1.E-04	0.70	4.10	5.19	18.18	2.44	9.98	14870	0.338
	12	4.E-04	1.E-04	1.20	6.73	11.76	33.16	5.54	19.69	28648	0.338
	13	5.E-04	1.E-04	2.02	10.23	20.82	53.54	9.81	33.08	44732	0.301
	14	5.E-04	1.E-04	3.08	14.62	31.30	78.23	14.75	49.00	61982	0.267
	15	6.E-04	1.E-04	4.04	19.01	41.06	102.12	19.35	64.10	73955	0.251
	16	5.E-04	2.E-04	0.66	4.11	8.17	21.17	3.85	12.94	17444	0.348
	17	5.E-04	2.E-04	1.22	6.74	18.32	39.76	8.64	26.28	33493	0.363
	18	6.E-04	2.E-04	2.04	10.24	31.04	63.81	14.63	43.33	49645	0.351
	19	7.E-04	3.E-04	3.10	14.63	45.95	92.92	21.66	63.67	62988	0.361
	20	8.E-04	3.E-04	4.01	19.02	60.89	121.95	28.70	83.92	73275	0.378
	21	7.E-04	3.E-04	0.72	4.12	14.34	27.41	6.76	19.18	21273	0.394
	22	8.E-04	4.E-04	1.25	6.75	30.85	52.34	14.54	38.85	38715	0.444
	23	1.E-03	5.E-04	2.04	10.26	50.71	83.53	23.91	63.01	53322	0.521
	24	1.E-03	7.E-04	3.07	14.64	75.53	122.51	35.60	93.24	65868	0.593
	25	1.E-03	9.E-04	4.08	19.02	100.46	161.60	47.36	123.56	78478	0.695
	26	9.E-04	5.E-04	0.71	4.13	20.69	33.79	9.76	25.54	22509	0.527
	27	1.E-03	7.E-04	1.24	6.76	43.24	64.77	20.38	51.24	41763	0.633
	28	1.E-03	1.E-03	2.14	10.26	70.67	103.61	33.32	83.08	61427	0.866
	29	1.E-03	2.E-03	3.20	14.64	104.65	151.78	49.33	122.49	85478	1.446
	30	2.E-03	2.E-09	4.21	19.04	140.25	201.57	66.11	163.50	88595	0.000
S11_mid	1	1.E-04	3.E-05	0.65	3.95	1.25	13.74	0.59	5.85	9035	0.181
	2	2.E-04	5.E-05	1.20	6.58	2.92	23.84	1.38	10.69	16411	0.264
	3	2.E-04	5.E-05	1.99	10.07	5.12	37.32	2.41	17.18	30976	0.310
	4	1.E-04	3.E-05	3.03	14.46	7.73	54.15	3.64	25.22	53768	0.238
	5	1.E-04	3.E-05	3.99	18.86	10.50	71.07	4.95	33.35	79642	0.202
	6	3.E-04	5.E-05	0.63	3.97	2.64	15.19	1.25	7.25	8683	0.170
	7	3.E-04	1.E-04	1.23	6.59	5.99	27.00	2.82	13.82	18422	0.309
	8	3.E-04	1.E-04	2.01	10.10	10.41	42.71	4.91	22.51	32077	0.321

TABLE B-7
TEST DATA FOR ADDITIONAL TESTS

Test ID (Table B-2)	Sequence	Vertical Strain	Horizontal Strain	Contact Stress (psi)	Confining Pressure (psi)	Cyclic Stress (psi)	θ (psi)	τ_{oct} (psi)	σ_1 (psi)	Mr (psi)	ν
	9	3.E-04	9.E-05	3.04	14.48	15.75	62.22	7.43	33.27	49453	0.273
	10	3.E-04	8.E-05	4.01	18.87	20.93	81.56	9.87	43.82	68202	0.258
	11	5.E-04	9.E-05	0.68	3.99	4.91	17.56	2.32	9.58	10459	0.198
	12	5.E-04	2.E-04	1.24	6.62	11.72	32.82	5.53	19.58	22659	0.334
	13	5.E-04	2.E-04	2.03	10.11	20.76	53.13	9.79	32.91	38314	0.381
	14	6.E-04	2.E-04	3.08	14.51	31.22	77.83	14.72	48.81	52871	0.365
	15	7.E-04	2.E-04	4.04	18.89	41.05	101.75	19.35	63.97	62203	0.324
	16	6.E-04	1.E-04	0.67	4.01	7.99	20.69	3.77	12.67	12707	0.229
	17	7.E-04	3.E-04	1.26	6.64	18.15	39.31	8.56	26.04	27193	0.379
	18	7.E-04	3.E-04	2.06	10.13	30.99	63.42	14.61	43.17	41848	0.449
	19	9.E-04	4.E-04	3.09	14.51	45.87	92.49	21.62	63.47	49682	0.418
	20	1.E-03	4.E-04	4.09	18.90	60.79	121.57	28.66	83.77	58496	0.421
	21	9.E-04	3.E-04	0.73	4.03	14.34	27.16	6.76	19.10	16276	0.306
	22	1.E-03	5.E-04	1.29	6.65	30.86	52.10	14.55	38.80	31250	0.465
	23	1.E-03	6.E-04	2.08	10.15	50.83	83.35	23.96	63.06	44631	0.556
	24	1.E-03	8.E-04	3.15	14.53	75.34	122.07	35.52	93.02	56529	0.600
	25	1.E-03	1.E-03	4.16	18.91	100.72	161.61	47.48	123.79	70212	0.698
	26	1.E-03	5.E-04	0.68	4.04	20.99	33.80	9.89	25.71	20134	0.483
	27	1.E-03	7.E-04	1.28	6.66	43.25	64.52	20.39	51.19	38696	0.642
	28	1.E-03	1.E-03	2.14	10.16	70.37	102.99	33.17	82.67	54308	0.801
	29	2.E-03	2.E-03	3.18	14.54	104.89	151.68	49.45	122.61	63023	0.953
	30	2.E-03	1.E-03	4.20	18.93	139.71	200.72	65.86	162.85	86649	0.903
S11_wet	1	2.E-04	8.E-05	0.65	4.22	1.35	14.66	0.64	6.22	6160	0.387
	2	2.E-04	1.E-04	1.20	6.84	3.12	24.85	1.47	11.17	13391	0.412
	3	2.E-04	1.E-04	1.99	10.35	5.26	38.30	2.48	17.60	21512	0.446
	4	2.E-04	1.E-04	3.04	14.73	7.86	55.09	3.71	25.63	31614	0.440
	5	3.E-04	1.E-04	4.00	19.11	10.47	71.79	4.93	33.58	41811	0.404
	6	5.E-04	2.E-04	0.65	4.23	2.85	16.17	1.34	7.72	5802	0.468
	7	4.E-04	2.E-04	1.22	6.84	6.38	28.12	3.01	14.44	15768	0.568
	8	4.E-04	2.E-04	2.01	10.35	10.67	43.73	5.03	23.03	25236	0.591
	9	4.E-04	2.E-04	3.05	14.73	16.03	63.26	7.55	33.80	36820	0.549
	10	4.E-04	2.E-04	4.02	19.11	21.13	82.49	9.96	44.26	47200	0.500
	11	7.E-04	3.E-04	0.67	4.22	5.45	18.78	2.57	10.34	7990	0.494
	12	6.E-04	4.E-04	1.21	6.86	12.71	34.49	5.99	20.78	20505	0.664
	13	7.E-04	5.E-04	2.02	10.35	21.40	54.46	10.09	33.77	30445	0.710
	14	8.E-04	6.E-04	3.07	14.73	31.11	78.38	14.66	48.91	39774	0.717
	15	9.E-04	6.E-04	4.04	19.12	40.71	102.09	19.19	63.86	47194	0.692
	16	3.E-06	1.E-06	1.14	4.22	0.03	13.83	0.01	5.38	10437	0.408
	17	9.E-04	7.E-04	1.25	6.85	19.57	41.38	9.23	27.68	21341	0.749
	18	1.E-03	9.E-04	2.05	10.35	31.78	64.86	14.98	44.17	30175	0.833
	19	1.E-03	1.E-03	3.10	14.72	46.62	93.88	21.98	64.44	38979	0.855
	20	4.E-03	1.E-03	4.11	19.12	55.99	117.45	26.39	79.22	15774	0.378
	21	2.E-03	1.E-03	0.77	4.21	9.14	22.55	4.31	14.13	4855	0.691
S7_dry	1	5.E-06	2.E-06	0.37	3.26	1.09	11.24	0.51	4.72	208954	0.366
	2	2.E-05	4.E-06	0.81	5.00	2.06	17.88	0.97	7.88	105564	0.196
	3	5.E-05	6.E-06	1.19	6.76	3.14	24.63	1.48	11.10	62935	0.116
	4	7.E-05	4.E-06	1.60	8.51	4.09	31.22	1.93	14.20	56846	0.050
	5	1.E-04	5.E-06	2.38	12.01	6.12	44.52	2.88	20.50	50840	0.045
	6	2.E-05	2.E-06	0.41	3.27	2.12	12.34	1.00	5.80	96501	0.096

TABLE B-7
TEST DATA FOR ADDITIONAL TESTS

Test ID (Table B-2)	Sequence	Vertical Strain	Horizontal Strain	Contact Stress (psi)	Confining Pressure (psi)	Cyclic Stress (psi)	θ (psi)	τ_{oct} (psi)	σ_1 (psi)	Mr (psi)	ν
	7	7.E-05	5.E-06	0.81	5.02	4.05	19.92	1.91	9.88	54784	0.067
	8	1.E-04	9.E-06	1.18	6.76	6.10	27.57	2.88	14.04	41396	0.064
	9	2.E-04	1.E-05	1.57	8.52	8.17	35.29	3.85	18.26	35339	0.060
	10	4.E-04	2.E-05	2.41	12.01	12.36	50.81	5.83	26.79	29963	0.048
	11	7.E-05	4.E-06	0.39	3.27	4.08	14.27	1.92	7.73	57291	0.057
	12	2.E-04	2.E-05	0.79	5.02	8.22	24.08	3.87	14.03	33545	0.061
	13	5.E-04	3.E-05	1.21	6.77	12.22	33.73	5.76	20.19	24879	0.066
	14	7.E-04	5.E-05	1.62	8.52	16.28	43.47	7.68	26.43	21962	0.069
	15	1.E-03	1.E-04	2.42	12.00	24.65	63.07	11.62	39.07	19856	0.089
	16	2.E-04	8.E-06	0.39	3.27	6.10	16.30	2.88	9.76	35476	0.048
	17	5.E-04	4.E-05	0.81	5.02	12.11	27.98	5.71	17.94	22854	0.071
	18	1.E-03	9.E-05	1.21	6.76	18.21	39.71	8.58	26.18	18388	0.095
	19	1.E-03	1.E-04	1.61	8.51	24.53	51.68	11.56	34.66	17418	0.100
	20	2.E-03	3.E-04	2.46	12.01	36.56	75.05	17.24	51.03	16811	0.123
S7_high	1	7.E-05	8.E-07	0.41	3.20	1.13	11.13	0.53	4.74	17211	0.013
	2	2.E-04	3.E-06	0.80	4.95	2.02	17.66	0.95	7.77	12605	0.017
	3	3.E-04	1.E-05	1.20	6.69	3.00	24.28	1.41	10.89	10704	0.035
	4	3.E-04	2.E-05	1.60	8.44	4.00	30.94	1.89	14.05	11689	0.046
	5	5.E-04	2.E-05	2.40	11.94	6.12	44.36	2.89	20.47	12887	0.048
	6	1.E-04	5.E-06	0.41	3.20	1.96	11.98	0.92	5.57	13874	0.032
	7	4.E-04	2.E-05	0.81	4.96	3.73	19.41	1.76	9.49	8573	0.056
	8	7.E-04	5.E-05	1.20	6.70	5.65	26.95	2.67	13.55	8056	0.070
	9	9.E-04	7.E-05	1.60	8.45	7.87	34.81	3.71	17.92	8394	0.073
	10	1.E-03	1.E-04	2.42	11.94	12.09	50.34	5.70	26.46	8767	0.104
	11	5.E-04	2.E-05	0.49	3.21	3.57	13.69	1.68	7.27	7926	0.054
	12	1.E-03	1.E-04	0.78	4.95	7.14	22.77	3.37	12.87	5725	0.101
	13	2.E-03	2.E-04	1.35	6.69	11.24	32.67	5.30	19.28	5789	0.125
	14	2.E-03	4.E-04	1.64	8.44	15.39	42.37	7.25	25.48	6225	0.148
	15	4.E-03	6.E-04	2.49	11.94	24.32	62.64	11.47	38.76	6517	0.170
	16	8.E-04	6.E-05	0.43	3.21	5.37	15.42	2.53	9.00	7141	0.074
	17	2.E-03	3.E-04	0.86	4.95	10.78	26.49	5.08	16.59	4996	0.142
	18	4.E-03	6.E-04	1.26	6.70	17.04	38.41	8.03	25.00	4844	0.167
	19	4.E-03	8.E-04	1.66	8.44	24.26	51.24	11.44	34.36	5428	0.179
	20	6.E-03	1.E-03	2.47	11.94	38.70	77.00	18.24	53.11	6267	0.199
S7_low	1	3.E-04	2.E-05	0.40	2.99	0.89	10.26	0.42	4.28	3264	0.061
	2	6.E-04	5.E-05	0.80	4.75	1.62	16.67	0.76	7.17	2922	0.085
	3	8.E-04	8.E-05	1.21	6.49	2.52	23.19	1.19	10.21	3192	0.105
	4	9.E-04	1.E-04	1.60	8.25	3.51	29.86	1.66	13.36	3823	0.110
	5	1.E-03	1.E-04	2.41	11.75	5.50	43.16	2.59	19.66	4426	0.120
	6	7.E-04	7.E-05	0.40	2.99	1.45	10.83	0.68	4.85	2223	0.101
	7	1.E-03	2.E-04	0.82	4.76	2.83	17.93	1.34	8.41	2022	0.135
	8	2.E-03	3.E-04	1.22	6.51	4.66	25.40	2.20	12.39	2362	0.154
	9	2.E-03	4.E-04	1.63	8.25	6.79	33.17	3.20	16.67	2826	0.160
	10	3.E-03	6.E-04	2.43	11.75	10.67	48.34	5.03	24.85	3267	0.186
	11	2.E-03	2.E-04	0.42	3.00	2.59	12.02	1.22	6.01	1680	0.131
	12	3.E-03	6.E-04	0.84	4.75	5.70	20.80	2.69	11.29	1666	0.170
	13	5.E-03	9.E-04	1.23	6.52	9.85	30.63	4.64	17.60	2164	0.189
	14	5.E-03	1.E-03	1.65	8.25	13.92	40.33	6.56	23.82	2715	0.221
	15	5.E-03	1.E-03	2.44	11.75	22.80	60.51	10.75	37.00	4916	0.319

TABLE B-7
TEST DATA FOR ADDITIONAL TESTS

Test ID (Table B-2)	Sequence	Vertical Strain	Horizontal Strain	Contact Stress (psi)	Confining Pressure (psi)	Cyclic Stress (psi)	θ (psi)	τ_{oct} (psi)	σ_1 (psi)	Mr (psi)	ν
	16	2.E-03	3.E-04	0.42	3.02	4.37	13.83	2.06	7.80	2484	0.167
	17	4.E-03	9.E-04	0.84	4.78	9.60	24.77	4.53	15.22	2488	0.235
	18	5.E-03	1.E-03	1.25	6.51	16.26	37.05	7.67	24.02	3287	0.274
	19	5.E-03	2.E-03	1.65	8.26	23.04	49.45	10.86	32.94	4955	0.340
	20	2.E-03	4.E-04	2.45	11.77	35.04	72.80	16.52	49.26	23097	0.276
S7_mid	1	1.E-05	1.E-06	0.39	2.93	1.08	10.27	0.51	4.40	106479	0.111
	2	7.E-05	6.E-07	0.80	4.70	1.92	16.82	0.90	7.42	27058	0.009
	3	2.E-04	2.E-06	1.22	6.43	2.83	23.33	1.33	10.47	18175	0.013
	4	2.E-04	4.E-06	1.61	8.19	3.78	29.96	1.78	13.58	17354	0.019
	5	3.E-04	1.E-05	2.40	11.70	5.81	43.30	2.74	19.91	17580	0.031
	6	8.E-05	4.E-06	0.40	2.96	1.84	11.10	0.87	5.19	22533	0.049
	7	3.E-04	2.E-05	0.82	4.71	3.56	18.50	1.68	9.08	11179	0.064
	8	5.E-04	4.E-05	1.20	6.45	5.41	25.96	2.55	13.06	9891	0.075
	9	7.E-04	5.E-05	1.60	8.20	7.35	33.55	3.47	17.15	9930	0.073
	10	1.E-03	1.E-04	2.41	11.70	11.13	48.66	5.25	25.25	10391	0.091
	11	3.E-04	2.E-05	0.40	2.96	3.37	12.67	1.59	6.74	11026	0.062
	12	9.E-04	9.E-05	0.83	4.71	6.68	21.64	3.15	12.22	7360	0.097
	13	1.E-03	2.E-04	1.24	6.48	10.33	31.02	4.87	18.05	6900	0.111
	14	2.E-03	2.E-04	1.65	8.21	14.34	40.61	6.76	24.20	7176	0.123
	15	3.E-03	5.E-04	2.46	11.72	22.63	60.24	10.67	36.81	7546	0.156
	16	6.E-04	5.E-05	0.42	2.97	5.07	14.41	2.39	8.47	8456	0.088
	17	2.E-03	2.E-04	0.85	4.73	9.93	24.96	4.68	15.51	5960	0.133
	18	3.E-03	4.E-04	1.27	6.48	15.81	36.53	7.45	23.57	5738	0.155
	19	4.E-03	6.E-04	1.66	8.20	22.58	48.85	10.65	32.45	6337	0.163
	20	5.E-03	1.E-03	2.46	11.72	35.26	72.88	16.62	49.44	6853	0.188
S7_wet	1	2.E-04	1.E-05	0.39	3.25	0.94	11.07	0.44	4.58	4083	0.051
	2	5.E-04	4.E-05	0.81	5.01	1.63	17.46	0.77	7.45	3344	0.080
	3	7.E-04	8.E-05	1.20	6.75	2.55	24.00	1.20	10.50	3562	0.105
	4	8.E-04	1.E-04	1.60	8.50	3.57	30.66	1.68	13.67	4214	0.112
	5	1.E-03	1.E-04	2.40	12.00	5.58	43.98	2.63	19.97	4770	0.122
	6	6.E-04	5.E-05	0.41	3.26	1.48	11.66	0.70	5.15	2655	0.084
	7	1.E-03	2.E-04	0.82	5.02	2.87	18.74	1.35	8.70	2261	0.126
	8	2.E-03	3.E-04	1.21	6.76	4.69	26.17	2.21	12.66	2541	0.146
	9	2.E-03	4.E-04	1.63	8.51	6.81	33.97	3.21	16.95	2986	0.154
	10	3.E-03	6.E-04	2.44	12.01	10.78	49.25	5.08	25.23	3353	0.176
	11	1.E-03	2.E-04	0.40	3.26	2.66	12.85	1.25	6.33	1960	0.119
	12	3.E-03	5.E-04	0.84	5.01	5.72	21.60	2.70	11.57	1799	0.158
	13	4.E-03	8.E-04	1.24	6.76	9.98	31.52	4.71	17.99	2226	0.176
	14	5.E-03	1.E-03	1.65	8.52	14.20	41.42	6.69	24.37	2660	0.196
	15	6.E-03	1.E-03	2.51	12.01	23.26	61.81	10.97	37.79	4032	0.251
	16	2.E-03	2.E-04	0.42	3.27	4.45	14.68	2.10	8.14	2534	0.142
	17	4.E-03	9.E-04	0.86	5.02	9.77	25.69	4.61	15.65	2324	0.204
	18	6.E-03	1.E-03	1.25	6.77	16.51	38.08	7.78	24.53	2861	0.235
	19	6.E-03	2.E-03	1.66	8.52	23.63	50.84	11.14	33.80	3759	0.268
	20	4.E-03	1.E-03	2.43	12.02	36.14	74.63	17.04	50.59	9617	0.294
S13_dry	1	5.E-06	3.E-06	0.39	3.09	1.26	10.92	0.59	4.74	242949	0.496
	2	3.E-06	2.E-06	0.79	4.84	2.16	17.48	1.02	7.80	746741	0.763
	3	3.E-06	7.E-06	1.20	6.58	3.17	24.13	1.50	10.96	970705	2.109
	4	7.E-06	1.E-05	1.59	8.35	4.11	30.74	1.94	14.05	598960	1.753

