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16. Abstract

In Year 3 the laboratory test protocols for measuring the resilient modulus and permanent deformation properties of granular bases were further developed. A repeatability study was conducted, and studies were also made on the influence of sample size. A comparison was made with samples molded to the recommended dimensions (6 inches by 12 inches high) to the standard Texas Department of Transportation (TxDOT) size, 6 by 8 inch. Using a high-quality base material from Spicewood Springs, it was found statistically that the resilient modulus values were not affected by using a smaller sample size.

Experimental test sections were also constructed with three premium bases that meet the proposed Item 245 specification. Preliminary laboratory test results are presented on these bases together with details of the test section construction. The Tube Suction Test continues to be a good test to identify good base materials; it clearly distinguished between the Item 245 and Item 247 materials. No clear distinction could be made with other tests such as resilient modulus.

Numerous problems were encountered with running the low-fines bases through the traditional strength testing. We found problems with both the compaction and testing. A new vibratory compaction system was built, and it will be evaluated in Year 4 of this project.

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HEAVY-DUTY FLEXIBLE BASES: YEAR 3 PROGRESS REPORT

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DISCLAIMER

The contents of this report reflect the views of the authors, who are responsible for the opinions, findings, and conclusions presented herein. The contents do not necessarily reflect the official views or policies of the Texas Department of Transportation (TxDOT), or the Federal Highway Administration (FHWA). This report does not constitute a standard, specification, or regulation, nor is it intended for construction, bidding, or permit purposes. Trade names were used solely for information and not for product endorsement. The engineer in charge of the project was Tom Scullion, P.E. #62683.

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Dr. Jacob Uzan of Technion is recognized for assistance in establishing the resilient modulus test program. Dr. Fujie Zhou provided software to interpret the results of the resilient modulus test.

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CHAPTER 1
INTRODUCTION

New specifications proposed by Texas Department of Transportation (TxDOT) for base materials aim to improve the quality of base materials used for pavement construction. Numerous research efforts have been devoted to characterizing the behavior of granular materials, which is one of the main concerns of pavement engineers (*1*). The major structural function of a granular base layer is to contribute to the distribution of stresses applied to the pavement surface by traffic loading. These stresses must be reduced to levels that do not overstress the underlying base, subbase, and subgrade. Overstressing unbound granular material can produce unacceptable levels of resilient pavement deflections under moving wheel loads or can cause accumulation of excessive amounts of permanent deformation, ultimately affecting the pavement performance (*2*). Thus, researchers need better understanding of the behavior of base materials obtained by applying laboratory tests where insitu stress conditions and traffic loads are adequately simulated.

This report summarizes the project conducted as part of the research for upgrading the quality of base materials. Researchers evaluated material properties using different testing procedures. The resilient modulus and permanent deformation test procedure was modified based on recommendations in the National Cooperative Highway Research Program (NCHRP) 1-28A report. A repeatability analysis was carried out on the proposed test procedure. Further, laboratory evaluation was conducted on three base materials for different performance parameters such as moisture susceptibility, strength, resistance to permanent deformation, and resilient modulus. These materials are used in the test sections built at the Texas Transportation Institute (TTI) at College Station, Texas. The test sections were built as part of the final phase of this project, wherein field tests would be conducted to estimate their performance. Also, the performance of these test sections will be monitored over a period of time.

The documentation of this project is mainly divided into two parts. The first part focuses on the development of the resilient modulus and permanent deformation test procedure and the repeatability analysis of this test procedure. The second part focuses on the evaluation of various base materials and their performance. The description of the test procedures conducted is provided, followed by a discussion on the test results and analysis.

RESEARCH OBJECTIVES

It is critical to conduct a rigorous evaluation of the properties of base materials to facilitate TxDOT's efforts to improve the quality of base materials used in pavement construction. The following were the objectives of this project:

1. Evaluation of a modified test procedure to estimate the minimum number of samples necessary to test for a reliable level of accuracy for the resilient modulus and permanent deformation test:
   - Evaluate the variability of the test results determined from the test.
   - Estimate the number of test specimens required for a given tolerance level of the test results.
   - Evaluate the influence of sample size on test results. If possible TxDOT would prefer to use standard samples 6 inches in diameter by 8 inches tall, as opposed to the recommended 6- by 12-inch samples.

2. Laboratory evaluation of base materials used in Texas using the standard test procedures of the Texas manual of testing procedures (*6*). All strength tests were conducted at both optimum and moisture conditioned states.
   - Evaluate the moisture susceptibility of base materials.
   - Evaluate the compressive strength of material.
   - Evaluate the stiffness of the material under repeated loading.
   - Evaluate the resistance to permanent deformation under repeated loading.

CHAPTER 2

MODIFIED RESILIENT MODULUS AND PERMANENT DEFORMATION TEST PROCEDURE

There has been a significant amount of research in the determination of resilient properties of base materials (*1*). Several agencies have specified different test methods for resilient modulus testing, and some agencies have modified the current American Association of State Highway and Transportation Officials (AASHTO) test protocol to their need and convenience. Hence, there is a need to develop a unified test method that would also represent field conditions. NCHRP project 1-28A "Harmonized Test Methods for Laboratory Determination of Resilient Modulus for Flexible Pavement Design" was initiated to combine the best features of the resilient modulus testing procedures in current usage (*3*).

The literature suggests that the Strategic Highway Research Program (SHRP)-46 protocol is one of the methods that closely represents the field stress state conditions (*4, 5*); however, AASHTO deleted this SHRP-46 protocol for resilient modulus testing from the standard specification due to lack of use. The standard test protocol for the resilient modulus test, AASHTO T307, measures only the resilient modulus. The present study made use of an expanded test protocol including resilient modulus as well as permanent deformation testing. Henceforth, this test will be referred to as the performance test.

The present project made use of an expanded test protocol which included measurement of nonlinear resilient modulus parameters (k_1, k_2, k_3) and permanent deformation parameters (α, μ). The resilient modulus test result is a required input in the level I analysis or most sophisticated analysis of the newly proposed 2002 design guide to be released soon. Also, both resilient modulus and permanent deformation test results provide material property input to the VESYS5 computer model used to predict pavement performance.

This section consists of a description of the research methodology adopted for the repeatability analysis of the performance test procedure including the experimental setup and test matrix. The tests conducted are briefly described with a sample test result. Further, the salient features of this test procedure are discussed. A description of this procedure is provided in the following subsections including the test apparatus and the test specimen preparation.

EXPERIMENTAL DESIGN

Researchers conducted a within-laboratory study to evaluate the modified test procedure. For any test method it is necessary that the inherent variability in the test procedure be minimized. Specimens of Spicewood Springs crushed limestone base material were compacted to two different sizes: (1) 6 in. (152 mm) diameter by 12 in. (305 mm) height and (2) 6 in. (152 mm) diameter by 8 in. (203 mm) height to be used in the proposed performance test. The present study evaluated the variability between independent test results obtained within a single laboratory in the shortest practical period of time by a single operator with a specific test apparatus using test specimens (or test units) taken at random from a single quantity of homogeneous material obtained or prepared for the study. Further, the influence of reducing the specimen height from 12 in. (305 mm) to 8 in. (203 mm) was investigated.

It was necessary to conduct a preliminary assessment of the mechanical properties of the materials such as the gradation, dry density, and moisture content, which influence the compaction and specimen preparation characteristics for the proposed test procedure.

PRELIMINARY TESTING

Preliminary testing of the material was conducted and the mechanical properties were determined according to the Texas manual of testing procedures (*6*). After completion of the preliminary tests, the gradation and optimum moisture content results were used in the preparation and compaction of test specimens. The preliminary tests that were conducted are:

- particle size analysis,
- determination of liquid limit,
- determination of plastic limit,
- determination of plasticity index, and
- determination of moisture-density relationship.

The results of these tests are provided in Table 1.

The optimum moisture content determined using standard test procedure (*7*) was found to be 5.6 percent with a corresponding maximum dry density of 146.8 lb/ft^3 (2352.6 kg/m^3). This result is graphically shown in Figure 1.

Table 1. Preliminary Test Results.

Test	TxDOT Test Procedure	Property Measured
Particle Size Analysis	Tex-110-E	Gradation
Determination of Liquid Limit	Tex-104-E	Liquid Limit – 19
Determination of Plastic Limit	Tex-105-E	Plastic Limit – 16
Determination of Plasticity Index	Tex-106-E	Plasticity Index– 3
Laboratory Compaction Characteristics and Moisture-Density Relationship of Base Materials	Tex-113 E	Moisture-Density Relationship

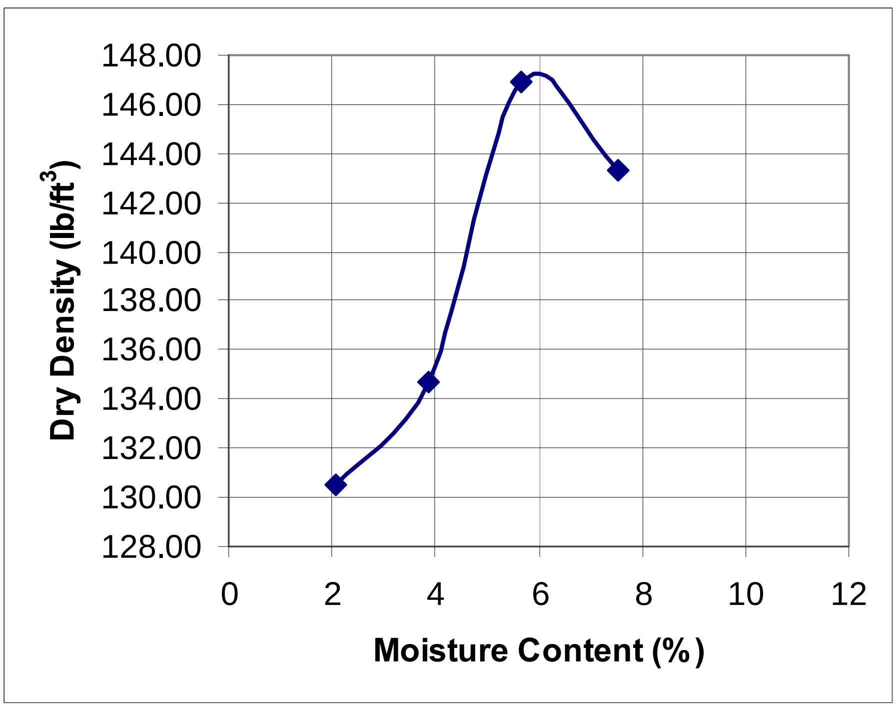


Figure 1. Moisture-Density Relationship for Spicewood Material.

Following determination of the dry weight of aggregate necessary for construction of a single cylindrical specimen, the aggregate was recombined into the required number of replicate samples, based on the master gradation.

CHAPTER 3
PERFORMANCE TEST SEQUENCE

After completion of the preliminary testing of the material, the proposed performance test was conducted. The proposed performance test sequence is described in detail in this section including the test apparatus, test specimen preparation, and the test sequence.

PROPOSED PERFORMANCE TEST

Previous research studies focused on the determination of resilient modulus; relatively little research has been conducted on determination of permanent deformation properties of granular materials. NCHRP 1-37A "Development of the 2002 Guide for the Design of New and Rehabilitated Pavement Structures" also requires the resilient modulus value as an input for level I design. It further recommends AASHTO T307 specification for the determination of resilient modulus value, which does not include determination of permanent deformation properties. The proposed performance test procedure integrates determination of permanent deformation properties along with determination of resilient modulus values of unbound granular materials.

The test sequence is adapted from the standard test methods given by the VESYS user manual, NCHRP 1-28A report, and AASHTO T307 and TP46 (*4, 8, 9, 10*). The data acquisition system is completely automated. The stress sequence follows the recommendations of the NCHRP 1-28A project, which is a more rational approach than the stress sequences followed by current standards (*4*, *9*) that maintain a constant stress ratio (ratio of maximum axial stress to confining pressure, σ_1/σ_3) by increasing both the principal stresses simultaneously. Since the selected sequence starts with the minimum stress ratio, the possibility of failing the sample early in the test is minimized. The method is illustrated in Figure 2, which indicates the sequence of the confining pressure and the deviatoric stress applied. Both the confining pressure and the deviatoric stress are varied such that increasing stress levels are applied on the specimen while keeping the stress ratio constant. This method prevents premature failure of the specimen, as the specimen is not subjected to high stress ratios in the earlier sequences. Also, this enables testing the specimen beyond the line of failure and studying the behavior of material as the stress levels increase beyond the line of failure.

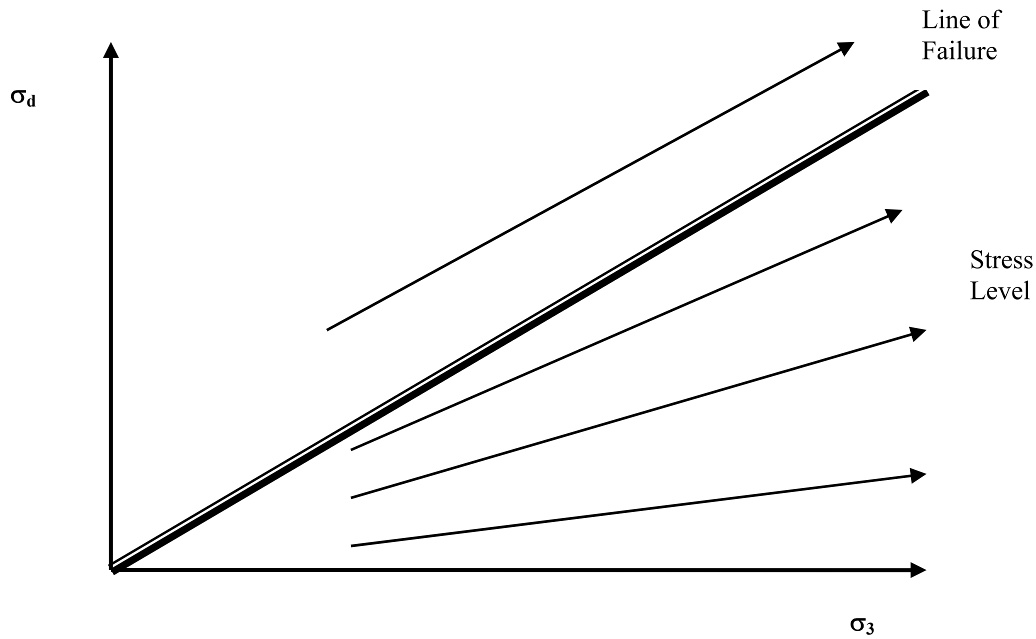


Figure 2. Stress Sequence Compared for Granular Materials.

TEST APPARATUS

The test apparatus consists of a triaxial chamber, loading device, response measuring equipment, and data acquisition system. The triaxial pressure chamber contains the test specimen and the confining fluid during the test as shown in Figure 3. Air is used in the triaxial chamber as the confining fluid for all testing. The axial deformation is measured internally, directly on the specimen using Linear Variable Differential Transducers (LVDT) as shown in Figure 4.

The loading device consists of a top-loading, closed-loop electro-hydraulic testing machine capable of applying repeated cycles of a haversine-shaped load pulse (0.1 sec loading and 0.9 sec unloading). The data acquisition system is completely automated. The test apparatus complies with the specifications of AASHTO T307 (9).

Figure 3. Test Setup for Resilient Modulus.

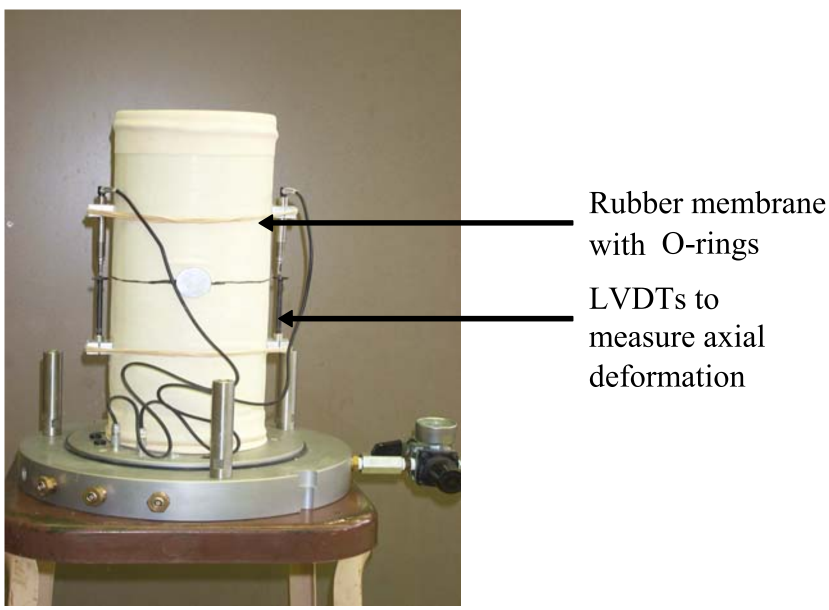


Figure 4. Specimen Prepared for Testing.

TEST SPECIMEN PREPARATION

Preparation of the specimens included:

- dry mechanical sieving into various size fractions,
- determining the optimum moisture content,
- maximum dry density,
- recombining the aggregate into replicate samples,
- and compaction.

The standard method of sample preparation was followed as given in AASHTO (9). The optimum moisture content and maximum dry density results are used for the compaction of the specimen for the performance test. The required amount of material is mixed with the optimum amount of water and compacted to the specified dimensions. In this study, the specimen dimensions used are 6 in. (152 mm) diameter by 12 in. (305 mm) height and 6 in. (152 mm) diameter by 8 in. (203 mm) height. The compaction and molding equipment are shown in Figure 5.

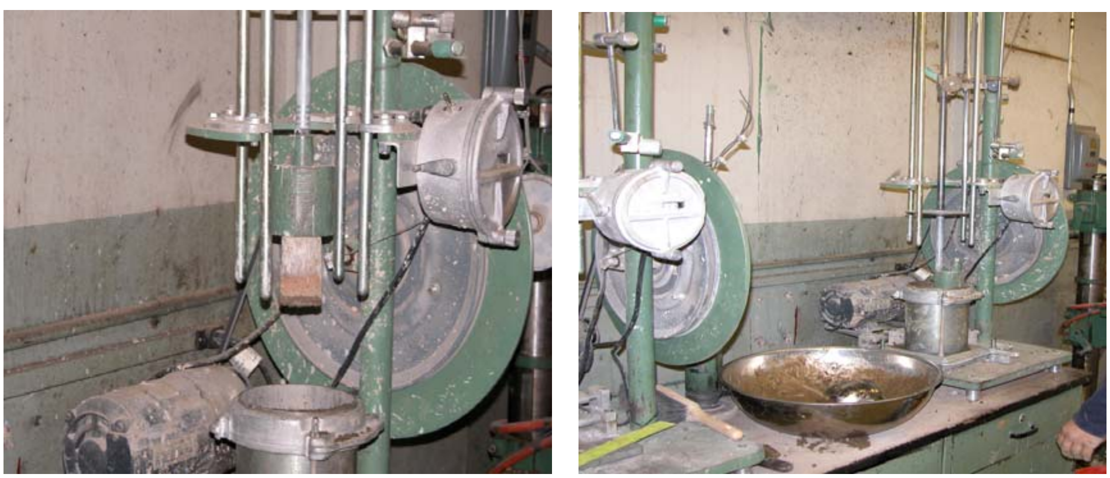


Figure 5. Molding and Compacting Equipment.

After compaction of the specimen, it was extruded from the compaction mold as shown in Figure 6.

Figure 6. Extrusion of Specimen from the Compaction Mold.

The specimen was placed on a porous stone/base after extrusion from the compaction mold. After placing the rubber membrane around the specimen, it was kept in the humidity chamber for approximately 16 hours or overnight, to allow for uniform distribution of the water within the specimen. After preparation of the test specimen, it was subjected to triaxial testing. The compacted specimen was prepared for testing by placing a rubber membrane around it. The membrane was sealed to the top and bottom platens with rubber "O" rings as shown in Figure 7.

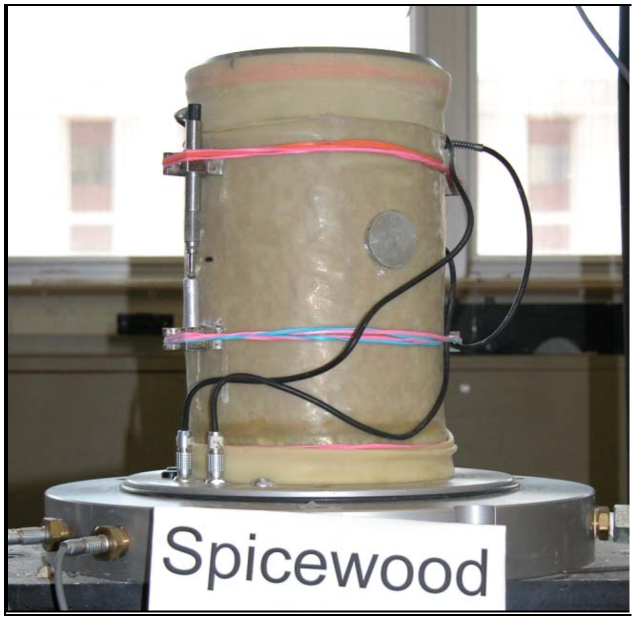


Figure 7. Test Specimen Prepared for Testing.

TEST SEQUENCE

After the preparation of the test specimen, the following testing sequence was used. The stress sequence follows the recommendations by NCHRP 1-28A for base/subbase materials, which maintains a constant stress ratio by increasing both the principal stresses simultaneously. The test sequence consisted of three stages:

- preliminary conditioning,
- permanent deformation test, and
- resilient modulus test.

Conditioning

The specimen was preconditioned before testing by applying 100 repetitions of a load equivalent to a maximum axial stress of 6 psi (41.4 kPa) and a corresponding cyclic stress of 3 psi (20.7 kPa) using a haversine-shaped 0.1 second load pulse followed by a 0.9 second rest period. A confining pressure of 15 psi (103.4 kPa) was applied to the test specimen. A schematic representation of the load and the placement of LVDT are shown in Figure 8. σ_d is the axial deviatoric stress, and σ_3 is the confining pressure. LVDTs 1 and 2 measure the axial displacement, and LVDTs 3 and 4 measure the radial displacement.

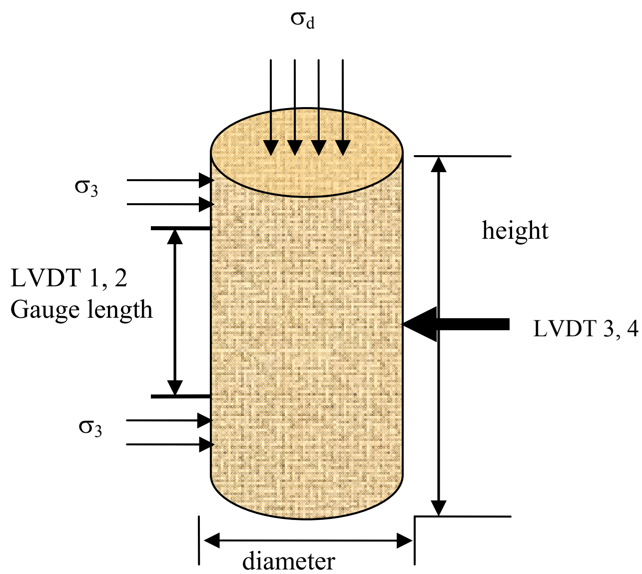


Figure 8. Representation of Load and Position of LVDTs on Specimen.

Permanent Deformation Test

A haversine load equivalent to a maximum axial stress of 33 psi (of 227.7 kPa) and a corresponding cyclic stress of 30 psi (207 kPa) with a 0.1 second load pulse followed by a 0.9 second rest period continues until 10,000 load applications or until the vertical permanent strain reaches 3 percent during the testing, whichever comes first. During load applications, the load applied and the axial deformation measured from two LVDTs through the data acquisition system were recorded. In order to save storage space during data acquisition, the data were recorded at specified intervals shown in Table 2.

Resilient Modulus Test

The same specimen was used to perform the resilient modulus test if the vertical permanent strain did not reach 3 percent. Otherwise, a new specimen was molded, and the permanent deformation test was performed with the load repetitions reduced to 5,000 from 10,000. If the sample again reached 3 percent total permanent strain, the test was terminated. If not, the resilient modulus test was performed by initially decreasing the axial stress to 2.1 psi (14.5 kPa) and setting the confining pressure to 3 psi (20.7 kPa). The test was performed by following the sequence of loading at regular intervals shown in Table 3, which was recommended in NCHRP project 1-28A *(4)*.

The test was stopped and the result reported when the total permanent strain of the sample exceeded 3 percent. After completion of the test, the confining pressure was reduced to zero and the specimen was removed from the triaxial chamber. The moisture content of the specimen was determined at the end of the test using AASHTO T265-93 *(7)*. The testing sequence is shown schematically in Figure 9.

Table 2. Suggested Data Collection for Permanent Deformation Test.

Data Collection during Cycles			
1-15	450	1300	4000
20	500	1400	4500
30	550	1500	5000
40	600	1600	5500
60	650	1700	6000
80	700	1800	6500
100	750	1900	7000
130	800	2000	7500
160	850	2200	8000
200	900	2400	8500
250	950	2600	9000
300	1000	2800	9500
350	1100	3000	10000
400	1200	3500	

Table 3. Permanent Deformation and Resilient Modulus Test Sequence for Granular Base.

Sequence	Confining Pressure		Contact Stress		Cyclic Stress		Maximum Stress		N_{rep}
	kPa	Psi	kPa	Psi	kPa	psi	kPa	Psi	
Preconditioning									
	103.5	15.0	20.7	3.0	20.7	3.0	41.4	6.0	100
Permanent Deformation									
	103.5	7.0	20.7	3.0	193.0	28.0	213.7	31.0	10000
Resilient Modulus									
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	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	20.0	151.8	22.0	100

Table 3. Permanent Deformation and Resilient Modulus Test Sequence for Granular Base (Continued).

Sequence	Confining Pressure		Contact Stress		Cyclic Stress		Maximum Stress		N_{rep}
	kPa	psi	kPa	psi	kPa	psi	kPa	Psi	
Resilient Modulus									
14	103.5	15.0	20.7	3.0	207	30.0	227.7	33.0	100
15	138.0	20.0	27.6	4.0	276	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	124.4	18.0	132.5	19.2	100
18	69.0	10.0	13.8	2.0	207	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	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

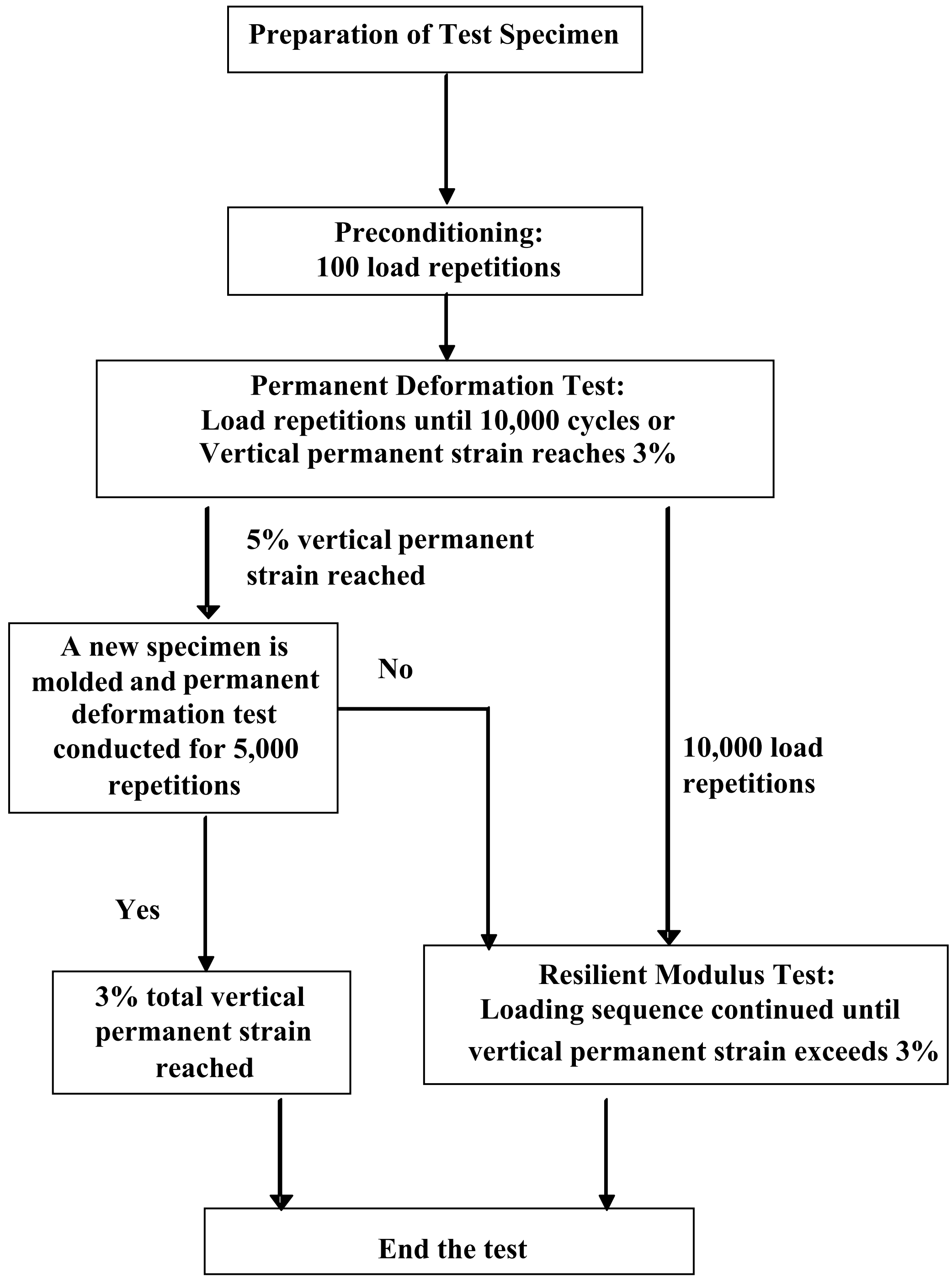


Figure 9. Flowchart of the Test Procedure for Permanent Deformation and Resilient Modulus.