TABLE B-7
TEST DATA FOR ADDITIONAL TESTS

Test ID (Table B-2)	Sequence	Vertical Strain	Horizontal Strain	Contact Stress (psi)	Confining Pressure (psi)	Cyclic Stress (psi)	θ (psi)	τ_{oct} (psi)	σ_1 (psi)	Mr (psi)	ν
	5	1.E-05	1.E-05	2.40	11.86	6.04	44.02	2.85	20.30	471611	1.157
	6	2.E-06	2.E-06	0.39	3.11	2.20	11.92	1.04	5.70	889968	0.667
	7	3.E-06	3.E-06	0.81	4.86	4.12	19.51	1.94	9.79	1371622	0.899
	8	1.E-05	6.E-06	1.21	6.61	6.03	27.06	2.84	13.85	603169	0.648
	9	2.E-05	2.E-05	1.61	8.36	8.06	34.75	3.80	18.03	380491	0.726
	10	1.E-04	8.E-06	2.41	11.87	12.25	50.27	5.78	26.53	123270	0.083
	11	3.E-06	2.E-06	0.41	3.12	4.05	13.80	1.91	7.57	1163435	0.586
	12	3.E-05	4.E-06	0.81	4.88	7.99	23.44	3.77	13.68	256815	0.120
	13	1.E-04	9.E-06	1.21	6.62	12.08	33.15	5.69	19.91	99765	0.071
	14	3.E-04	1.E-05	1.61	8.37	16.13	42.85	7.61	26.12	58590	0.054
	15	6.E-04	5.E-05	2.43	11.87	24.44	62.49	11.52	38.75	44434	0.093
	16	3.E-05	4.E-06	0.41	3.13	5.95	15.74	2.81	9.49	194778	0.144
	17	2.E-04	2.E-05	0.82	4.89	11.94	27.42	5.63	17.64	64187	0.081
	18	4.E-04	3.E-05	1.23	6.63	18.16	39.29	8.56	26.03	45790	0.083
	19	6.E-04	6.E-05	1.63	8.38	24.47	51.25	11.54	34.49	40709	0.096
	20	1.E-03	1.E-04	2.47	11.88	36.35	74.45	17.14	50.69	33999	0.114
S13_high	1	1.E-05	4.E-06	0.41	3.02	1.25	10.72	0.59	4.68	88883	0.256
	2	3.E-05	5.E-06	0.83	4.77	2.10	17.25	0.99	7.71	67374	0.175
	3	5.E-05	8.E-06	1.19	6.53	3.17	23.95	1.50	10.89	65071	0.156
	4	7.E-05	1.E-05	1.59	8.29	4.08	30.53	1.92	13.95	62550	0.148
	5	9.E-05	1.E-05	2.39	11.80	6.00	43.78	2.83	20.19	64257	0.125
	6	3.E-05	6.E-06	0.40	3.05	2.16	11.70	1.02	5.61	76406	0.201
	7	6.E-05	1.E-05	0.79	4.80	4.05	19.24	1.91	9.64	67377	0.159
	8	1.E-04	2.E-05	1.18	6.54	5.96	26.77	2.81	13.68	58336	0.153
	9	1.E-04	2.E-05	1.61	8.30	7.97	34.47	3.76	17.88	57577	0.144
	10	2.E-04	3.E-05	2.39	11.81	12.09	49.90	5.70	26.29	51074	0.146
	11	6.E-05	1.E-05	0.38	3.06	4.02	13.56	1.89	7.45	67792	0.170
	12	2.E-04	2.E-05	0.79	4.81	7.95	23.18	3.75	13.55	52362	0.157
	13	3.E-04	4.E-05	1.22	6.56	11.86	32.75	5.59	19.64	47424	0.154
	14	4.E-04	6.E-05	1.62	8.31	15.76	42.30	7.43	25.68	43955	0.160
	15	6.E-04	1.E-04	2.44	11.81	23.94	61.82	11.28	38.19	36870	0.179
	16	1.E-04	2.E-05	0.41	3.06	5.80	15.40	2.74	9.28	60274	0.214
	17	3.E-04	5.E-05	0.82	4.82	11.61	26.91	5.47	17.26	45095	0.184
	18	5.E-04	9.E-05	1.20	6.57	17.80	38.72	8.39	25.58	37526	0.182
	19	7.E-04	1.E-04	1.62	8.33	24.03	50.64	11.33	33.98	34256	0.180
	20	1.E-03	2.E-04	2.50	11.83	35.86	73.85	16.91	50.19	28725	0.197
S13_low	1	1.E-05	2.E-06	0.40	3.18	1.26	11.19	0.59	4.84	103401	0.184
	2	4.E-05	3.E-06	0.79	4.92	2.11	17.65	0.99	7.81	54947	0.081
	3	5.E-05	4.E-06	1.21	6.68	3.04	24.29	1.43	10.93	60774	0.076
	4	6.E-05	6.E-06	1.59	8.43	3.98	30.85	1.88	14.00	63904	0.098
	5	8.E-05	1.E-05	2.39	11.95	5.92	44.17	2.79	20.26	71967	0.181
	6	2.E-05	5.E-06	0.41	3.18	2.09	12.03	0.99	5.68	102629	0.248
	7	7.E-05	1.E-05	0.80	4.93	3.93	19.53	1.85	9.67	56664	0.167
	8	1.E-04	2.E-05	1.20	6.69	5.87	27.14	2.77	13.76	47682	0.157
	9	2.E-04	3.E-05	1.61	8.43	7.88	34.76	3.71	17.91	40755	0.139
	10	3.E-04	4.E-05	2.41	11.94	11.95	50.19	5.63	26.30	35001	0.130
	11	9.E-05	1.E-05	0.40	3.21	3.93	13.95	1.85	7.54	43811	0.141
	12	2.E-04	3.E-05	0.81	4.94	7.81	23.45	3.68	13.56	31974	0.134
	13	4.E-04	6.E-05	1.22	6.70	11.67	32.99	5.50	19.60	28704	0.139

TABLE B-7
TEST DATA FOR ADDITIONAL TESTS

Test ID (Table B-2)	Sequence	Vertical Strain	Horizontal Strain	Contact Stress (psi)	Confining Pressure (psi)	Cyclic Stress (psi)	θ (psi)	τ_{oct} (psi)	σ_1 (psi)	Mr (psi)	ν
	14	6.E-04	9.E-05	1.64	8.43	15.73	42.67	7.42	25.80	26105	0.149
	15	1.E-03	2.E-04	2.44	11.92	23.92	62.14	11.28	38.29	23952	0.169
	16	2.E-04	3.E-05	0.39	3.19	5.85	15.81	2.76	9.43	33910	0.147
	17	5.E-04	7.E-05	0.82	4.92	11.51	27.09	5.42	17.25	24574	0.151
	18	8.E-04	1.E-04	1.24	6.68	17.52	38.82	8.26	25.45	21539	0.160
	19	1.E-03	2.E-04	1.66	8.43	23.69	50.65	11.17	33.79	21295	0.176
	20	2.E-03	4.E-04	2.48	11.93	35.56	73.83	16.76	49.97	20222	0.206
S13_mid	1	2.E-05	3.E-06	0.40	3.16	1.13	11.02	0.53	4.69	50035	0.125
	2	4.E-05	6.E-06	0.81	4.91	2.07	17.60	0.98	7.79	53664	0.162
	3	7.E-05	1.E-05	1.20	6.66	3.06	24.23	1.44	10.92	46698	0.167
	4	9.E-05	1.E-05	1.61	8.41	4.00	30.84	1.88	14.02	46144	0.135
	5	1.E-04	9.E-06	2.40	11.92	5.97	44.13	2.81	20.28	45506	0.066
	6	4.E-05	2.E-07	0.40	3.18	2.07	12.01	0.97	5.65	48133	0.004
	7	9.E-05	5.E-06	0.81	4.94	4.01	19.64	1.89	9.76	42268	0.056
	8	1.E-04	1.E-05	1.20	6.67	5.97	27.18	2.81	13.83	40083	0.082
	9	2.E-04	2.E-05	1.60	8.42	8.00	34.86	3.77	18.02	40481	0.084
	10	3.E-04	4.E-05	2.39	11.93	12.12	50.29	5.71	26.44	37500	0.123
	11	9.E-05	8.E-06	0.41	3.19	3.96	13.94	1.87	7.56	41713	0.082
	12	2.E-04	2.E-05	0.81	4.94	7.99	23.64	3.77	13.75	36926	0.113
	13	4.E-04	4.E-05	1.21	6.68	11.93	33.18	5.62	19.82	33563	0.124
	14	5.E-04	7.E-05	1.62	8.43	15.86	42.77	7.48	25.91	31490	0.129
	15	9.E-04	1.E-04	2.43	11.93	23.98	62.19	11.30	38.34	27860	0.150
	16	2.E-04	2.E-05	0.41	3.18	5.80	15.75	2.73	9.39	37334	0.125
	17	4.E-04	5.E-05	0.82	4.94	11.63	27.26	5.48	17.39	31156	0.142
	18	7.E-04	1.E-04	1.24	6.69	17.62	38.93	8.31	25.55	26817	0.151
	19	9.E-04	1.E-04	1.65	8.43	23.88	50.83	11.26	33.96	25261	0.154
	20	2.E-03	3.E-04	2.50	11.93	35.72	74.00	16.84	50.14	23112	0.189
S13_wet	1	2.E-04	2.E-05	0.40	3.15	0.94	10.79	0.44	4.49	5975	0.127
	2	3.E-04	5.E-05	0.81	4.90	1.68	17.18	0.79	7.38	5529	0.153
	3	5.E-04	8.E-05	1.21	6.64	2.52	23.65	1.19	10.37	5285	0.173
	4	6.E-04	1.E-04	1.61	8.39	3.38	30.17	1.60	13.39	5747	0.171
	5	9.E-04	2.E-04	2.41	11.90	5.10	43.22	2.41	19.42	5779	0.207
	6	3.E-04	5.E-05	0.41	3.15	1.59	11.47	0.75	5.16	4785	0.150
	7	8.E-04	1.E-04	0.81	4.92	3.04	18.60	1.43	8.77	3959	0.173
	8	1.E-03	2.E-04	1.22	6.66	4.58	25.80	2.16	12.47	4047	0.200
	9	2.E-03	3.E-04	1.62	8.40	6.33	33.16	2.99	16.36	4105	0.211
	10	2.E-03	6.E-04	2.45	11.91	9.72	47.91	4.58	24.08	3950	0.245
	11	8.E-04	1.E-04	0.42	3.16	2.85	12.75	1.34	6.43	3396	0.164
	12	2.E-03	4.E-04	0.84	4.92	5.60	21.19	2.64	11.36	2860	0.203
	13	3.E-03	7.E-04	1.25	6.67	9.04	30.29	4.26	16.96	3010	0.229
	14	4.E-03	1.E-03	1.66	8.40	12.97	39.84	6.11	23.03	3222	0.243
	15	4.E-03	1.E-03	2.45	11.92	22.29	60.49	10.51	36.66	5089	0.285
	16	1.E-03	2.E-04	0.42	3.17	4.81	14.74	2.27	8.40	4741	0.209
	17	3.E-03	6.E-04	0.84	4.94	9.67	25.32	4.56	15.45	3747	0.244
	18	4.E-03	1.E-03	1.25	6.68	15.85	37.15	7.47	23.78	4013	0.270
	19	5.E-03	1.E-03	1.65	8.42	22.55	49.47	10.63	32.63	4772	0.288
	20	3.E-03	1.E-03	2.46	11.92	34.76	72.97	16.39	49.14	11934	0.374

TABLE C-1
REGRESSION CONSTANTS AND STATISTICS FOR ALL TESTS/MODELS

Test ID	Resilient Modulus Models *all models normalized by p_a	k1	k2	k3	k4	k5 β	k6	Se/Sy	R^2
S12_1	log-log k1, k2 (θ)	1488.575	0.678					0.373	0.866
	log-log k1, k2, k3 (θ, τ_{oct})	786.529	1.058	-0.255				0.210	0.959
	log-log k1, k2, k3 (σ_3, σ_{cyc})	4540.545	0.694	0.123				0.127	0.985
	log-log k1, k2, k3, k6 (θ, τ_{oct})	627.807	1.154	-0.262			-1.370	0.210	0.961
	log-log k1, k2, k3, k6 (σ_3, σ_{cyc})	4099.155	0.819	0.126			-0.601	0.126	0.986
	semi-log k1, k2 (θ)	3.283	0.065					0.491	0.769
	semi-log k1, k2,k3 (θ, τ_{oct})	3.198	0.123	-0.197				0.227	0.952
	semi-log k1, k2, k3 (σ_3, σ_{cyc})	3.194	0.397	0.031				0.233	0.950
	semi-log k1, k2, k3, k6 (θ, τ_{oct})	3.198	0.123	-0.197			0.000	0.232	0.952
	semi-log k1, k2, k3, k6 (σ_3, σ_{cyc})	3.194	0.397	0.031			0.000	0.238	0.950
	SHRP-Superpave k1-k6	786.000	1.080	0.040	0.435	-0.615	-0.800	0.692	0.576
	log-log k1, k2, k3 (θ, τ_{oct}+1)	1248.821	1.062	-0.617				0.172	0.973
	log-log k1, k2, k3, k6 (θ, τ_{oct}+1)	450.959	1.501	-0.707			-6.406	0.134	0.984
	log-log k1, k2, k3, k6 (θ, τ_{oct}+β)	21362.918	1.751	-2.562		6.057	-10.466	0.094	0.993
S12_2	log-log k1, k2 (θ)	1560.753	0.677					0.363	0.873
	log-log k1, k2, k3 (θ, τ_{oct})	825.807	1.056	-0.253				0.195	0.965
	log-log k1, k2, k3 (σ_3, σ_{cyc})	4758.936	0.678	0.119				0.115	0.988
	log-log k1, k2, k3, k6 (θ, τ_{oct})	995.771	0.974	-0.248			1.160	0.196	0.966
	log-log k1, k2, k3, k6 (σ_3, σ_{cyc})	4758.936	0.678	0.119			0.000	0.117	0.988
	semi-log k1, k2 (θ)	3.307	0.064					0.494	0.765
	semi-log k1, k2,k3 (θ, τ_{oct})	3.230	0.120	-0.193				0.260	0.938
	semi-log k1, k2, k3 (σ_3, σ_{cyc})	3.228	0.384	0.029				0.260	0.938
	semi-log k1, k2, k3, k6 (θ, τ_{oct})	3.230	0.120	-0.193			0.000	0.265	0.938
	semi-log k1, k2, k3, k6 (σ_3, σ_{cyc})	3.228	0.384	0.029			0.000	0.265	0.938
	SHRP-Superpave k1-k6	793.000	1.090	0.049	0.422	-0.630	-1.100	0.708	0.557
	log-log k1, k2, k3 (θ, τ_{oct}+1)	1326.918	1.057	-0.623				0.134	0.983
	log-log k1, k2, k3, k6 (θ, τ_{oct}+1)	845.681	1.260	-0.670			-2.913	0.126	0.986
	log-log k1, k2, k3, k6 (θ, τ_{oct}+β)	27616.179	1.435	-2.303		5.676	-5.682	0.090	0.993
S12_5	log-log k1, k2 (θ)	1446.341	0.629					0.354	0.879
	log-log k1, k2, k3 (θ, τ_{oct})	771.600	1.004	-0.232				0.191	0.966
	log-log k1, k2, k3 (σ_3, σ_{cyc})	4051.275	0.652	0.119				0.162	0.976