CALCULATIONS

The following results are computed from the test:

Permanent deformation properties

- Average axial deformation is determined for each specimen by averaging the readings from the two axial LVDTs. The total axial strain is determined by dividing by the gauge length (L). Cumulative axial permanent strain and resilient strain at the 500th load repetition are calculated.
- A graph is plotted between the cumulative axial permanent strain and the number of loading cycles in log space (shown in Figure 10). The permanent deformation parameters, intercept (a) and slope (b), are determined from the linear portion of the permanent strain curve (log-log scale), which is also demonstrated in Figure 10.
    - Rutting parameters α and μ are determined using the following equations as shown below:

$$\alpha = 1 - b$$

$$\mu = \frac{a \times b}{\varepsilon_r}$$

Resilient Modulus parameter

- The resilient modulus values are computed from each of the last five cycles of each load sequence, which are then averaged.
- The data obtained from the applied procedure are fit to the following resilient modulus model using nonlinear regression techniques as shown in Figure 11.

The resilient modulus is calculated by the following equation, which is adapted from NCHRP 1-37A project *(21)*:

$$M_r = k_1 P_a \left(\frac{\theta}{P_a} \right)^{k_2} \left(\frac{\tau_{oct}}{P_a} + 1 \right)^{k_3}$$

where:

$k_1, k_2 \geq 0$,

$k_3 \leq 0$,

M_r = resilient modulus,

τ_{oct} = octahedral shear stress $= \frac{1}{3}\sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2 + (\sigma_2 - \sigma_3)^2}$,

θ = bulk stress = $\sigma_1 + \sigma_2 + \sigma_3$,

σ_1, σ_2, σ_3 = principal stresses,

k_i = regression constants, and

P_a = atmospheric pressure.

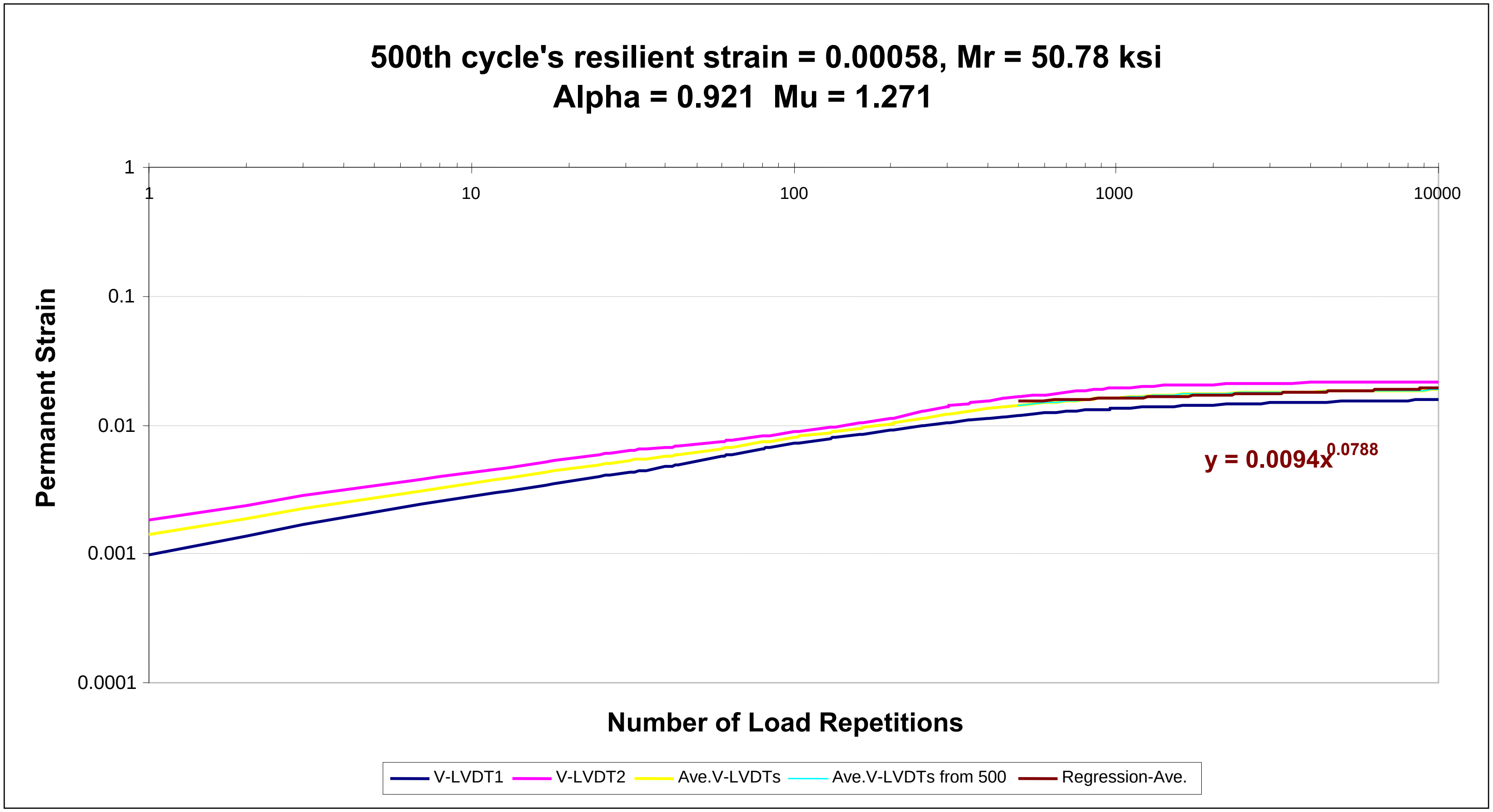


Figure 10. Sample Plot of Permanent Strain versus Number of Load Cycles.

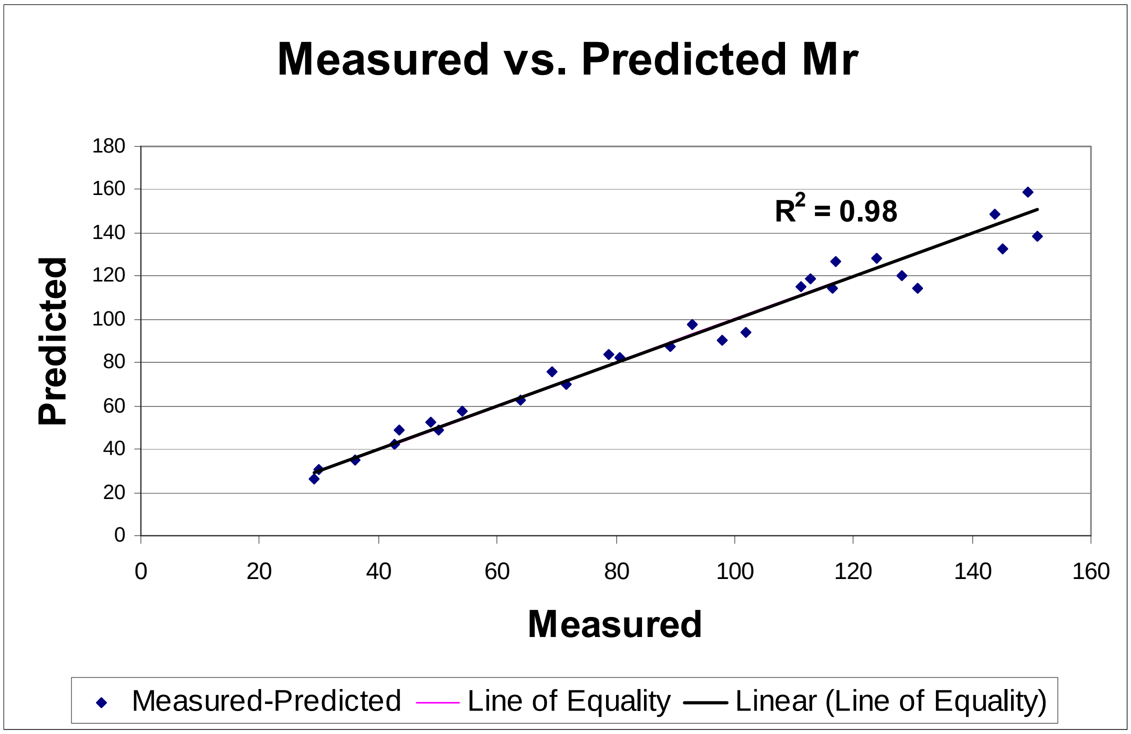


Figure 11. Sample Regression Plot of Measured versus Predicted Values.

The permanent deformation properties were determined at a confining pressure of 7 psi (49.2 kPa) and a deviatoric stress of 28 psi (193 kPa). The resilient modulus values were reported at 5 psi (34.4 kPa) confining pressure and 15 psi (103.4 kPa) deviatoric stress.

WITHIN-LAB REPEATABILITY MEASUREMENTS

Seven specimens were compacted for determination of resilient modulus and permanent deformation using the proposed performance test. Within-laboratory variability analysis was performed on the test results. Based on this analysis, the within-laboratory repeatability of the test method was estimated. It is noted that this is within a single laboratory, using a single operator with a single piece of equipment.

INFLUENCE OF SPECIMEN SIZE

The influence of preparing samples with a specimen height of 8 in. (203 mm) instead of the 12 in. (305 mm) height in the proposed performance test was investigated. For the 6 in. (152 mm) by 12 in. (305 mm) (diameter by height) specimens, the gauge length for measuring the axial strains is 6 in. (152 mm). The length to diameter ratio and the length to gauge length ratio used were in accordance with standard practices (*9, 10*). However, for the use of an 8 in. (203 mm) height specimen, the gauge length should also be changed. A gauge length ratio of 0.5 or lower is recommended by researchers (*11*). Hence, for the 8 in. (203 mm) high specimen, a gauge length of 4 in. (102 mm) was used. This enables placement of the LVDTs and measurement of the axial deformations at a distance considerably far from the end platens. Measuring axial deformation closer to the end platens will result in overestimation of the modulus value of the material. Conversely, measuring axial deformation closer to the center of the specimen will lead to accurate estimation of the stiffness parameters (*11*). Hence, the configuration of an 8 in. specimen with a gauge length of 4 in. (102 mm) is reasonable for the determination of modulus values. Figure 12 shows the specimen with height 8 in. (203 mm) after testing.

Figure 12. Specimen after Testing.

CHAPTER 4
TEST RESULTS

This chapter presents the permanent deformation and resilient modulus results. An analysis on the influence of stress ratios on the test results was conducted. The within-laboratory variability of the test results was evaluated. Also, the number of test specimens required for desired reliability of this test method was estimated. Further, the within-laboratory precision of the test method was established. Subsequently, the influence of specimen size on test results was investigated.

PERFORMANCE TEST RESULTS

In this section, the permanent deformation properties are presented followed by the resilient modulus parameters for a 6 in. (152 mm) diameter by 12 in. (305 mm) height (6 in. by 12 in.) specimen.

Permanent Deformation Properties

The individual plots for all the specimens tested are presented in Appendix C. Table 4 provides a summary of the test results of the permanent deformation parameters. Thompson stated that for reasonable stress states, the "b" term in equation for soils and granular materials is generally within the range of 0.12 to 0.2. The lower values are for soils. He also indicated that the "a" term was quite variable and is dependent on material type, repeated stress state, and factors influencing material shear strength (*12*).

Table 4. Permanent Deformation Test Results for Specimen Size 6 in. by 12 in.

Specimen	ε_r at 500th load cycle	M_r (ksi)	Rutting parameters	
			μ	α
1	0.000546	54.18	1.478	0.860
2	0.000485	59.73	0.799	0.925
3	0.000580	50.78	1.271	0.921
4	0.000619	48.71	1.280	0.912
5	0.000641	45.51	1.470	0.911
6	0.000687	43.33	0.844	0.933
7	0.000589	50.07	1.544	0.926

From Table 4, the μ values range from 0.79 to 1.5 and α values range from 0.86 to 0.93. Also, the resilient strain at the 500th repetition is used to compute the resilient modulus values at 7 psi (48 kPa) confining pressure and 28 psi (193 kPa) deviatoric stress.

Bonaquist and Witzack *(13)* indicated that the typical values of α and μ range between 0.85 to 0.95 and 0.1 to 0.4, respectively. The higher the value of α, the lower the slope of the curve and the lower the rate of accumulated strain. The values of μ are high compared to the values reported by Bonaquist and Witzack *(13)*. This is due to the high stress level at which the testing was conducted. These properties depend on the ratio of maximum axial stress to the confining pressure (σ_1/σ_3), termed the stress ratio. The higher the stress ratio, the higher the accumulation of permanent strain.

Figure 13 shows the relationship between the ratio of permanent strain to resilient strain ($\varepsilon_p/\varepsilon_r$) and the number of load cycles for all specimens. The results indicate a linear relationship. Thus, as the number of load cycles increased, the ratio $\varepsilon_p/\varepsilon_r$ increased.

RESILIENT MODULUS TEST RESULTS

The regression parameters k_1, k_2, and k_3 computed by this model for each of the specimens are presented in Table 5. These parameters are used to calculate the resilient modulus value at a specific confining pressure and deviatoric stress. Here, the resilient modulus value at 5 psi (34.5 kPa) confining pressure and 15 psi (103.4 kPa) deviatoric stress are computed for comparison. The individual regression plots for each of the seven specimens are provided in Appendix B.

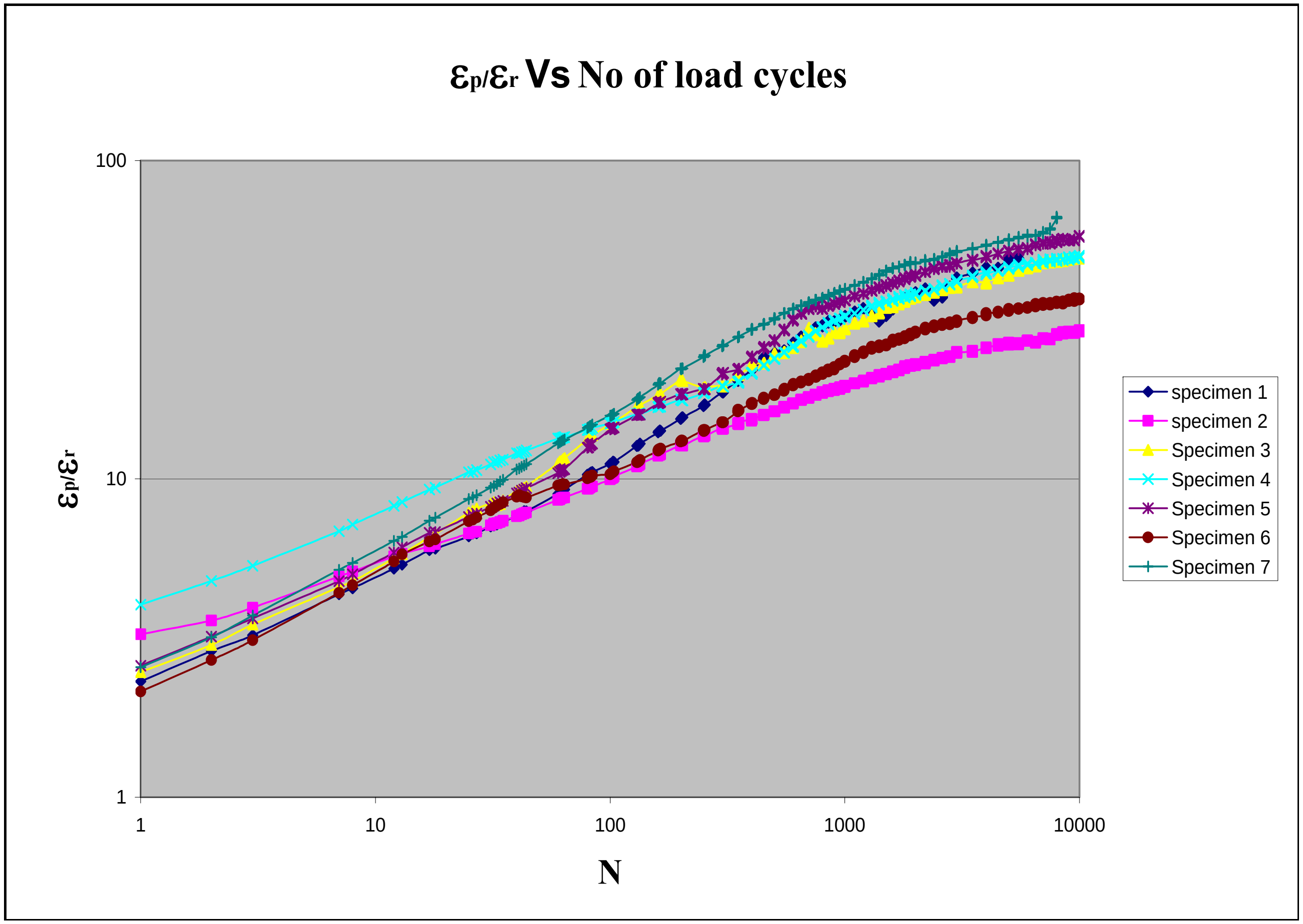


Figure 13. Plot of $\varepsilon_p/\varepsilon_r$ with Number of Load Cycles.

Table 5. Resilient Modulus Test Results for Specimen Size 6 in. by 12 in. at 5 psi Confining Pressure and 15 psi Deviatoric Stress.

Specimen	k_1	k_2	k_3	M_r (ksi)
1	1699.49	0.71	0.04	42.15
2	2424.13	1.13	-0.99	54.21
3	2591.25	1.02	-0.98	53.63
4	2406.69	0.81	-0.55	50.73
5	2321.15	1.05	-0.83	51.97
6	2002.96	0.74	-0.45	41.94
7	2057.65	1.25	-1.26	45.02

The results of Table 5 are used to estimate the repeatability of the test method, which will be discussed subsequently.

From Table 5, the average resilient modulus value was 48.5 ksi (334.4 MPa), which is typical of a good unbound granular base material. Figure 14 shows the resilient modulus values for each of the seven specimens tested. It indicates that there is not much variation among the results for resilient modulus values.

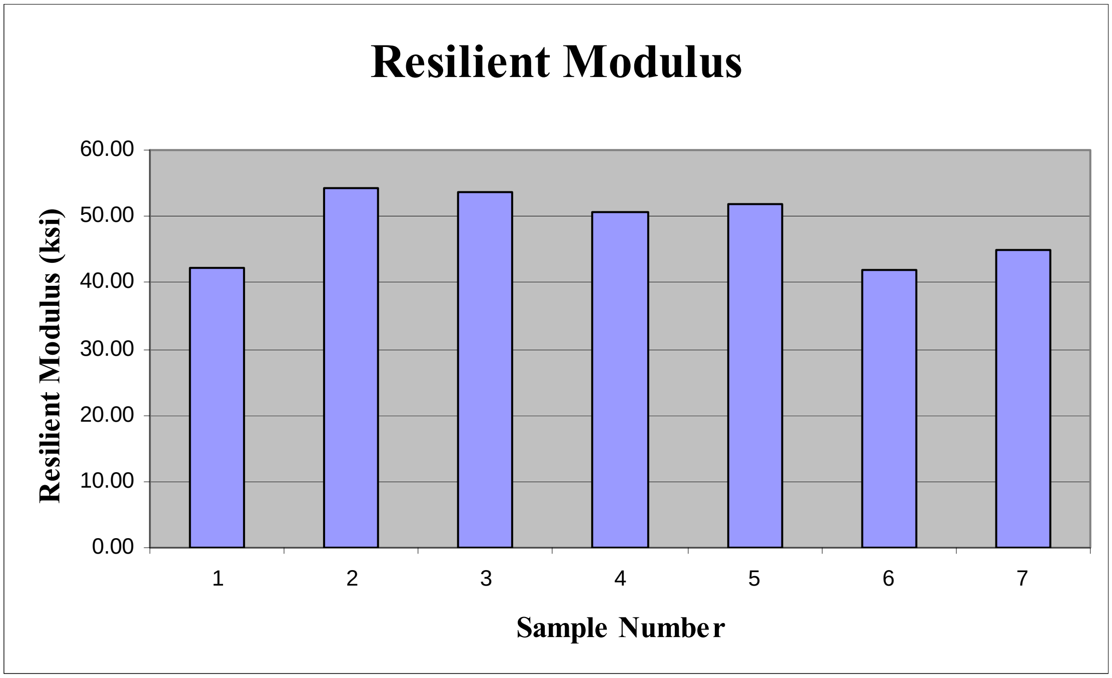


Figure 14. Resilient Modulus Values at 5 psi Confining Pressure and 15 psi Deviatoric Stress.

STATISTICAL ANALYSIS OF TEST RESULTS

Analysis of the test results obtained from the seven replicate specimens is presented in this section. As the present study was completed in a single laboratory, the precision statement is expressed in terms of the repeatability within the laboratory. Repeatability concerns the variability between independent test results obtained within a single laboratory, in the shortest practical period of time, by a single operator, with a specific set of test apparatus using test specimens (or test units) taken at random from a single quantity of homogeneous material obtained or prepared for the laboratory study (*14*). Seven replicate specimens were prepared and tested with the same equipment by the same operator. Repeatability is expressed in terms of the standard deviation of test results (*15*). These values for the test results are shown in Table 6. From these values the variability within the test results is estimated.

Table 6. Average and Standard Deviations of Test Results.

Specimen	Resilient Modulus (ksi)	Permanent Strain at 5000 cycles
1	42.15	0.01873
2	54.21	0.01800
3	53.63	0.01830
4	50.73	0.01910
5	51.97	0.02200
6	41.94	0.01790
7	45.02	0.02300
Average	48.52	0.01958
Std Dev	5.34	0.00206
coeff of var	11.02	10.52349

From standard practice American Society for Testing and Materials (ASTM) E 691, the repeatability limit for the result is 2.8 times the standard deviation for a confidence level of 95 percent in test results. Thus, the repeatability limits for the results for resilient modulus and permanent deformation are as shown below in Table 7.

Table 7. Repeatability Limits for Resilient Modulus and Permanent Strain.

Test property	Average	Standard deviation (std dev)	95% repeatability limit= 2.8* std dev
Resilient Modulus	48.52 ksi	5.345	15 ksi
Permanent Strain	0.01958	0.00206	0.0057

Sample Size Calculations

Statistical methods estimated the number of specimens required for a desired tolerance level in the test results. The number of observations included in the sample is a compromise between the desired accuracy of the sample statistic as an estimate of the population parameter and the required time and cost to achieve this degree of accuracy.

The sample size is determined by the following equation (*16*):

$$n = \frac{(z_{\alpha/2})^2 \sigma^2}{E^2}$$

where

n = sample size,

$Z_{\alpha/2}$ = Z value used for a desired confidence level,

σ = standard deviation, and

E = half of the width of the confidence interval.

At a confidence level of 95 percent, the Z value is 1.96 from a statistical table of standard normal curve areas (*16*). The standard deviation values are obtained from Table 7. The sample size calculations are made for different tolerable errors from the mean of the resilient modulus values and the permanent deformation. Graphs plotted between the sample size and the percent errors of the results are presented in Figure 15 and Figure 16.

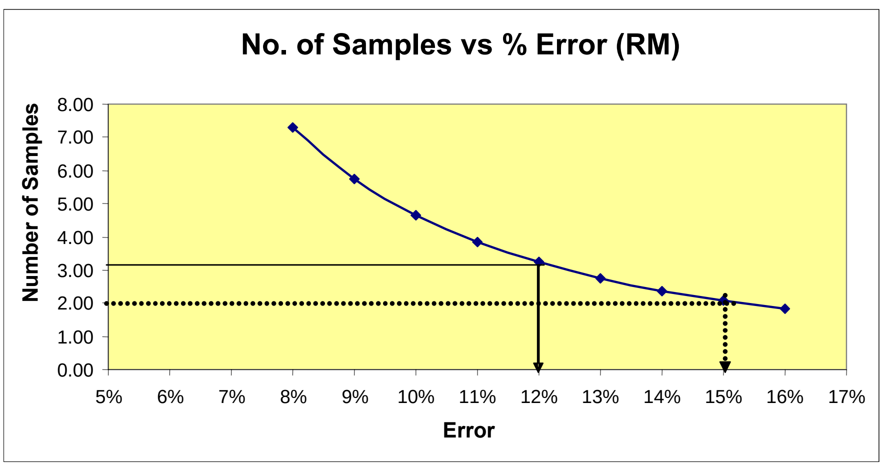


Figure 15. Plot of Number of Samples versus Percent Error of Resilient Modulus Value.

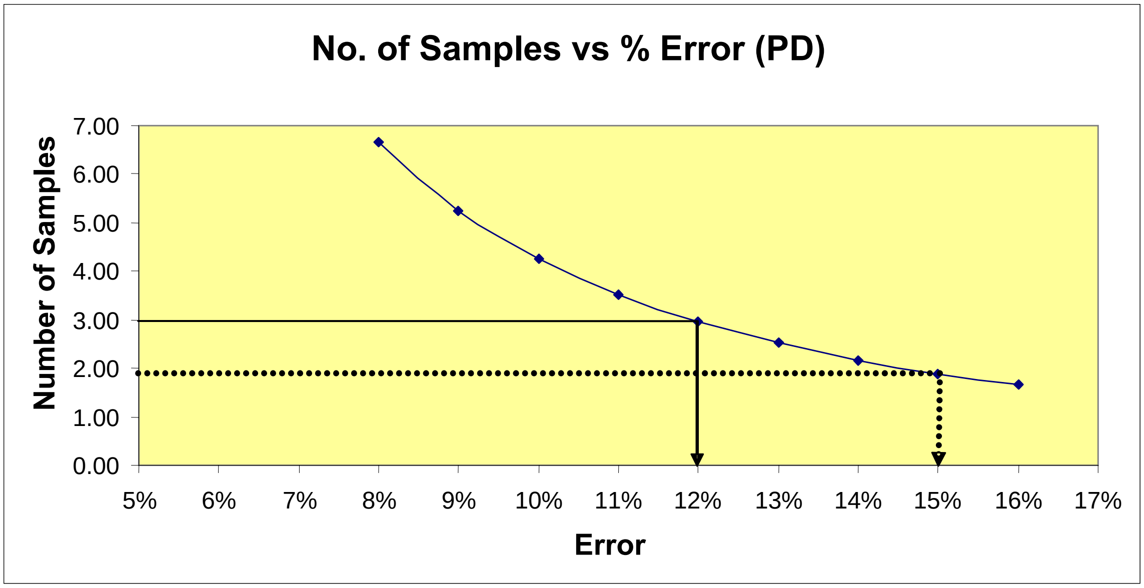


Figure 16. Plot of Number of Samples versus Percent Error of Permanent Deformation Values.

Figure 15 and Figure 16 indicate that the determination of the resilient modulus and permanent deformation properties using the proposed performance test requires a sample size of three for a tolerance level of 12 percent.

INFLUENCE OF SPECIMEN SIZE ON TEST RESULTS

Three specimens were tested with a specimen size of 6 in. (152 mm) diameter by 8 in. (203 mm) height. The results of permanent deformation properties and resilient modulus values are shown in Table 8, Table 9, and Figure 17.

Table 8. Permanent Deformation Test Results for 6 in. by 8 in. Specimens.

Specimen	ε_r	M_r	Rutting parameters	
			μ	α
1	0.000525	55.2381	0.5750	0.8560
2	0.000527	55.0285	1.2459	0.9294
3	0.000535	54.2056	0.8401	0.6337

Table 9. Resilient Modulus Test Results for 6 in. by 8 in. Specimens.

Specimen	k_1	k_2	k_3	M_r (ksi)
1	2740.55	0.97	-0.67	61.59
2	1880.56	0.98	-0.38	47.86
3	2377.63	0.82	-0.42	53.38

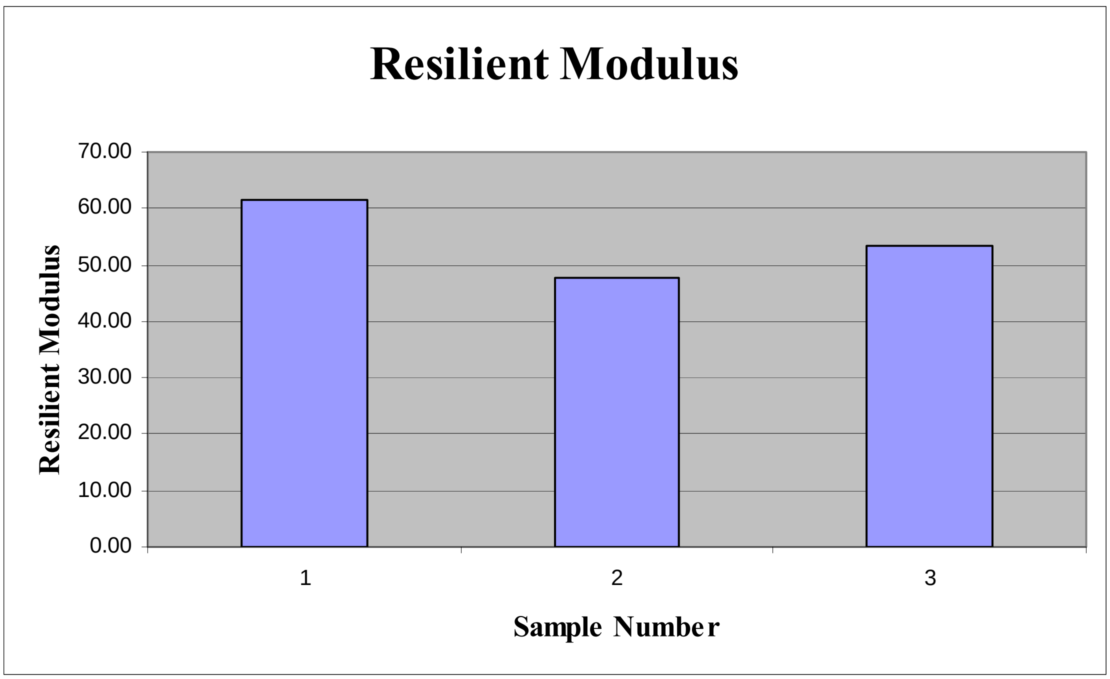


Figure 17. Resilient Modulus Values for 6 in. by 8 in. Specimens.

The maximum aggregate size is 1-2 in. (25 – 50 mm), requiring a large specimen size of at least 6 in. (152 mm) to maintain a 1:6 ratio of maximum aggregate size to diameter of specimen as recommended by NCHRP 1-37A. Further, a diameter to height ratio of 1:2 is recommended by literature to reduce the end effects on the deformation measurements made on the full length of the sample (9).

Statistical analysis of the test results determined the influence of specimen size on the measured resilient modulus. The student's t-test was used to statistically evaluate the impact of different specimen sizes.

Sample sizes and standard deviations for the two populations for the calculation of the pooled standard deviation based on resilient modulus and permanent deformation values are shown in Table 10 and Table 11. Using the average and standard deviation values of the samples from Table 8, the t-statistic is calculated.

Table 10. Calculation of Pooled Standard Deviation for Resilient Modulus Values.

population one, height 12 in.		**population two, height 8 in.**	
n_1	7	n_2	3
y_1	48.52	y_2	54.28
s_1	5.345	s_2	6.9
s_1^2	28.56903	s_2^2	47.61
S p	5.773150678		
df	8		
t\`	1.445836679		

Table 11. Calculation of Pooled Standard Deviation for Permanent Deformation Values at 5000 Load Cycles.

population one, height 12 in.		**population two, height 8 in.**	
n_1	7	n_2	3
y_1	0.000592	y_2	0.0048
s_1	0.000066	s_2	8.27E-05
s_1^2	4.356E-09	s_2^2	6.84E-09
S_P	0.008377052		
df	8		
t\`	0.727937626		

For α = 5 percent and df = 8, the $t_{\alpha/2}$ determined from table of critical values for the student's t-distribution is 2.3.

Since $|t| \le t_{\alpha/2}$, for both the permanent deformation and resilient modulus values the null hypothesis cannot be rejected. Thus, there is no difference in the test results when the specimen size is reduced to 8 in. (203 mm) from 12 in. (305 mm) for the resilient modulus value.

CHAPTER 5
EVALUATION OF GRANULAR BASE MATERIALS

Three samples of premium base coarse aggregates; Granite Mountain (granite), Springdale Arkansas (limestone), and Sawyer Pit Oklahoma (sandstone) were tested in the laboratory to evaluate their engineering properties. These materials were also incorporated into test sections built at the Riverside campus of Texas A&M University. Figures 18-21 show the test sections built using the various base materials.

Figure 18. Test Sections Built at Texas A&M University Riverside Campus.

Figure 19. Test Section Built with Granite Mountain as Base Material.

Figure 20. Test Section Built with Springdale Material.

Figure 21. Test Sections Built with Sawyer Pit Material.

The significant engineering properties that affect the performance of the flexible pavements are moisture susceptibility, strength, resilient modulus, and permanent deformation. This section provides a brief description of the historic work of the test methods used to determine these properties.

TUBE SUCTION TEST

The Tube Suction Test (TST) was developed in a cooperative effort between the Finnish National Road Administration and the Texas Transportation Institute to assess the moisture susceptibility of granular base materials (*17*). Moisture ingress degrades the engineering properties of aggregate base layers, reducing the performance of the pavement. Research studies demonstrated that moisture susceptibility is related to both the matric and osmotic suction properties of aggregates. Matric suction is mainly responsible for the capillary phenomenon in aggregate layers, and osmotic suction is the suction potential resulting from salts present in the aggregate matrix.

Important factors for determining moisture susceptibility include soil suction, permeability, and the state of bonding of water that accumulates within the aggregate matrix. Soil suction is a measure of the affinity of a material for water, and permeability controls the rate of moisture migration within the aggregate layer. The state of bonding of water describes the structuring of the water molecules within the aggregate matrix. Water is classified as both bonded and un-bonded moisture. The bound (adsorbed) water molecules are arranged in layers around aggregate particles, where the electrical attraction between water molecules is relatively strong. This moisture is very difficult to displace and generally does not have a large impact on base performance. The unbound (viscous or capillary) water is beyond the zone of electrical capture. This moisture is loosely bound to the aggregates but it can migrate within the base under the influence of environmental factors (freeze-thaw cycles) or heavy loads. It is the amount of unbound water in a base that influences the engineering properties in the field, including load-carrying capability and resistance to freeze-thaw cycles. The quantity and distribution of unbound water thus plays a very important role in the moisture damage mechanism. The amount of unbound water that exists within an aggregate base material is directly related to the dielectric value of the base as measured in the TST (*18, 19*).

TEXAS TRIAXIAL TEST

In this project the Texas triaxial test was conducted as part of the TST. This is one of the advantages of the TST, wherein the Texas triaxial test is merged within the TST, enabling the determination of moisture susceptibility and strength on the same specimen (*20*). The TST is currently run using Tex Method 144 E where the sample is enclosed in a latex membrane. After moisture conditioning the unconfined compressive strength is measured on the moisture conditioned sample. Thus, estimation of strength in soaked condition gives an estimate of the property of the granular material under the worst circumstances.

PERMANENT DEFORMATION AND RESILIENT MODULUS TEST

The resilient properties of the base materials are determined using the repeated load triaxial test. Repeated loading properties like resilient modulus and permanent deformation accumulation are major factors that influence the structural response and performance of conventional flexible pavements. These parameters are typically determined in a resilient modulus test, which determines the permanent deformation property and the resilient modulus. It is performed by placing a specimen in a triaxial cell and applying repeated axial load. After subjecting the specimen to confining pressure, measurements are taken of the recoverable axial deformation and the applied load. Both resilient (recoverable) and permanent axial deformation responses of the specimen are recorded and used to calculate the resilient modulus and the permanent deformation, respectively. Permanent deformation is the unrecovered deformation during the testing, and resilient modulus is the ratio of the peak axial repeated deviator stress to the peak recoverable axial strain of the specimen.

The test procedure followed for the present project is adapted from the standard test methods given by the VESYS user manual, NCHRP 1-28A report, and AASHTO T307, TP46 (4, *8, 9, 10*).

Laboratory tests were conducted on these materials to determine the engineering properties. The gradation and moisture content test results for these samples are provided in Appendix C. The engineering properties of these materials are shown in Table 12. Detailed test results for the tube suction test are provided in Appendix F.

Table 12. Results of Engineering Properties of Granite Mountain, Springdale, and Sawyer Pit Samples.

Test		Granite Mountain	Springdale	Sawyer Pit
Tex-110-E	Percent of Fines	7.2 %	8.0 %	10.67 %
Tex-105-E	Liquid Limit	20	19	24
Tex-106-E	Plasticity Index	Non-Plastic (NP)	4	6
Tex-113-E	Optimum Moisture Content	6.0 %	5.5 %	5.5 %
	Max Dry Density	137.4 lb/ft^3	147 lb/ft^3	138 lb/ft^3
Tex-116-E	Wet Ball Mill Value	19.7	20	36.5
Tex-116-E	% Increase in fines (- 40)	5	8	10
Tex-117-E	Strength @ 0 psi	36 psi	65 psi	44 psi
	Strength @ 15 psi	218 psi	213.2 psi	209 psi
Tex-144-E	Dielectric value	5.5	9.8	10.5

The three materials, Granite Mountain, Springdale, and Sawyer Pit, have the fines content close to the proposed Item 245 specifications (<10 percent, the sandstone was slightly higher than the limit). With the exception of the strength requirement at 0 psi, confining the engineering properties of all three bases are well above the traditional Item 247 requirement. In particular, the percent increase in wet ball mill were all less than or equal to 10, well below the allowable Item 247 value of 20. The strengths at 15 psi confining were all well above the 175 psi required in Item 247. The origin of these materials influences their quality and engineering properties. The Plasticity Index (PI's) of the materials are also very low; well below the 10 limit of Grade 1 base in Item 247. It is the combination of the low fines and low plasticity that directly impacts these materials strength at zero confining. Unlike typical Texas bases that contain substantial fines, these materials have low strength in an unconfined state; however, these bases will never be unconfined in the highway so the significance of that test on long-term performance is questionable.

The Tube Suction test was conducted on two specimens of each material. The details are presented in detail in the Appendix F; the summary of the results is presented in Table 13.

Table 13. Summary of TST Results.

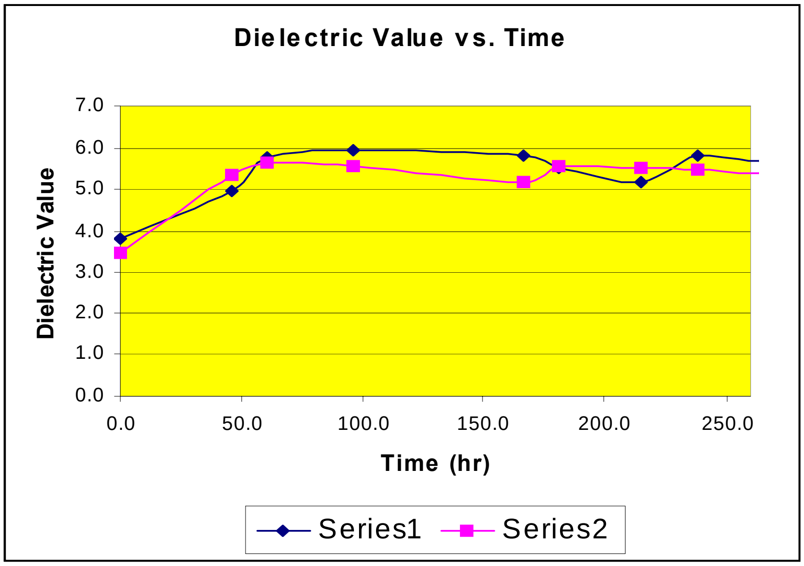
Sample	Asymptotic Dielectric Value, ϵ	Gravimetric Water Content, W (%) after TST	% Water Loss in Drying	Actual Density (dry) (lb/ft^3)	Actual Compaction Moisture (%)	Target Dry Density, lb/ft^3	Target Compaction Moisture (%)
Granite Mountain	5.5	6.0	54	135.5	6.0	137.4	6.0
Springdale	9.8	5.1	41.5	141.5	5.3	147.0	5.5
Sawyer Pit	10.5	5.2	52.1	137.1	5.6	138	5.5

The asymptotic dielectric value is the final value attained at the end of the 10-day capillary rise. This value is used to assess the material's resistance to moisture ingress via capillary rise. Based on the results shown in Table 13, the aggregates were ranked as shown in Table 14.

Table 14. Resistance to Moisture Ingress as Measured by the TST.

Rank	Sample	Final Dielectric Value	Rank
1	Granite Mountain	5.5	Excellent
2	Springdale	9.8	Excellent
3	Sawyer Pit	10.5	Good

Table 14 shows that both Granite Mountain and Springdale classify as excellent materials in terms of resistance to moisture ingress. The results of TST are shown graphically in Figure 22, Figure 23, and Figure 24.



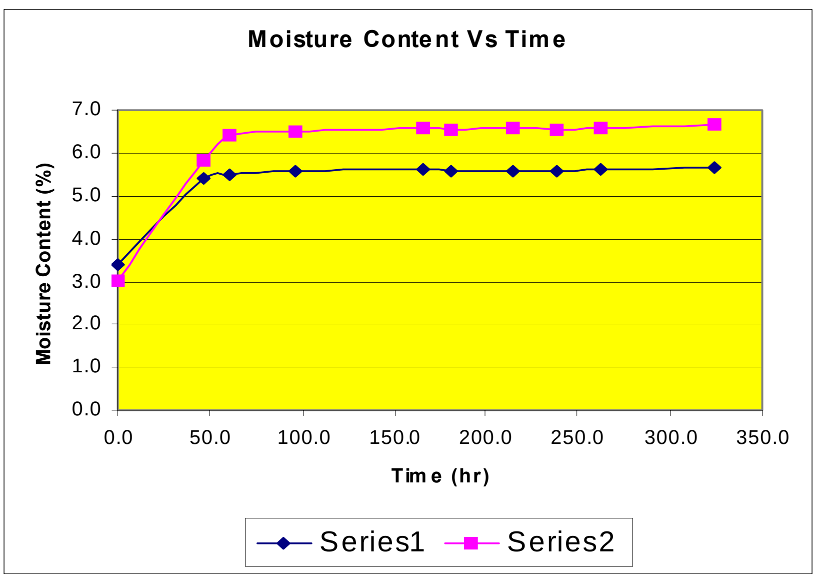


Figure 22. Tube Suction Test Results for Granite Mountain.

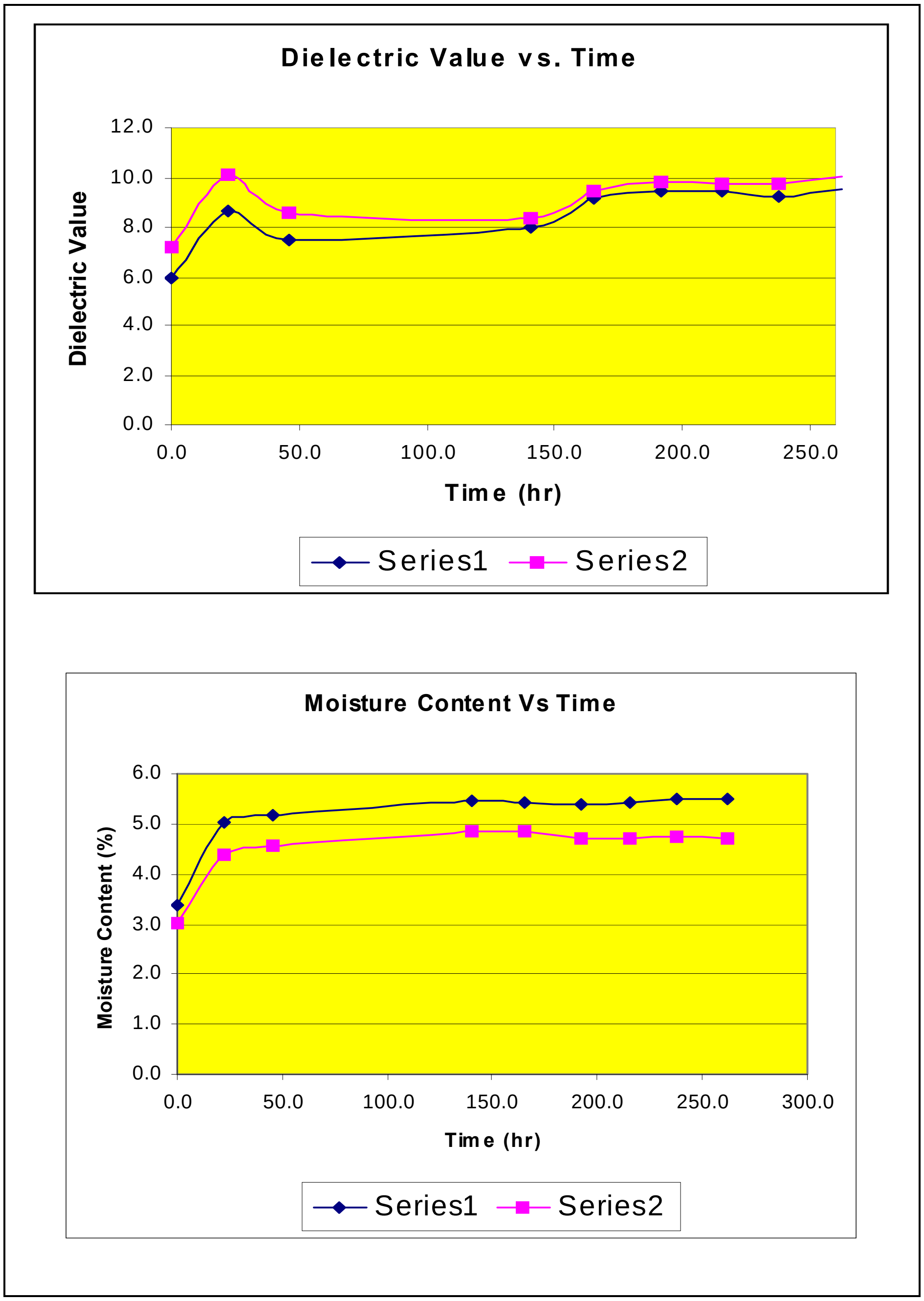


Figure 23. Tube Suction Test Results for Springdale.

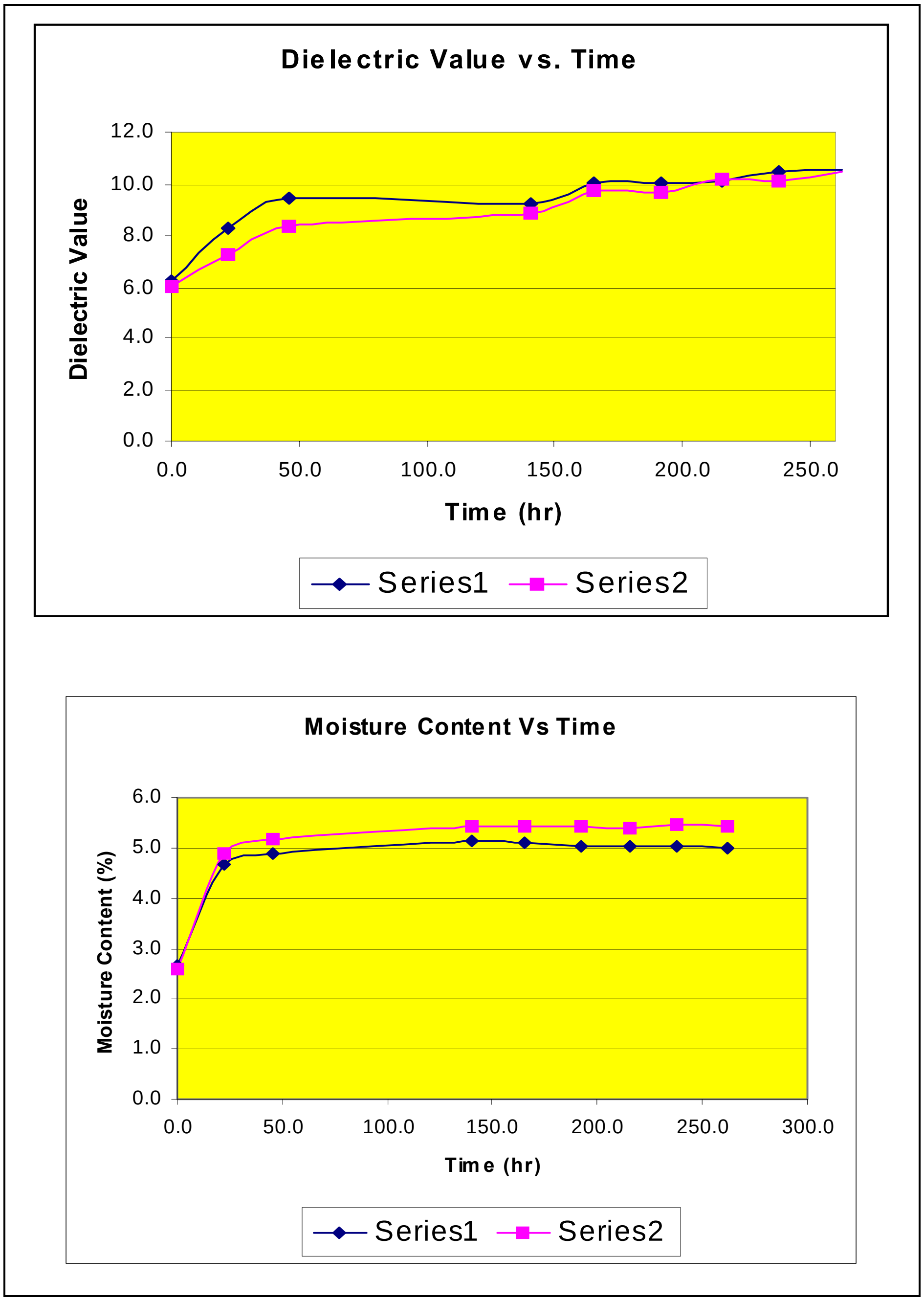


Figure 24. Tube Suction Test Results for Sawyer Pit.

Two test specimens were prepared for the performance test for each sample of material at the moisture content shown in Table 15. The results of the resilient modulus and permanent deformation test are presented in Table 15. Detailed results are provided in Appendix G. Rutting parameters μ and α are also shown.

Table 15. Results of Resilient Modulus and Permanent Deformation Test.

Specimen	Water content (%)	Resilient Modulus (ksi)	ε_r	Rutting parameters μ	Rutting parameters α
Granite Mountain	5.0	36.66	Failed		
Springdale	4.5	58.18	0.000407	0.920	2.131
Sawyer Pit	4.5	31.1	Failed		

The resilient modulus values for Granite Mountain, Springdale, and Sawyer Pit were 36.66 ksi, 58.18 ksi, and 31.1 ksi, respectively, typical for a granular base materials. Springdale was better in terms of resilient modulus value than Granite Mountain and Sawyer Pit. The Granite Mountain and Sawyer Pit materials failed in less than 500 cycles during the permanent deformation test procedure. Failure being defined as exceeding 3 percent strain.

The performance of the materials in the permanent deformation test was particularly surprising. The same test has been performed on traditional Texas high fines bases and no dramatic failures occurred. The authors believe that these results from these tests do not represent true engineering properties of these materials. There are several contributing factors, but one of the prime problems appears to be with the method used to compact the samples in the laboratory. Researchers were concerned that the drop hammer procedures used with traditional TxDOT bases may not be ideal for these very granular materials. These aggregates are angular and appear to require vibration of kneading to obtain adequate compaction without aggregate breakage. Substantial breakage of aggregates occurred, primarily with the Sawyer Pit sandstone aggregates. A higher compactive effort (no blows) with the drop hammer did not appear.

These problems led the research team to evaluate how these low-fines granular bases are compacted in other Departments of Transportation (DOTs) and research agencies around the world. Contacts were made with the Minnesota DOT and with researchers in Finland and Israel. The main conclusion from these surveys was that the drop hammer is not ideal for these materials and that the compaction procedure should include some form of vibration similar to the vibratory rollers used to compact these bases in the field. Consequently, in Year 3 of this project TTI designed and built the new vibratory compactor shown in Figure 25, largely based on recommendations from Dr. Jacob Uzan in Technion in Israel.

Figure 25. TTI's New Base Vibratory Compactor.

In the final year of project 0-4358 the research team proposes to use this compactor to study its efficiency at compacting heavy-duty bases. Comparative studies on parameters such as aggregate breakage, sample uniformity, and particle orientation will be undertaken.

CHAPTER 6
SUMMARY

Repeatability analysis of the modified resilient modulus and permanent deformation test procedure was conducted on the 6 in. (152 mm) diameter by 12 in. (305 mm) height specimen. Further, the influence of stress ratios on these properties was discussed. Statistical procedures estimated the number of test specimens necessary for a desired level of tolerance. After estimation of sample size, it was found that for a tolerance level of 12 percent three replicate specimens must be tested. Three specimens of 6 in. (152 mm) diameter by 8 in. (203 mm) height were prepared for conducting the performance test. The Student's t-test was used to investigate the influence of the specimen size on the test results. There was no statistically significant difference for a confidence level of 95 percent between the test results for both resilient modulus and permanent deformation properties.

Three materials, Granite Mountain, Springdale, and Sawyer Pit, were evaluated using laboratory test procedures for their performance parameters. Granite Mountain performed best in the Tube Suction Test (TST), and all three materials were classified as either excellent or good materials in terms of the TST results. In the laboratory all of the materials had properties well in excess of those required for standard Item 247 bases, except in the unconfined strength test conducted as part of Tex Method 117-E.

All three materials were incorporated into experimental sections being constructed at TTI's Riverside campus. The performance of these sections will be discussed in the final year of Project 0-4358.

Problems were encountered with running resilient modulus and in particular permanent deformation tests on samples of these materials molded with the Tex Method 113-E drop hammer. In general, molding these low fines bases with this procedure is problematic. In several instances the samples collapsed when extruded from the compaction mold. The resilient modulus and permanent deformation values obtained were not thought to be related to the true engineering properties (or reported field performance) of these materials. Instead it was assumed that these values are more related to compaction problems with drop hammer compaction of bases with low fines contents. These results led us to review the methods used to compact samples. As a result, a new vibratory compaction system has been built. It is proposed that this system be studied further in the final year of this project. Also it is recommended that this new compaction procedure be incorporated into the work plan of Project 0-5136 "Improving Correlation between Field Construction of Soils and Bases and Laboratory Prepared Samples."

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APPENDIX A:

TEST PROTOCOLS

TUBE SUCTION TEST

This test method evaluates the moisture susceptibility of granular base materials used in pavements.

Significance and Use

The selection of base materials with adequate resistance to damage under traffic and environmental loading is important in maximizing the life of a pavement. Moisture ingress is a primary catalyst for pavement damage, and moisture susceptibility, or the degree to which moisture ingress degrades the engineering properties of aggregates, plays a key role in the performance of these materials in the field.

Research studies demonstrate that moisture susceptibility is related to the matric and osmotic suction properties of aggregates. Matric suction is mainly responsible for the capillary phenomenon in aggregate layers, and osmotic suction is the suction potential resulting from salts present in the pore water of an aggregate matrix.

The tube suction test (TST) rates the resistance of aggregates to moisture damage as very good, good, marginal, and poor. This moisture susceptibility ranking is based on the final surface dielectric values of compacted specimens after a 10-day capillary soak in the laboratory. The Adek Percometer™, a 50 MHz dielectric probe, is employed in the test to measure the dielectric values of specimens.

The dielectric value of a three-phase system comprising aggregate particles, air, and water depends on the volumetric percentages and dielectric values of each constituent. The dielectric value of dry aggregate particles generally varies from 4 to 6, and the dielectric value of air is 1. The dielectric value of water depends on its state of bonding in the aggregate matrix. Tightly bound, or adsorbed, water has a dielectric value of about 3 or 4, but the dielectric value of unbound water is substantially higher at 81. Unbound water can migrate within the pavement structure to balance changes in suction caused by chemical contamination, changes in the pore structure, or fluctuations in the water content.

For materials with high suction potential and sufficient permeability, substantial amounts of unbound water rise within the aggregate matrix during soaking and lead to higher dielectric values in the test. Conversely, non-moisture-susceptible materials maintain a strong moisture gradient throughout the test, with little moisture reaching the surface, and have lower dielectric values at the end of testing. Beneficiation techniques such as stabilization, blending, or reducing the fines content should be considered for effectively reducing the moisture susceptibility of poor-performing aggregates.

Apparatus

- Apparatus outlined in test method Tex-101-E, part II
- Apparatus outlined in test method Tex-103-E, part I
- Apparatus outlined in test method Tex-113-E
- Triaxial cells, lightweight stainless steel cylinders
- Cylindrical plastic molds with inside diameter of 6 in. (152.4 mm) and minimum height of 50.8 mm (2 in.)
- Power drill with 1.5 mm (1/16 in.) drill bit
- Drying oven maintained at 60 $\pm$ 5 ^{o}C (140 $\pm$ 9 ^{o}F)
- Flat-bottomed plastic pan, wide and shallow, for soaking specimens
- Adek Percometer^{TM}
- Ice chest for enclosing cylindrical specimens

Materials

- Distilled water

Sample Preparation

- Prepare the sample as in Test Method-101-E, part II

Test Record Forms

- Record sample preparation and testing data on the Tube Suction Test Data Collection Form.
- After tests are completed, summarize results on the Tube Suction Test Data Analysis Report.

Procedure

- Use test method Tex-113-E for determining the optimum moisture content (OMC) and maximum dry density (MDD) of the material for molding the test specimens.
- Obtain cylindrical plastic molds. At approximately 1/4 in. (6 mm) above the outside bottom of each mold, drill 1/16 in. (1.5 mm) diameter holes around the circumference of the mold at a horizontal spacing of 1/2 in. (12.5 mm). This equates to 38 or 39 holes around the mold base. Also drill one 1/16 in. (1.5 mm) diameter hole in each quadrant of the bottom of the mold about 2 in. (50 mm) from the center. Trim the cylinder as necessary to a height of 2 in. (50 mm) to create a reusable plastic base cap. Make two vertical cuts in each base cap, equally spaced around the circumference, to enable easier installation and removal. Place a 6 in. (152.4 mm) diameter circle of filter paper or paper towel in the bottom of each cap. Weigh the caps to the nearest 0.0022 lb (1 g) and record as W_{CAP}.
- Obtain a representative sample of prepared material in sufficient quantity to prepare three specimens. Bring the material to optimum moisture using distilled water. (Ions in regular tap water can influence the results of the test by increasing the osmotic suction component of the aggregate.)
- Compact three specimens at optimum moisture and maximum dry density according to test method Tex-113-E. The specimens should be 6 in. (152.4 mm) in diameter and 8 $\pm$ 0.25 in. (203.2 $\pm$ 6.4 mm) in height and should be wetted, mixed, molded, and finished as nearly identical as possible. The surface of each specimen should be made as smooth as possible after compaction. Remove or reposition any coarse aggregate protruding from the specimen surface and fill any large voids as necessary. (Application of fines across the whole specimen surface should be avoided, however.)
- After removal of specimens from the compaction sleeve, install a base cap on the bottom of each specimen. Weigh three clean, dry triaxial cells to the nearest 1 g (0.0022 lb), and record as W_{CELL}. Slide the triaxial cell down over the specimen so that only lower 1 in. (25 mm) of the base cap remains exposed. Weigh the specimen with the base cap and triaxial cell to the nearest 0.0022 lb (1 g) and record as W_{OMC}.
- Place the specimens in an oven maintained at 140 $\pm$ 9 ^oF (60 $\pm$ 5 ^oC) for 48 $\pm$ 4 hours.
- Remove the specimens from the drying oven and weigh each specimen with base cap and triaxial cell to the nearest 0.0022 lb (1 g) and record as W_{DRY}. Use the Adek Percometer™ to

take six initial dielectric readings on each specimen surface. Five readings should be equally spaced around the perimeter of the specimen, and the sixth should be in the center. Press down on the probe with a force of 20 ± 5 lb (9.1 ± 2.3 kg) to ensure adequate contact of the probe on the specimen surface. Follow this pattern each time dielectric values are measured.