TABLE C-1
REGRESSION CONSTANTS AND STATISTICS FOR ALL TESTS/MODELS

Test ID	Resilient Modulus Models *all models normalized by p_a	k1	k2	k3	k4	k5 β	k6	Se/Sy	R^2
	log-log k1, k2, k3, k6 (θ, τ_{oct})	1070.591	0.861	-0.226			2.257	0.180	0.971
	log-log k1, k2, k3, k6 (σ_3, σ_{cyc})	4051.275	0.652	0.119			0.000	0.165	0.976
	semi-log k1, k2 (θ)	3.273	0.059					0.490	0.769
	semi-log k1, k2,k3 (θ, τ_{oct})	3.190	0.113	-0.177				0.282	0.927
	semi-log k1, k2, k3 (σ_3, σ_{cyc})	3.186	0.365	0.029				0.282	0.927
	semi-log k1, k2, k3, k6 (θ, τ_{oct})	3.190	0.113	-0.177			0.000	0.288	0.927
	semi-log k1, k2, k3, k6 (σ_3, σ_{cyc})	3.186	0.365	0.029			0.000	0.288	0.927
	SHRP-Superpave k1-k6	782.000	1.050	0.043	0.360	-0.581	-0.600	0.857	0.351
	log-log k1, k2, k3 (θ, $\tau_{oct}+1$)	1205.432	1.005	-0.586				0.123	0.986
	log-log k1, k2, k3, k6 (θ, $\tau_{oct}+1$)	915.947	1.131	-0.617			-1.905	0.120	0.987
	log-log k1, k2, k3, k6 (θ, $\tau_{oct}+\beta$)	5394.689	1.255	-1.560		3.945	-4.083	0.104	0.991
S12_6	log-log k1, k2 (θ)	1533.777	0.633					0.366	0.871
	log-log k1, k2, k3 (θ, τ_{oct})	778.674	1.039	-0.251				0.170	0.973
	log-log k1, k2, k3 (σ_3, σ_{cyc})	4374.052	0.678	0.113				0.117	0.987
	log-log k1, k2, k3, k6 (θ, τ_{oct})	900.446	0.976	-0.248			0.958	0.172	0.974
	log-log k1, k2, k3, k6 (σ_3, σ_{cyc})	4374.052	0.678	0.113			0.000	0.120	0.987
	semi-log k1, k2 (θ)	3.296	0.060					0.478	0.780
	semi-log k1, k2,k3 (θ, τ_{oct})	3.209	0.116	-0.185				0.227	0.952
	semi-log k1, k2, k3 (σ_3, σ_{cyc})	3.205	0.377	0.029				0.227	0.952
	semi-log k1, k2, k3, k6 (θ, τ_{oct})	3.209	0.116	-0.185			0.000	0.232	0.952
	semi-log k1, k2, k3, k6 (σ_3, σ_{cyc})	3.205	0.377	0.029			0.000	0.232	0.952
	SHRP-Superpave k1-k6	786.000	1.070	0.050	0.357	-0.623	-1.500	0.871	0.329
	log-log k1, k2, k3 (θ, $\tau_{oct}+1$)	1269.022	1.021	-0.598				0.142	0.981
	log-log k1, k2, k3, k6 (θ, $\tau_{oct}+1$)	555.158	1.381	-0.674			-5.466	0.114	0.988
	log-log k1, k2, k3, k6 (θ, $\tau_{oct}+\beta$)	4549.647	1.654	-1.926		4.526	-10.197	0.094	0.992
S12_1,2, 5,6	log-log k1, k2 (θ)	1508.482	0.657					0.388	0.851
	log-log k1, k2, k3 (θ, τ_{oct})	781.396	1.049	-0.251				0.240	0.943
	log-log k1, k2, k3 (σ_3, σ_{cyc})	4445.819	0.681	0.118				0.198	0.962
	log-log k1, k2, k3, k6 (θ, τ_{oct})	826.412	1.025	-0.250			0.356	0.241	0.944
	log-log k1, k2, k3, k6 (σ_3, σ_{cyc})	4254.245	0.737	0.120			-0.275	0.198	0.962

TABLE C-1
REGRESSION CONSTANTS AND STATISTICS FOR ALL TESTS/MODELS

Test ID	**Resilient Modulus Models** ***all models normalized by p_a**	**k1**	**k2**	**k3**	**k4**	**k5** β	**k6**	**Se/Sy**	**R^2**
	semi-log k1, k2 (θ)	3.295	0.061					0.499	0.753
	semi-log k1, k2,k3 (θ, τ_{oct})	3.210	0.118	-0.189				0.275	0.926
	semi-log k1, k2, k3 (σ_3, σ_{cyc})	3.206	0.380	0.029				0.276	0.925
	semi-log k1, k2, k3, k6 (θ, τ_{oct})	3.210	0.118	-0.189			0.000	0.277	0.926
	semi-log k1, k2, k3, k6 (σ_3, σ_{cyc})	3.195	0.380	0.029			-0.028	0.277	0.925
	SHRP-Superpave k1-k6	781.000	1.080	0.040	0.428	-0.615	-1.000	0.722	0.498
	log-log k1, k2, k3 (θ, τ_{oct}+1)	1252.156	1.046	-0.610				0.206	0.959
	log-log k1, k2, k3, k6 (θ, τ_{oct}+1)	605.149	1.364	-0.679			-4.687	0.191	0.964
	log-log k1, k2, k3, k6 (θ, τ_{oct}+β)	16230.866	1.582	-2.290		5.594	-8.309	0.174	0.971
NS12_2	log-log k1, k2 (θ)	1829.149	0.676					0.480	0.786
	log-log k1, k2, k3 (θ, τ_{oct})	775.652	0.991	-0.352				0.090	0.993
	log-log k1, k2, k3 (σ_3, σ_{cyc})	4092.352	0.830	-0.183				0.096	0.992
	log-log k1, k2, k3, k6 (θ, τ_{oct})	382.660	1.358	-0.344			-3.733	0.054	0.998
	log-log k1, k2, k3, k6 (σ_3, σ_{cyc})	3027.767	1.258	-0.170			-1.451	0.063	0.997
	semi-log k1, k2 (θ)	3.180	0.130					0.470	0.795
	semi-log k1, k2,k3 (θ, τ_{oct})	3.194	0.183	-0.678				0.135	0.984
	semi-log k1, k2, k3 (σ_3, σ_{cyc})	3.193	0.564	-0.137				0.135	0.984
	semi-log k1, k2, k3, k6 (θ, τ_{oct})	3.194	0.183	-0.678			0.000	0.141	0.984
	semi-log k1, k2, k3, k6 (σ_3, σ_{cyc})	3.193	0.564	-0.137			0.000	0.141	0.984
	SHRP-Superpave k1-k6								
	log-log k1, k2, k3 (θ, τ_{oct}+1)	2126.092	0.930	-1.909				0.184	0.971
	log-log k1, k2, k3, k6 (θ, τ_{oct}+1)	546.411	1.588	-1.934			-7.110	0.118	0.989
	log-log k1, k2, k3, k6 (θ, τ_{oct}+β)	702.031	1.058	-0.328		-0.011	-0.574	0.083	0.995
NS12_3	log-log k1, k2 (θ)	2006.955	0.679					0.266	0.934
	log-log k1, k2, k3 (θ, τ_{oct})	1285.839	0.847	-0.181				0.060	0.997
	log-log k1, k2, k3 (σ_3, σ_{cyc})	4859.637	0.706	-0.036				0.075	0.995
	log-log k1, k2, k3, k6 (θ, τ_{oct})	927.656	1.022	-0.176			-2.107	0.043	0.999
	log-log k1, k2, k3, k6 (σ_3, σ_{cyc})	4261.295	0.917	-0.028			-0.841	0.062	0.997
	semi-log k1, k2 (θ)	3.223	0.130					0.281	0.927
	semi-log k1, k2,k3 (θ, τ_{oct})	3.228	0.157	-0.347				0.139	0.983

TABLE C-1
REGRESSION CONSTANTS AND STATISTICS FOR ALL TESTS/MODELS

Test ID	Resilient Modulus Models *all models normalized by p_a	k1	k2	k3	k4	k5 β	k6	Se/Sy	R^2
	semi-log k1, k2, k3 (σ_3, σ_{cyc})	3.227	0.486	-0.006				0.139	0.983
	semi-log k1, k2, k3, k6 (θ, τ_{oct})	3.228	0.157	-0.347			0.000	0.145	0.983
	semi-log k1, k2, k3, k6 (σ_3, σ_{cyc})	3.227	0.486	-0.006			0.000	0.145	0.983
	SHRP-Superpave k1-k6								
	log-log k1, k2, k3 (θ, $\tau_{oct}+1$)	2158.395	0.816	-0.981				0.107	0.990
	log-log k1, k2, k3, k6 (θ, $\tau_{oct}+1$)	1017.248	1.201	-1.030			-4.694	0.061	0.997
	log-log k1, k2, k3, k6 (θ, $\tau_{oct}+\beta$)	1043.380	0.958	-0.186		0.008	-1.347	0.047	0.998
NS12_4	log-log k1, k2 (θ)	1763.960	0.701					0.246	0.944
	log-log k1, k2, k3 (θ, τ_{oct})	1166.380	0.855	-0.170				0.070	0.996
	log-log k1, k2, k3 (σ_3, σ_{cyc})	4434.092	0.711	-0.022				0.078	0.995
	log-log k1, k2, k3, k6 (θ, τ_{oct})	791.830	1.062	-0.165			-2.431	0.052	0.998
	log-log k1, k2, k3, k6 (σ_3, σ_{cyc})	3792.523	0.960	-0.013			-0.969	0.060	0.997
	semi-log k1, k2 (θ)	3.160	0.135					0.264	0.935
	semi-log k1, k2,k3 (θ, τ_{oct})	3.166	0.162	-0.329				0.139	0.983
	semi-log k1, k2, k3 (σ_3, σ_{cyc})	3.165	0.500	0.007				0.139	0.983
	semi-log k1, k2, k3, k6 (θ, τ_{oct})	3.166	0.162	-0.329			0.000	0.145	0.983
	semi-log k1, k2, k3, k6 (σ_3, σ_{cyc})	3.165	0.500	0.007			0.000	0.146	0.983
	SHRP-Superpave k1-k6								
	log-log k1, k2, k3 (θ, $\tau_{oct}+1$)	1896.421	0.828	-0.927				0.101	0.991
	log-log k1, k2, k3, k6 (θ, $\tau_{oct}+1$)	901.601	1.204	-0.933			-4.523	0.049	0.998
	log-log k1, k2, k3, k6 (θ, $\tau_{oct}+\beta$)	845.154	1.021	-0.190		0.025	-1.994	0.052	0.998
NS12_5	log-log k1, k2 (θ)	2035.129	0.590					0.300	0.916
	log-log k1, k2, k3 (θ, τ_{oct})	1349.954	0.765	-0.148				0.094	0.992
	log-log k1, k2, k3 (σ_3, σ_{cyc})	4412.992	0.653	-0.027				0.081	0.994
	log-log k1, k2, k3, k6 (θ, τ_{oct})	760.410	1.049	-0.143			-4.210	0.078	0.995
	log-log k1, k2, k3, k6 (σ_3, σ_{cyc})	2908.385	1.124	-0.018			-2.303	0.052	0.998
	semi-log k1, k2 (θ)	3.261	0.106					0.291	0.921
	semi-log k1, k2,k3 (θ, τ_{oct})	3.253	0.134	-0.301				0.090	0.993
	semi-log k1, k2, k3 (σ_3, σ_{cyc})	3.251	0.416	-0.008				0.091	0.993
	semi-log k1, k2, k3, k6 (θ, τ_{oct})	3.253	0.134	-0.301			0.000	0.094	0.993
	semi-log k1, k2, k3, k6 (σ_3, σ_{cyc})	3.251	0.416	-0.008			0.000	0.095	0.993

TABLE C-1
REGRESSION CONSTANTS AND STATISTICS FOR ALL TESTS/MODELS

Test ID	**Resilient Modulus Models** ***all models normalized by p_a**	**k1**	**k2**	**k3**	**k4**	**k5** β	**k6**	**Se/Sy**	**R^2**
	SHRP-Superpave k1-k6								
	log-log k1, k2, k3 (θ, $\tau_{oct}+1$)	2089.614	0.737	-0.844				0.129	0.986
	log-log k1, k2, k3, k6 (θ, $\tau_{oct}+1$)	772.816	1.208	-0.856			-7.012	0.069	0.996
	log-log k1, k2, k3, k6 (θ, $\tau_{oct}+\beta$)	423.793	1.280	-0.279		0.175	-7.986	0.057	0.998
NS12_2, 3,4,5	log-log k1, k2 (θ)	1907.878	0.666					0.362	0.871
	log-log k1, k2, k3 (θ, τ_{oct})	1121.567	0.869	-0.211				0.199	0.962
	log-log k1, k2, k3 (σ_3, σ_{cyc})	4474.673	0.729	-0.065				0.199	0.962
	log-log k1, k2, k3, k6 (θ, τ_{oct})	742.669	1.085	-0.208			-2.544	0.195	0.964
	log-log k1, k2, k3, k6 (σ_3, σ_{cyc})	3808.055	0.973	-0.058			-0.951	0.194	0.964
	semi-log k1, k2 (θ)	3.210	0.124					0.369	0.866
	semi-log k1, k2,k3 (θ, τ_{oct})	3.214	0.158	-0.413				0.225	0.951
	semi-log k1, k2, k3 (σ_3, σ_{cyc})	3.212	0.489	-0.036				0.224	0.951
	semi-log k1, k2, k3, k6 (θ, τ_{oct})	3.214	0.158	-0.413			0.000	0.227	0.951
	semi-log k1, k2, k3, k6 (σ_3, σ_{cyc})	3.212	0.489	-0.036			0.000	0.226	0.951
	SHRP-Superpave k1-k6								
	log-log k1, k2, k3 (θ, $\tau_{oct}+1$)	2060.330	0.834	-1.156				0.220	0.953
	log-log k1, k2, k3, k6 (θ, $\tau_{oct}+1$)	912.046	1.234	-1.154			-4.980	0.201	0.962
	log-log k1, k2, k3, k6 (θ, $\tau_{oct}+\beta$)	948.166	0.959	-0.216		0.005	-1.044	0.198	0.963
S1_1	log-log k1, k2 (θ)	3714.773	0.112					1.023	0.012
	log-log k1, k2, k3 (θ, τ_{oct})	274.153	1.504	-0.943				0.281	0.930
	log-log k1, k2, k3 (σ_3, σ_{cyc})	5218.192	1.243	-0.623				0.267	0.936
	log-log k1, k2, k3, k6 (θ, τ_{oct})	47.497	2.398	-0.985			-5.099	0.261	0.943
	log-log k1, k2, k3, k6 (σ_3, σ_{cyc})	3015.744	2.114	-0.625			-1.699	0.259	0.944
	semi-log k1, k2 (θ)	3.576	0.012					1.027	0.004
	semi-log k1, k2,k3 (θ, τ_{oct})	3.385	0.262	-1.484				0.449	0.821
	semi-log k1, k2, k3 (σ_3, σ_{cyc})	3.376	0.851	-0.434				0.447	0.822
	semi-log k1, k2, k3, k6 (θ, τ_{oct})	3.385	0.262	-1.484			0.000	0.463	0.821
	semi-log k1, k2, k3, k6 (σ_3, σ_{cyc})	3.375	0.851	-0.434			0.000	0.462	0.822
	SHRP-Superpave k1-k6								
	log-log k1, k2, k3 (θ, $\tau_{oct}+1$)	4137.347	1.192	-4.252				0.471	0.803
	log-log k1, k2, k3, k6 (θ, $\tau_{oct}+1$)	104.916	2.915	-4.464			-13.000	0.428	0.847

TABLE C-1
REGRESSION CONSTANTS AND STATISTICS FOR ALL TESTS/MODELS

Test ID	Resilient Modulus Models *all models normalized by p_a	1	k2	k3	k4	k5 β	k6	Se/Sy	R^2
S1_2	log-log k1, k2 (θ)	3341.133	-0.001					1.029	0.000
	log-log k1, k2, k3 (θ, τ_{oct})	289.417	1.439	-0.959				0.335	0.900
	log-log k1, k2, k3 (σ_3, σ_{cyc})	5001.394	1.104	-0.600				0.362	0.884
	log-log k1, k2, k3, k6 (θ, τ_{oct})	2.031	3.669	-1.067			-13.287	0.222	0.959
	log-log k1, k2, k3, k6 (σ_3, σ_{cyc})	5.285	6.130	-0.620			-10.591	0.287	0.932
	semi-log k1, k2 (θ)	3.528	-0.002					1.029	0.000
	semi-log k1, k2,k3 (θ, τ_{oct})	3.348	0.245	-1.218				0.583	0.698
	semi-log k1, k2, k3 (σ_3, σ_{cyc})	3.340	0.796	-0.329				0.583	0.698
	semi-log k1, k2, k3, k6 (θ, τ_{oct})	3.348	0.245	-1.219			0.000	0.602	0.698
	semi-log k1, k2, k3, k6 (σ_3, σ_{cyc})	3.340	0.796	-0.329			0.000	0.602	0.698
	SHRP-Superpave k1-k6								
	log-log k1, k2, k3 (θ, τ_{oct}+1)	3790.017	1.078	-3.535				0.634	0.643
	log-log k1, k2, k3, k6 (θ, τ_{oct}+1)	2.738	4.130	-3.931			-24.198	0.535	0.761
	log-log k1, k2, k3, k6 (θ, τ_{oct}+β)	3.759	3.435	-1.048		-0.003	-11.742	0.230	0.959
S1_3	log-log k1, k2 (θ)	4616.876	-0.070					1.028	0.005
	log-log k1, k2, k3 (θ, τ_{oct})	409.990	1.356	-0.952				0.347	0.894
	log-log k1, k2, k3 (σ_3, σ_{cyc})	6270.083	1.053	-0.620				0.338	0.899
	log-log k1, k2, k3, k6 (θ, τ_{oct})	6.604	3.193	-1.014			-12.958	0.304	0.924
	log-log k1, k2, k3, k6 (σ_3, σ_{cyc})	17.150	5.429	-0.640			-10.085	0.296	0.928
	semi-log k1, k2 (θ)	3.679	-0.016					1.027	0.007
	semi-log k1, k2,k3 (θ, τ_{oct})	3.507	0.238	-1.307				0.534	0.749
	semi-log k1, k2, k3 (σ_3, σ_{cyc})	3.500	0.771	-0.377				0.534	0.748
	semi-log k1, k2, k3, k6 (θ, τ_{oct})	3.507	0.238	-1.307			0.000	0.552	0.749
	semi-log k1, k2, k3, k6 (σ_3, σ_{cyc})	3.500	0.771	-0.377			0.000	0.553	0.748
	SHRP-Superpave k1-k6								
	log-log k1, k2, k3 (θ, τ_{oct}+1)	5268.636	1.096	-3.867				0.554	0.729
	log-log k1, k2, k3, k6 (θ, τ_{oct}+1)	7.943	3.835	-4.151			-22.768	0.486	0.805
	log-log k1, k2, k3, k6 (θ, τ_{oct}+β)	2.094	3.618	-1.025		0.010	-16.154	0.303	0.924
S1_1,2,3	log-log k1, k2 (θ)	3892.612	0.021					1.009	0.000
	log-log k1, k2, k3 (θ, τ_{oct})	358.542	1.391	-0.900				0.441	0.813
	log-log k1, k2, k3 (σ_3, σ_{cyc})	5613.109	1.118	-0.578				0.434	0.818