- Place the samples inside an ice chest on a level surface in a laboratory room maintained at 77 ± 9 ^oF (25 ± 5 ^oC) and fill the ice chest with distilled water to a depth of 1/2 ± 1/8 in. (12.5 ± 3.2 mm). Maintain the water bath at this depth throughout the testing. Avoid splashing the specimen surfaces with water during the test. Close the ice chest lid.
- Take six dielectric readings on each specimen surface once a day for 10 days. If the water content is to be monitored through time, record the sample weight daily to the nearest 0.0022 lb (1 g) as W_{WET} at each time interval. Wipe the bottom of the mold dry before weighing. Close the ice chest lid after taking measurements.
- The test is complete when the elapsed time exceeds 240 hours. Measure and record final surface dielectric values and weights. If triaxial strength testing is desired in this soaked condition, carefully remove the base cap and peform the test.
- Determine the final moisture content of each specimen according to test method Tex-103-E, part I but use the entire sample in the procedure. Wash all aggregate particles from the base cap and interior of the triaxial cell, as well as from any porous stones used in triaxial testing, into the drying pan. Record the weight of the oven-dry aggregate particles as W_S. Though the moisture content determined in this way after triaxial testing may not represent the moisture content at the conclusion of soaking, the value of the latter can be calculated using W_S as shown in the next section.

Calculations

- Calculate the actual gravimetric water content (WC_{OMC}, %) of each specimen just after compaction at the optimum moisture content,

$$WC_{OMC} = 100\ (W_{OMC} - W_{CAP} - W_{CELL} - W_S)/W_S$$

where:

W_{OMC} = weight of specimen with base cap and triaxial cell just after compaction, lb (g)

W_{CAP} = weight of specimen with base cap and triaxial cell just after compaction, lb (g)

W_{CELL} = weight of clean, dry triaxial cell, lb (g)

W_S = weight of oven-dry aggregate particles, lb (g)

- Calculate the gravimetric water content (WC_{DRY}, %) of each specimen just after the two-day drying period,

$$WC_{DRY} = 100\ (W_{DRY} - W_{CAP} - W_{CELL} - W_S)/W_S$$

where:

W_{DRY} = weight of specimen with base cap and triaxial cell after two-day drying period, g (lb.)

W_{CAP} = weight of plastic base cap, lb (g)

W_{CELL} = weight of clean, dry triaxial cell, lb (g)

W_S = weight of oven-dry aggregate particles, lb (g)

- Calculate the percentage of water loss (P_{LOSS}, % of OMC) for each specimen during the two-day period,

$$P_{LOSS} = 10000\ [(W_{OMC} - W_{DRY}) / W_S] / WC_{OMC}$$

where:

W_{OMC} = weight of specimen with base cap and triaxial cell just after compaction, lb (g)

W_{DRY} = weight of specimen with base cap and triaxial cell after two-day drying period, lb (g)

W_S = weight of oven-dry aggregate particles, lb (g)

WC_{OMC} = gravimetric water content just after compaction, %

- Calculate the average percentage of water loss for the three specimens.
- Calculate the gravimetric water content (WC_{WET}, %) of each specimen at each time interval during the soaking period,

$$WC_{WET} = 100\ (W_{WET} - W_{CAP} - W_{CELL} - W_S)/W_S$$

where:

W_{WET} = weight of specimen with base cap and triaxial mold at time of interest during soaking period, lb (g)

W_{CAP} = weight of plastic base cap, lb (g)

W_{CELL} = weight of clean, dry triaxial cell, lb (g)

W_S = weight of oven-dry aggregate particles, lb (g)

- Calculate the average gravimetric water content of the three specimens at the end of the soaking period.

- For each specimen at each time interval, discard the highest and lowest dielectric readings. Calculate the average dielectric value from the remaining four readings for plotting against time.
- Calculate the average final mean dielectric value of the three specimens to determine an overall moisture susceptibility ranking. Aggregates with final dielectric values less than 10 are expected to provide good performance, while those with dielectric values above 16 are expected to provide poor performance as base materials. Aggregates having final dielectric values between 10 and 16 are expected to be marginally moisture susceptible.

Graphs

- Plot the dielectric-time curve for each specimen.
- Plot the moisture-time curve for each specimen if requested.

Test Report

- Report the average final dielectric value after soaking and the corresponding moisture susceptibility ranking of good, marginal, or poor.
- Report the average final gravimetric water content of the specimens after soaking and the average percentage of water loss with respect to OMC during the two-day drying period.
- The former is indicative of the water content this aggregate may attain in the field given the availability of water, and the latter, if less than 50 percent, suggests that special construction considerations may be required in moist conditions to avoid trapping water in the pavement.

Tube Suction Test Data Collection Form

Aggregate ____________________ Technician ____________________

Source ____________________ Year ________ Lab. No. ________

Specimen Preparation		Measurement	0	1	2	3	4	5	6	7	8	9	10
OMC, %		Date, mm/dd											
MDD, kg/m^3 (pcf)		Time, hr:min											

Specimen No.		W_{WET}, g (lb)												
Specimen Testing		Dielectric Value	1											
W_{CAP}, g (lb)			2											
W_{CELL}, g (lb)			3											
W_{OMC}, g (lb)			4											
W_{DRY}, g (lb)			5											
W_S, g (lb)			6											

Specimen No.		W_{WET}, g (lb)												
Specimen Testing		Dielectric Value	1											
W_{CAP}, g (lb)			2											
W_{CELL}, g (lb)			3											
W_{OMC}, g (lb)			4											
W_{DRY}, g (lb)			5											
W_S, g (lb)			6											

Recommended Standard Method for Permanent Deformation and Resilient Modulus Testing of Unbound Granular Base/Subbase Materials

1 Scope

1.1 This test method is used to determine the permanent deformation properties, k_1, k_2, k_3 parameters along with the resilient modulus (Mr) values of unbound granular base/subbase materials for pavement performance prediction. The stress conditions used in this test represent the range of stress states likely to be developed beneath flexible pavements subjected to moving wheel loads. This test procedure has been adapted from the standard test methods given by VESYS user manual, NCHRP 1-28A report, and AASHTO designations: T307 and TP46.

1.2 The method described herein is applicable to laboratory-molded samples of unbound granular base/subbase materials.

1.3 The stress-dependency of materials is considered in determining the permanent deformation and resilient modulus values. These values are the measures of the permanent deformation properties and the elastic modulus of unbound granular base/subbase materials.

1.4 K_1, K_2, K_3 values are used to calculate the resilient modulus values, which can be used with structural analysis models to calculate the pavement structural response to wheel loads. Also, resilient modulus and permanent deformation properties are used with pavement design procedures to predict rutting performance.

1.5 This standard may involve the use of 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 the user of this standard to consult and establish appropriate safety and health practices and to determine the applicability of regulatory limitations prior to use.

2 Referenced Documents

2.1 AASHTO Standards:

2.1.1 T88 Particle size analysis of soils

2.1.2 T89 Determining the liquid limit of soils

2.1.3 T90 Determining the plastic limit and the plasticity index of soils

2.1.4 T100 Specific gravity of soils

2.1.5 T180 Moisture – Density relations of soils using a 10 lb (4.54 kg) rammer and 18 in. (457 mm) drop

2.1.6 T233 Density of soil-in-place by block, chunk, or core sampling

2.1.7 T292-91 Resilient modulus of subgrade soils and untreated base/subbase materials

2.1.8 T296 Strength parameters of soils by triaxial compression

2.1.9 T265 Laboratory determination of moisture content of soils

3 Terminology

3.1 Unbound granular base and subbase materials – These include soil-aggregate mixtures and naturally occurring materials. A binding or stabilizing agent is not used to prepare unbound granular base or subbase layers. These materials are classified as Type 1 and Type 2, defined subsequently in Sections 3.2 and 3.3.

3.2 Material Type 1 – Includes all unbound granular base and subbase materials with maximum particle sizes greater than 3/8 in. (9.5 mm). All material greater than 1.0 in. (25.4 mm) shall be scalped off prior to testing. Materials classified as Type 1 shall be modified in either a 6 in. (152 mm) diameter mold or a 4 in. (102 mm) diameter mold. Materials classified as Type 1 shall be compacted by impact or vibratory compaction.

3.3 Material Type 2 – Includes all unbound granular base and subbase materials, which have a maximum particle size less than 3/8 in. (9.5 mm) and which meet the criteria of less than 10 percent passing the 75 μm (no. 200) sieve. Materials classified as Type 2 shall be molded in a 4 in. (102 mm) diameter mold and compacted by vibratory compaction.

3.4 Permanent Deformation – Permanent deformation is the unrecovered deformation during the testing, determined by repeated load compression tests on specimens of the unbound materials.

3.5 Resilient Modulus – Resilient modulus (M_R) is the ratio of the peak axial repeated deviatoric stress to the peak recoverable axial strain of the specimen, determined by repeated load compression tests on specimens of the unbound materials.

3.6 Loading WaveForm – Test specimens are loaded using a haversine-shaped load pulse with 0.1 second loading time and 0.9 second rest period.

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

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

3.8 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 top cap and the static load applied by the ram of the loading system.

3.9 Cyclic Axial Load – Repetitive load applied to a test specimen:

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

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

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

where: A = cross sectional area of the sample.

3.11 Cyclic Axial Stress – The cyclic (resilient) stress applied on sample:

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

3.12 Contact Stress ($S_{contact}$) – Axial stress applied on 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 to apply a constant anisotropic confining stress ratio:

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

where: S_3 = the confining pressure.

3.13 S_3 is the applied confining pressure in the triaxial chamber (that is, the minor principal stress σ_3).

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

3.15 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.

3.16 e_p is the permanent (unrecoverable) axial deformation due to S_{cyclic}.

3.17 ε_p is the permanent (unrecoverable) axial strain due to S_{cyclic}:

$$\varepsilon_p = e_p / L$$

where: L = distance between measurement points for permanent axial deformation, e_p.

3.18 Resilient Modulus (M_R) is defined as:

$$M_r = S_{cyclic} / \varepsilon_r$$

3.19 Load duration is the time interval for which 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 This test is performed by placing a specimen in a triaxial cell and applying repeated axial load. After subjecting the specimen to all-round confining pressure, measurements are taken of the recoverable axial deformation and the applied load. Both total resilient (recoverable) and permanent axial deformation responses of the specimen are recorded and used to calculate the permanent deformation property and the resilient modulus. Permanent deformation is the unrecovered deformation during the testing, and resilient modulus is the ratio of the peak axial repeated deviatoric stress to the peak recoverable axial strain of the specimen.

5. Significance and Use

5.1 The permanent deformation and resilient modulus test simulates the conditions in a pavement with moving wheel loads. The resilient modulus test results provide a basic constitutive relationship between stiffness and stress state of pavement materials for use in the structural analysis of layered pavement systems. Further, permanent deformation properties of pavement materials can be determined from initially repeated load test, which are critical for pavement rutting performance prediction. Both these properties are used in advanced analysis and design systems of pavements.

6. Permanent Deformation and Resilient Modulus Test Apparatus

6.1 Triaxial Pressure Chamber – The pressure chamber contains the test specimen and the confining fluid during the test. A typical triaxial chamber suitable for use in resilient modulus testing is shown in Figure A-1. The axial deformation is measured internally, directly on the specimen using normal gauges with a rubber band (shown in Figure A-2), an optical extensometer, non-contact sensors, or clamps. For soft and very soft subgrade specimens (i.e., the undrained shear strength for the soil [S_u] < 36 kPa or 750 psf), rubber bands or clamps should not be used since they may damage the specimen. Further, a pair of Linear Variable Transformers (LVTs) extending between the top and bottom platens can be used to measure axial deformation of these weak soils.

Figure A-1. Test setup of Resilient Modulus.

Figure A-2. Specimen prepared for Testing.

The following guidelines are to be checked for the triaxial chamber.

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 suitable transparent material (such as polycarbonate).

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

6.2.1 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, which shall preferably be located inside the triaxial cell. The load cell should have the capacities, presented in Table A-1.

Table A-1. Load Cell Capacity.

Sample Diameter mm (in.)	Max. Load Capacity kN (lb)	Required Accuracy N (lb)
102 (4.0)	8.9 (2000)	± 17.8 (± 4)
152 (6.0)	22.24 (5000)	± 22.24 (± 5)

Note 1: During periods of permanent deformation and resilient modulus testing, the load cell shall be monitored and checked once every two weeks or after every 50 permanent deformation and resilient modulus tests with a calibrated proving ring to ensure that the load cell is operating properly. An alternative to using a proving ring is to inset an additional calibrated load cell and independently measuring 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. The test shall not be conducted if the testing system is found to be out of calibration.

6.3.2 The chamber pressures shall be monitored with conventional pressure gauges, manometers, or pressure transducers accurate to 0.69 kPa (0.1 psi)

6.3.3 Axial Deformation – Axial deformation is to be measured with the displacement transducers referenced to gauge points contacting the specimen with rubber band as shown in Figure A-2. Deformation shall be measured over approximately the middle ½ of the specimen. Axial deformation shall be measured at a minimum of two locations 180^o apart (in plan view), and a pair of spring-loaded LVDTs are placed on the specimen at ¼ point. Spring-loaded LVDTs maintain a positive contact between the LVDTs and the surface on which the tips of the transducers rest. Table A-2 summarizes the specifications for spring-loaded LVDTs.

Table A-2. Specifications for Axial LVDTs.

Material/Specimen Size		Min. range (in.)	Approximate resilient specimen displacement (in.)
Aggregate Base	6 in. diameter specimen	± 0.25	0.001
	4 in. diameter specimen	± 0.10	0.00065
Subgrade soil (sand and cohesive)	4 in. diameter	± 0.25	0.0014

Note 2: 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 the LVDT back and forth a number of times prior to each test to ensure 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 (A/D) data acquisition system is required. The overall system should include automatic data reduction to minimize production. Suitable signal excitation, conditioning, and recording equipment is 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 percent; and (6) nonlinearity (LSBS) of ± 0.5 percent. The signal shall be clean and free of noise. Filtering the output signal during or after data acquisition is discouraged. If a filter is used, it should have a frequency of 10 to 20 Hz. A supplemental study should be made to ensure correct peak readings are obtained with filtered data compared to unfiltered data. A minimum of 200 points from each LVDT shall be recorded per load cycle.

6.4 Specimen Preparation Equipment – A variety of equipment is required to prepare compacted specimens that are representative of field conditions. Use of different materials and different compaction methods in the field requires the use of varying compaction techniques in the laboratory. Specimen preparation is described in Appendix B.

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

6.6 Periodic System Calibration – The entire system (transducers, signal conditioning, and recording devices) shall be calibrated every two weeks or after every 50 tests. Daily and other periodic checks of the system may also be performed as necessary. No permanent deformation and resilient modulus testing will be conducted unless the entire system meets the established calibration requirements.

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

7.1.2 Use 4.0 in. (102 mm) diameter by 8.0 in. (203 mm) high specimens for all materials with maximum particle sizes less than 0.75 in. (19 mm).

7.2 Laboratory Compacted Specimens – Reconstituted test specimens of all types shall be prepared to the specified or insitu dry density (γ_d) and moisture content (w). Laboratory compacted specimens shall be prepared for all unbound granular base and subbase materials.

7.2.1 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 AASHTO T238. If data are not available on in situ moisture content, refer to Section 7.2.3.

7.2.1.1 The moisture content of the laboratory compacted specimen should not vary from the required value by more than ±0.5 percent for all materials.

7.2.2 Density: The density of a compacted specimen shall be the in-place dry density obtained in the field for that layer using AASHTO T239 or other suitable methods. If these data are not available on in situ density, then refer to Section 7.2.3.

7.2.2.1 The dry density of a laboratory compacted specimen should not vary more than ±1.0 percent from the target dry density for that layer.

7.2.3 If either the in situ moisture content or the in-place dry density is not available, then use the optimum moisture content and 95 percent of the maximum dry density by using AASHTO T180 for the base/subbase.

7.2.3.1 The moisture content of the laboratory compacted specimen should not vary from the required value by more than ±0.5 percent for all materials. The dry density of a laboratory compacted specimen should not vary more than ±1.0 percent from the target dry density for that layer.

7.2.4 Sample Reconstitution: Reconstitute the specimen for all materials in accordance with the provisions given in Appendix B. The target moisture content and density to be used in determining the required qualities are given in Section 7.2. Appendix B also provides guidelines to obtain a sufficient amount of material to prepare the appropriate specimen type at the designated moisture content and density. After ascertaining the amount of material required, begin the specimen compaction.

7.3 Compaction Methods and Equipment for Reconstituting Specimens:

7.3.1 Specimens of type 1 materials shall be compacted by vibratory or impact compaction. The general method of vibratory compaction is given in AASHTO T307. The general method of impact compaction is given in AASHTO T307.

7.3.2 Specimens of type 2 materials shall be compacted by vibratory compaction. The general method of vibratory compaction is presented in AASHTO T307.

8. Test Procedure

The permanent deformation and resilient modulus test is performed using the following test procedure. This procedure is applicable to all granular bases and subbases.

8.1 Assembly of the triaxial cell: If not already in place, place the specimen with end platens into a position on the pedestal of the triaxial cell. 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 that applies the load (watch the gap around the ball). Shift the specimen laterally to achieve a concentric loading.

8.2 Check and adjust the axial displacement measurement system, load cell, and data acquisition system and make sure they are working properly.

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

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

8.5 Apply the specified confining pressure of 103.5 kPa (15.0 psi) to the test specimen. A contact stress equal to 20 percent 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.

8.6 Preconditioning: Apply 100 repetitions of a load equivalent to a maximum axial stress of 41.4 kPa (6.0 psi) and a corresponding cyclic stress of 20.7 kPa (3 psi) using a haversine-shaped, 0.1 second load pulse followed by 0.9 second rest period.

8.7 Permanent Deformation Test

8.7.1 Apply the haversine loading (P_{cyclic}) 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, and continue until 10,000 cycles (2.8 hours) or until the vertical permanent strain reaches 5 percent during the testing, whichever comes first. The total number of cycles or the testing time will depend on the stress levels applied.

8.7.2 During the load applications, record the load applied and the axial deformation measured from the two LVDTs through the data acquisition system. Signal-to-noise ratio should be at least 10. All data should be collected in real time and collected/processed so as to minimize phase errors due to sequential channel sampling. In order to save storage space during data acquisition for 10,000 cycles, it is recommended to use the data acquisition of the cycles shown in Table A-3.

Table A-3. Suggested Data Collection for Triaxial Repeated Load Permanent Deformation Test.

Data Collection during Cycles	Data Collection during Cycles	Data Collection during Cycles	Data Collection during Cycles
1-15	450	1300	4000
20	500	1400	4500
30	550	1500	5000
40	600	1600	5500
60	650	1700	6000
80	700	1800	6500
100	750	1900	7000
130	800	2000	7500
160	850	2200	8000
200	900	2400	8500
250	950	2600	9000
300	1000	2800	9500
350	1100	3000	10000
400	1200	3500	

8 Resilient Modulus Test

8.8.1 Specimen Testing – If the vertical permanent strain did not reach 5 percent during the permanent deformation test, use the same specimen to perform the resilient modulus test following the load sequence shown in Table A-4. 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 (3.0 psi).

8.8.2 If the vertical permanent strain reached 5 percent during the permanent deformation test, mold a new specimen and repeat the process described in Sections 8.1 to 8.7. In addition, reduce the load repetitions from 10,000 to 5,000 during repeated load permanent deformation test. If the sample again reaches 5 percent total vertical permanent strain during the repeated load test, then terminate the test. No further testing of this material is necessary. If not, perform the resilient modulus test following the load sequence in Table A-4. 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).

Table A-4. Permanent Deformation and Resilient Modulus Test Sequence for Granular Base and Subbase.

Sequence	Confining Pressure		Contact Stress		Cyclic Stress		Maximum Stress		N_{rep}
	kPa	Psi	kPa	Psi	kPa	Psi	kPa	Psi	
Preconditioning									
	103.5	15.0	20.7	3.0	20.7	3.0	41.4	6.0	100
Permanent Deformation									
	103.5	15.0	20.7	3.0	207.0	30.0	227.7	33.0	10000
Resilient Modulus									
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	20.0	165.6	24.0	100
11	20.7	3.0	4.1	0.6	1.4	6.0	5.5	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	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	124.4	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	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

8.8.3 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 from each LVDT separately for the last five cycles.

8.8.4 Increase the maximum axial stress to a 30 kPa (4.2 psi) and the confining pressure to 41.4 kPa (6.0 psi) (Sequence No. 2 Table A-4) and repeat the previous step at this new stress level.

8.8.5 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 percent, end the test and report the result on the appropriate worksheet.

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

8.8.7 Remove the membrane from the specimen and use the entire specimen to determine moisture content in accordance with AASHTO T265.

9.0 Calculations

Calculation of Permanent Strain

9.1 Calculate the average axial deformation for each specimen by averaging the readings from the two axial LVDTs. Convert the average deformation values to the total axial strain by dividing with the gauge length, L (6 in. [152 mm] for 6 in. diameter sample; 4 in. (102 mm) for 4 in. diameter sample).

9.2 Compute the cumulative axial permanent strain and resilient strain (ε_r) at the 200th load repetition.

9.3 Plot the cumulative axial permanent strain versus the number of loading cycles in log space (shown in Figure A-3). Determine the permanent deformation parameters, intercept (a) and slope (b), from the linear portion of the permanent strain curve (log-log scale), which is also demonstrated on Figure A-3.

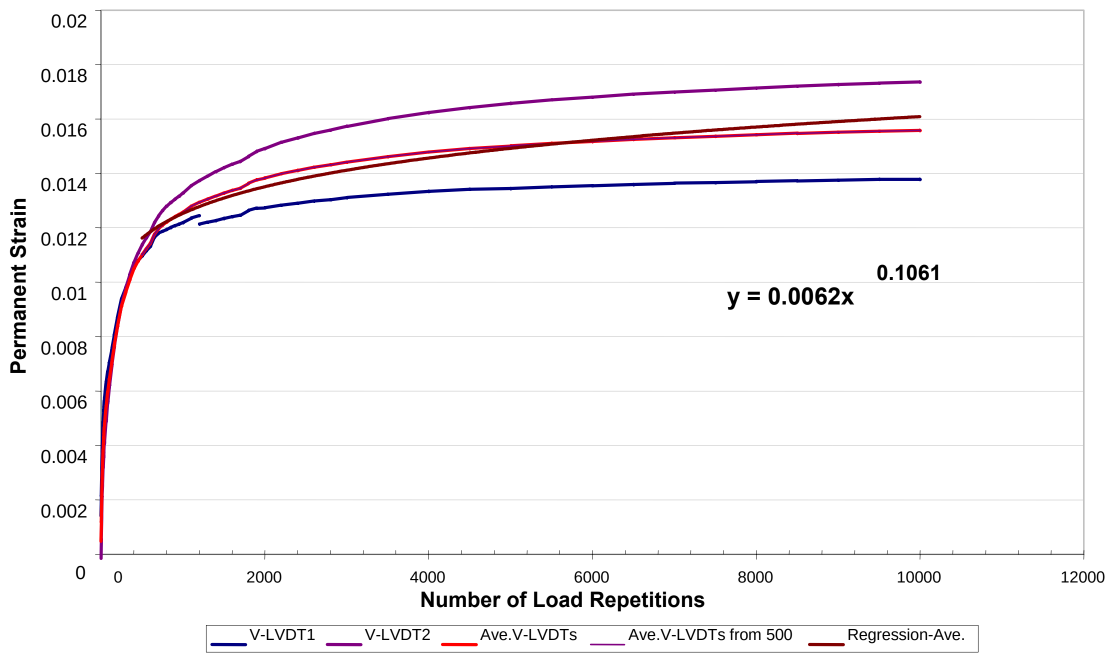


Figure A-3. Permanent Strain vs. Number of Load Applications.

9.4 Compute the rutting parameters – Alpha (α) and Mu (μ)

$$\alpha = 1 - b$$

$$\mu = \frac{ab}{\varepsilon_r}$$

Calculation of Resilient Modulus

9.5 Perform the calculations to obtain the resilient modulus values and then average the resilient modulus values computed from each of the last five cycles of each load sequence. The data reduction process should be fully automated to minimize the chance for human error.

9.6 Fit using nonlinear regression techniques the following resilient modulus model to the data obtained from the applied procedure.

The resilient modulus is calculated by the following:

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

$k_1, k_2 \geq 0$

$k_3, k_6 \leq 0$

$k_7 \geq 1$

where:

M_r = resilient modulus

θ = bulk stress = $\sigma_1 + \sigma_2 + \sigma_3$

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

τ_{oct} = octahedral shear stress

σ_1, σ_2, σ_3 = πrincipal stresses

k_i = regression constants

P_a = atmospheric pressure

Assign initial values of $k_6 = 0$ and $k_7 = 1$; 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.

10 Report

10.1 Permanent deformation test:

10.1.1 Report all specimen basic information including specimen identification, dates of manufacturing and testing, specimen diameter, and length.

10.1.2 Report confining pressure, stress levels used, and axial permanent deformation parameters: α and μ (or ε_r, a, and b).

10.2 Resilient Modulus Test:

10.2.1 Report all specimen basic information including specimen identification, dates of manufacturing and testing, specimen diameter, and length.

10.2.2 Report the average peak stress (σ_o) and strain (ε_o) for each confining pressure-cyclic stress combination tested.

10.2.3 Report for each confining pressure-cyclic stress combination tested, the resilient modulus for each replicate test specimen.

10.2.4 Report the nonlinear resilient modulus model and the model parameters: k_1, k_2, k_3, k_6, and k_7.

APPENDIX B:

SAMPLE PREPARATION

1. Scope

1.1 The following information provides guidelines for reconstituting the material to be tested so as to produce a sufficient amount of material 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 ^{o}C (140 ^{o}F). Then thoroughly break up the aggregations in such a manner so as to avoid reducing the natural size of individual particles. Moderate pressure is applied 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 AASHTO T265. The mass of the sample for moisture determination shall not weigh less than 200 g for samples with a maximum particle size smaller than the 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 is based on the height of 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 (W_s) 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

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

$$W_{aw} = (W_s + W_{as})\left(\frac{w - w_1}{100}\right)$$

where:

W_{aw} = mass of water needed to obtain water content w, g

w = desired water content of compacted material, percent

2.2.4 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.

$$W_{ad} = (W_s + W_{as})\left[1 + \frac{w_1}{100}\right]$$

where:

W_{ad} = mass of sample at water content w_1, g

W_{as} = mass of moisture content specimen (usually 500 g), g

w_1 = Water content of prepared material, percent

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 4 hours, determine the mass of wet soil and container to the nearest gram and record this value as appropriate.

2.2.8 The material is now ready for compaction.

2.3 Compaction

2.3.1 Refer to ASTM 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 as appropriate.

2.3.3 Protect coarse-grained subgrade specimens 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.

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

3.3 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.

3.4 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 the holes in the membrane can frequently be eliminated by coating the surface of 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 that the O-rings will contact.

3.5 The specimen is now ready for testing.

APPENDIX C:

PERMANENT DEFORMATION RESULTS FOR SPICEWOOD SPRINGS

SPECIMEN # 1

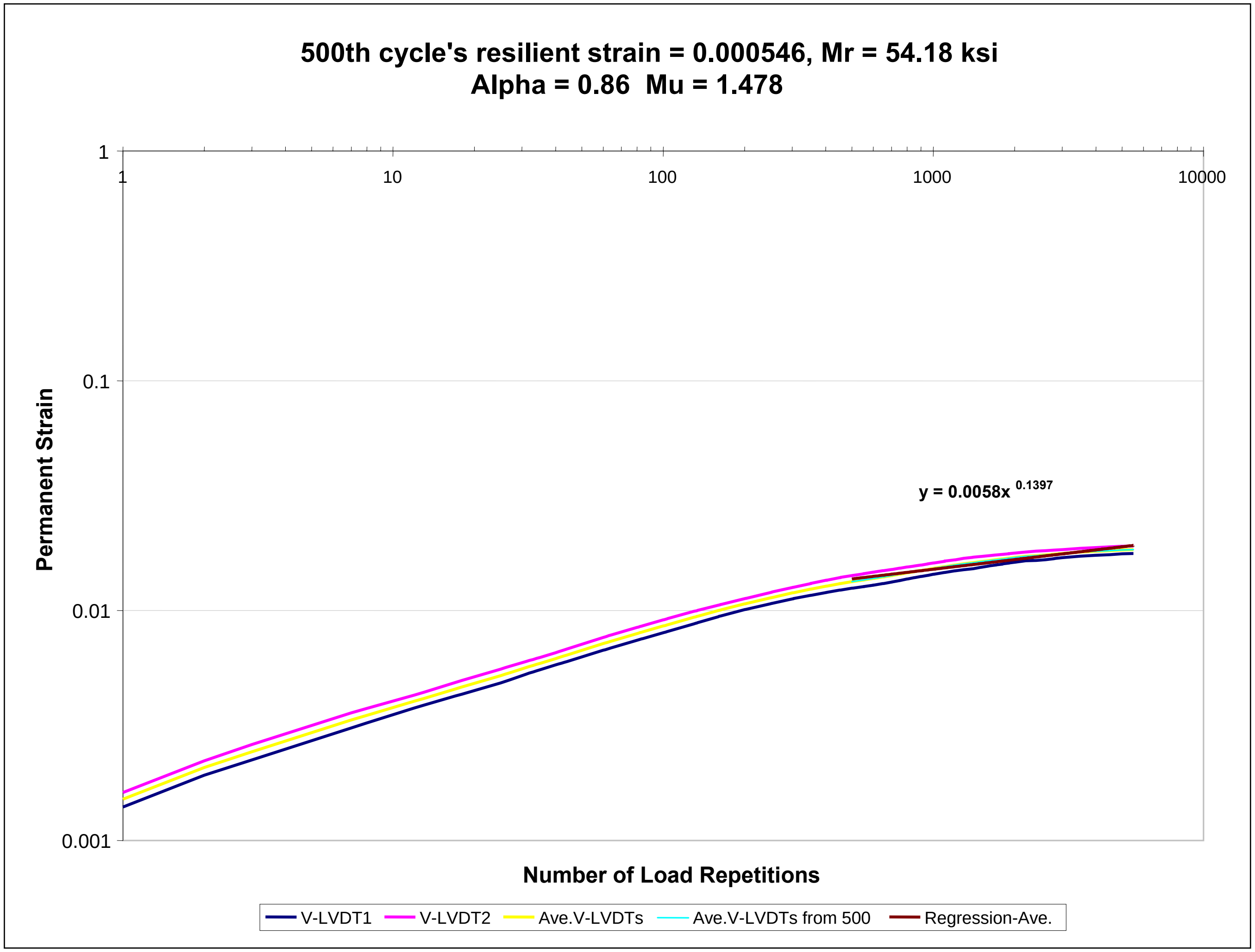


Figure C- 1. Permanent Deformation Result for Specimen #1.

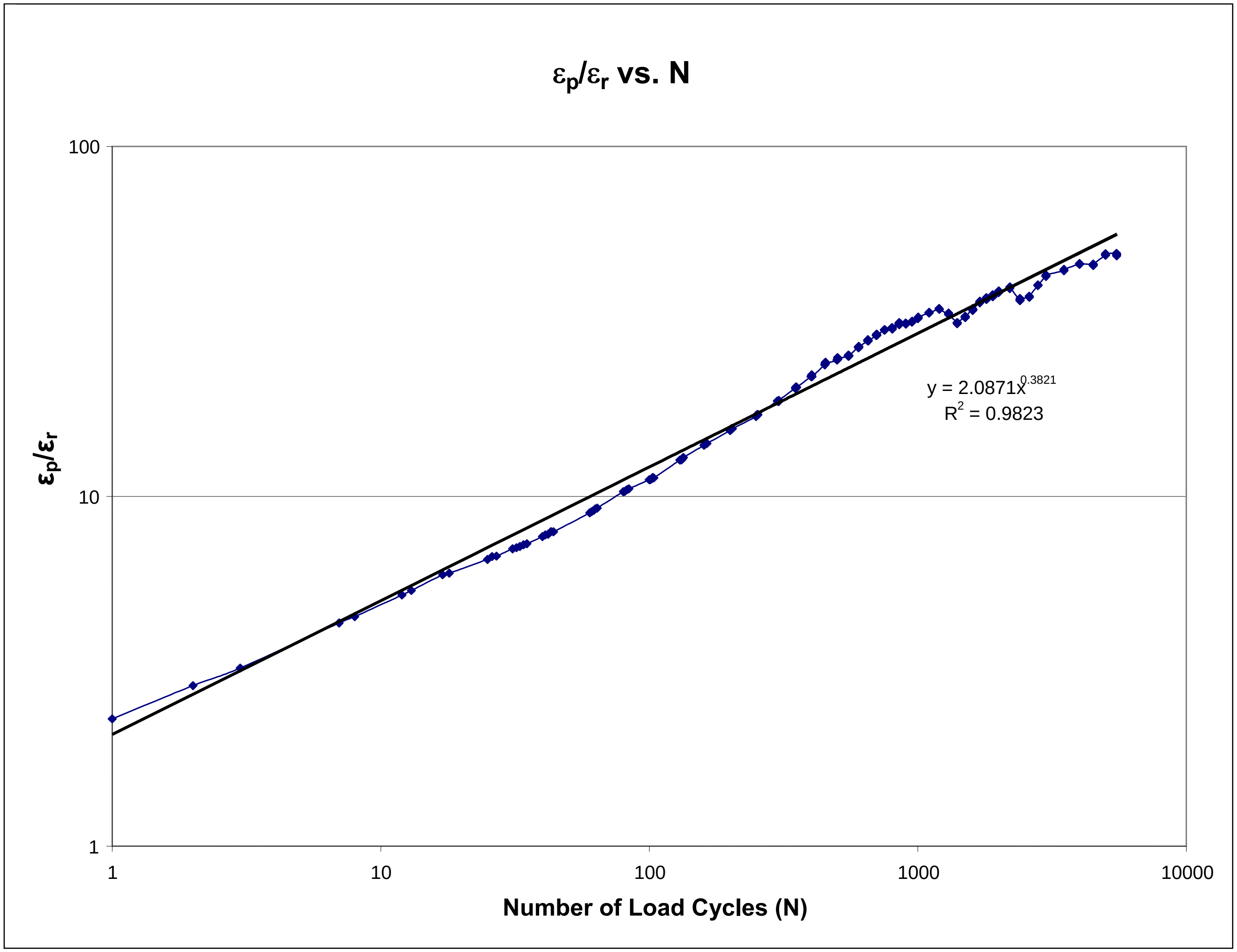


Figure C- 2. $\varepsilon_p/\varepsilon_r$ vs. Number of Load Cycles for Specimen #1.

SPECIMEN # 2

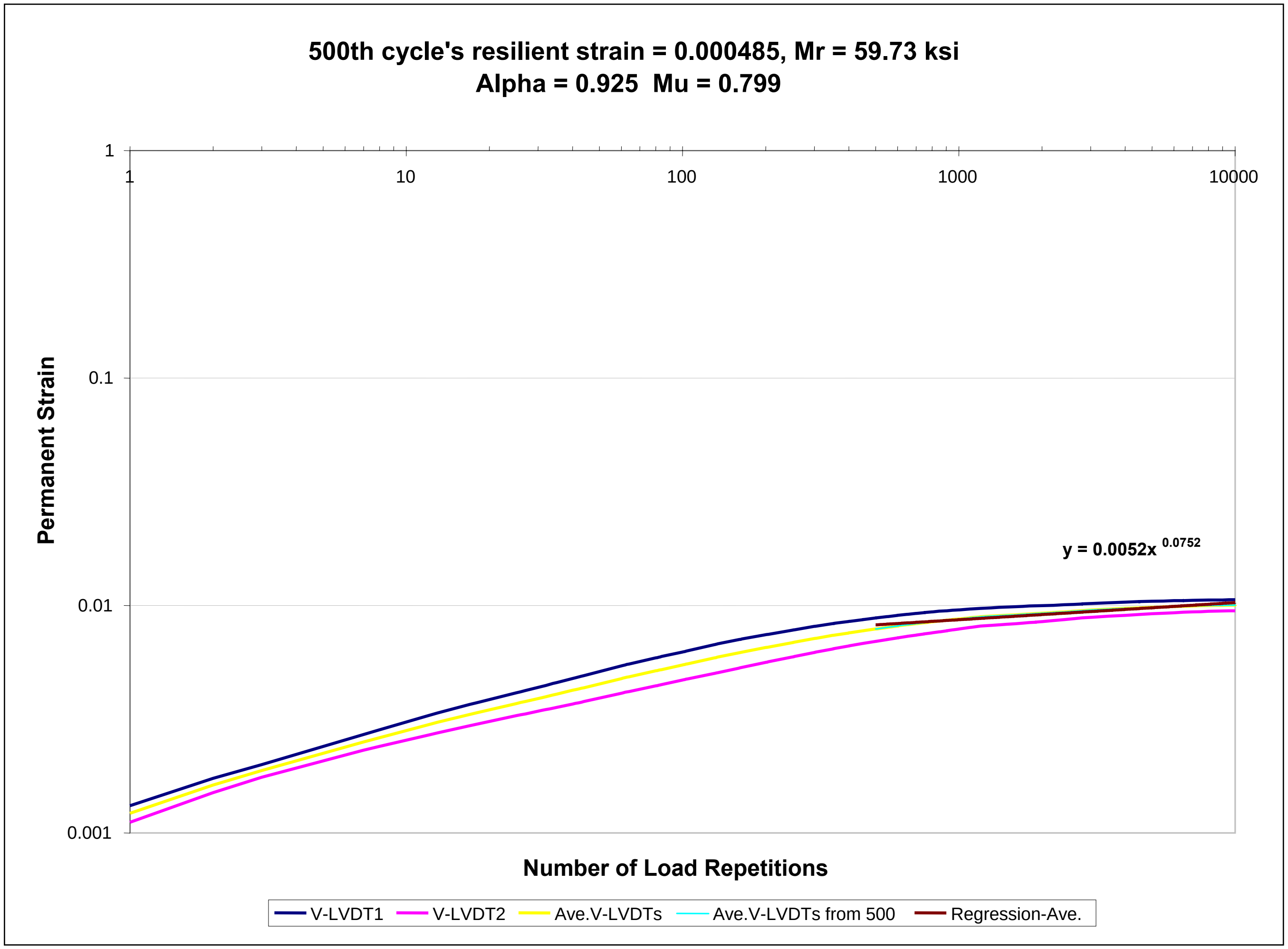


Figure C- 3. Permanent Deformation Result for Specimen #2.

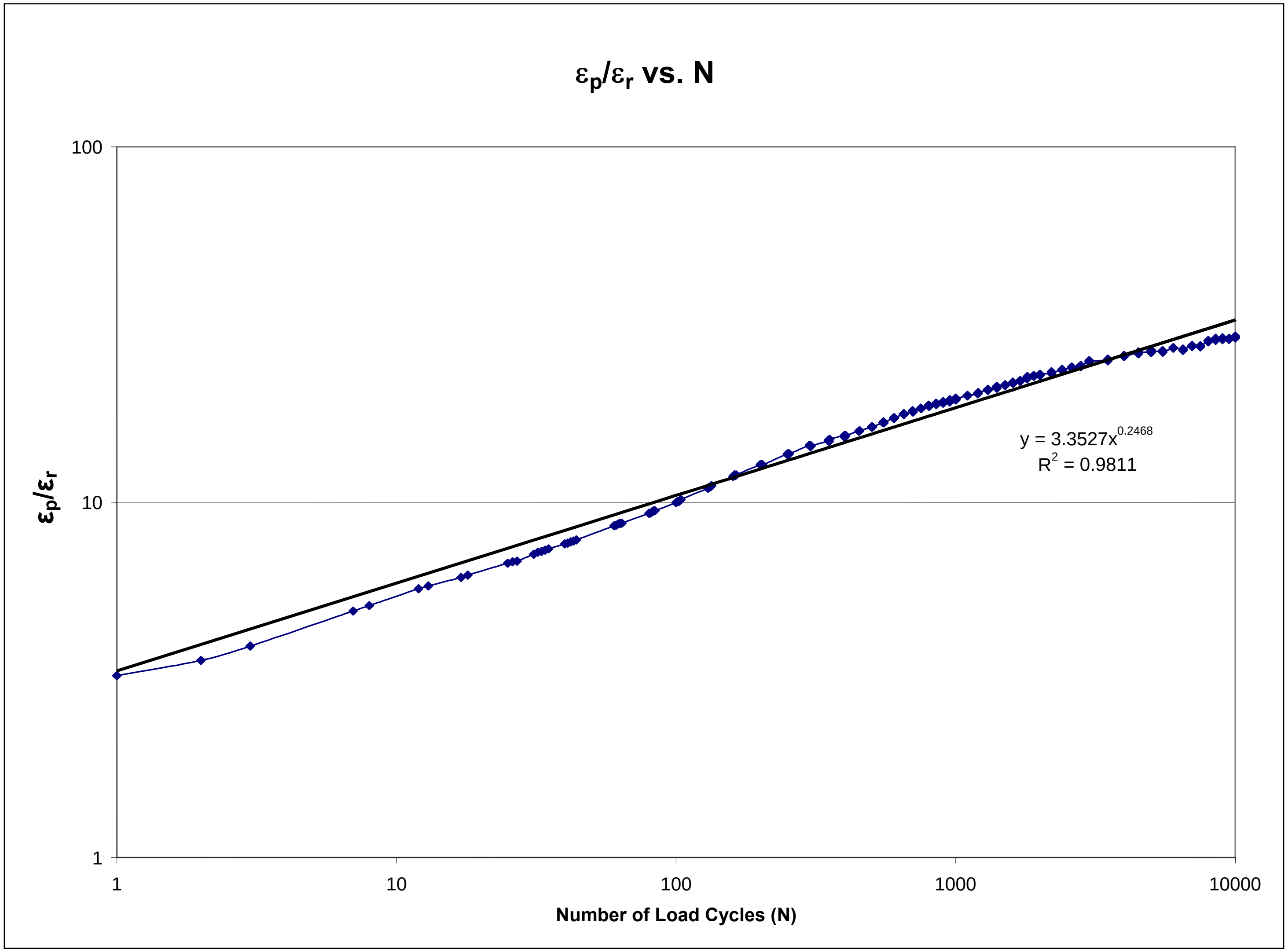


Figure C- 4. $\varepsilon_p/\varepsilon_r$ vs. Number of Load Cycles for Specimen #2.

SPECIMEN # 3

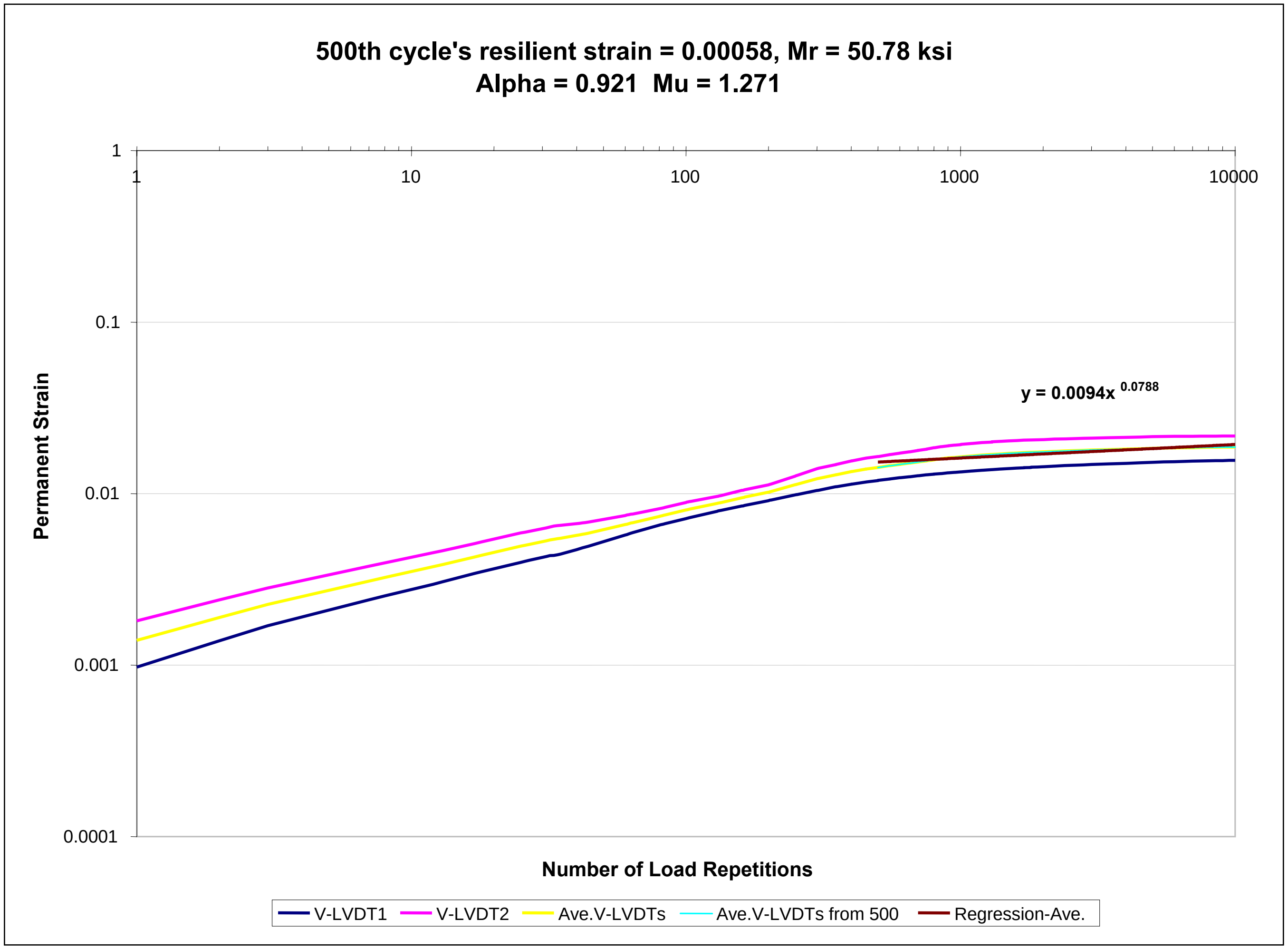


Figure C- 5. Permanent Deformation Result for Specimen #3.

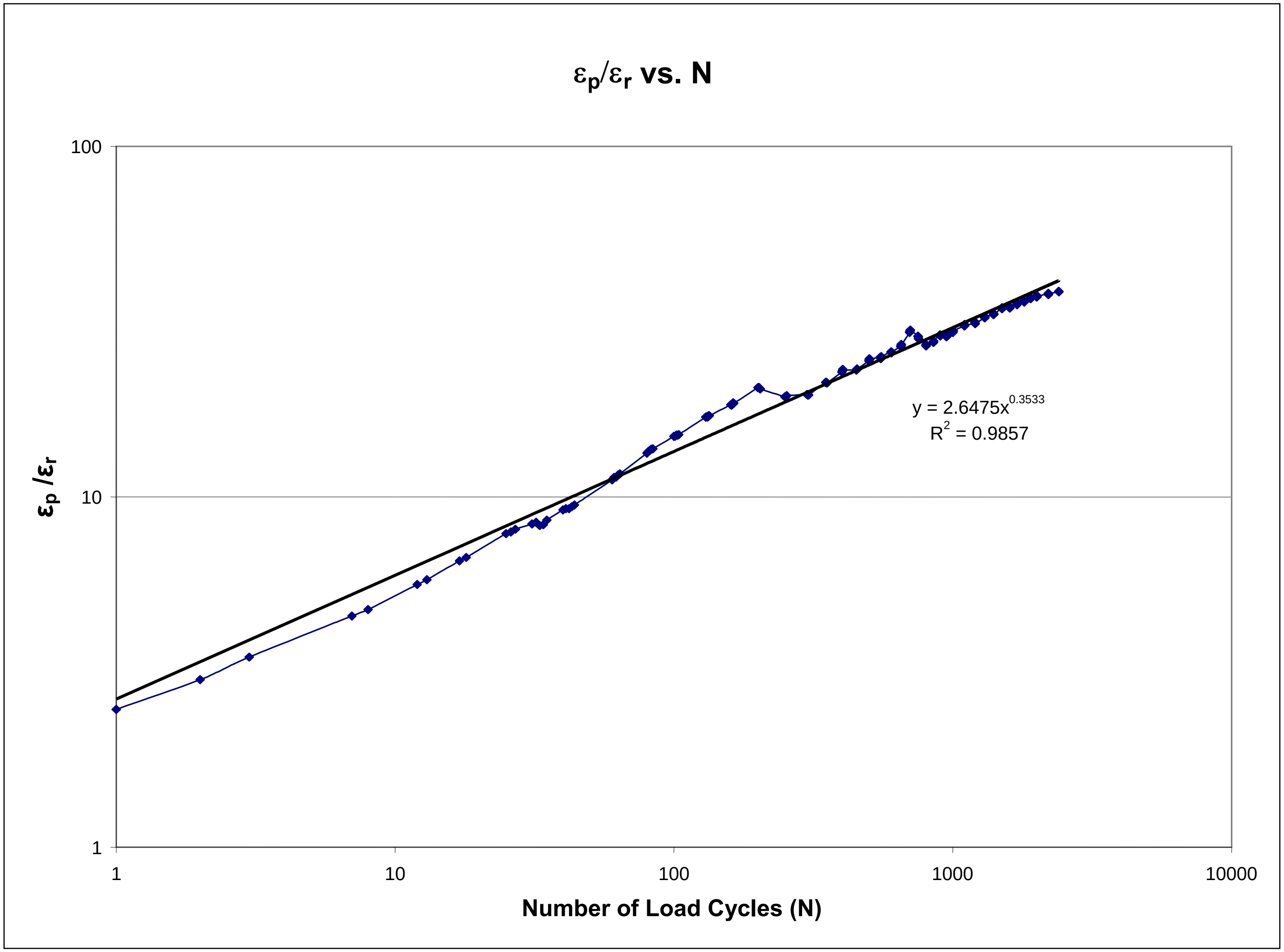


Figure C- 6. $\varepsilon_p/\varepsilon_r$ vs. Number of Load Cycles for Specimen #3.

SPECIMEN # 4

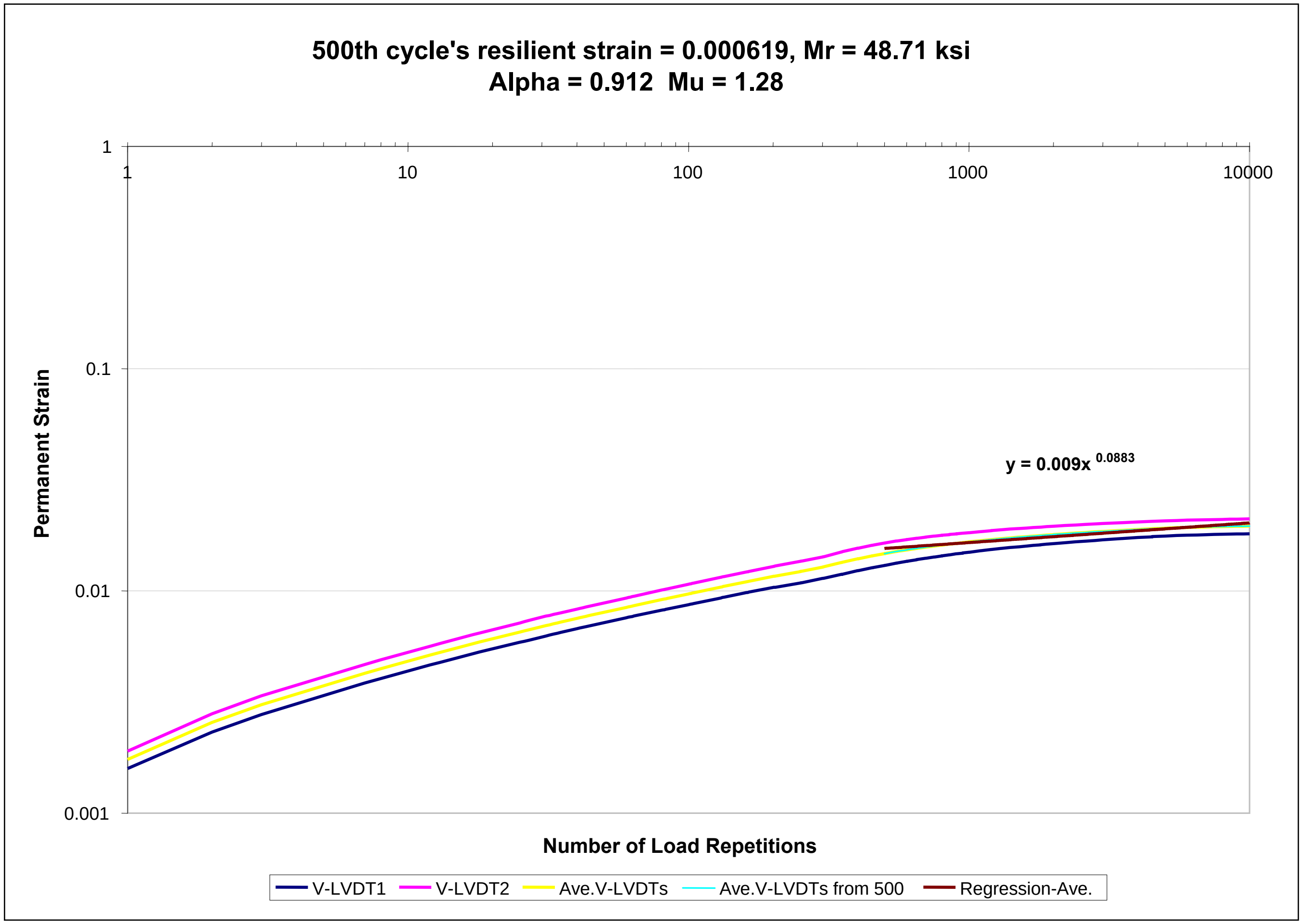


Figure C- 7.   Permanent Deformation Result for Specimen #4.

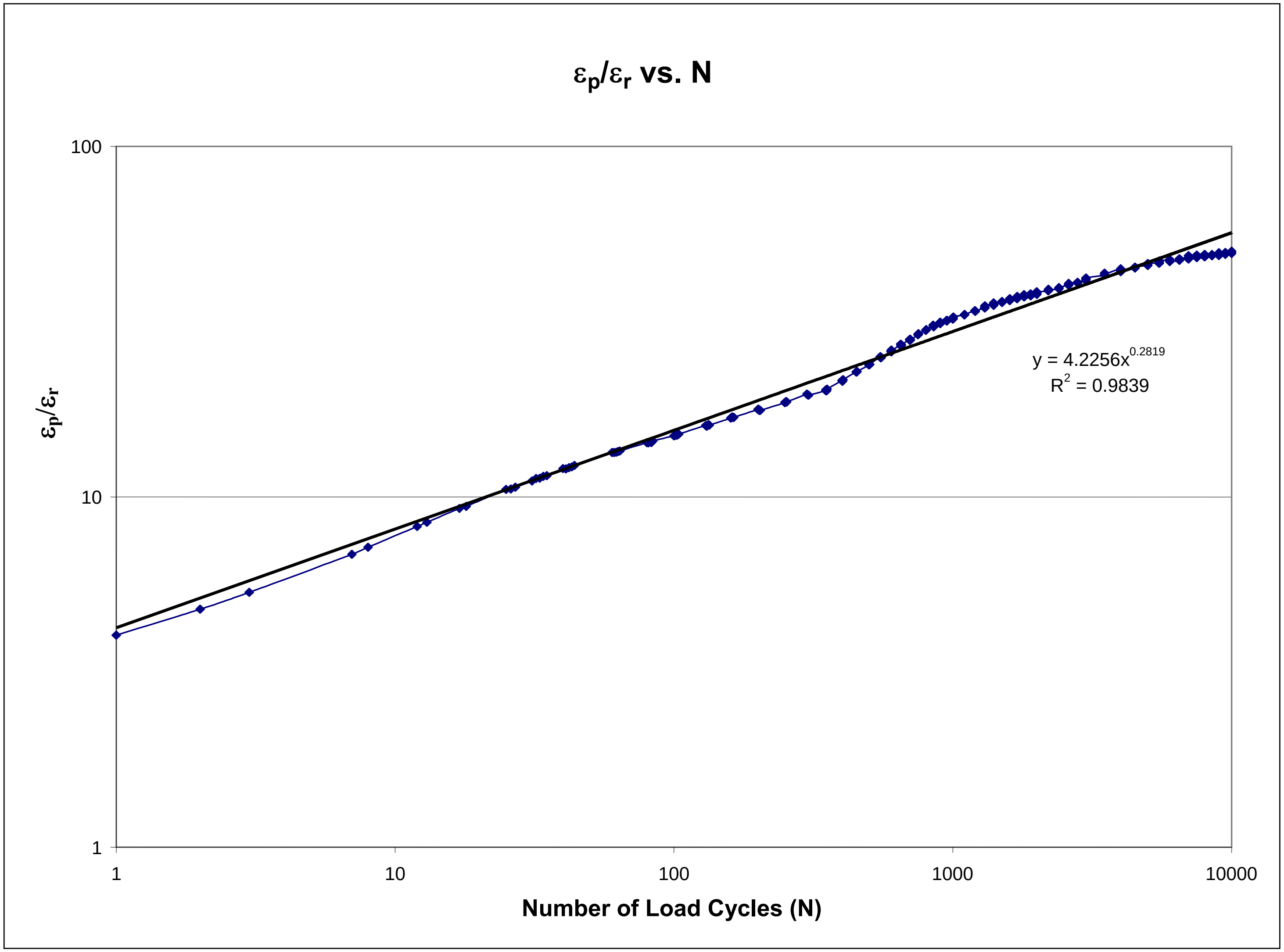


Figure C- 8. $\varepsilon_p/\varepsilon_r$ vs. Number of Load Cycles for Specimen #4.

SPECIMEN # 5

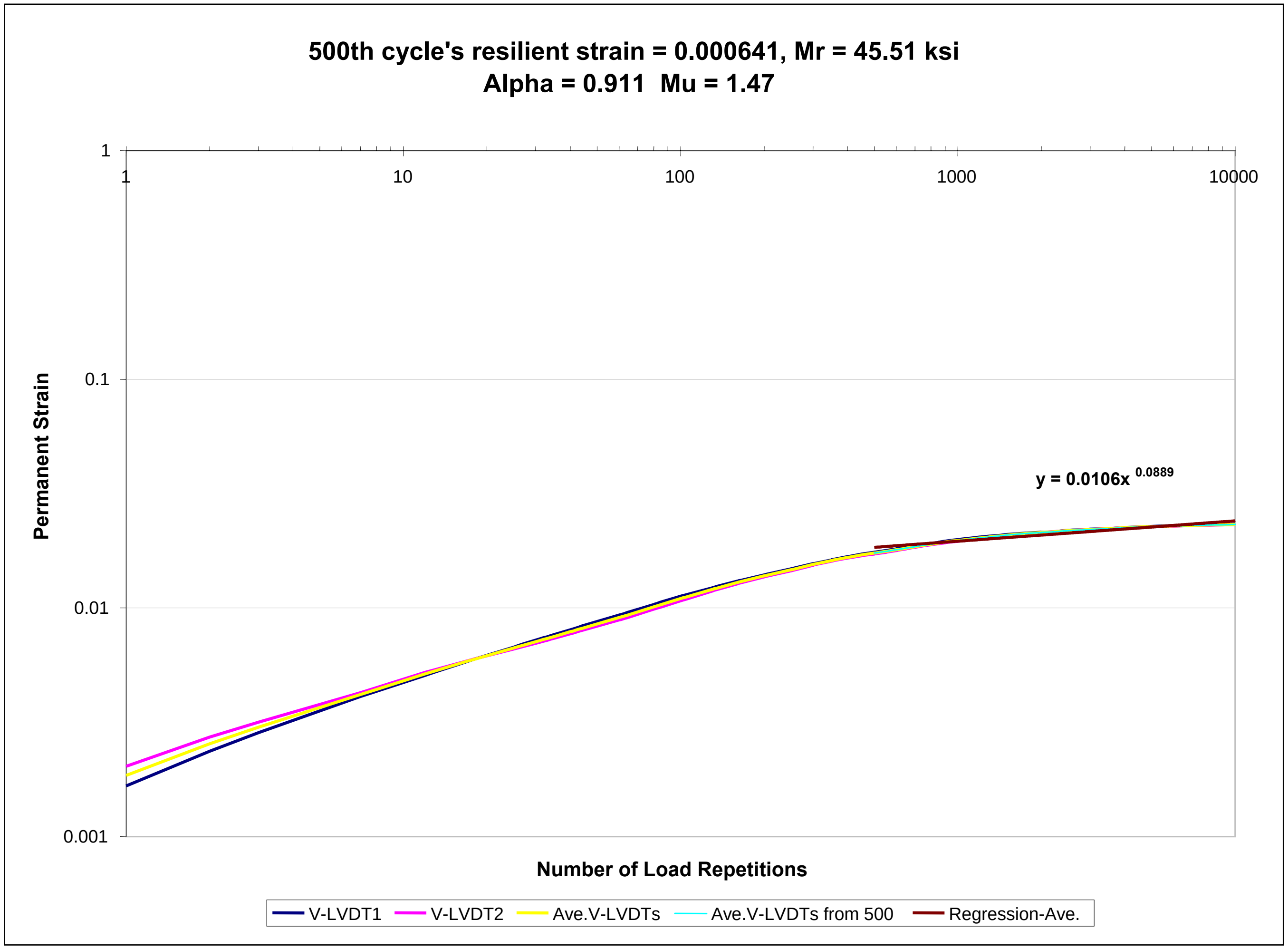


Figure C- 9. Permanent Deformation Result for Specimen #5.