TABLE C-1
REGRESSION CONSTANTS AND STATISTICS FOR ALL TESTS/MODELS

Test ID	Resilient Modulus Models *all models normalized by p_a	k1	k2	k3	k4	k5 β	k6	Se/Sy	R^2
	log-log k1, k2, k3, k6 (θ, τ_{oct})	55.248	2.317	-0.944			-5.881	0.428	0.827
	log-log k1, k2, k3, k6 (σ_3, σ_{cyc})	589.824	3.390	-0.582			-4.935	0.420	0.833
	semi-log k1, k2 (θ)	3.601	-0.002					1.009	0.000
	semi-log k1, k2,k3 (θ, τ_{oct})	3.416	0.244	-1.286				0.558	0.700
	semi-log k1, k2, k3 (σ_3, σ_{cyc})	3.408	0.792	-0.360				0.557	0.701
	semi-log k1, k2, k3, k6 (θ, τ_{oct})	3.416	0.244	-1.286			0.000	0.563	0.700
	semi-log k1, k2, k3, k6 (σ_3, σ_{cyc})	3.407	0.792	-0.360			0.000	0.563	0.701
	SHRP-Superpave k1-k6								
	log-log k1, k2, k3 (θ, τ_{oct}+1)	4288.471	1.121	-3.785				0.578	0.678
	log-log k1, k2, k3, k6 (θ, τ_{oct}+1)	116.003	2.799	-3.988			-13.599	0.531	0.733
	log-log k1, k2, k3, k6 (θ, τ_{oct}+β)	37.121	2.459	-1.043		0.024	-7.363	0.426	0.832
NS1_1	log-log k1, k2 (θ)	3808.744	-0.344					0.940	0.179
	log-log k1, k2, k3 (θ, τ_{oct})	488.581	0.672	-0.915				0.526	0.763
	log-log k1, k2, k3 (σ_3, σ_{cyc})	2589.416	0.538	-0.764				0.517	0.771
	log-log k1, k2, k3, k6 (θ, τ_{oct})	0.236	3.838	-0.951			-30.111	0.450	0.841
	log-log k1, k2, k3, k6 (σ_3, σ_{cyc})	6.244	4.919	-0.787			-13.002	0.459	0.834
	semi-log k1, k2 (θ)	3.643	-0.076					0.980	0.109
	semi-log k1, k2,k3 (θ, τ_{oct})	3.643	0.180	-2.264				0.617	0.674
	semi-log k1, k2, k3 (σ_3, σ_{cyc})	3.638	0.585	-0.889				0.616	0.675
	semi-log k1, k2, k3, k6 (θ, τ_{oct})	3.643	0.180	-2.264			0.000	0.644	0.674
	semi-log k1, k2, k3, k6 (σ_3, σ_{cyc})	3.638	0.585	-0.889			0.000	0.643	0.675
	SHRP-Superpave k1-k6								
	log-log k1, k2, k3 (θ, τ_{oct}+1)	6663.972	0.447	-5.373				0.691	0.590
	log-log k1, k2, k3, k6 (θ, τ_{oct}+1)	2.865	3.689	-6.216			-35.997	0.630	0.688
	log-log k1, k2, k3, k6 (θ, τ_{oct}+β)	0.278	3.816	-0.810		-0.019	-30.398	0.465	0.845
NS1_2	log-log k1, k2 (θ)	2529.843	-0.021					1.037	0.002
	log-log k1, k2, k3 (θ, τ_{oct})	870.707	0.493	-0.472				0.724	0.550
	log-log k1, k2, k3 (σ_3, σ_{cyc})	2546.404	0.392	-0.360				0.717	0.560
	log-log k1, k2, k3, k6 (θ, τ_{oct})	0.506	3.412	-0.511			-37.492	0.589	0.727
	log-log k1, k2, k3, k6 (σ_3, σ_{cyc})	777.929	1.751	-0.366			-5.803	0.662	0.656
	semi-log k1, k2 (θ)	3.387	0.008					1.036	0.004

TABLE C-1
REGRESSION CONSTANTS AND STATISTICS FOR ALL TESTS/MODELS

Test ID	Resilient Modulus Models *all models normalized by p_a	k1	k2	k3	k4	k5 β	k6	Se/Sy	R^2
	semi-log k1, k2,k3 (θ, τ_{oct})	3.382	0.124	-1.004				0.824	0.418
	semi-log k1, k2, k3 (σ_3, σ_{cyc})	3.379	0.400	-0.350				0.823	0.420
	semi-log k1, k2, k3, k6 (θ, τ_{oct})	3.382	0.124	-1.004			0.000	0.861	0.418
	semi-log k1, k2, k3, k6 (σ_3, σ_{cyc})	3.379	0.400	-0.350			0.000	0.859	0.420
	SHRP-Superpave k1-k6								
	log-log k1, k2, k3 (θ, τ_{oct}+1)	3155.820	0.312	-2.199				0.928	0.263
	log-log k1, k2, k3, k6 (θ, τ_{oct}+1)	7.468	2.716	-2.680			-41.243	0.852	0.430
	log-log k1, k2, k3, k6 (θ, τ_{oct}+β)	9.587	2.504	-0.267		-0.055	-27.561	0.407	0.870
NS1_3	log-log k1, k2 (θ)	3125.433	-0.216					0.937	0.186
	log-log k1, k2, k3 (θ, τ_{oct})	1062.709	0.309	-0.475				0.677	0.607
	log-log k1, k2, k3 (σ_3, σ_{cyc})	2384.793	0.250	-0.406				0.673	0.612
	log-log k1, k2, k3, k6 (θ, τ_{oct})	1.556	2.770	-0.531			-44.373	0.607	0.711
	log-log k1, k2, k3, k6 (σ_3, σ_{cyc})	56.072	2.779	-0.432			-15.212	0.641	0.677
	semi-log k1, k2 (θ)	3.527	-0.044					0.984	0.101
	semi-log k1, k2,k3 (θ, τ_{oct})	3.522	0.075	-1.045				0.813	0.433
	semi-log k1, k2, k3 (σ_3, σ_{cyc})	3.520	0.244	-0.419				0.813	0.434
	semi-log k1, k2, k3, k6 (θ, τ_{oct})	3.522	0.075	-1.045			0.000	0.850	0.433
	semi-log k1, k2, k3, k6 (σ_3, σ_{cyc})	3.520	0.244	-0.419			0.000	0.849	0.434
	SHRP-Superpave k1-k6								
	log-log k1, k2, k3 (θ, τ_{oct}+1)	3896.078	0.123	-2.231				0.850	0.380
	log-log k1, k2, k3, k6 (θ, τ_{oct}+1)	29.391	2.056	-2.932			-49.421	0.832	0.456
	log-log k1, k2, k3, k6 (θ, τ_{oct}+β)	35.080	1.831	-0.255		-0.059	-31.127	0.470	0.842
NS_1,2,3	log-log k1, k2 (θ)	3208.216	-0.210					0.971	0.078
	log-log k1, k2, k3 (θ, τ_{oct})	842.743	0.445	-0.591				0.809	0.376
	log-log k1, k2, k3 (σ_3, σ_{cyc})	2514.300	0.357	-0.492				0.806	0.380
	log-log k1, k2, k3, k6 (θ, τ_{oct})	1.178	3.056	-0.639			-35.194	0.775	0.441
	log-log k1, k2, k3, k6 (σ_3, σ_{cyc})	9.789	3.986	-0.519			-15.788	0.784	0.427
	semi-log k1, k2 (θ)	3.534	-0.041					0.992	0.038
	semi-log k1, k2,k3 (θ, τ_{oct})	3.529	0.117	-1.379				0.852	0.307
	semi-log k1, k2, k3 (σ_3, σ_{cyc})	3.526	0.378	-0.532				0.853	0.306

TABLE C-1
REGRESSION CONSTANTS AND STATISTICS FOR ALL TESTS/MODELS

Test ID	Resilient Modulus Models *all models normalized by p_a	k1	k2	k3	k4	k5 β	k6	Se/Sy	R^2
	semi-log k1, k2, k3, k6 (θ, τ_{oct})	3.529	0.117	-1.379			0.000	0.863	0.307
	semi-log k1, k2, k3, k6 (σ_3, σ_{cyc})	3.526	0.378	-0.532			0.000	0.863	0.306
	SHRP-Superpave k1-k6								
	log-log k1, k2, k3 (θ, τ_{oct}+1)	4380.570	0.263	-3.104				0.885	0.253
	log-log k1, k2, k3, k6 (θ, τ_{oct}+1)	2.404	3.132	-3.779			-49.300	0.855	0.318
	log-log k1, k2, k3, k6 (θ, $\tau_{oct}+\beta$)	2.358	2.870	-0.424		-0.041	-34.565	0.758	0.465
S3_1	log-log k1, k2 (τ_{oct})	1948.052		-0.222				0.323	0.903
	log-log k1, k2, k3 (θ, τ_{oct})	1784.339	0.084	-0.246				0.282	0.931
	log-log k1, k2, k3 (σ_3, σ_{cyc})	2443.493	0.069	-0.222				0.265	0.939
	log-log k1, k2, k3, k6 (θ, τ_{oct})	1747.243	0.096	-0.246			-1.298	0.293	0.931
	log-log k1, k2, k3, k6 (σ_3, σ_{cyc})	1401.832	0.476	-0.222			-11.739	0.274	0.940
	semi-log k1, k2 (τ_{oct})	3.530		-0.385				0.235	0.948
	semi-log k1, k2,k3 (θ, τ_{oct})	3.499	0.022	-0.432				0.129	0.986
	semi-log k1, k2, k3 (σ_3, σ_{cyc})	3.498	0.072	-0.181				0.129	0.986
	semi-log k1, k2, k3, k6 (θ, τ_{oct})	3.499	0.022	-0.432			0.000	0.134	0.986
	semi-log k1, k2, k3, k6 (σ_3, σ_{cyc})	3.498	0.072	-0.181			0.000	0.135	0.986
	SHRP-Superpave k1-k6								
	log-log k1, k2, k3 (θ, τ_{oct}+1)	3382.377	0.092	-1.266				0.157	0.979
	log-log k1, k2, k3, k6 (θ, τ_{oct}+1)	3187.740	0.127	-1.267			-3.209	0.161	0.979
	log-log k1, k2, k3, k6 (θ, $\tau_{oct}+\beta$)	7108.769	1.536	-4.270		4.012	-137.890	0.147	0.984
S3_2	log-log k1, k2 (τ_{oct})	1813.676		-0.239				0.479	0.786
	log-log k1, k2, k3 (θ, τ_{oct})	1561.253	0.157	-0.293				0.323	0.909
	log-log k1, k2, k3 (σ_3, σ_{cyc})	2429.816	0.099	-0.241				0.345	0.897
	log-log k1, k2, k3, k6 (θ, τ_{oct})	1619.550	0.129	-0.293			1.204	0.336	0.910
	log-log k1, k2, k3, k6 (σ_3, σ_{cyc})	339.078	1.336	-0.242			-17.976	0.341	0.907
	semi-log k1, k2 (τ_{oct})	3.517		-0.415				0.476	0.788
	semi-log k1, k2,k3 (θ, τ_{oct})	3.468	0.045	-0.516				0.320	0.911
	semi-log k1, k2, k3 (σ_3, σ_{cyc})	3.467	0.146	-0.198				0.319	0.912
	semi-log k1, k2, k3, k6 (θ, τ_{oct})	3.468	0.045	-0.516			0.000	0.333	0.911
	semi-log k1, k2, k3, k6 (σ_3, σ_{cyc})	3.467	0.146	-0.198			0.000	0.332	0.912

TABLE C-1
REGRESSION CONSTANTS AND STATISTICS FOR ALL TESTS/MODELS

Test ID	Resilient Modulus Models *all models normalized by p_a	k1	k2	k3	k4	k5 β	k6	Se/Sy	R^2
	SHRP-Superpave k1-k6								
	log-log k1, k2, k3 (θ, τ_{oct}+1)	3356.343	0.161	-1.511				0.301	0.921
	log-log k1, k2, k3, k6 (θ, τ_{oct}+1)	3262.496	0.180	-1.511			-0.869	0.313	0.922
	log-log k1, k2, k3, k6 (θ, τ_{oct}+β)	1657.318	0.163	-0.761		0.373	-0.063	0.323	0.923
S3_3	log-log k1, k2 (τ_{oct})	1919.081		-0.218				0.261	0.936
	log-log k1, k2, k3 (θ, τ_{oct})	1936.794	-0.010	-0.215				0.269	0.937
	log-log k1, k2, k3 (σ_3, σ_{cyc})	2263.015	0.001	-0.218				0.271	0.936
	log-log k1, k2, k3, k6 (θ, τ_{oct})	1936.795	-0.010	-0.215			0.000	0.280	0.937
	log-log k1, k2, k3, k6 (σ_3, σ_{cyc})	2263.015	0.001	-0.218			0.000	0.282	0.936
	semi-log k1, k2 (τ_{oct})	3.522		-0.391				0.125	0.985
	semi-log k1, k2,k3 (θ, τ_{oct})	3.522	0.000	-0.392				0.130	0.985
	semi-log k1, k2, k3 (σ_3, σ_{cyc})	3.522	0.001	-0.184				0.130	0.985
	semi-log k1, k2, k3, k6 (θ, τ_{oct})	3.522	0.000	-0.392			0.000	0.135	0.985
	semi-log k1, k2, k3, k6 (σ_3, σ_{cyc})	3.522	0.001	-0.184			0.000	0.135	0.985
	SHRP-Superpave k1-k6								
	log-log k1, k2, k3 (θ, τ_{oct}+1)	3415.632	-0.003	-1.140				0.147	0.981
	log-log k1, k2, k3, k6 (θ, τ_{oct}+1)	3415.825	-0.003	-1.140			-0.093	0.153	0.981
	log-log k1, k2, k3, k6 (θ, τ_{oct}+β)	9582.012	-0.003	-1.830		1.766	-2.981	0.152	0.983
S3_1,2,3	log-log k1, k2 (τ_{oct})	2773.624	-0.103					0.864	0.266
	log-log k1, k2, k3 (θ, τ_{oct})	1772.080	0.085	-0.253				0.310	0.907
	log-log k1, k2, k3 (σ_3, σ_{cyc})	2430.493	0.060	-0.226				0.305	0.910
	log-log k1, k2, k3, k6 (θ, τ_{oct})	1674.671	0.119	-0.254			-2.967	0.313	0.907
	log-log k1, k2, k3, k6 (σ_3, σ_{cyc})	1231.664	0.553	-0.227			-12.925	0.303	0.913
	semi-log k1, k2 (τ_{oct})	3.468	-0.027					0.863	0.268
	semi-log k1, k2,k3 (θ, τ_{oct})	3.499	0.025	-0.444				0.258	0.936
	semi-log k1, k2, k3 (σ_3, σ_{cyc})	3.498	0.081	-0.184				0.256	0.937
	semi-log k1, k2, k3, k6 (θ, τ_{oct})	3.499	0.025	-0.444			0.000	0.260	0.936
	semi-log k1, k2, k3, k6 (σ_3, σ_{cyc})	3.498	0.081	-0.184			0.000	0.259	0.937
	SHRP-Superpave k1-k6								
	log-log k1, k2, k3 (θ, τ_{oct}+1)	3425.160	0.091	-1.299				0.263	0.933

TABLE C-1
REGRESSION CONSTANTS AND STATISTICS FOR ALL TESTS/MODELS

Test ID	**Resilient Modulus Models** ***all models normalized by p_a**	**k1**	**k2**	**k3**	**k4**	**k5** β	**k6**	**Se/Sy**	**R^2**
	log-log k1, k2, k3, k6 (θ, τ_{oct}+1)	3035.058	0.162	-1.306			-5.516	0.263	0.934
	log-log k1, k2, k3, k6 (θ, τ_{oct}+β)	3842.472	0.696	-2.440		2.103	-49.882	0.263	0.936
NS3_1	log-log k1, k2 (τ_{oct})	1531.586		-0.127				0.199	0.970
	log-log k1, k2 (σ_{cyc})	1685.141		-0.127				0.243	0.970
	semi-log k1, k2 (τ_{oct})	3.354		-0.384				0.086	0.995
	semi-log k1, k2 (σ_{cyc})	3.354		-0.181				0.105	0.995
	SHRP-Superpave k1-k6								
NS3_3	log-log k1, k2 (τ_{oct})	1937.054		-0.123				0.254	0.952
	log-log k1, k2 (σ_{cyc})	2124.187		-0.123				0.311	0.952
	semi-log k1, k2 (τ_{oct})	3.447		-0.357				0.045	0.998
	semi-log k1, k2 (σ_{cyc})	3.447		-0.168				0.056	0.998
	SHRP-Superpave k1-k6								
NS3_4	log-log k1, k2 (τ_{oct})	1598.348		-0.176				0.266	0.947
	log-log k1, k2 (σ_{cyc})	1824.565		-0.176				0.326	0.947
	semi-log k1, k2 (τ_{oct})	3.433		-0.508				0.136	0.986
	semi-log k1, k2 (σ_{cyc})	3.433		-0.240				0.166	0.986
	SHRP-Superpave k1-k6								
NS3_1,3,4	log-log k1, k2 (τ_{oct})	1725.712		-0.130				0.871	0.295
	log-log k1, k2 (σ_{cyc})	1902.324		-0.130				0.907	0.295
	semi-log k1, k2 (τ_{oct})	3.408		-0.387				0.858	0.316
	semi-log k1, k2 (σ_{cyc})	3.408		-0.183				0.893	0.316
	SHRP-Superpave k1-k6								
S11_dry	log-log k1, k2 (τ_{oct})	4212.030	0.122					1.003	0.031
	log-log k1, k2, k3 (θ, τ_{oct})	564.180	1.310	-0.778				0.341	0.892
	log-log k1, k2, k3 (σ_3, σ_{cyc})	7175.346	0.882	-0.361				0.361	0.880
	log-log k1, k2, k3, k6 (θ, τ_{oct})	414.228	1.448	-0.790			-1.292	0.344	0.895
	log-log k1, k2, k3, k6 (σ_3, σ_{cyc})	5314.595	1.241	-0.361			-1.282	0.361	0.884
	semi-log k1, k2 (τ_{oct})	3.646	0.011					1.008	0.022
	semi-log k1, k2,k3 (θ, τ_{oct})	3.502	0.135	-0.456				0.576	0.693
	semi-log k1, k2, k3 (σ_3, σ_{cyc})	3.499	0.436	-0.080				0.576	0.693