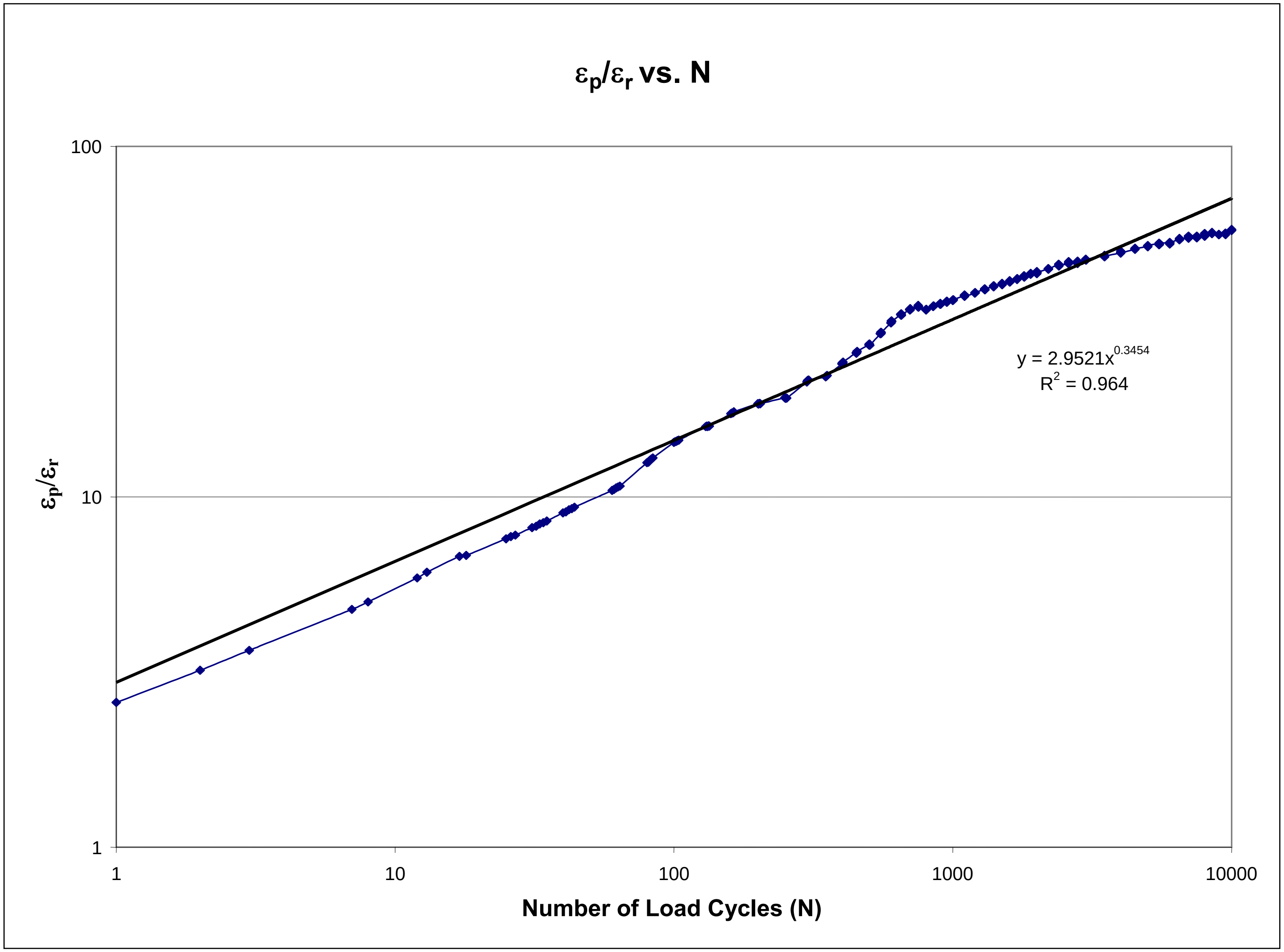


Figure C- 10. $\varepsilon_p/\varepsilon_r$ **vs. Number of Load Cycles for Specimen #5.**

SPECIMEN # 6

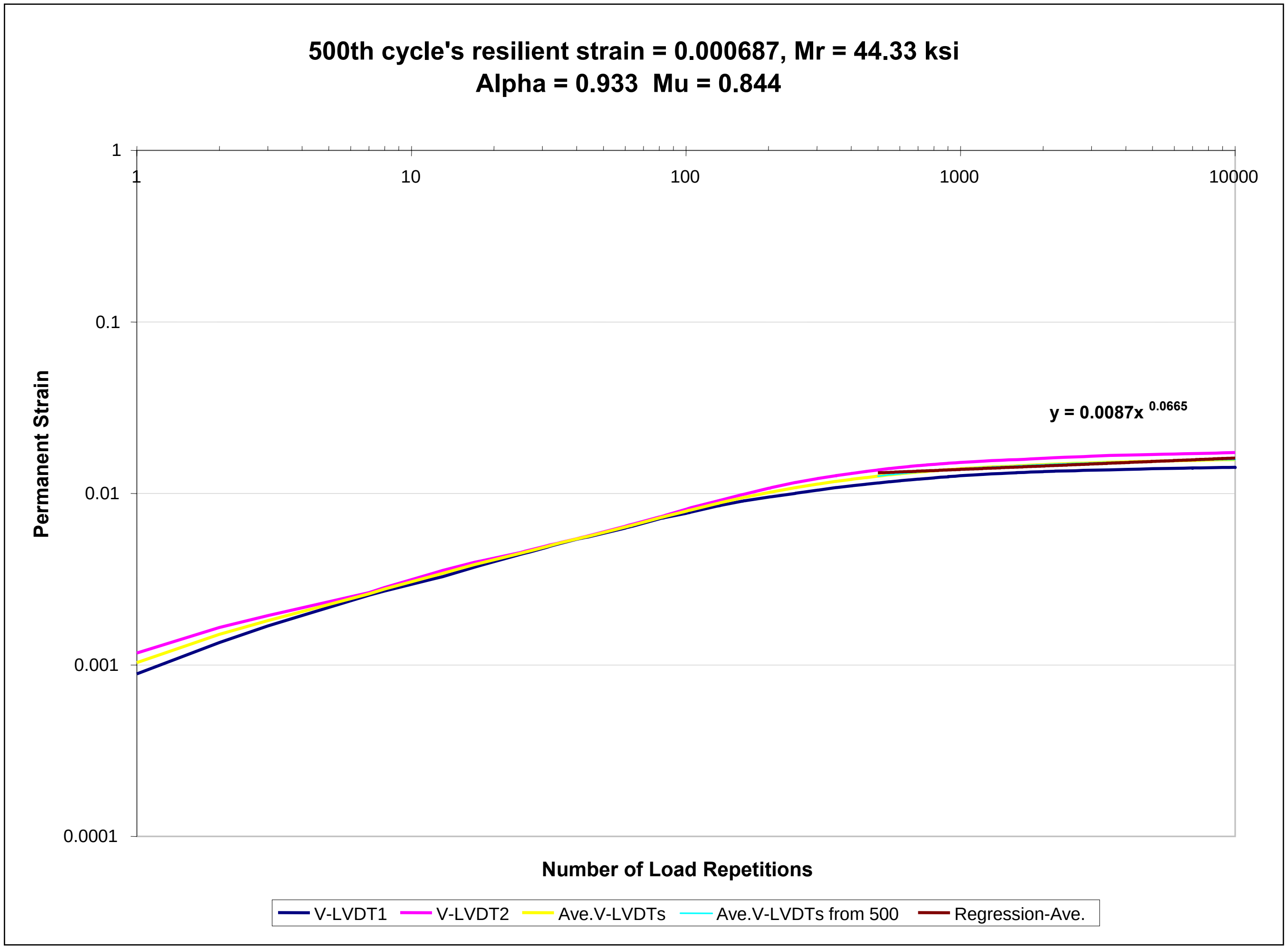


Figure C- 11. Permanent Deformation Result for Specimen #6.

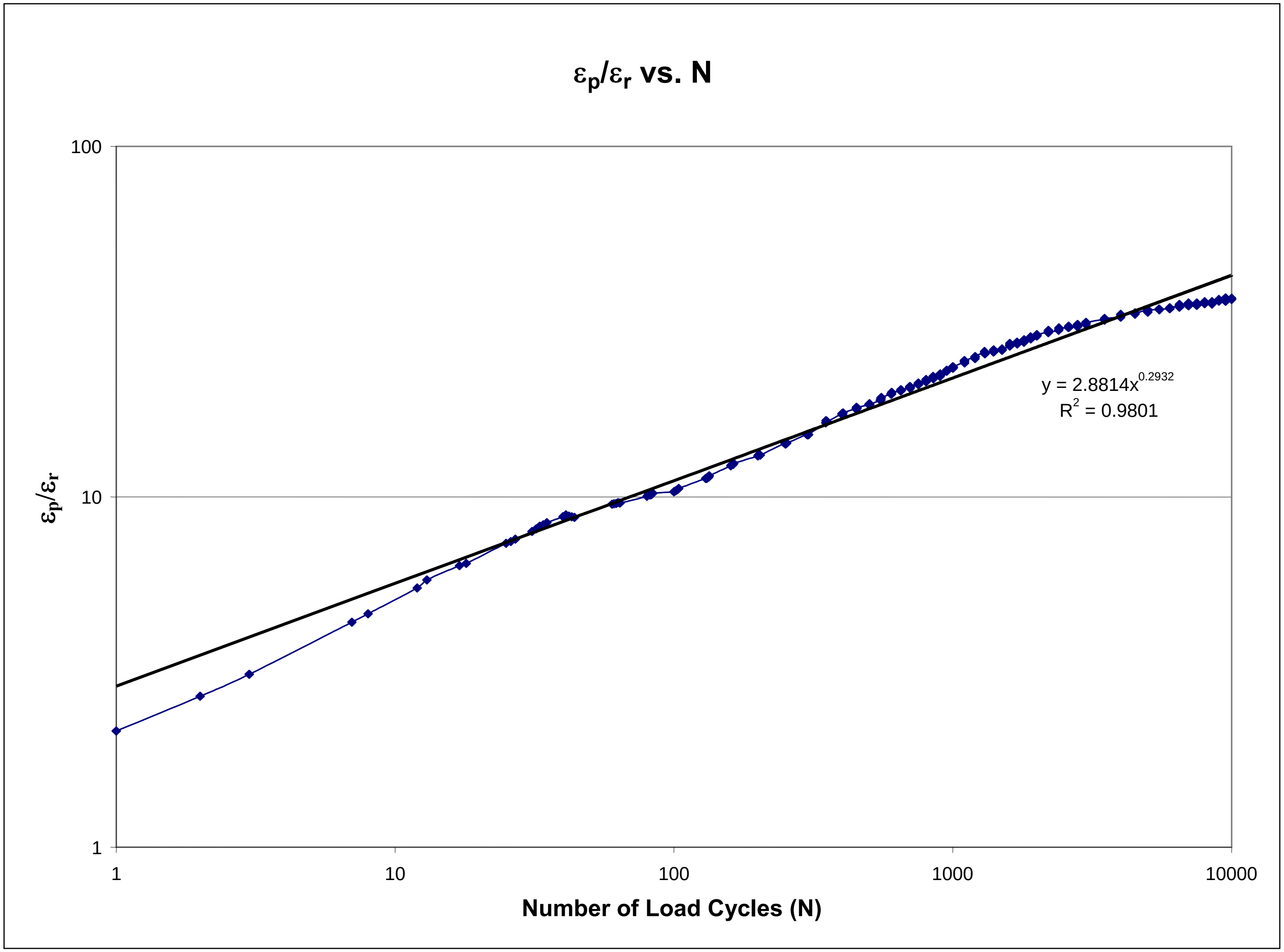


Figure C- 12. $\varepsilon_p/\varepsilon_r$ vs. Number of Load Cycles for Specimen #6.

SPECIMEN # 7

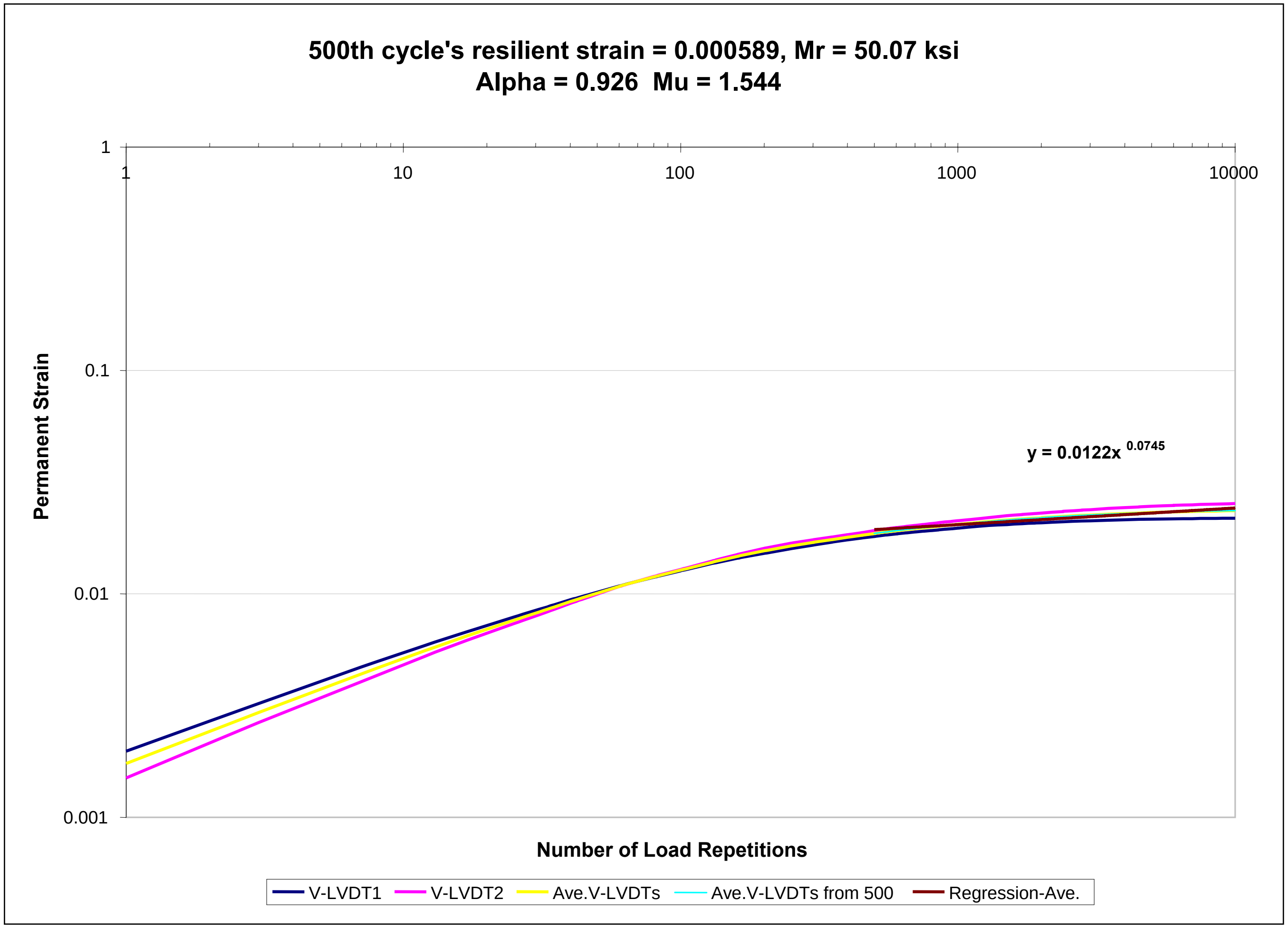


Figure C- 13. Permanent Deformation Result for Specimen #7.

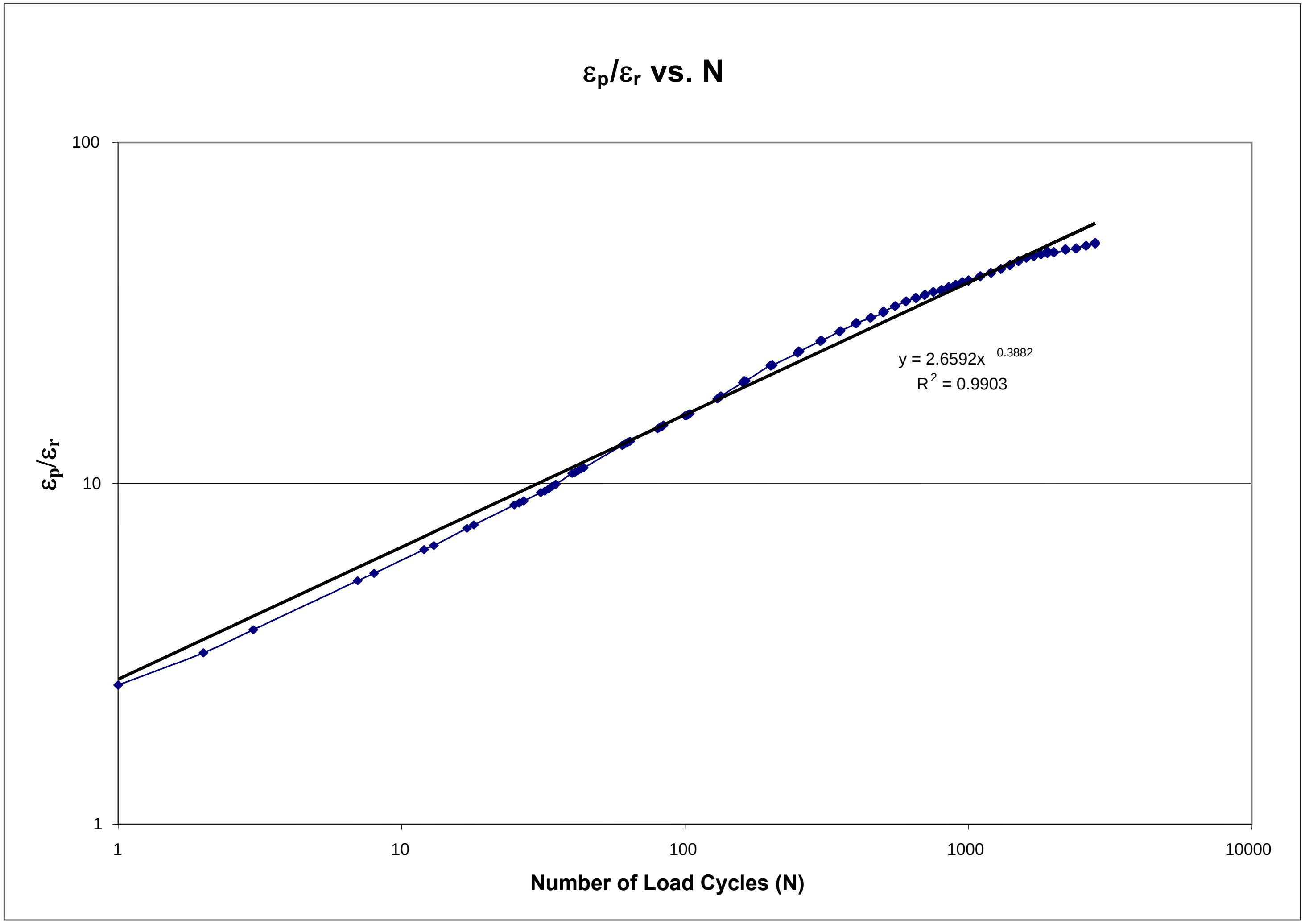


Figure C- 14. $\varepsilon_p/\varepsilon_r$ vs. Number of Load Cycles for Specimen #7.

APPENDIX D:

RESILIENT MODULUS RESULTS FOR SPICEWOOD SPRINGS

SPECIMEN # 1

2002 Design Guide, Granular Base Resilient Modulus Mr-v, for Level I analysis

Regression Equation (as defined in Chapter 3 of this report):

$$M_r = k_1 P_a \left(\frac{\theta}{P_a}\right)^{k_2} \left(\frac{\tau_{oct}}{P_a} + 1\right)^{k_3}$$

$k_1 = 1699.46$

$k_2 = 0.71$

$k_3 = 0.04$

Resilient Vertical Modulus at Confining Pressure = 5 psi and Deviatoric Stress = 15 psi

Mr-v = 42.15 ksi

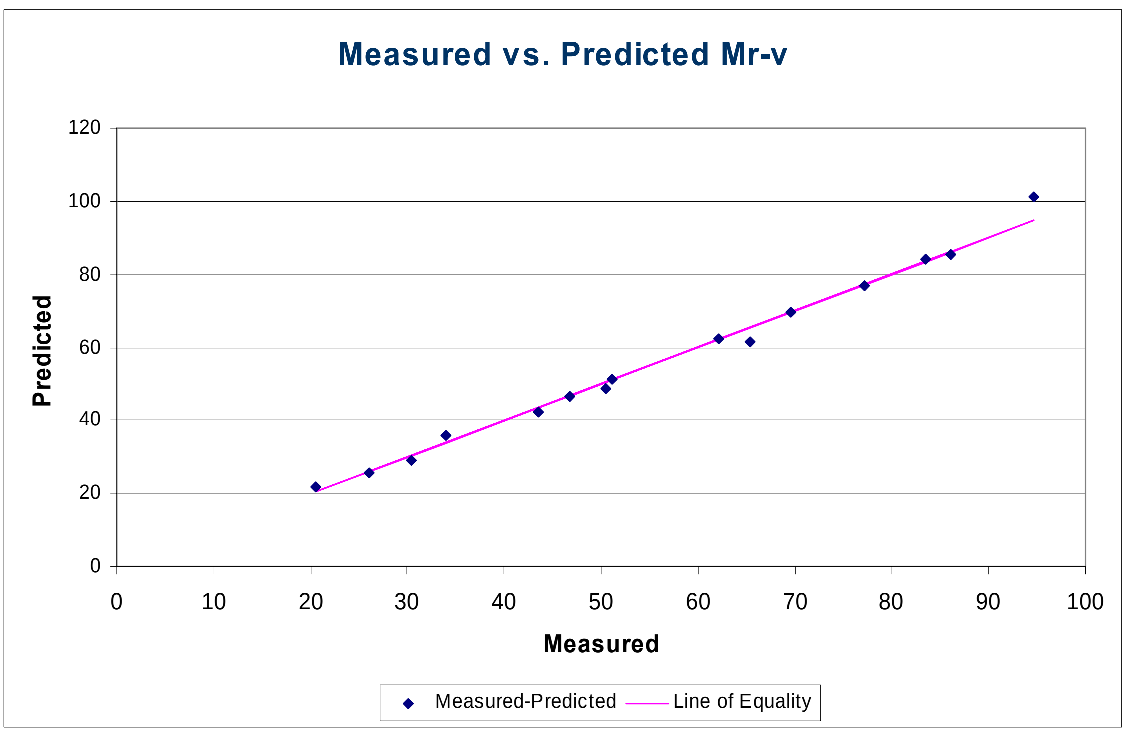


Figure D-1. Regression Plot of Resilient Modulus Results for Specimen #1.

SPECIMEN # 2

2002 Design Guide, Granular Base Resilient Modulus Mr-v, for Level I analysis

Regression Equation:

$$M_r = k_1 P_a \left(\frac{\theta}{P_a}\right)^{k_2} \left(\frac{\tau_{oct}}{P_a} + 1\right)^{k_3}$$

$k_1 = 2424.13$

$k_2 = 1.13$

$k_3 = -0.99$

Resilient Vertical Modulus at Confining Pressure = 5 psi and Deviatoric Stress = 15 psi

Mr-v = 54.21 ksi

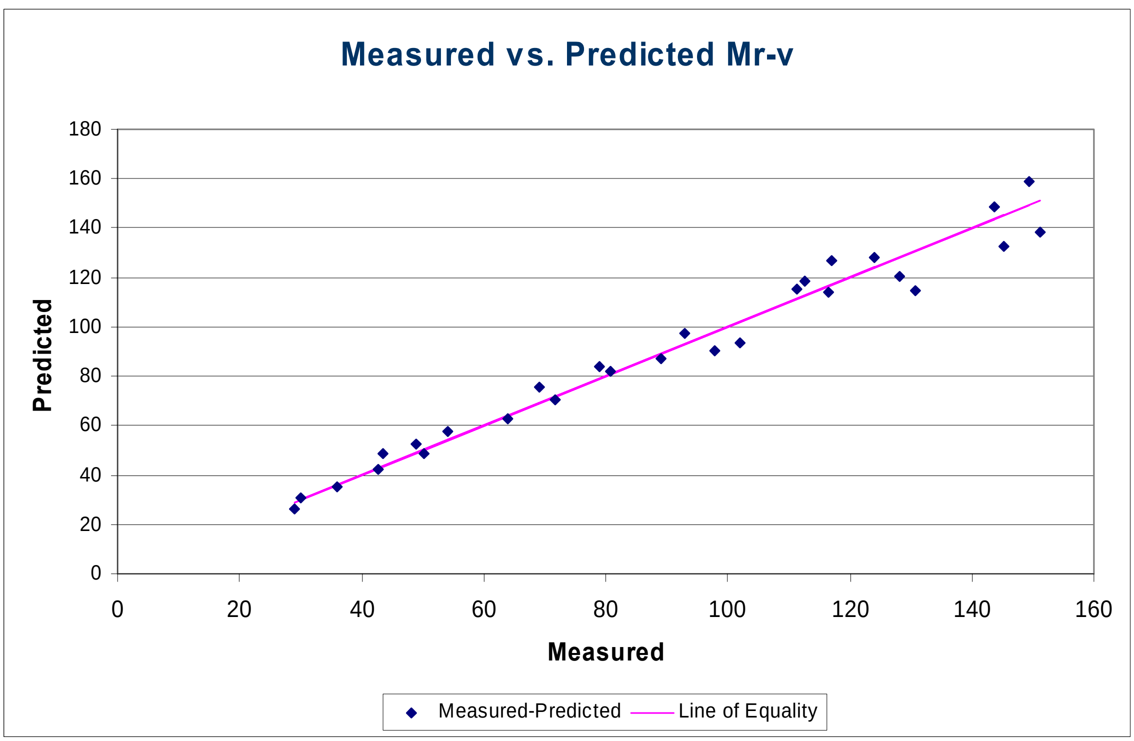


Figure D-2. Regression Plot of Resilient Modulus Results for Specimen #2.

SPECIMEN # 3

2002 Design Guide, Granular Base Resilient Modulus Mr-v, for Level I analysis

Regression Equation:

$$M_r = k_1 P_a \left(\frac{\theta}{P_a} \right)^{k_2} \left(\frac{\tau_{oct}}{P_a} + 1 \right)^{k_3}$$

$k_1 = 2591.25$

$k_2 = 1.02$

$k_3 = -0.98$

Resilient Vertical Modulus at Confining Pressure = 5 psi and Deviatoric Stress = 15 psi

Mr-v = 53.63 ksi

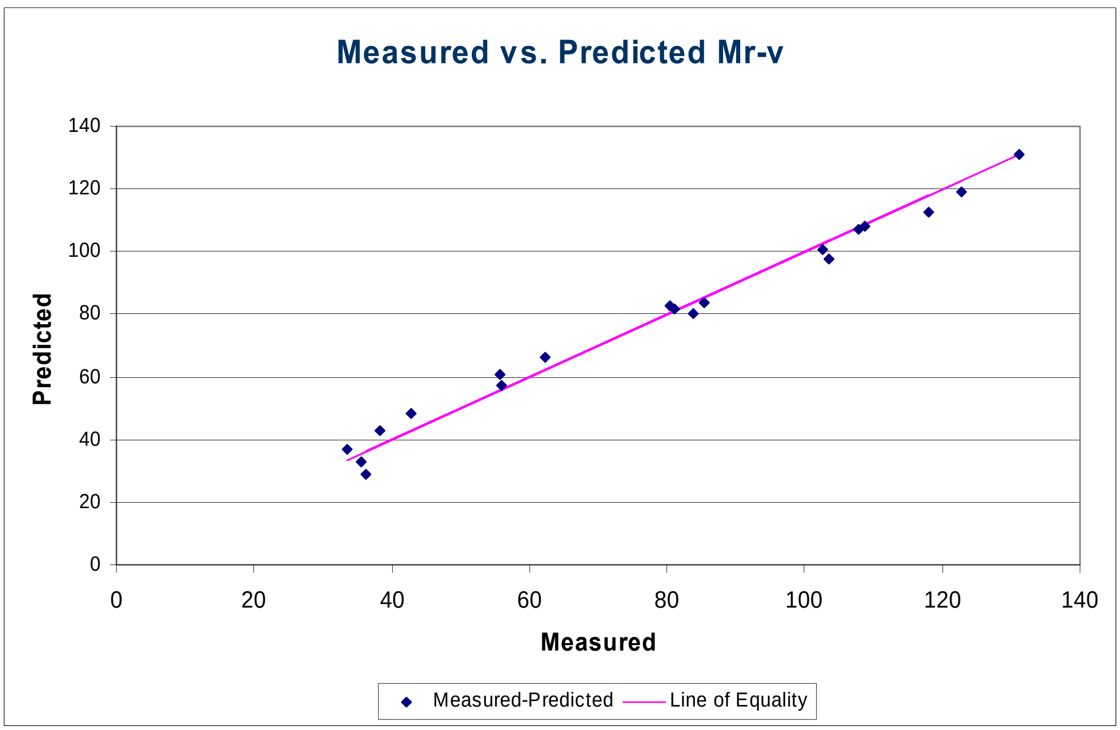


Figure D-3. Regression Plot of Resilient Modulus Results for Specimen #3.