TABLE C-1

REGRESSION CONSTANTS AND STATISTICS FOR ALL TESTS/MODELS

Test ID	**Resilient Modulus Models** ***all models normalized by p_a**	**k1**	**k2**	**k3**	**k4**	**k5** β	**k6**	**Se/Sy**	**R^2**
	semi-log k1, k2, k3, k6 (θ, τ_{oct})	3.502	0.135	-0.456			0.000	0.587	0.693
	semi-log k1, k2, k3, k6 (σ_3, σ_{cyc})	3.499	0.436	-0.080			0.000	0.588	0.693
	SHRP-Superpave k1-k6								
	log-log k1, k2, k3 (θ, $\tau_{oct}+1$)	3417.193	1.021	-1.753				0.557	0.713
	log-log k1, k2, k3, k6 (θ, $\tau_{oct}+1$)	27.805	2.858	-2.031			-24.505	0.421	0.842
	log-log k1, k2, k3, k6 (θ, $\tau_{oct}+\beta$)	16.975	2.680	-1.135		0.171	-17.274	0.302	0.923
S11_high	log-log k1, k2 (τ_{oct})	827.058	0.741					0.319	0.902
	log-log k1, k2, k3 (θ, τ_{oct})	474.407	1.076	-0.211				0.261	0.937
	log-log k1, k2, k3 (σ_3, σ_{cyc})	2729.171	0.697	0.185				0.230	0.951
	log-log k1, k2, k3, k6 (θ, τ_{oct})	474.407	1.076	-0.211			0.000	0.267	0.937
	log-log k1, k2, k3, k6 (σ_3, σ_{cyc})	2729.171	0.697	0.185			0.000	0.235	0.951
	semi-log k1, k2 (τ_{oct})	3.104	0.057					0.549	0.710
	semi-log k1, k2,k3 (θ, τ_{oct})	2.981	0.129	-0.218				0.415	0.840
	semi-log k1, k2, k3 (σ_3, σ_{cyc})	2.978	0.415	0.026				0.415	0.840
	semi-log k1, k2, k3, k6 (θ, τ_{oct})	2.981	0.129	-0.218			0.000	0.424	0.840
	semi-log k1, k2, k3, k6 (σ_3, σ_{cyc})	2.978	0.415	0.026			0.000	0.424	0.840
	SHRP-Superpave k1-k6								
	log-log k1, k2, k3 (θ, $\tau_{oct}+1$)	634.713	1.210	-0.653				0.144	0.981
	log-log k1, k2, k3, k6 (θ, $\tau_{oct}+1$)	1173.253	0.889	-0.525			3.938	0.083	0.994
	log-log k1, k2, k3, k6 (θ, $\tau_{oct}+\beta$)	2752.321	0.913	-0.952		2.725	3.632	0.068	0.996
S11_low	log-log k1, k2 (τ_{oct})	1207.874	0.672					0.295	0.916
	log-log k1, k2, k3 (θ, τ_{oct})	652.912	1.045	-0.234				0.194	0.965
	log-log k1, k2, k3 (σ_3, σ_{cyc})	3631.641	0.654	0.167				0.198	0.964
	log-log k1, k2, k3, k6 (θ, τ_{oct})	1058.461	0.839	-0.217			3.196	0.151	0.980
	log-log k1, k2, k3, k6 (σ_3, σ_{cyc})	3631.641	0.654	0.167			0.000	0.202	0.964
	semi-log k1, k2 (τ_{oct})	3.241	0.053					0.498	0.761
	semi-log k1, k2,k3 (θ, τ_{oct})	3.129	0.118	-0.190				0.352	0.885
	semi-log k1, k2, k3 (σ_3, σ_{cyc})	3.127	0.380	0.029				0.353	0.884
	semi-log k1, k2, k3, k6 (θ, τ_{oct})	3.129	0.118	-0.190			0.000	0.359	0.885
	semi-log k1, k2, k3, k6 (σ_3, σ_{cyc})	3.127	0.380	0.029			0.000	0.360	0.884

TABLE C-1
REGRESSION CONSTANTS AND STATISTICS FOR ALL TESTS/MODELS

Test ID	**Resilient Modulus Models** ***all models normalized by p_a**	**k1**	**k2**	**k3**	**k4**	**k5** β	**k6**	**Se/Sy**	**R^2**
	SHRP-Superpave k1-k6	0.744	1.054	0.052	0.518	-0.590	2.000	0.538	0.759
	log-log k1, k2, k3 (θ, τ_{oct}+1)	955.947	1.091	-0.571				0.124	0.986
	log-log k1, k2, k3, k6 (θ, τ_{oct}+1)	1102.288	1.019	-0.544			0.950	0.124	0.986
	log-log k1, k2, k3, k6 (θ, $\tau_{oct}+\beta$)	1082.278	1.014	-0.527		0.940	1.017	0.127	0.986
S11_mid	log-log k1, k2 (τ_{oct})	1082.752	0.654					0.486	0.773
	log-log k1, k2, k3 (θ, τ_{oct})	306.126	1.415	-0.467				0.281	0.927
	log-log k1, k2, k3 (σ_3, σ_{cyc})	3516.909	0.869	0.068				0.318	0.906
	log-log k1, k2, k3, k6 (θ, τ_{oct})	681.941	1.066	-0.431			3.816	0.198	0.965
	log-log k1, k2, k3, k6 (σ_3, σ_{cyc})	3516.909	0.869	0.068			0.000	0.324	0.906
	semi-log k1, k2 (τ_{oct})	3.190	0.050					0.648	0.595
	semi-log k1, k2,k3 (θ, τ_{oct})	3.015	0.153	-0.300				0.405	0.848
	semi-log k1, k2, k3 (σ_3, σ_{cyc})	3.012	0.493	0.012				0.405	0.848
	semi-log k1, k2, k3, k6 (θ, τ_{oct})	3.015	0.153	-0.300			0.000	0.413	0.848
	semi-log k1, k2, k3, k6 (σ_3, σ_{cyc})	3.012	0.493	0.012			0.000	0.413	0.848
	SHRP-Superpave k1-k6								
	log-log k1, k2, k3 (θ, τ_{oct}+1)	697.824	1.431	-1.064				0.165	0.975
	log-log k1, k2, k3, k6 (θ, τ_{oct}+1)	913.851	1.296	-1.014			1.403	0.165	0.976
	log-log k1, k2, k3, k6 (θ, $\tau_{oct}+\beta$)	681.051	1.217	-0.720		0.428	2.385	0.155	0.979
S11_wet	log-log k1, k2 (τ_{oct})	627.340	0.871					0.253	0.939
	log-log k1, k2, k3 (θ, τ_{oct})	431.190	1.084	-0.115				0.216	0.959
	log-log k1, k2, k3 (σ_3, σ_{cyc})	2384.680	0.842	0.128				0.183	0.970
	log-log k1, k2, k3, k6 (θ, τ_{oct})	688.245	0.871	-0.173			3.455	0.153	0.980
	log-log k1, k2, k3, k6 (σ_3, σ_{cyc})	2384.680	0.842	0.128			0.000	0.189	0.970
	semi-log k1, k2 (τ_{oct})	2.887	0.097					0.419	0.834
	semi-log k1, k2,k3 (θ, τ_{oct})	2.817	0.148	-0.218				0.325	0.906
	semi-log k1, k2, k3 (σ_3, σ_{cyc})	2.814	0.477	0.045				0.325	0.906
	semi-log k1, k2, k3, k6 (θ, τ_{oct})	2.817	0.148	-0.218			0.000	0.336	0.906
	semi-log k1, k2, k3, k6 (σ_3, σ_{cyc})	2.814	0.477	0.045			0.000	0.335	0.906
	SHRP-Superpave k1-k6								
	log-log k1, k2, k3 (θ, τ_{oct}+1)	559.569	1.157	-0.575				0.146	0.981

TABLE C-1
REGRESSION CONSTANTS AND STATISTICS FOR ALL TESTS/MODELS

Test ID	**Resilient Modulus Models** ***all models normalized by p_a**	**k1**	**k2**	**k3**	**k4**	**k5** β	**k6**	**Se/Sy**	**R^2**
	log-log k1, k2, k3, k6 (θ, τ_{oct}+1)	749.574	1.006	-0.530			1.683	0.144	0.983
	log-log k1, k2, k3, k6 (θ, τ_{oct}+β)	8184.905	1.037	-1.651		4.515	1.303	0.136	0.986
S7_dry	log-log k1, k2 (τ_{oct})	4942.556	-0.865					0.699	0.538
	log-log k1, k2, k3 (θ, τ_{oct})	724.233	0.116	-0.815				0.174	0.973
	log-log k1, k2, k3 (σ_3, σ_{cyc})	1585.453	0.091	-0.788				0.175	0.973
	log-log k1, k2, k3, k6 (θ, τ_{oct})	2.544	1.956	-0.852			-78.760	0.159	0.979
	log-log k1, k2, k3, k6 (σ_3, σ_{cyc})	37.223	1.920	-0.799			-30.755	0.172	0.975
	semi-log k1, k2 (τ_{oct})	3.884	-0.207					0.720	0.511
	semi-log k1, k2,k3 (θ, τ_{oct})	3.882	-0.004	-1.793				0.449	0.821
	semi-log k1, k2, k3 (σ_3, σ_{cyc})	3.882	-0.013	-0.849				0.449	0.821
	semi-log k1, k2, k3, k6 (θ, τ_{oct})	3.882	-0.004	-1.793			0.000	0.463	0.821
	semi-log k1, k2, k3, k6 (σ_3, σ_{cyc})	3.882	-0.013	-0.849			0.000	0.463	0.821
	SHRP-Superpave k1-k6								
	log-log k1, k2, k3 (θ, τ_{oct}+1)	8000.734	-0.066	-4.775				0.401	0.857
	log-log k1, k2, k3, k6 (θ, τ_{oct}+1)	3.266	1.853	-5.186			-328.395	0.417	0.855
	log-log k1, k2, k3, k6 (θ, τ_{oct}+β)	80.393	1.036	-0.626		-0.033	-41.062	0.120	0.989
S7_high	log-log k1, k2 (τ_{oct})	754.310	-0.412					0.858	0.303
	log-log k1, k2, k3 (θ, τ_{oct})	180.635	0.441	-0.550				0.406	0.852
	log-log k1, k2, k3 (σ_3, σ_{cyc})	530.886	0.429	-0.521				0.386	0.867
	log-log k1, k2, k3, k6 (θ, τ_{oct})	0.110	3.342	-0.706			-35.101	0.237	0.953
	log-log k1, k2, k3, k6 (σ_3, σ_{cyc})	0.772	4.458	-0.541			-17.181	0.306	0.921
	semi-log k1, k2 (τ_{oct})	2.932	-0.077					0.910	0.216
	semi-log k1, k2,k3 (θ, τ_{oct})	2.860	0.077	-0.922				0.726	0.528
	semi-log k1, k2, k3 (σ_3, σ_{cyc})	2.859	0.249	-0.358				0.726	0.529
	semi-log k1, k2, k3, k6 (θ, τ_{oct})	2.860	0.077	-0.922			0.000	0.748	0.528
	semi-log k1, k2, k3, k6 (σ_3, σ_{cyc})	2.859	0.248	-0.358			0.000	0.748	0.529
	SHRP-Superpave k1-k6								
	log-log k1, k2, k3 (θ, τ_{oct}+1)	922.638	0.132	-2.354				0.716	0.542
	log-log k1, k2, k3, k6 (θ, τ_{oct}+1)	0.119	3.242	-2.991			-73.058	0.673	0.619
	log-log k1, k2, k3, k6 (θ, τ_{oct}+β)	1.226	2.565	-0.661		-0.006	-25.236	0.239	0.952

TABLE C-1
REGRESSION CONSTANTS AND STATISTICS FOR ALL TESTS/MODELS

Test ID	Resilient Modulus Models *all models normalized by p_a	k1	k2	k3	k4	k5 β	k6	Se/Sy	R^2
S7_low	log-log k1, k2 (τ_{oct})	152.431	0.466					0.740	0.482
	log-log k1, k2, k3 (θ, τ_{oct})	95.049	0.735	-0.184				0.712	0.549
	log-log k1, k2, k3 (σ_3, σ_{cyc})	311.663	0.491	0.015				0.776	0.465
	log-log k1, k2, k3, k6 (θ, τ_{oct})	0.032	3.797	-0.231			-34.482	0.626	0.674
	log-log k1, k2, k3, k6 (σ_3, σ_{cyc})	28.687	2.426	0.022			-8.803	0.777	0.496
	semi-log k1, k2 (τ_{oct})	2.088	0.105					0.671	0.575
	semi-log k1, k2,k3 (θ, τ_{oct})	2.084	0.112	-0.036				0.691	0.576
	semi-log k1, k2, k3 (σ_3, σ_{cyc})	2.081	0.362	0.095				0.690	0.577
	semi-log k1, k2, k3, k6 (θ, τ_{oct})	2.084	0.112	-0.036			0.000	0.713	0.576
	semi-log k1, k2, k3, k6 (σ_3, σ_{cyc})	2.081	0.362	0.095			0.000	0.713	0.577
	SHRP-Superpave k1-k6								
	log-log k1, k2, k3 (θ, $\tau_{oct}+1$)	151.159	0.419	0.165				0.761	0.485
	log-log k1, k2, k3, k6 (θ, $\tau_{oct}+1$)	0.030	3.514	-0.249			-51.060	0.717	0.572
	log-log k1, k2, k3, k6 (θ, $\tau_{oct}+\beta$)	11.682	18.356	-14.013		226.392	-349.511	0.740	0.574
S7_mid	log-log k1, k2 (τ_{oct})	1034.015	-0.476					0.910	0.218
	log-log k1, k2, k3 (θ, τ_{oct})	105.817	0.657	-0.958				0.332	0.902
	log-log k1, k2, k3 (σ_3, σ_{cyc})	569.652	0.517	-0.811				0.345	0.894
	log-log k1, k2, k3, k6 (θ, τ_{oct})	0.019	4.062	-1.053			-33.553	0.228	0.957
	log-log k1, k2, k3, k6 (σ_3, σ_{cyc})	1.436	4.542	-0.841			-14.217	0.313	0.918
	semi-log k1, k2 (τ_{oct})	3.105	-0.104					0.924	0.193
	semi-log k1, k2,k3 (θ, τ_{oct})	3.103	0.117	-1.989				0.660	0.613
	semi-log k1, k2, k3 (σ_3, σ_{cyc})	3.101	0.378	-0.821				0.660	0.613
	semi-log k1, k2, k3, k6 (θ, τ_{oct})	3.103	0.117	-1.989			0.000	0.682	0.613
	semi-log k1, k2, k3, k6 (σ_3, σ_{cyc})	3.101	0.378	-0.821			0.000	0.681	0.613
	SHRP-Superpave k1-k6								
	log-log k1, k2, k3 (θ, $\tau_{oct}+1$)	1745.161	0.356	-5.157				0.644	0.632
	log-log k1, k2, k3, k6 (θ, $\tau_{oct}+1$)	0.023	4.210	-5.428			-66.023	0.625	0.674
	log-log k1, k2, k3, k6 (θ, $\tau_{oct}+\beta$)	11.627	1.940	-0.742		-0.037	-10.451	0.112	0.990
S7_wet	log-log k1, k2 (τ_{oct})	180.466	0.226					0.942	0.162
	log-log k1, k2, k3 (θ, τ_{oct})	70.145	0.751	-0.355				0.674	0.597

TABLE C-1
REGRESSION CONSTANTS AND STATISTICS FOR ALL TESTS/MODELS

Test ID	**Resilient Modulus Models** ***all models normalized by p_a**	**k1**	**k2**	**k3**	**k4**	**k5** **β**	**k6**	**Se/Sy**	**R^2**
	log-log k1, k2, k3 (σ_3, σ_{cyc})	280.127	0.599	-0.193				0.746	0.505
	log-log k1, k2, k3, k6 (θ, τ_{oct})	0.060	3.624	-0.441			-27.663	0.549	0.749
	log-log k1, k2, k3, k6 (σ_3, σ_{cyc})	6.365	3.413	-0.191			-10.542	0.724	0.563
	semi-log k1, k2 (τ_{oct})	2.202	0.055					0.911	0.217
	semi-log k1, k2,k3 (θ, τ_{oct})	2.151	0.128	-0.392				0.830	0.388
	semi-log k1, k2, k3 (σ_3, σ_{cyc})	2.148	0.414	-0.056				0.829	0.389
	semi-log k1, k2, k3, k6 (θ, τ_{oct})	2.151	0.128	-0.392			0.000	0.857	0.388
	semi-log k1, k2, k3, k6 (σ_3, σ_{cyc})	2.148	0.414	-0.056			0.000	0.856	0.389
	SHRP-Superpave k1-k6								
	log-log k1, k2, k3 (θ, τ_{oct}+1)	189.053	0.475	-0.921				0.908	0.268
	log-log k1, k2, k3, k6 (θ, τ_{oct}+1)	0.056	3.526	-1.347			-44.844	0.831	0.425
	log-log k1, k2, k3, k6 (θ, τ_{oct}+β)	0.060	3.624	-0.441		0.000	-27.663	0.568	0.749
S13_dry	log-log k1, k2 (τ_{oct})	17161.697	-0.818					0.923	0.234
	log-log k1, k2, k3 (θ, τ_{oct})	85.245	1.703	-3.101				0.345	0.905
	log-log k1, k2, k3 (σ_3, σ_{cyc})	10198.249	1.205	-2.582				0.346	0.904
	log-log k1, k2, k3, k6 (θ, τ_{oct})	329.647	0.510	-3.105			4.962	0.187	0.975
	log-log k1, k2, k3, k6 (σ_3, σ_{cyc})	10198.249	1.205	-2.582			0.000	0.370	0.904
	semi-log k1, k2 (τ_{oct})	4.389	-0.181					0.897	0.276
	semi-log k1, k2,k3 (θ, τ_{oct})	4.719	0.306	-4.200				0.440	0.845
	semi-log k1, k2, k3 (σ_3, σ_{cyc})	4.712	0.988	-1.674				0.441	0.845
	semi-log k1, k2, k3, k6 (θ, τ_{oct})	4.719	0.306	-4.200			0.000	0.471	0.845
	semi-log k1, k2, k3, k6 (σ_3, σ_{cyc})	4.712	0.988	-1.674			0.000	0.471	0.845
	SHRP-Superpave k1-k6								
	log-log k1, k2, k3 (θ, τ_{oct}+1)	########	1.506	-13.031				0.322	0.917
	log-log k1, k2, k3, k6 (θ, τ_{oct}+1)	3075.749	3.322	-13.055			-10.841	0.412	0.881
	log-log k1, k2, k3, k6 (θ, τ_{oct}+β)	379.590	0.506	-3.564		0.063	4.905	0.221	0.971
S13_high	log-log k1, k2 (τ_{oct})	4829.812	-0.412					0.546	0.717
	log-log k1, k2, k3 (θ, τ_{oct})	2464.486	-0.010	-0.278				0.280	0.930
	log-log k1, k2, k3 (σ_3, σ_{cyc})	3023.275	0.009	-0.286				0.280	0.930
	log-log k1, k2, k3, k6 (θ, τ_{oct})	2464.493	-0.010	-0.278			0.000	0.289	0.930

TABLE C-1
REGRESSION CONSTANTS AND STATISTICS FOR ALL TESTS/MODELS

Test ID	Resilient Modulus Models *all models normalized by p_a	k1	k2	k3	k4	k5 β	k6	Se/Sy	R^2
	log-log k1, k2, k3, k6 (σ_3, σ_{cyc})	612.665	0.695	-0.293			-45.450	0.285	0.931
	semi-log k1, k2 (τ_{oct})	3.772	-0.094					0.569	0.693
	semi-log k1, k2,k3 (θ, τ_{oct})	3.726	-0.006	-0.467				0.351	0.890
	semi-log k1, k2, k3 (σ_3, σ_{cyc})	3.727	-0.020	-0.226				0.351	0.890
	semi-log k1, k2, k3, k6 (θ, τ_{oct})	3.726	-0.006	-0.467			0.000	0.362	0.890
	semi-log k1, k2, k3, k6 (σ_3, σ_{cyc})	3.727	-0.020	-0.226			0.000	0.362	0.890
	SHRP-Superpave k1-k6								
	log-log k1, k2, k3 (θ, $\tau_{oct}+1$)	5480.789	-0.077	-1.353				0.284	0.928
	log-log k1, k2, k3, k6 (θ, $\tau_{oct}+1$)	5508.671	0.000	-1.564	0.000			0.309	0.919
	log-log k1, k2, k3, k6 (θ, $\tau_{oct}+\beta$)	2291.613	0.000	-0.459	0.000	0.102		0.255	0.945
S13_low	log-log k1, k2 (τ_{oct})	3407.184	-0.330					0.948	0.154
	log-log k1, k2, k3 (θ, τ_{oct})	588.538	0.672	-0.719				0.382	0.871
	log-log k1, k2, k3 (σ_3, σ_{cyc})	2765.219	0.544	-0.562				0.358	0.887
	log-log k1, k2, k3, k6 (θ, τ_{oct})	610.185	0.651	-0.718			0.266	0.395	0.871
	log-log k1, k2, k3, k6 (σ_3, σ_{cyc})	76.796	3.183	-0.579			-10.769	0.343	0.903
	semi-log k1, k2 (τ_{oct})	3.596	-0.074					0.926	0.192
	semi-log k1, k2,k3 (θ, τ_{oct})	3.493	0.137	-1.249				0.344	0.896
	semi-log k1, k2, k3 (σ_3, σ_{cyc})	3.490	0.443	-0.451				0.344	0.896
	semi-log k1, k2, k3, k6 (θ, τ_{oct})	3.493	0.137	-1.249			0.000	0.356	0.896
	semi-log k1, k2, k3, k6 (σ_3, σ_{cyc})	3.490	0.443	-0.451			0.000	0.356	0.896
	SHRP-Superpave k1-k6								
	log-log k1, k2, k3 (θ, $\tau_{oct}+1$)	4315.463	0.617	-3.690				0.313	0.914
	log-log k1, k2, k3, k6 (θ, $\tau_{oct}+1$)	1858.963	1.054	-3.739			-6.338	0.301	0.925
	log-log k1, k2, k3, k6 (θ, $\tau_{oct}+\beta$)	22.419	2.074	-1.706		0.268	-18.750	0.243	0.955
S13_mid	log-log k1, k2 (τ_{oct})	3116.131	-0.287					0.730	0.494
	log-log k1, k2, k3 (θ, τ_{oct})	1387.206	0.200	-0.324				0.302	0.919
	log-log k1, k2, k3 (σ_3, σ_{cyc})	2405.813	0.172	-0.281				0.277	0.931
	log-log k1, k2, k3, k6 (θ, τ_{oct})	1387.206	0.200	-0.324			0.000	0.311	0.919
	log-log k1, k2, k3, k6 (σ_3, σ_{cyc})	2405.813	0.172	-0.281			0.000	0.285	0.931
	semi-log k1, k2 (τ_{oct})	3.555	-0.065					0.708	0.525

TABLE C-1
REGRESSION CONSTANTS AND STATISTICS FOR ALL TESTS/MODELS

Test ID	**Resilient Modulus Models** ***all models normalized by p_a**	**k1**	**k2**	**k3**	**k4**	**k5** β	**k6**	**Se/Sy**	R^2
	semi-log k1, k2,k3 (θ, τ_{oct})	3.498	0.032	-0.508				0.327	0.905
	semi-log k1, k2, k3 (σ_3, σ_{cyc})	3.498	0.105	-0.207				0.327	0.904
	semi-log k1, k2, k3, k6 (θ, τ_{oct})	3.498	0.032	-0.508			0.000	0.337	0.905
	semi-log k1, k2, k3, k6 (σ_3, σ_{cyc})	3.498	0.105	-0.207			0.000	0.337	0.904
	SHRP-Superpave k1-k6								
	log-log k1, k2, k3 (θ, $\tau_{oct}+1$)	3535.760	0.112	-1.538				0.287	0.926
	log-log k1, k2, k3, k6 (θ, $\tau_{oct}+1$)	1777.884	0.462	-1.671			-17.038	0.263	0.942
	log-log k1, k2, k3, k6 (θ, $\tau_{oct}+\beta$)	604.021	0.545	-0.643		0.176	-15.849	0.177	0.975
S13_wet	log-log k1, k2 (τ_{oct})	261.391	0.329					0.949	0.147
	log-log k1, k2, k3 (θ, τ_{oct})	185.991	0.522	-0.132				0.963	0.171
	log-log k1, k2, k3 (σ_3, σ_{cyc})	421.476	0.285	0.028				0.996	0.112
	log-log k1, k2, k3, k6 (θ, τ_{oct})	0.704	2.845	-0.279			-25.602	0.834	0.415
	log-log k1, k2, k3, k6 (σ_3, σ_{cyc})	0.974	3.720	0.007			-21.015	0.997	0.164
	semi-log k1, k2 (τ_{oct})	2.300	0.092					0.830	0.348
	semi-log k1, k2,k3 (θ, τ_{oct})	2.366	0.021	0.297				0.819	0.400
	semi-log k1, k2, k3 (σ_3, σ_{cyc})	2.362	0.080	0.159				0.819	0.400
	semi-log k1, k2, k3, k6 (θ, τ_{oct})	2.366	0.022	0.291			0.000	0.844	0.400
	semi-log k1, k2, k3, k6 (σ_3, σ_{cyc})	2.365	0.072	0.159			0.003	0.844	0.400
	SHRP-Superpave k1-k6								
	log-log k1, k2, k3 (θ, $\tau_{oct}+1$)	246.391	-0.182	1.538				0.882	0.304
	log-log k1, k2, k3, k6 (θ, $\tau_{oct}+1$)	0.733	2.118	0.498			-71.032	0.896	0.324
	log-log k1, k2, k3, k6 (θ, $\tau_{oct}+\beta$)	0.006	4.431	-0.316		0.000	-40.142	0.829	0.457

TABLE C-2
OPTIMIZATION OF THE SHRP-SUPERPAVE MODEL

Test ID	**Optimization Procedure**	**k1**	***k2***	***k3***	**k4**	**k5**	***k6***	***Mr model***		***ν model***	
								Se/Sy	**R²**	**Se/Sy**	**R²**
S12_1	*Mr independent optimization*	786.000	1.054	-0.255			0.000	0.216	0.959		
	ν independent optimization		1.104	0.052	0.435	-0.615	-1.127			0.452	0.827
	Simultaneos optimization	786.000	1.080	0.040	0.435	-0.615	-0.800	0.692	0.576	0.664	0.627
S12_2	*Mr independent optimization*	793.000	1.065	-0.256			-0.208	0.204	0.963		
	ν independent optimization		1.123	0.049	0.422	-0.630	-1.156			0.479	0.806
	Simultaneos optimization	793.000	1.090	0.049	0.422	-0.630	-1.100	0.708	0.557	0.878	0.347
S12_5	*Mr independent optimization*	782.000	1.002	-0.238			0.242	0.192	0.967		
	ν independent optimization		1.080	0.045	0.360	-0.581	-0.706			0.432	0.842
	Simultaneos optimization	782.000	1.050	0.043	0.360	-0.581	-0.600	0.857	0.351	0.792	0.469
S12_6	*Mr independent optimization*	786.000	1.037	-0.249			0.030	0.174	0.973		
	ν independent optimization		1.126	0.058	0.357	-0.623	-2.303			0.404	0.862
	Simultaneos optimization	786.000	1.070	0.050	0.357	-0.623	-1.500	0.871	0.329	0.997	0.159
S12_1,2,5,6	*Mr independent optimization*	781.000	1.049	-0.251			0.000	0.257	0.936		
	ν independent optimization		1.104	0.050	0.428	-0.615	-1.137			0.463	0.796
	Simultaneos optimization	781.000	1.080	0.040	0.428	-0.615	-1.000	0.722	0.498	0.619	0.637
NS12_2	*Mr independent optimization*	775.000	0.991	-0.352			0.000	0.093	0.993		
	ν independent optimization		0.996	0.000	0.314	-0.524	-0.093			1.023	0.253
	Simultaneos optimization										
NS12_3	*Mr independent optimization*	886.000	1.043	-0.186			-2.197	0.046	0.998		
	ν independent optimization		1.041	0.043	0.494	-0.599	-2.421			0.408	0.881
	Simultaneos optimization										
NS12_4	*Mr independent optimization*	894.000	0.997	-0.176			-1.527	0.056	0.998		
	ν independent optimization		1.002	0.050	0.489	-0.586	-2.127			1.154	0.049
	Simultaneos optimization										
NS12_5	*Mr independent optimization*	892.000	0.975	-0.162			-2.623	0.088	0.994		
	ν independent optimization		0.966	0.045	0.492	-0.574	-2.995			0.918	0.397
	Simultaneos optimization										
NS12_2,3,4,5	*Mr independent optimization*	742.669	1.085	-0.208			-2.544	0.195	0.964		
	ν independent optimization		1.085	0.048	0.500	-0.617	-2.544			0.982	0.101
	Simultaneos optimization										

TABLE C-2
OPTIMIZATION OF THE SHRP-SUPERPAVE MODEL

Test ID	**Optimization Procedure**	**k1**	***k2***	***k3***	**k4**	**k5**	***k6***	***Mr model***		***ν model***	
								Se/Sy	**R^2**	**Se/Sy**	**R^2**
S1_1	*Mr independent optimization*	47.497	2.398	-0.985			-5.099	0.261	0.943		
	ν independent optimization										
	Simultaneos optimization										
S1_2	*Mr independent optimization*	2.031	3.669	-1.067			-13.287	0.222	0.959		
	ν independent optimization										
	Simultaneos optimization										
S1_3	*Mr independent optimization*	6.604	3.193	-1.014			-12.958	0.304	0.924		
	ν independent optimization										
	Simultaneos optimization										
S1_1,2,3	*Mr independent optimization*	55.248	2.317	-0.944			-5.881	0.428	0.827		
	ν independent optimization										
	Simultaneos optimization										
NS1_1	*Mr independent optimization*	0.236	3.838	-0.951			-30.111	0.450	0.841		
	ν independent optimization										
	Simultaneos optimization										
NS1_2	*Mr independent optimization*	0.506	3.412	-0.511			-37.492	0.589	0.727		
	ν independent optimization										
	Simultaneos optimization										
NS1_3	*Mr independent optimization*	1.556	2.770	-0.531			-44.373	0.607	0.711		
	ν independent optimization										
	Simultaneos optimization										
NS1_1,2,3	*Mr independent optimization*	1.178	3.056	-0.639			-35.194	0.775	0.441		
	ν independent optimization										
	Simultaneos optimization										
S3_1	*Mr independent optimization*	1747.243	0.096	-0.246			-1.298	0.293	0.931		
	ν independent optimization										
	Simultaneos optimization										
S3_2	*Mr independent optimization*	1619.550	0.129	-0.293			1.204	0.336	0.910		
	ν independent optimization										

TABLE C-2
OPTIMIZATION OF THE SHRP-SUPERPAVE MODEL

Test ID	**Optimization Procedure**	**k1**	***k2***	***k3***	**k4**	**k5**	***k6***	***Mr model***		***ν model***	
								Se/Sy	**R^2**	**Se/Sy**	**R^2**
	Simultaneos optimization										
S3_3	*Mr independent optimization*	1936.795	-0.010	-0.215			0.000	0.280	0.937		
	ν independent optimization										
	Simultaneos optimization										
S3_1,2,3	*Mr independent optimization*	1674.671	0.119	-0.254			-2.967	0.313	0.907		
	ν independent optimization										
	Simultaneos optimization										
S13_dry	*Mr independent optimization*	1.025	0.176	-1.967			-12.034	0.393	0.892		
	ν independent optimization										
	Simultaneos optimization										
S13_high	*Mr independent optimization*	1.351	0.347	-0.407			-5.261	0.380	0.878		
	ν independent optimization										
	Simultaneos optimization										
S13_low	*Mr independent optimization*	1.315	0.069	-0.491			-1.922	0.604	0.699		
	ν independent optimization										
	Simultaneos optimization										
S13_mid	*Mr independent optimization*	0.799	0.525	-0.421			-3.452	0.421	0.851		
	ν independent optimization										
	Simultaneos optimization										
S13_wet	*Mr independent optimization*	0.128	0.833	-0.101			-2.055	0.990	0.174		
	ν independent optimization										
	Simultaneos optimization										
S7_dry	*Mr independent optimization*	0.519	0.332	-0.834			-6.097	0.175	0.975		
	ν independent optimization										
	Simultaneos optimization										
S7_high	*Mr independent optimization*	0.100	0.801	-0.644			-2.726	0.341	0.902		
	ν independent optimization										
	Simultaneos optimization										
S7_low	*Mr independent optimization*	0.093	0.826	-0.069			-1.374	0.768	0.508		
	ν independent optimization										

TABLE C-2
OPTIMIZATION OF THE SHRP-SUPERPAVE MODEL

Test ID	**Optimization Procedure**	**k1**	***k2***	***k3***	**k4**	**k5**	***k6***	***Mr model***		***ν model***	
								Se/Sy	**R^2**	**Se/Sy**	**R^2**
	Simultaneos optimization										
S7_mid	*Mr independent optimization*	0.101	0.765	-0.827			-3.035	0.339	0.904		
	ν independent optimization										
	Simultaneos optimization										
S7_wet	*Mr independent optimization*	0.081	0.750	-0.187			-1.923	0.788	0.483		
	ν independent optimization		0.857	0.036	0.199	-0.397	-3.160			0.494	0.810
	Simultaneos optimization										
S11_dry	*Mr independent optimization*	0.780	1.145	-0.701			0.325				
	ν independent optimization										
	Simultaneos optimization										
S11_high	*Mr independent optimization*	0.657	1.023	-0.157			2.885	0.100	0.992		
	ν independent optimization		1.102	0.046	0.437	-0.591	-1.627			0.875	0.415
	Simultaneos optimization										
S11_low	*Mr independent optimization*	0.744	1.034	-0.169			0.797	0.090	0.993		
	ν independent optimization		1.054	0.052	0.518	-0.590	2.531			0.473	0.826
	Simultaneos optimization	0.744	1.054	0.052	0.518	-0.590	2.000	0.538	0.759	0.527	0.784
S11_mid	*Mr independent optimization*	0.639	1.124	-0.398			3.517	0.193	0.969		
	ν independent optimization										
	Simultaneos optimization										
S11_wet	*Mr independent optimization*	0.680	0.880	-0.127			2.954	0.132	0.986		
	ν independent optimization										
	Simultaneos optimization										