SPECIMEN # 4

2002 Design Guide, Granular Base Resilient Modulus Mr-v, for Level I analysis

Regression Equation:

$$M_r = k_1 P_a \left(\frac{\theta}{P_a}\right)^{k_2} \left(\frac{\tau_{oct}}{P_a} + 1\right)^{k_3}$$

$k_1 = 2406.69$

$k_2 = 0.81$

$k_3 = -0.55$

Resilient Vertical Modulus at Confining Pressure = 5 psi and Deviatoric Stress = 15 psi

Mr-v = 50.73 ksi

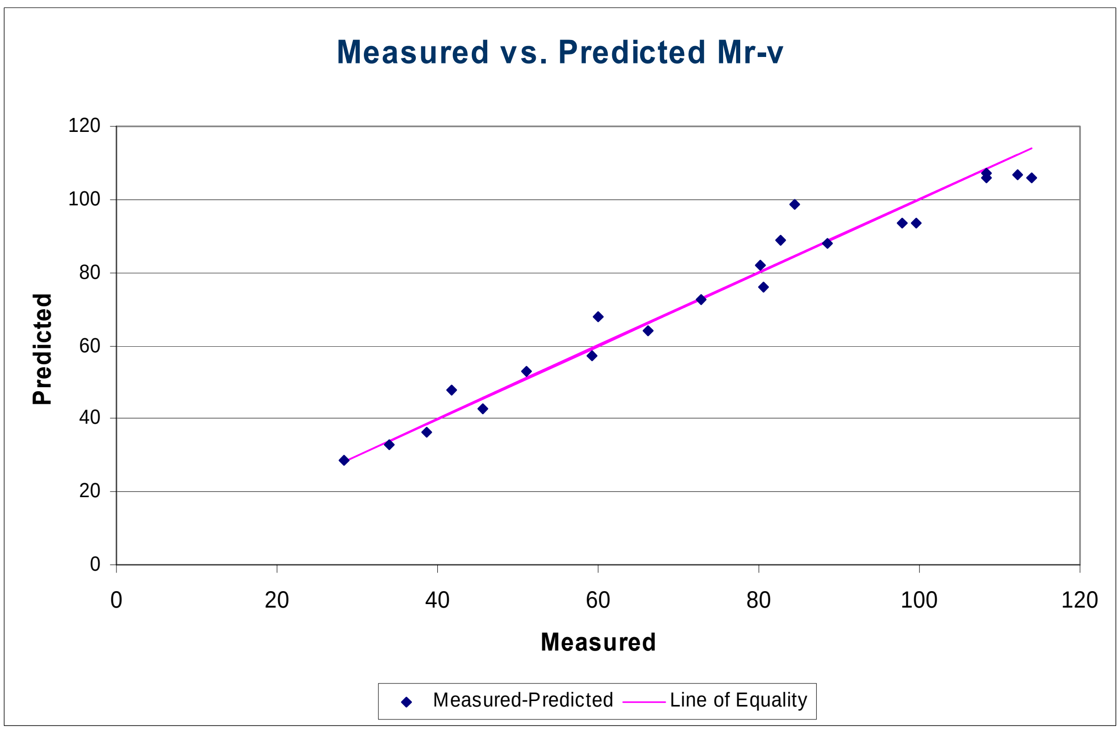


Figure D-4. Regression Plot of Resilient Modulus Results for Specimen #4.

SPECIMEN # 5

2002 Design Guide, Granular Base Resilient Modulus Mr-v, for Level I analysis

Regression Equation:

$$M_r = k_1 P_a \left(\frac{\theta}{P_a}\right)^{k_2} \left(\frac{\tau_{oct}}{P_a} + 1\right)^{k_3}$$

$k_1 = 2321.15$

$k_2 = 1.05$

$k_3 = -0.83$

Resilient Vertical Modulus at Confining Pressure = 5 psi and Deviatoric Stress = 15 psi

Mr-v = 51.97 ksi

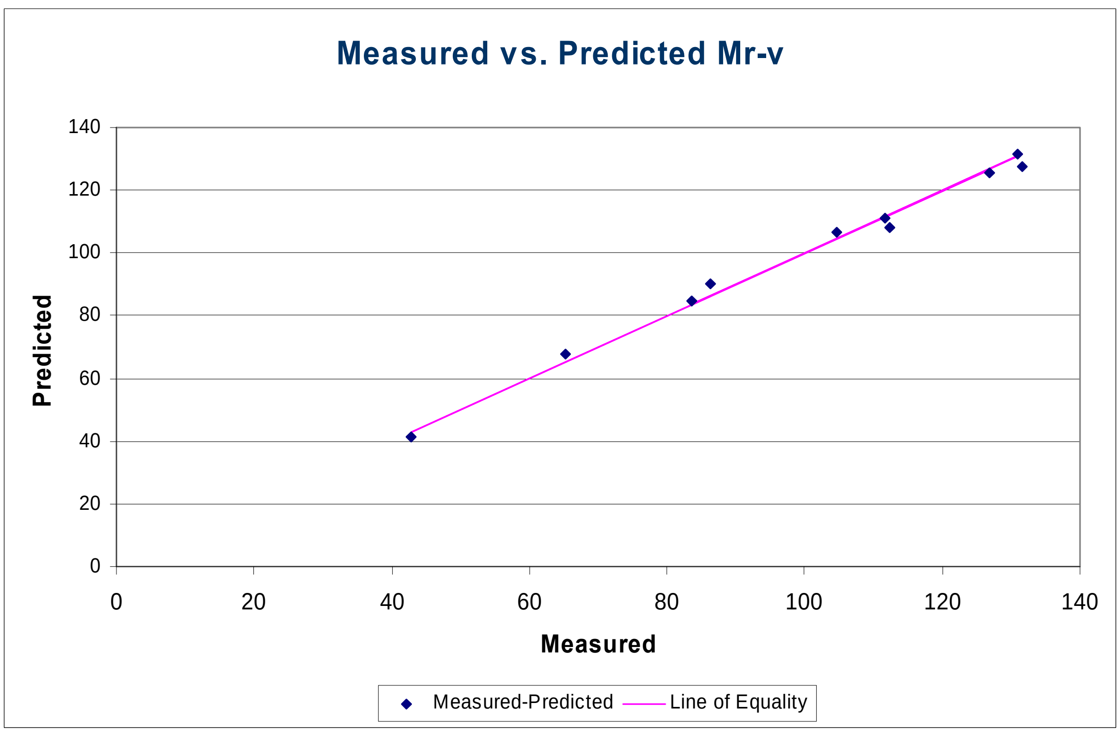


Figure D-5. Regression Plot of Resilient Modulus Results for Specimen #5.

SPECIMEN # 6

2002 Design Guide, Granular Base Resilient Modulus Mr-v, for Level I analysis

Regression Equation:

$$M_r = k_1 P_a \left(\frac{\theta}{P_a} \right)^{k_2} \left(\frac{\tau_{oct}}{P_a} + 1 \right)^{k_3}$$

$k_1 = 2002.96$

$k_2 = 0.74$

$k_3 = -0.45$

Resilient Vertical Modulus at Confining Pressure = 5 psi and Deviatoric Stress = 15 psi

Mr-v = 41.94 ksi

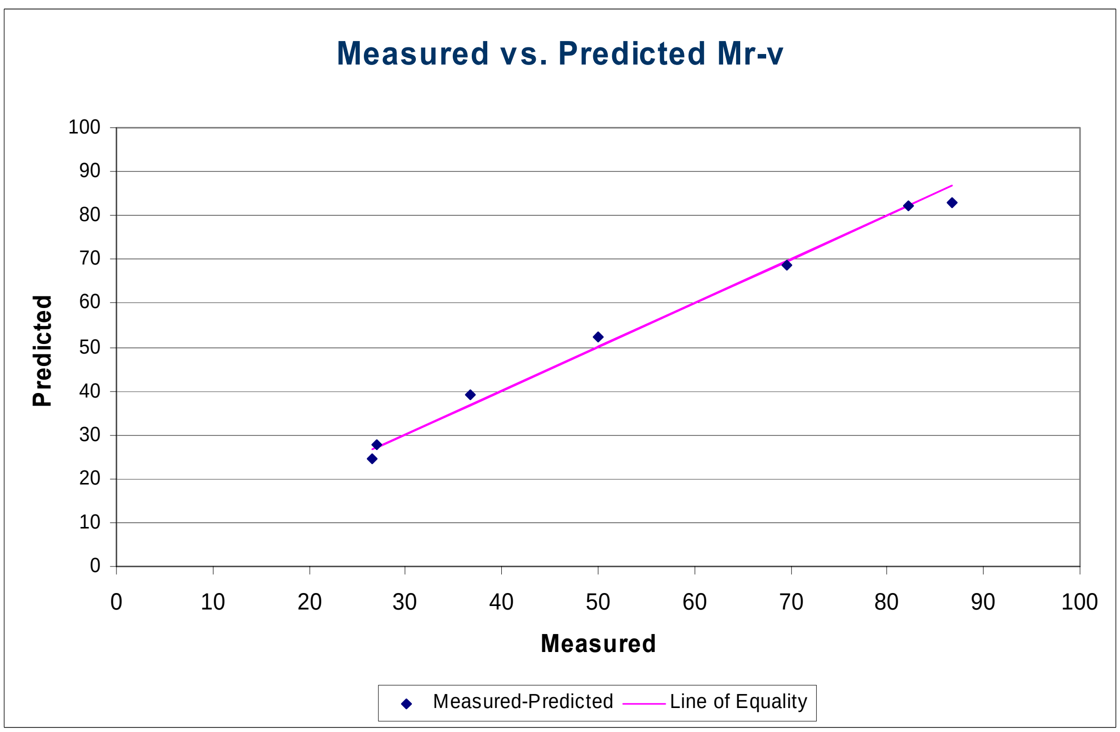


Figure D-6. Regression Plot of Resilient Modulus Results for Specimen #6.

SPECIMEN # 7

2002 Design Guide, Granular Base Resilient Modulus Mr-v, for Level I analysis

Regression Equation:

$$M_r = k_1 P_a \left(\frac{\theta}{P_a} \right)^{k_2} \left(\frac{\tau_{oct}}{P_a} + 1 \right)^{k_3}$$

$k_1 = 2057.65$

$k_2 = 1.25$

$k_3 = -1.26$

Recommended Resilient Vertical Modulus at Confining Pressure = 5 psi and Deviatoric Stress = 15 psi

Mr-v = 45.02 ksi

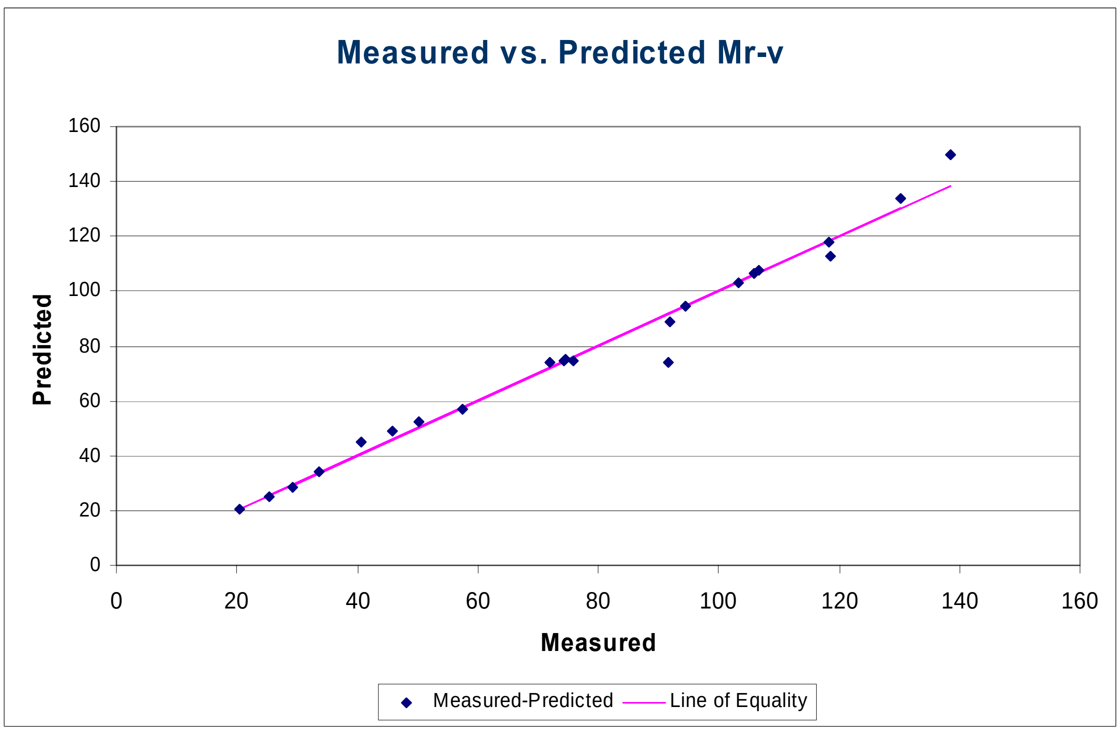


Figure D- 7. Regression Plot of Resilient Modulus Results for Specimen #7.

APPENDIX E:

PRELIMINARY TEST RESULTS FOR GRANITE MOUNTAIN AND SAWYER PIT MATERIALS

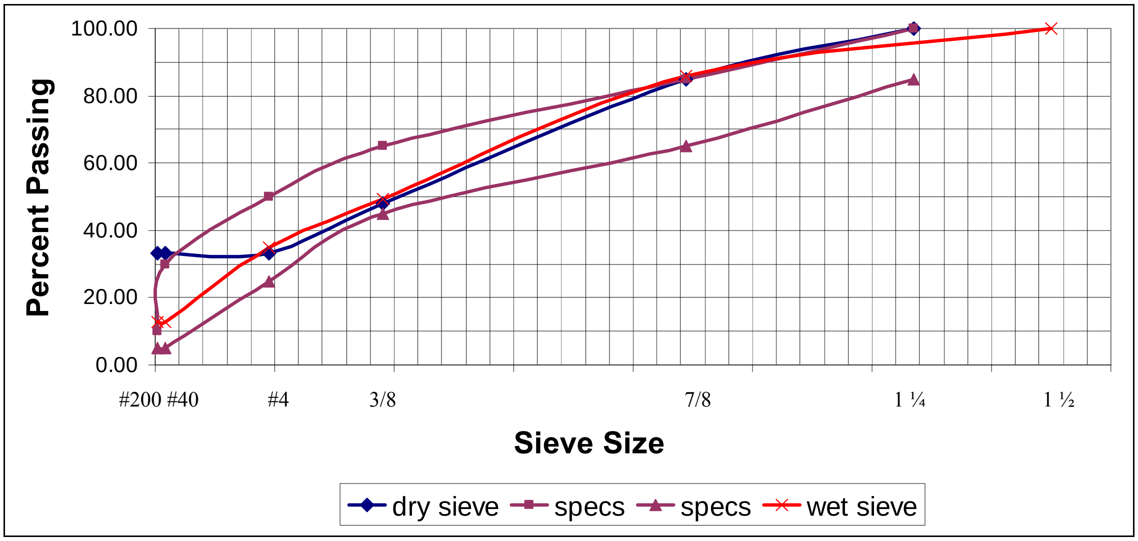


Figure E-1. Gradation on Granite Mountain.

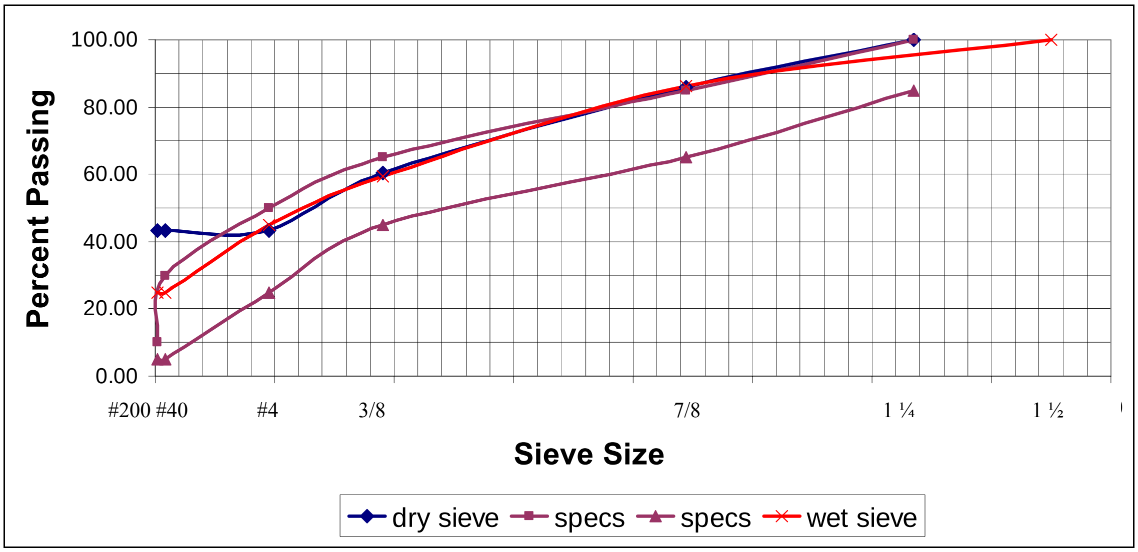


Figure E-2. Gradation on Sawyer Pit.

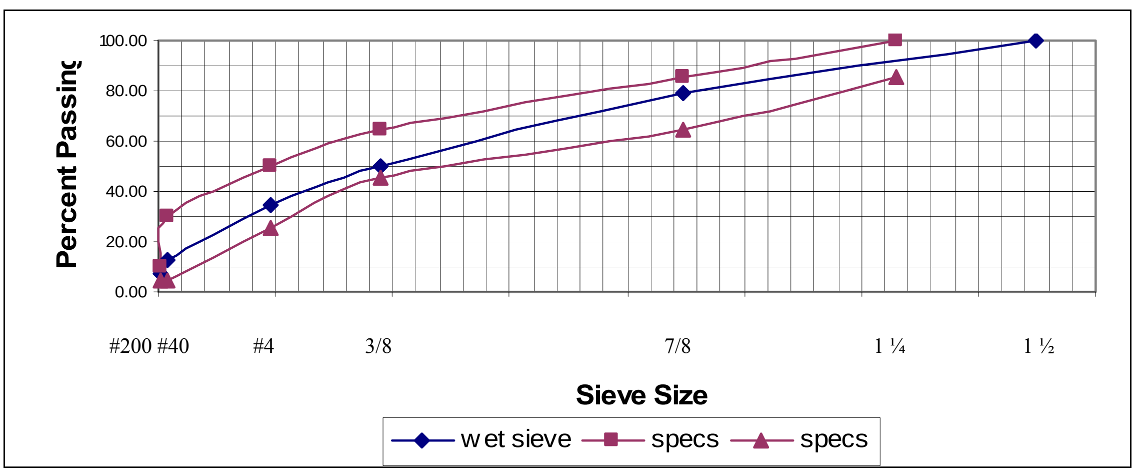


Figure E-3. Gradation on Springdale Pit.

Wet Ball Mill (WBM) for Granite Mountain

Weight before WBM wear = 3502.5 g

Sieve Analysis after WBM Wear

Sieve	Individual Weight (g)	Cumulative Weight (g)	Cumulative %
1 3/4			
1 1/4			
7/8	521.4		14.88651
5/8		946.2	27.014989
3/8		1468.2	41.91863
#4		1931	55.132049
#10		2330	66.523911
#20		2618.3	74.755175
#40		2812.6	80.302641
-40		2897	82.712348

Wet Ball Mill Value = 19.7%

Wet Ball Mill for Sawyer Pit

Weight before WBM wear = 3504.7 g

Sieve Analysis after WBM Wear

Sieve	Individual Weight (g)	Cumulative Weight (g)	Cumulative %
1 3/4			
1 1/4			
7/8	102.7		2.930351
5/8		497.7	14.20093
3/8		785	22.39849
#4		1133	32.32802
#10		1487.3	42.4373
#20		1934	55.18304
#40		2140.7	61.08083
-40		2226.8	63.53754
		2270.4	64.78158

Wet Ball Mill Value = 36.5%

APPENDIX F:

TUBE SUCTION TEST RESULTS

TUBE SUCTION TEST

Data Analysis Report

SPECIMEN 1:	**Granite Mountain**
Batch Date:	July 5, 2004

SAMPLE PREPARATION

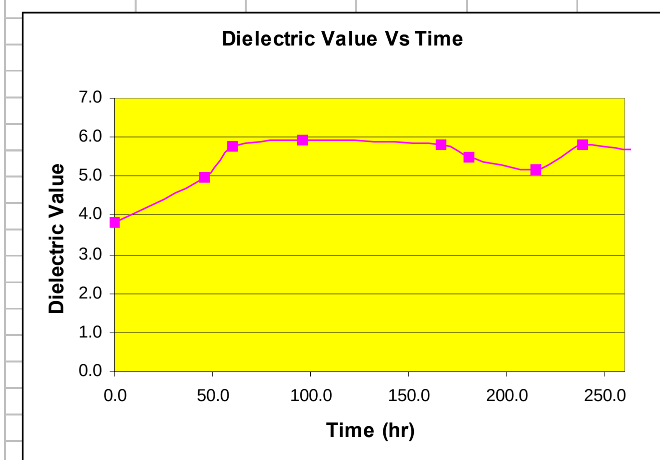
Base Cap Mass (g)	62	Wet Total Mass (g)	10675	Optimum Moisture Content (%)	7.0
Triaxial Cell Mass (g)	2166	Wet Soil Mass (g)	8447	Actual Compaction Moisture (%)	6.3
Sample Diameter (in)	6.00	Dry Soil Mass (g)	7947	Maximum Dry Density (lb/ft^3)	137.4
Sample Height (in)	8.00			Actual Dry Density (lb/ft^3)	133.8
Sample Volume (ft^3)	0.131			Relative Density (%)	97.4

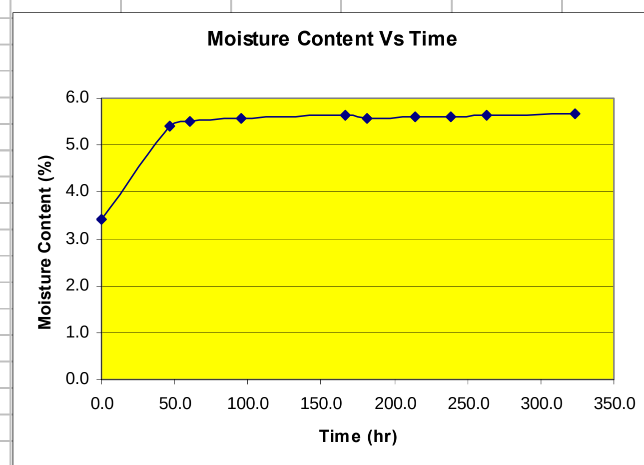
SAMPLE TESTING

Time (hr)	0.0	46.2	60.2	95.7	166.4	181.0	214.7	238.5	262.9	324.0	
Total Mass (g)	10446	10605	10613	10618	10622	10618	10620	10620	10623	10626	
Soil Mass (g)	8218	8377	8385	8390	8394	8390	8392	8392	8395	8398	
Moisture (%)	3.4	5.4	5.5	5.6	5.6	5.6	5.6	5.6	5.6	5.7	

Dielectric Values

No. 1	4.5	5.1	7.3	7.1	6.9	6.7	6.8	6.5	6.6	6.5	
No. 2	3.6	4.9	4.5	4.9	5.7	4.7	5.2	5.7	5.6	5.7	
No. 3	3.2	4.8	5.2	5.4	5.2	5.4	3.6	5.5	5.1	5.0	
No. 4	4.0	5.0	6.0	6.3	5.4	5.2	5.1	5.6	5.4	5.4	
Average	3.8	5.0	5.8	5.9	5.8	5.5	5.2	5.8	5.7	5.7	





TUBE SUCTION TEST

Data Analysis Report

SPECIMEN 2:	**Granite Mountain**
Batch Date:	July 5, 2004

SAMPLE PREPARATION

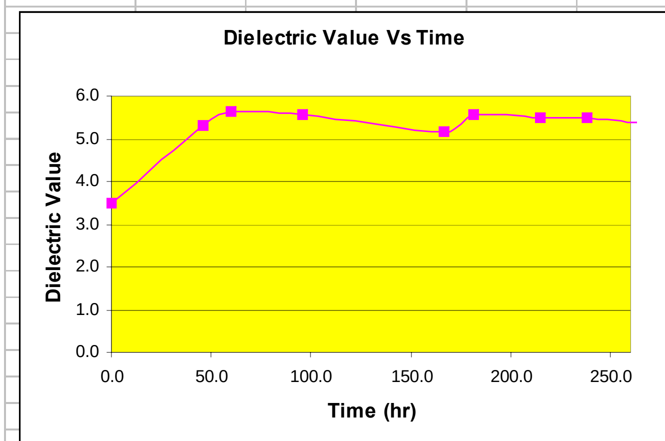
Base Cap Mass (g)	62	Wet Total Mass (g)	10811	Optimum Moisture Content (%)	7.0
Triaxial Cell Mass (g)	2085	Wet Soil Mass (g)	8664	Actual Compaction Moisture (%)	7.7
Sample Diameter (in)	6.00	Dry Soil Mass (g)	8047	Maximum Dry Density (lb/ft^3)	137.4
Sample Height (in)	7.90			Actual Dry Density (lb/ft^3)	137.2
Sample Volume (ft^3)	0.129			Relative Density (%)	99.9

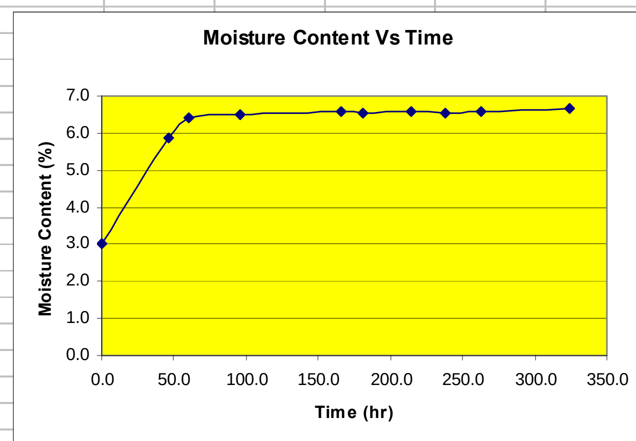
SAMPLE TESTING

Time (hr)	0.0	46.2	60.2	95.7	166.4	181.0	214.7	238.5	262.9	324.0	
Total Mass (g)	10438	10665	10709	10718	10724	10721	10722	10720	10725	10729	
Soil Mass (g)	8291	8518	8562	8571	8577	8574	8575	8573	8578	8582	
Moisture (%)	3.0	5.8	6.4	6.5	6.6	6.5	6.6	6.5	6.6	6.6	

Dielectric Values

No. 1	4.1	5.9	5.9	5.8	5.1	5.9	5.8	6.0	5.7	5.4	
No. 2	3.0	5.0	5.2	5.4	5.1	5.4	5.0	5.2	5.3	5.1	
No. 3	3.0	4.9	5.9	5.3	4.9	6.2	5.3	5.3	5.5	5.3	
No. 4	3.9	5.5	5.5	5.8	5.6	4.7	5.9	5.4	5.1	5.4	
Average	3.5	5.3	5.6	5.6	5.2	5.6	5.5	5.5	5.4	5.3	





TUBE SUCTION TEST

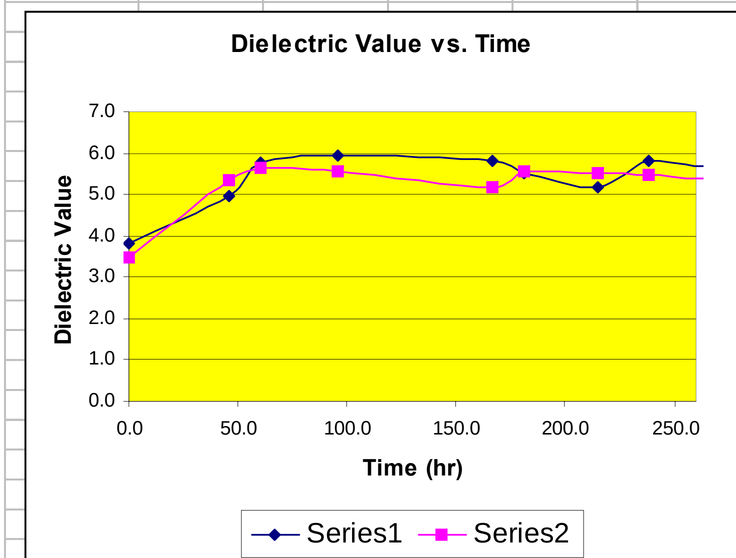
Data Analysis Report

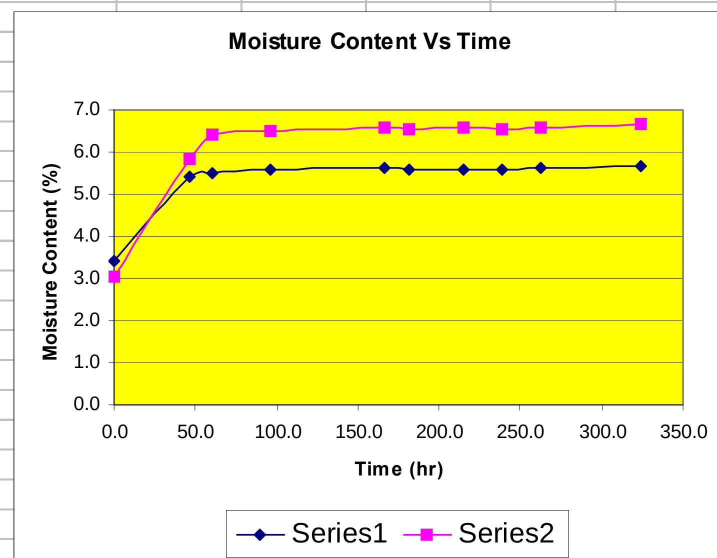
SUMMARY:	**Granite Mountain**
Batch Date:	July 5, 2004