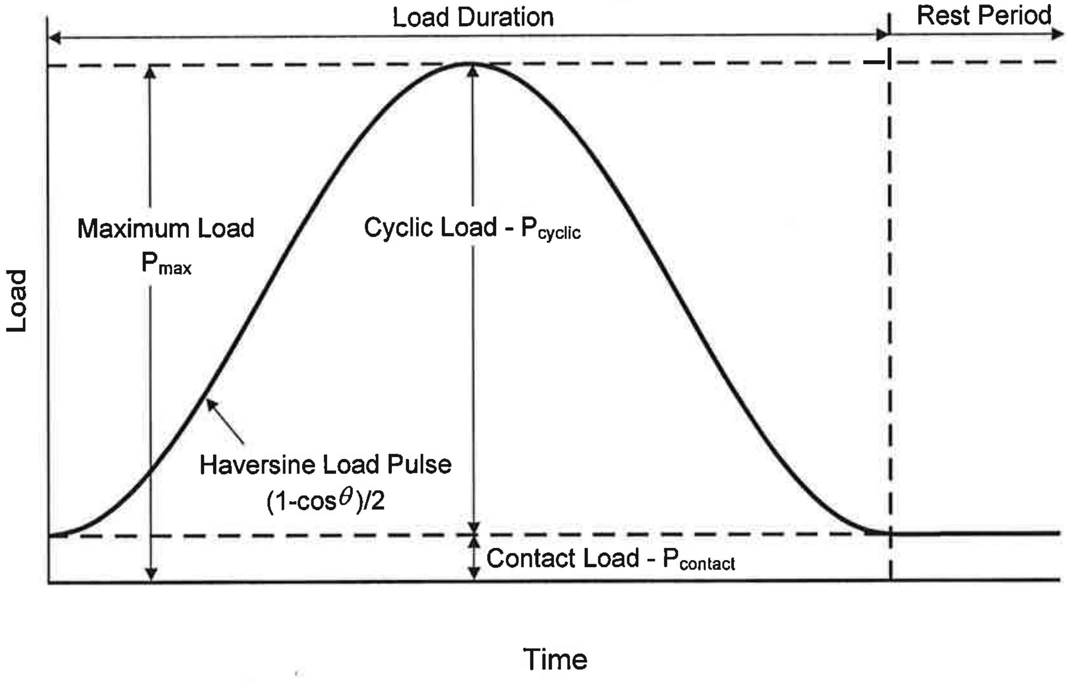


Figure A-1. Definition of Resilient Modulus Terms

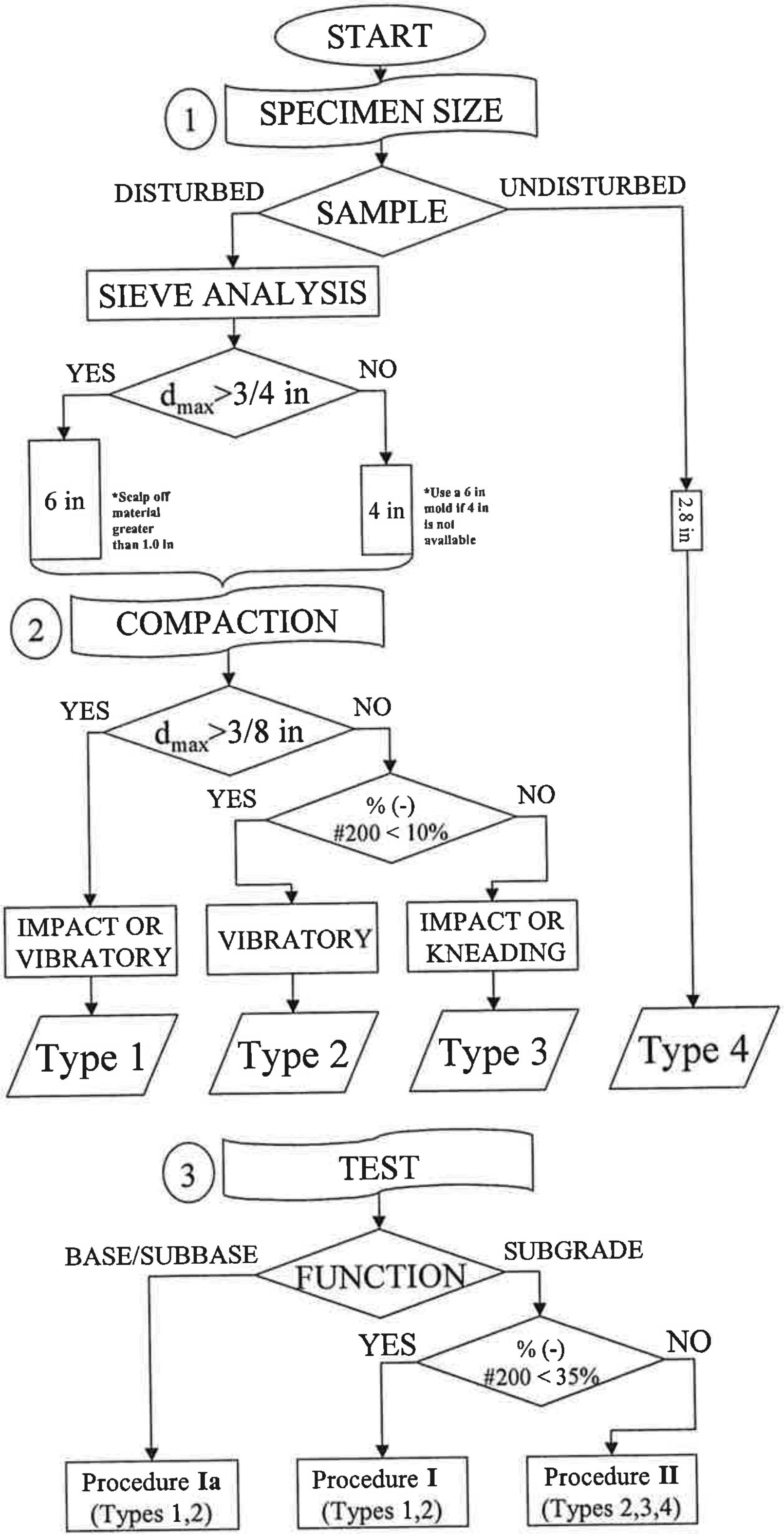
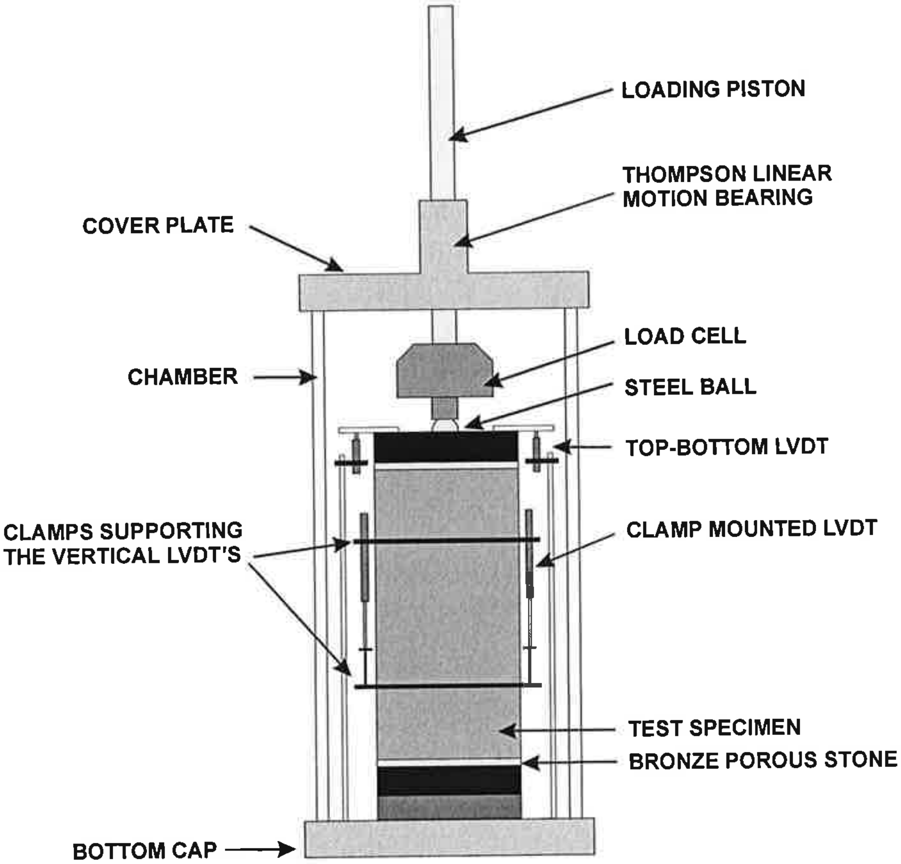
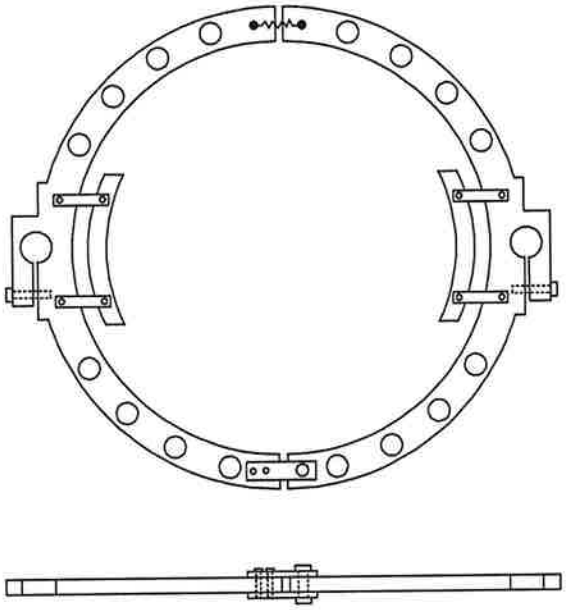


Figure A-2. Test Method Flowchart



a) Triaxial Cell



b) Typical Clamps Used To Measure Axial Deformation

Figure A-3. Triaxial Cell Set-up

REPORT FORM 1

1 SAMPLE NUMBER ____

2 SAMPLE DESCRIPTION ________

3 MATERIAL TYPE ☐

4 TEST DATE __.__.__

5 MATERIAL CONSTANTS K1 = K2 = K3 = K6 = K7 =

6 REFERENCE RESILIENT MODULUS _____Mpa _____(KSI)

7 RESILIENT MODULUS TESTING:

COLUMN #	1	2	3	4	5	6	7	8	9	10	11	12	13	14
PARAMETER	CHAMBER CONFINING PRESSURE	NOMINAL MAXIMUM AXIAL STRESS	CYCLE NO.	ACTUAL APPLIED MAX. AXIAL LOAD	ACTUAL APPLIED CYCLIC LOAD	ACTUAL APPLIED CONTACT LOAD	ACTUAL APPLIED MAXIMUM AXIAL STRESS	ACTUAL APPLIED CYCLIC STRESS	ACTUAL APPLIED CONTACT STRESS	RECOV. DEF. LVDT #1 READING	RECOV. DEF. LVDT #2 READING	AVERAGE RECOV. DEF. LVDT 1 AND 2	RESILIENT STRAIN	RESILIENT MODULUS
DESIGNATION	S_3	S_{CYCLIC}		P_{MAX}	P_{CYCLIC}	$P_{CONTACT}$	S_{MAX}	S_{CYCLIC}	$S_{CONTACT}$	H_1	H_2	H_{AVG}	ε_r	M_R
UNIT	kPa	kPa		N	N	N	kPa	kPa	kPa	mm	mm	mm	mm/mm	MPa
PRECISION	___._	___._		____._	____._	___._	___._	___._	__._	_._____	_._____	_._____		___.
SEQUENCE 1*			1											
			2											
			3											
			4											
			5											
	COLUMN AVERAGE													
	STANDARD DEVIATION													

* REPEAT FOR SEQUENCES 2 TO30

REPORT FORM 2 - LABORATORY COMPACTED SAMPLES

1 SAMPLING DATE	--.--.--
2 SAMPLE NUMBER	☐
3 MATERIAL TYPE (1,2,3 OR 4)	☐
4 TEST INFORMATION	
PRECONDITIONING - GREATER THAN 5% PERMANENT STRAIN ? (Y/N)	☐
TESTING - GREATER THAN 5% PERMANENT STRAIN ? (Y/N)	☐
TESTING - NUMBER OF LOAD SEQIENCES COMPLETED (1-30)	☐
5 SPECIMEN INFO	
DIAMETER, mm	
TOP	---.-
MIDDLE	---.-
BOTTOM	---.-
AVERAGE	---.-
MEMBRANE THICKNESS (1) mm	-.--
MEMBRANE THICKNESS (2) mm	-.--
NET DIAMETER, mm	---.-
HEIGHT OF SPECIMEN CAP AND BASE, mm	---.-
HEIGHT OF CAP AND BASE, mm	---.-
INITIAL LENGTH, L_0, mm	---.-
INITIAL AREA, A_0, mm^2	-----.
INITIAL VOLUME, A_0L_0, mm^3	-------.
6 SOIL SPECIMEN WEIGHT	
INITIAL WEIGHT OF CONTAINER AND WET SOIL, grams	-----.--
FINAL WEIGHT OF CONTAINER AND WET SOIL, grams	-----.--
WEIGHT OF WET SOIL USED, grams	-----.--
7 SOIL PROPERTIES	
IN SITU MOISTURE CONTENT (NUCLEAR), %	--.-
IN SITU WET DENSITY (NUCLEAR), %	----.-
OR	
OPTIMUM MOISTURE CONTENT, %	--.-
MAXIMUM DRY DENSITY, kg/m^3	----.-
95 % MAXIMUM DRY DENSITY, kg/m^3	----.-
8 SPECIMEN PROPERTIES	
COMPACTION MOISTURE CONTENT, %	--.-
MOISTURE CONTENT AFTER RESILIENT MODULUS TESTING, %	--.-
COMPACTION DRY DENSITY, γ_d, kg/m^3	----.-
9 TEST DATE	--.--.--
10 GENERAL REMARKS	

TESTED BY ____________________ **DATE** ____________________

REPORT FORM 3 - THINWALL TUBE SAMPLES

1 SAMPLING DATE --.--.--

2 SAMPLE NUMBER ☐

3 MATERIAL TYPE (1,2,3 OR 4) ☐

4 APPROX. DISTANCE FROM TOP OF SUBGRADE TO SAMPLE, m -.--

5 TEST INFORMATION

PRECONDITIONING - GREATER THAN 5% PERMANENT STRAIN ? (Y/N) ☐
TESTING - GREATER THAN 5% PERMANENT STRAIN ? (Y/N) ☐
TESTING - NUMBER OF LOAD SEQIENCES COMPLETED (1-30) ☐

6 SPECIMEN INFO

DIAMETER, mm
TOP ---.-
MIDDLE ---.-
BOTTOM ---.-
AVERAGE ---.-
MEMBRANE THICKNESS (1) mm -.--
MEMBRANE THICKNESS (2) mm -.--
NET DIAMETER, mm ---.-
HEIGHT OF SPECIMEN CAP AND BASE, mm ---.-
HEIGHT OF CAP AND BASE, mm ---.-
INITIAL LENGTH, L_0, mm ---.-
INITIAL AREA, A_0, mm^2 ------.
INITIAL VOLUME, A_0L_0, mm^3 --------.
INITIAL WEIGHT, grams -----.-

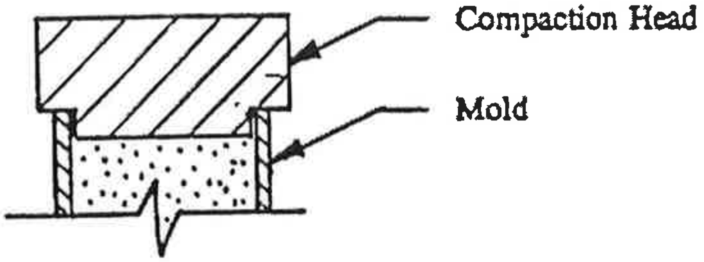
7 SOIL PROPERTIES

IN SITU MOISTURE CONTENT, % --.-
MOISTURE CONTENT AFTER RESILIENT MODULUS TESTING, % --.-
WET DENSITY, γ_w, kg/m^3 ----.-
DRY DENSITY, γ_d, kg/m^3 ----.-

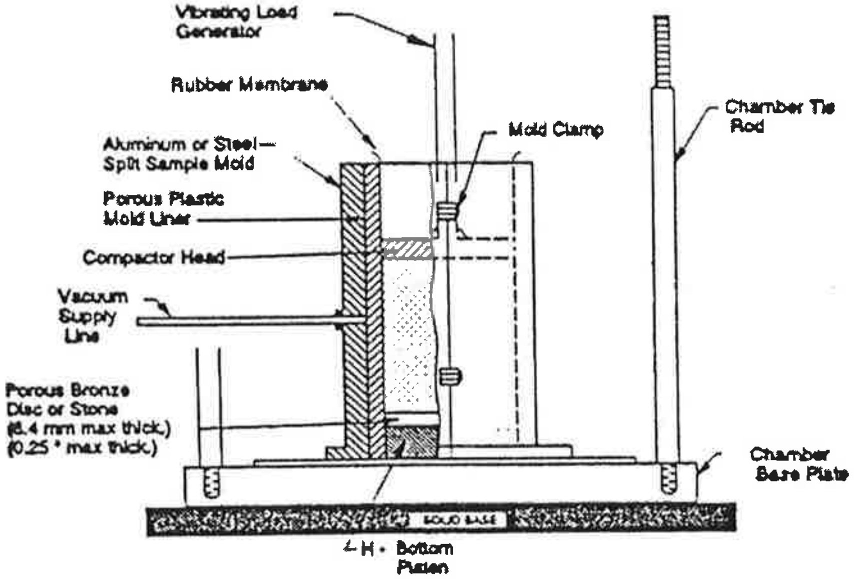
8 TEST DATE --.--.--

9 GENERAL REMARKS

TESTED BY ____________________ **DATE** ____________________

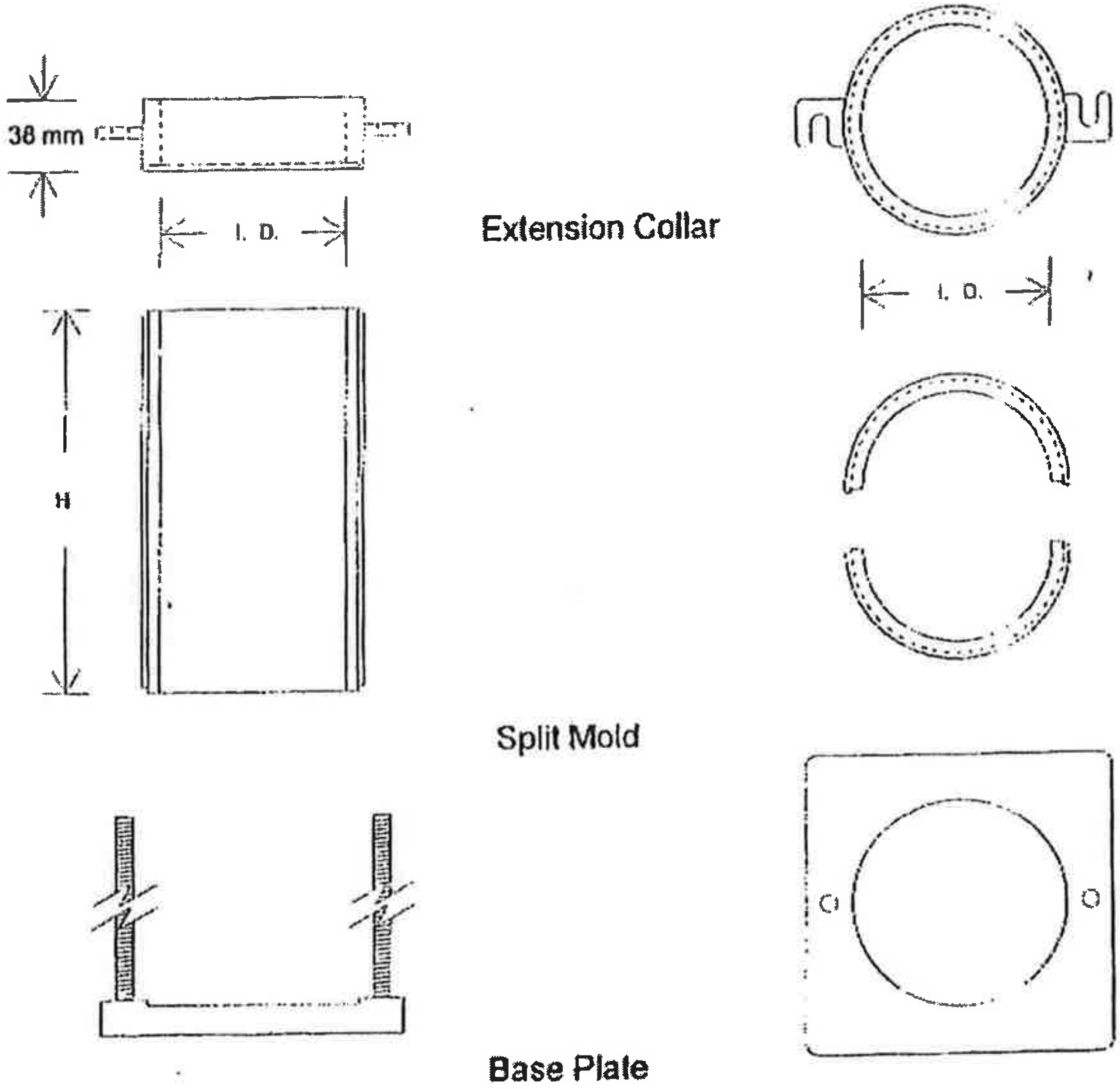


(b) Recommended head for final compaction



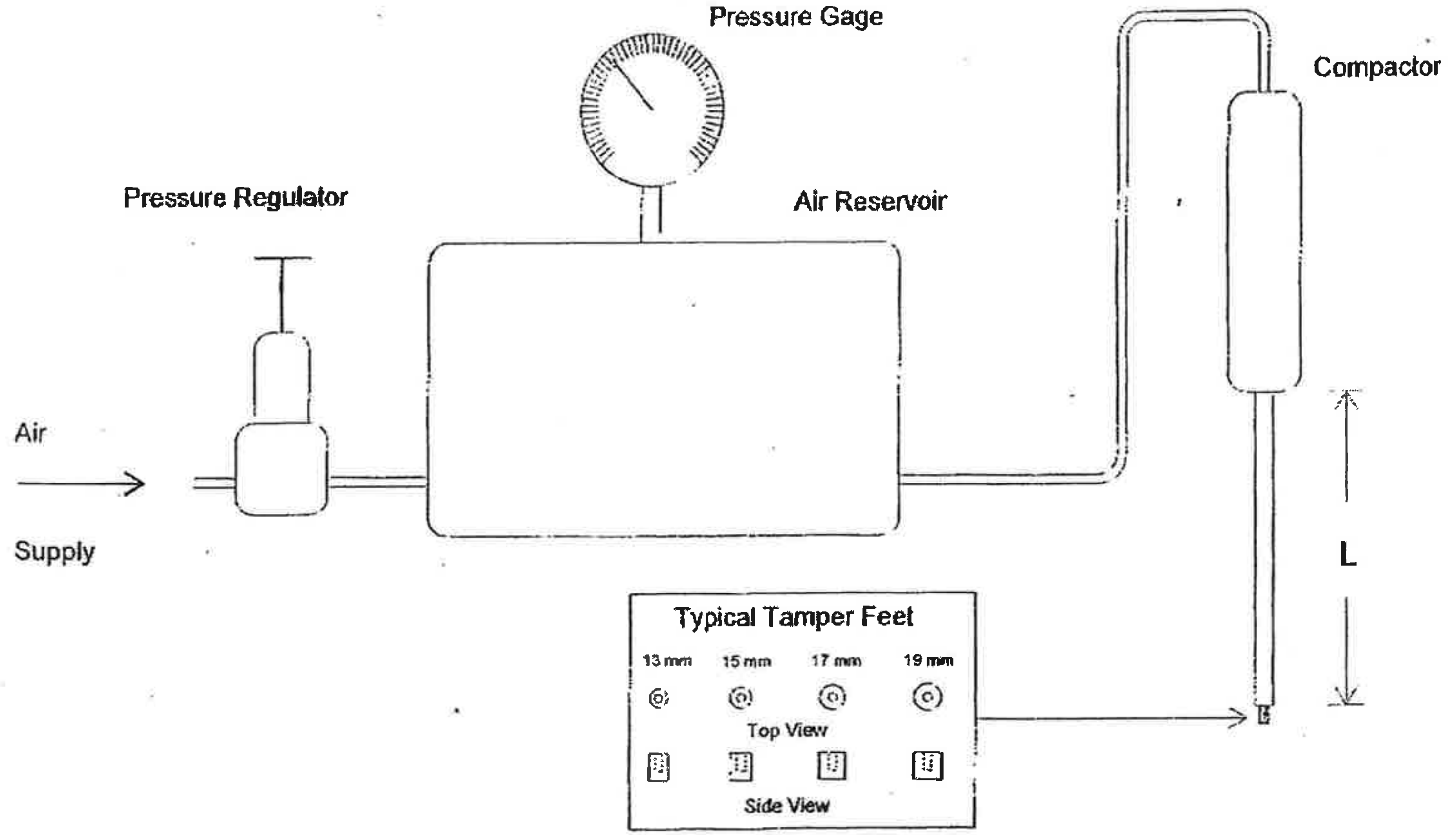
(a) Compaction Mold Assembly

Fig. A-2-1. Typical Apparatus for Vibratory Compaction



Notes:
1. Mold halves are connected with 2 hose clamps
2. H = I.D. x 2

Fig. A-4-1. Specimen Mold (AASHTO TP46)



Notes:
1. L = Specimen Ht. + Collar Ht. - Layer Ht. + 12 mm
2. Minimum reservoir volume = 200 x compactor volume
3. Minimum gage accuracy is 0.5 Pa
4. Compactor air cylinder is rolling diaphragm type

Fig. A-4-2. Pneumatic Kneading Compaction System (AASHTO TP-46)

PROJECT	

Target Moisture (%)		Target Dry Density (Kg/m^3)	

Mold Dimensions - diam. x ht. (mm)		Mold Volume (cm)		Mold Wt. (gms)	

Specimen No.				
Wt. of scalped soil (gms)				
No. Tamps per Layer				
Air or Tamper Foot Pressure (Pa)				
Wt. specimen & mold (gms)				
Wt. mold assembly (gms)				
Wt. moist soil (gms)				
Wt. dry soil (gms)				
Moisture Content (%)				
Dry Density (Kg/m^3)				
Wet Density (Kg/m^3)				

PERCENT DIFFERENCES

Target & Specimen Dry Density (%)				
Target & Specimen Moisture (%)				

Specimen No.	Soil Description

REMARKS

Fig. A-4-3. Kneading Compaction

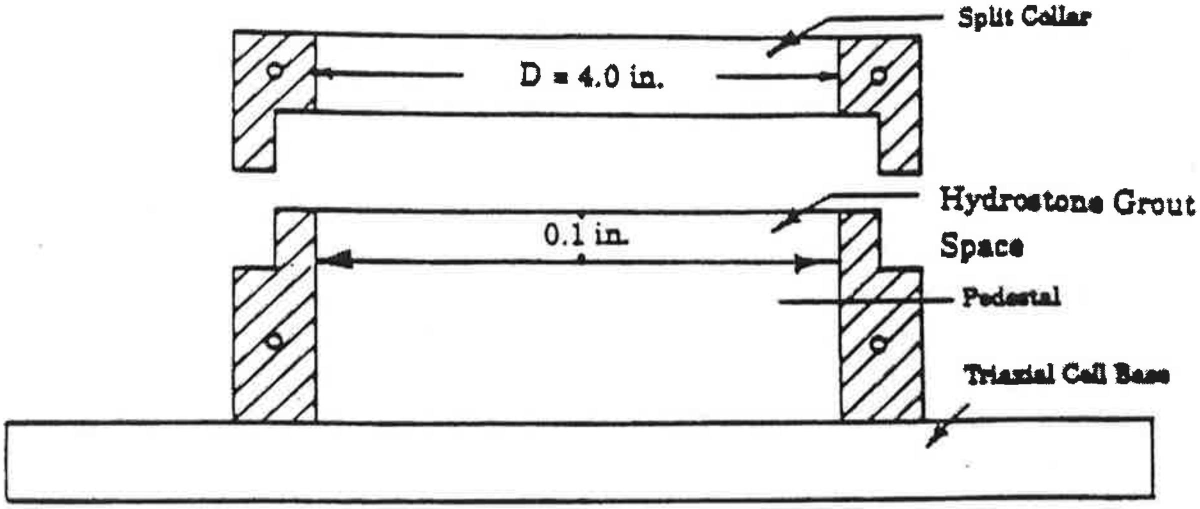
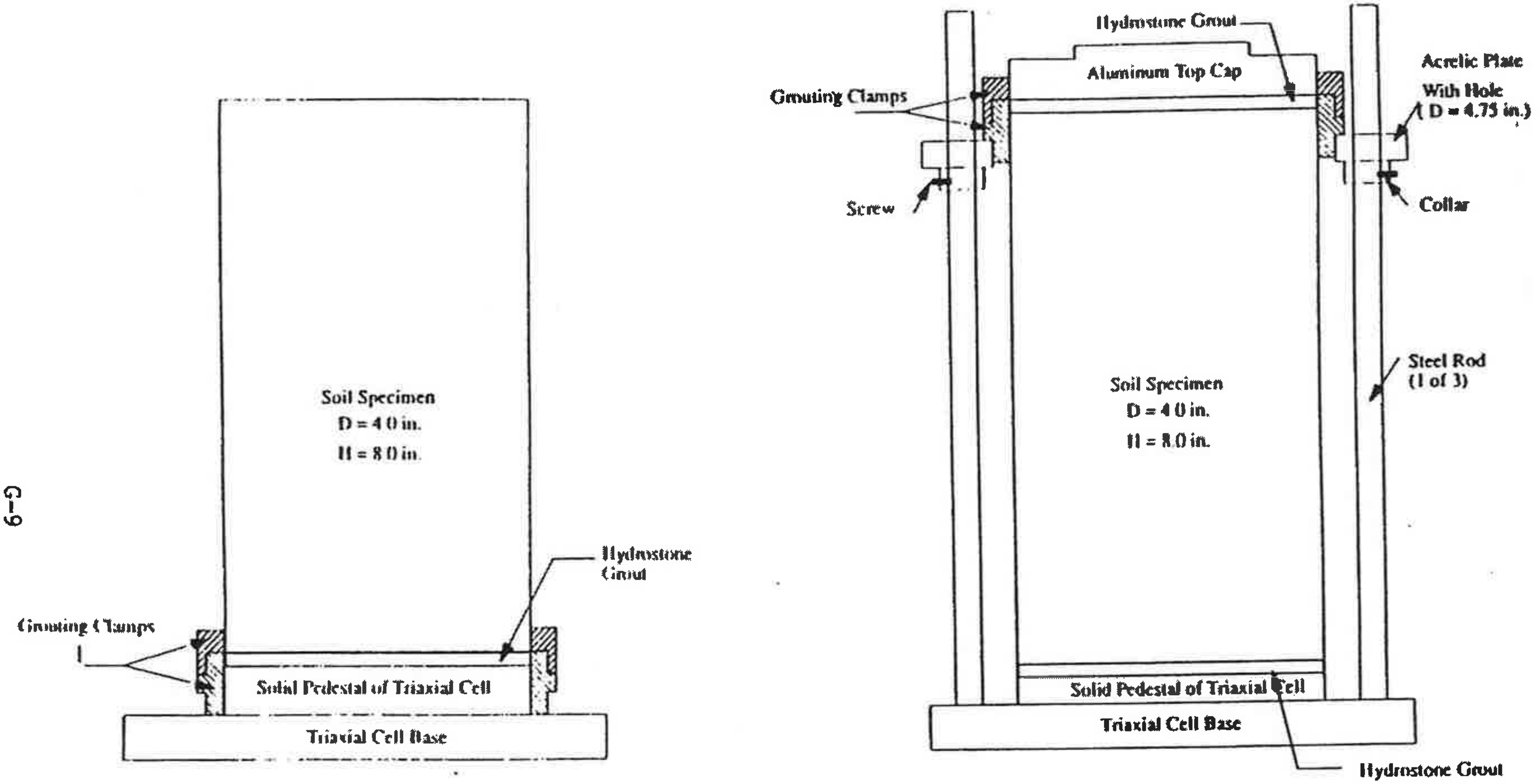


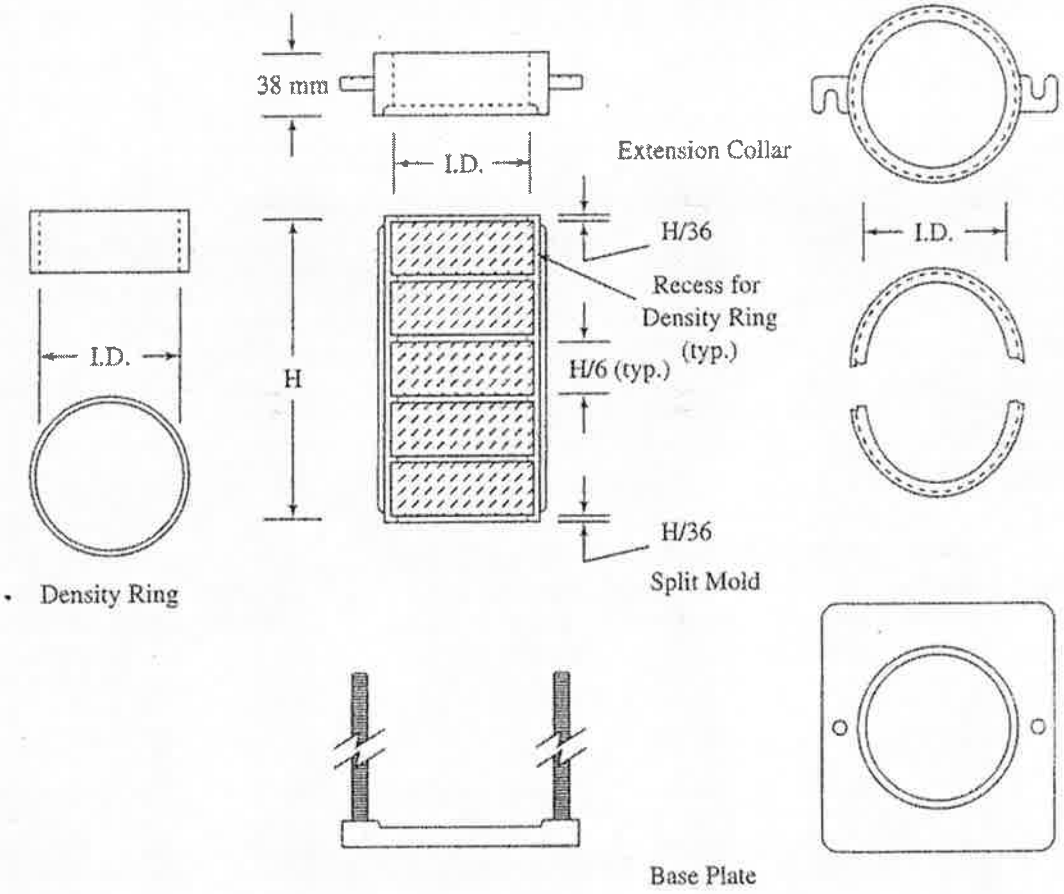
Fig. A-5-1. Clamps Used in Grouting the Ends of the Test Specimen



(a) Grouting the bottom end

(b) Grouting the top end

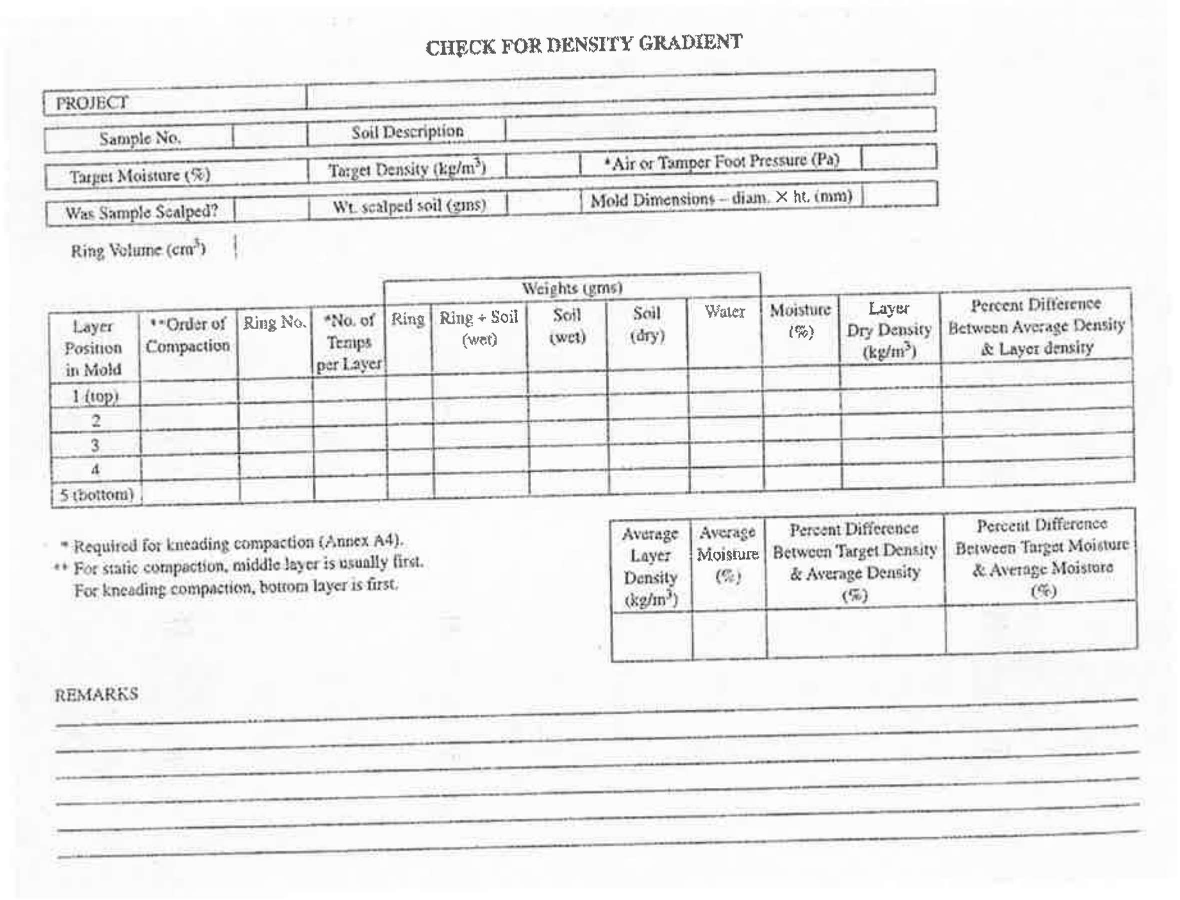
Fig. A-5-2. Setup for Grouting the Top and Bottom Ends of a Specimen



NOTES

1. Mold halves are connected with 2 hose clamps.
2. Depth of mold recesses equals Density Ring wall thickness.
3. H = I.D. × 2 (minimum).
4. Rings are machined to tolerances permitting interchanging.
5. Rings have an identifying designation on the outside.

Figure A-6-1. Density Gradient Mold



CHECK FOR DENSITY GRADIENT

PROJECT

Sample No. | Soil Description

Target Moisture (%) | Target Density (kg/m³) | *Air or Tamper Foot Pressure (Pa)

Was Sample Scalped? | Wt. scalped soil (gms) | Mold Dimensions – diam. × ht. (mm)

Ring Volume (cm³)

				Weights (gms)							
Layer Position in Mold	**Order of Compaction	Ring No.	*No. of Temps per Layer	Ring	Ring + Soil (wet)	Soil (wet)	Soil (dry)	Water	Moisture (%)	Layer Dry Density (kg/m³)	Percent Difference Between Average Density & Layer density
1 (top)											
2											
3											
4											
5 (bottom)											

* Required for kneading compaction (Annex A4).
** For static compaction, middle layer is usually first.
For kneading compaction, bottom layer is first.

Average Layer Density (kg/m³)	Average Moisture (%)	Percent Difference Between Target Density & Average Density (%)	Percent Difference Between Target Moisture & Average Moisture (%)

REMARKS

Figure A-6-2