SAMPLE TESTING

Time (hr)	0.0	46.2	60.2	95.7	166.4	181.0	214.7	238.5	262.9	324.0
Specimen No	**Average Dielectric Value**									
1	3.8	5.0	5.8	5.9	5.8	5.5	5.2	5.8	5.7	5.7
2	3.5	5.3	5.6	5.6	5.2	5.6	5.5	5.5	5.4	5.3
Specimen No	**Average Water Content During Soaking (%)**									
1	3.4	5.4	5.5	5.6	5.6	5.6	5.6	5.6	5.6	5.7
2	3.0	5.8	6.4	6.5	6.6	6.5	6.6	6.5	6.6	6.6

Average Final Dielectric Value	5.5	Average Final Gravimetric Water Content (%)	6.2
Moisture Susceptibility Ranking	Good	Average Water Loss in Drying (% of OMC)	54.0





TUBE SUCTION TEST

Data Analysis Report

SPECIMEN 1:	**Arkansas #1**
Batch Date:	June 23, 2004

SAMPLE PREPARATION

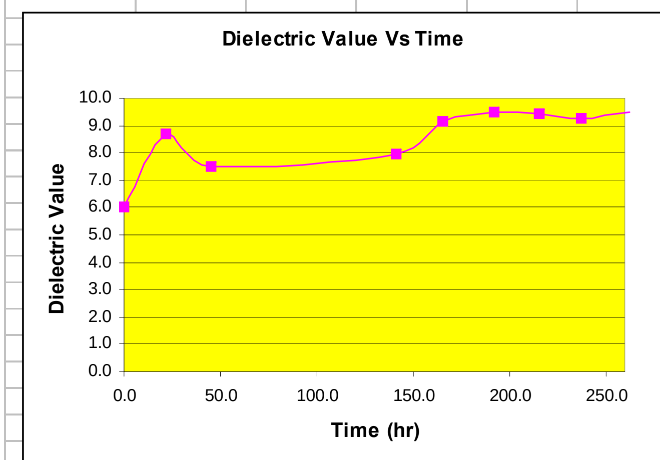
Base Cap Mass (g)	58	Wet Total Mass (g)	10448	Optimum Moisture Content (%)	5.5
Triaxial Cell Mass (g)	2162	Wet Soil Mass (g)	8228	Actual Compaction Moisture (%)	5.5
Sample Diameter (in)	6.00	Dry Soil Mass (g)	7801	Maximum Dry Density (lb/ft^3)	147.0
Sample Height (in)	7.50			Actual Dry Density (lb/ft^3)	140.1
Sample Volume (ft^3)	0.123			Relative Density (%)	95.3

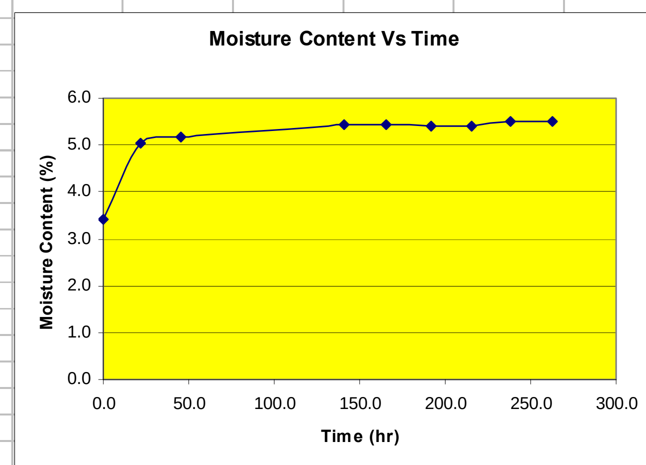
SAMPLE TESTING

Time (hr)	0.0	22.0	45.6	141.1	165.8	192.2	215.6	237.7	262.5		
Total Mass (g)	10287	10414	10424	10446	10445	10443	10443	10450	10450		
Soil Mass (g)	8067	8194	8204	8226	8225	8223	8223	8230	8230		
Moisture (%)	3.4	5.0	5.2	5.5	5.4	5.4	5.4	5.5	5.5		

Dielectric Values

No. 1	5.7	8.6	8.2	8.3	9.4	10.2	9.3	9.7	9.9		
No. 2	6.2	8.8	6.3	7.3	7.5	8.3	9.0	8.6	8.9		
No. 3	6.5	9.0	9.2	7.1	10.1	9.7	9.2	9.9	10.1		
No. 4	5.6	8.3	6.3	9.2	9.6	9.7	10.3	8.8	9.1		
Average	6.0	8.7	7.5	8.0	9.2	9.5	9.5	9.3	9.5		





TUBE SUCTION TEST

Data Analysis Report

SPECIMEN 2:	**Arkansas #1**
Batch Date:	June 23, 2004

SAMPLE PREPARATION

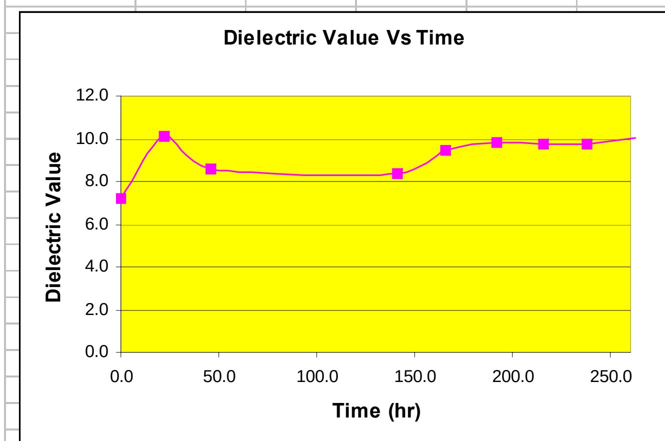
Base Cap Mass (g)	65	Wet Total Mass (g)	10439	Optimum Moisture Content (%)	5.5
Triaxial Cell Mass (g)	2121	Wet Soil Mass (g)	8253	Actual Compaction Moisture (%)	5.1
Sample Diameter (in)	6.00	Dry Soil Mass (g)	7851	Maximum Dry Density (lb/ft^3)	147.0
Sample Height (in)	7.40			Actual Dry Density (lb/ft^3)	143.0
Sample Volume (ft^3)	0.121			Relative Density (%)	97.2

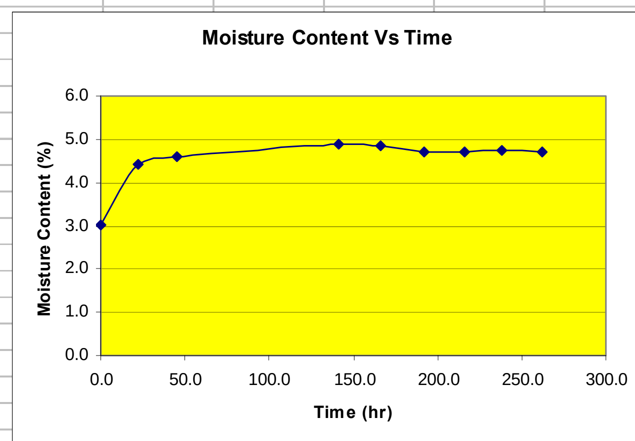
SAMPLE TESTING

Time (hr)	0.0	22.0	45.6	141.1	165.8	192.2	215.6	237.7	262.5		
Total Mass (g)	10276	10384	10397	10420	10418	10407	10408	10409	10406		
Soil Mass (g)	8090	8198	8211	8234	8232	8221	8222	8223	8220		
Moisture (%)	3.0	4.4	4.6	4.9	4.8	4.7	4.7	4.7	4.7		

Dielectric Values

No. 1	6.4	9.6	8.2	7.1	12.8	13.0	12.7	9.9	13.5		
No. 2	9.1	13.1	6.8	7.8	9.7	10.9	10.3	8.0	10.4		
No. 3	5.6	7.0	13.0	12.0	8.0	8.1	8.1	13.2	8.2		
No. 4	7.6	10.8	6.4	6.6	7.4	7.2	8.0	7.8	8.1		
Average	7.2	10.1	8.6	8.4	9.5	9.8	9.8	9.7	10.1		





TUBE SUCTION TEST

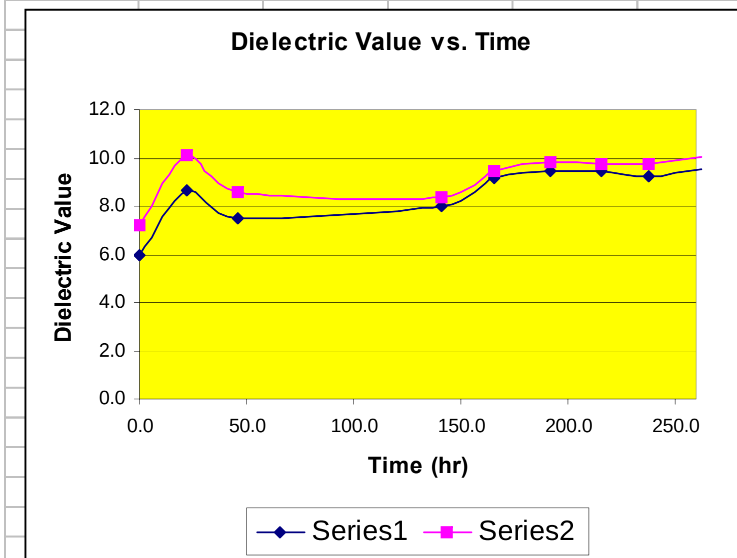
Data Analysis Report

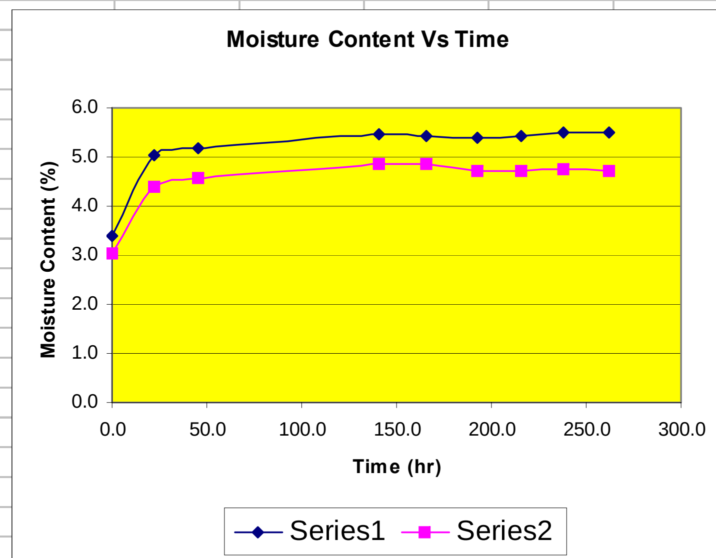
SUMMARY:	**Arkansas #1**
Batch Date:	June 23, 2004

SAMPLE TESTING

Time (hr)	0.0	22.0	45.6	141.1	165.8	192.2	215.6	237.7	262.5		
Specimen No	**Average Dielectric Value**										
1	6.0	8.7	7.5	8.0	9.2	9.5	9.5	9.3	9.5		
2	7.2	10.1	8.6	8.4	9.5	9.8	9.8	9.7	10.1		
Specimen No	**Average Water Content During Soaking (%)**										
1	3.4	5.0	5.2	5.5	5.4	5.4	5.4	5.5	5.5		
2	3.0	4.4	4.6	4.9	4.8	4.7	4.7	4.7	4.7		

Average Final Dielectric Value	9.8	Average Final Gravimetric Water Content (%)	0.0
Moisture Susceptibility Ranking	Good	Average Water Loss in Drying (% of OMC)	41.5





TUBE SUCTION TEST

Data Analysis Report

SPECIMEN 1:	**Sawyer Pit (Oklahoma)**
Batch Date:	June 23, 2004

SAMPLE PREPARATION

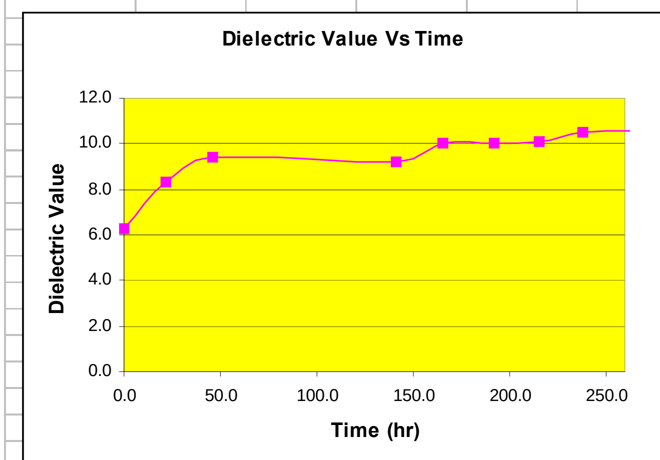
Base Cap Mass (g)	64	Wet Total Mass (g)	10641	Optimum Moisture Content (%)	5.5
Triaxial Cell Mass (g)	2124	Wet Soil Mass (g)	8454	Actual Compaction Moisture (%)	5.0
Sample Diameter (in)	6.00	Dry Soil Mass (g)	8054	Maximum Dry Density (lb/ft^3)	138.0
Sample Height (in)	7.90			Actual Dry Density (lb/ft^3)	137.4
Sample Volume (ft^3)	0.129			Relative Density (%)	99.5

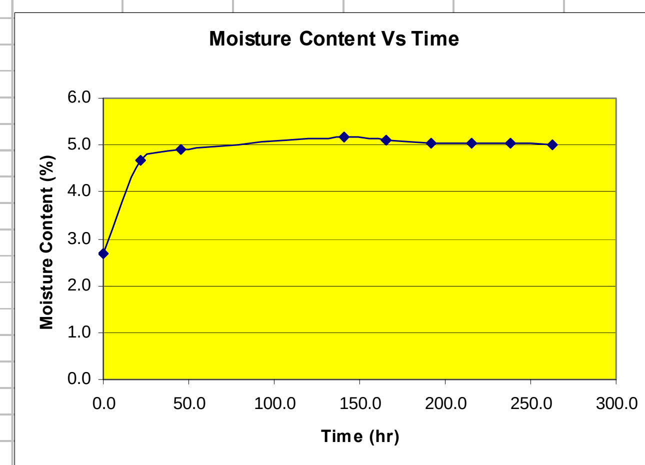
SAMPLE TESTING

Time (hr)	0.0	22.2	45.7	141.0	165.7	192.2	215.6	237.8	262.4		
Total Mass (g)	10458	10618	10636	10657	10654	10648	10646	10647	10644		
Soil Mass (g)	8270	8430	8449	8469	8466	8461	8459	8459	8457		
Moisture (%)	2.7	4.7	4.9	5.2	5.1	5.0	5.0	5.0	5.0		

Dielectric Values

No. 1	6.6	7.8	9.0	8.9	9.8	10.8	10.4	10.1	10.0		
No. 2	6.5	8.2	9.6	9.3	10.2	9.5	9.7	11.1	10.8		
No. 3	5.7	8.7	9.8	9.2	10.4	10.2	10.5	10.6	10.9		
No. 4	6.3	8.6	9.3	9.5	9.7	9.7	9.9	10.2	10.5		
Average	6.3	8.3	9.4	9.2	10.0	10.1	10.1	10.5	10.6		





TUBE SUCTION TEST

Data Analysis Report

SPECIMEN 2:	**Sawyer Pit (Oklahoma)**
Batch Date:	June 23, 2004

SAMPLE PREPARATION

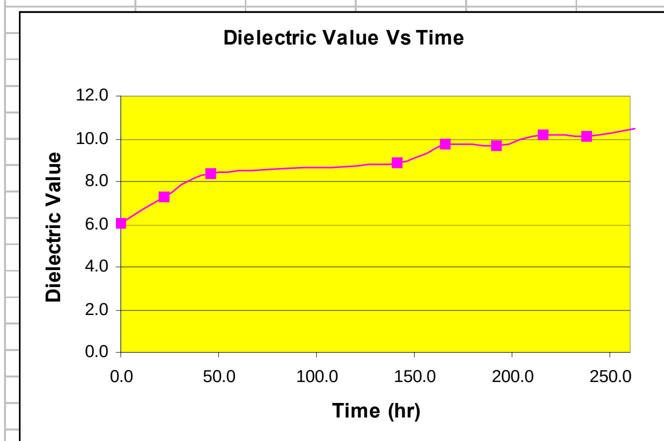
Base Cap Mass (g)	62	Wet Total Mass (g)	10765	Optimum Moisture Content (%)	5.5
Triaxial Cell Mass (g)	2184	Wet Soil Mass (g)	8519	Actual Compaction Moisture (%)	6.1
Sample Diameter (in)	6.00	Dry Soil Mass (g)	8027	Maximum Dry Density (lb/ft^3)	138.0
Sample Height (in)	7.90			Actual Dry Density (lb/ft^3)	136.9
Sample Volume (ft^3)	0.129			Relative Density (%)	99.2

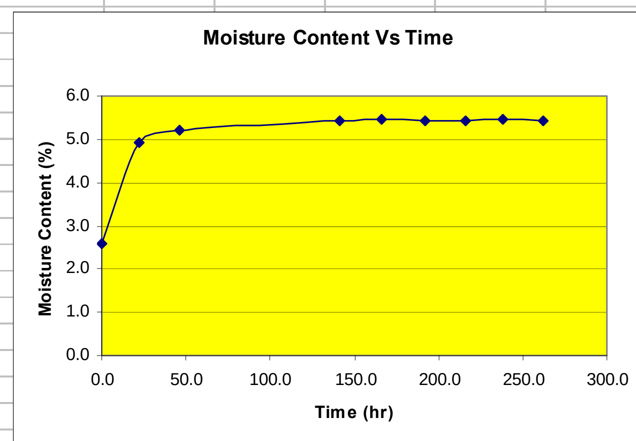
SAMPLE TESTING

Time (hr)	0.0	22.2	45.7	141.0	165.7	192.2	215.6	237.8	262.4		
Total Mass (g)	10481	10667	10690	10710	10710	10708	10707	10711	10709		
Soil Mass (g)	8235	8421	8444	8464	8464	8462	8461	8465	8463		
Moisture (%)	2.6	4.9	5.2	5.4	5.4	5.4	5.4	5.5	5.4		

Dielectric Values

No. 1	6.2	7.4	9.0	9.1	9.8	10.0	10.0	10.2	10.5		
No. 2	5.7	7.0	8.1	9.0	9.6	9.1	9.9	9.6	10.2		
No. 3	6.2	6.7	7.9	8.5	10.2	9.4	10.4	10.3	10.7		
No. 4	6.1	8.0	8.5	8.8	9.4	10.1	10.3	10.2	10.4		
Average	6.1	7.3	8.4	8.9	9.8	9.7	10.2	10.1	10.5		





TUBE SUCTION TEST

Data Analysis Report

SUMMARY:	**Sawyer Pit (Oklahoma)**
Batch Date:	June 23, 2004

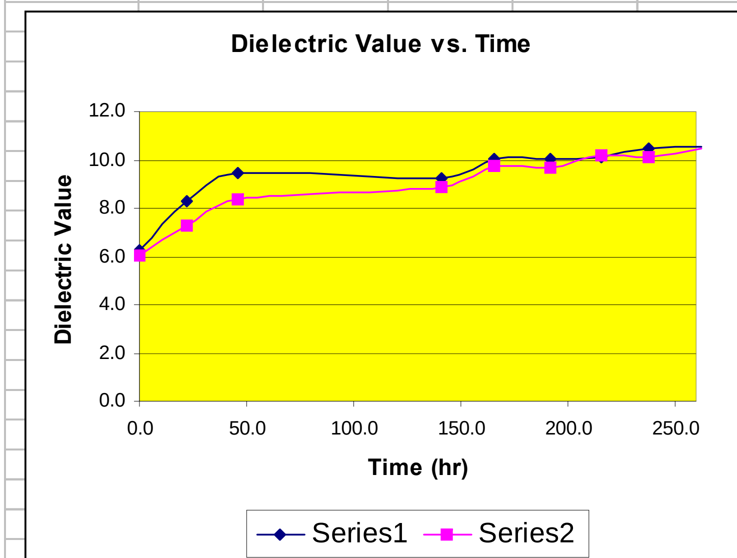
SAMPLE TESTING

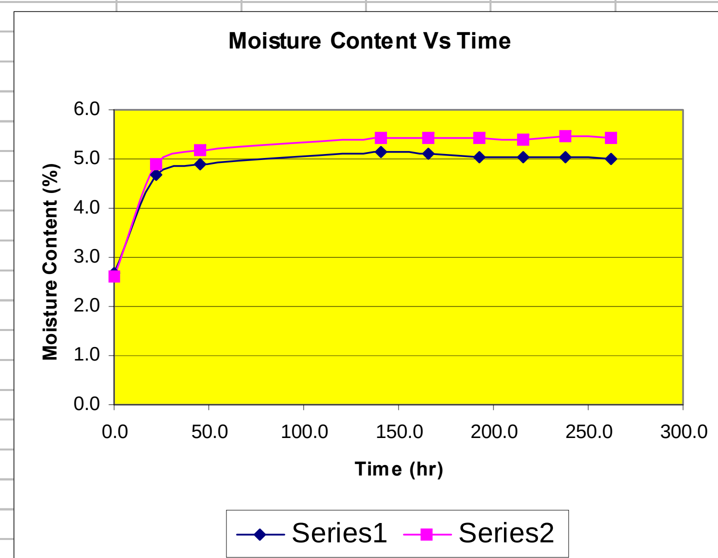
Time (hr)	0.0	22.2	45.7	141.0	165.7	192.2	215.6	237.8	262.4		

Specimen No	Average Dielectric Value										
1	6.3	8.3	9.4	9.2	10.0	10.1	10.1	10.5	10.6		
2	6.1	7.3	8.4	8.9	9.8	9.7	10.2	10.1	10.5		

Specimen No	Average Water Content During Soaking (%)										
1	2.7	4.7	4.9	5.2	5.1	5.0	5.0	5.0	5.0		
2	2.6	4.9	5.2	5.4	5.4	5.4	5.4	5.5	5.4		

Average Final Dielectric Value	10.5	Average Final Gravimetric Water Content (%)	5.2
Moisture Susceptibility Ranking	Good	Average Water Loss in Drying (% of OMC)	52.1





APPENDIX G:

RESILIENT MODULUS AND PERMANENT DEFORMATION TEST RESULTS

GRANITE MOUNTAIN

2002 Design Guide, Granular Base Resilient Modulus Mr-v, for Level I analysis

Regression Equation (as defined in Chapter 3 of this report):

$$M_r = k_1 P_a \left(\frac{\theta}{P_a} \right)^{k_2} \left(\frac{\tau_{oct}}{P_a} + 1 \right)^{k_3}$$

k_1 = 1785.57

k_2 = 0.60

k_3 = -1.04

Resilient Vertical Modulus at Confining Pressure = 5 psi and Deviatoric Stress = 15 psi

Mr-v= 58.18 ksi

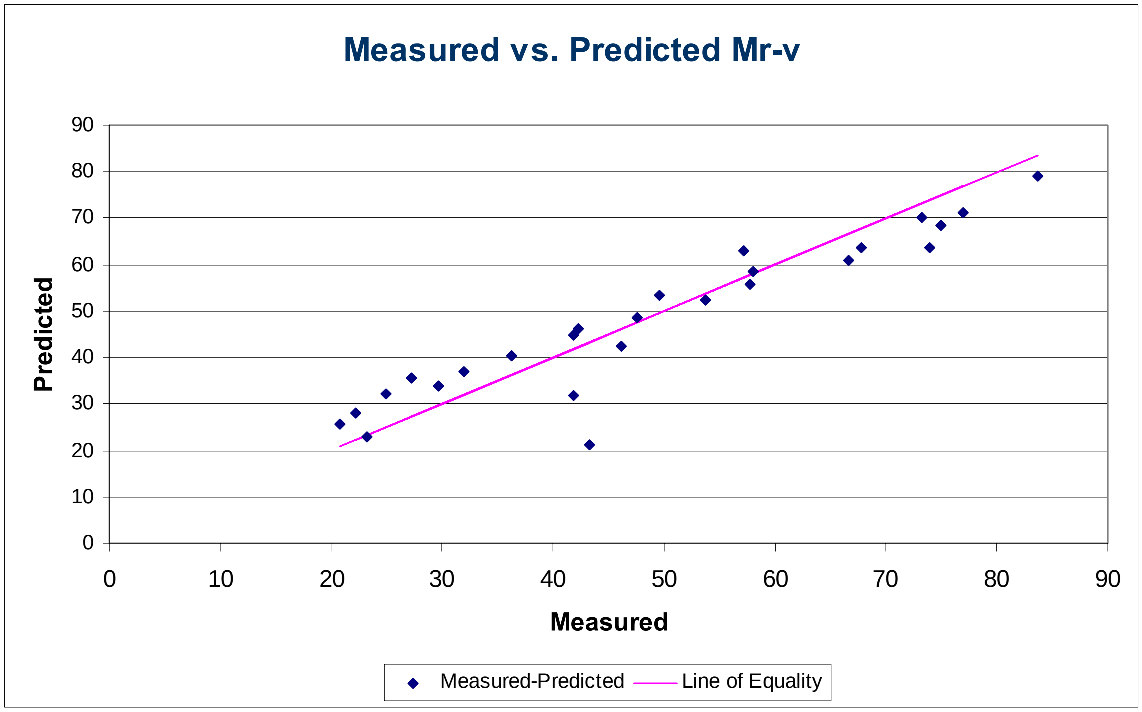


Figure G-1. Measured versus Predicted Resilient Modulus Valve for Granite Mountain.

SPRINGDALE

2002 Design Guide, Granular Base Resilient Modulus Mr-v, for Level I analysis

Regression Equation:

$$M_r = k_1 P_a \left(\frac{\theta}{P_a}\right)^{k_2} \left(\frac{\tau_{oct}}{P_a} + 1\right)^{k_3}$$

$k_1 = 2903.52$

$k_2 = 1.01$

$k_3 = -0.24$

Resilient Vertical Modulus at Confining Pressure = 5 psi and Deviatoric Stress = 15 psi

Mr-v= 36.66 ksi

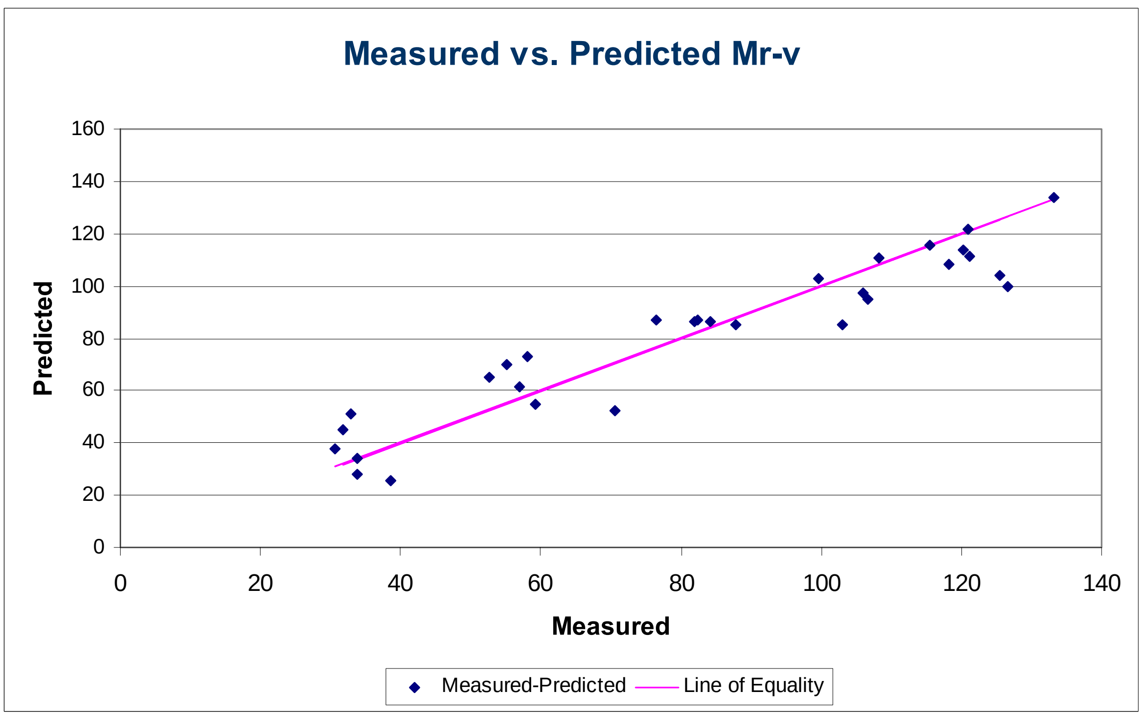


Figure G-2. Measured versus Predicted Resilient Modulus Valve for Springdale.

SAWYER PIT

2002 Design Guide, Granular Base Resilient Modulus Mr-v, for Level I analysis

Regression Equation:

$$M_r = k_1 P_a \left(\frac{\theta}{P_a}\right)^{k_2} \left(\frac{\tau_{oct}}{P_a} + 1\right)^{k_3}$$

$k_1 = 1525.34$

$k_2 = 0.64$

$k_3 = -0.34$

Resilient Vertical Modulus at Confining Pressure = 5 psi and Deviator Stress = 15 psi

Mr-v= 31.11 ksi

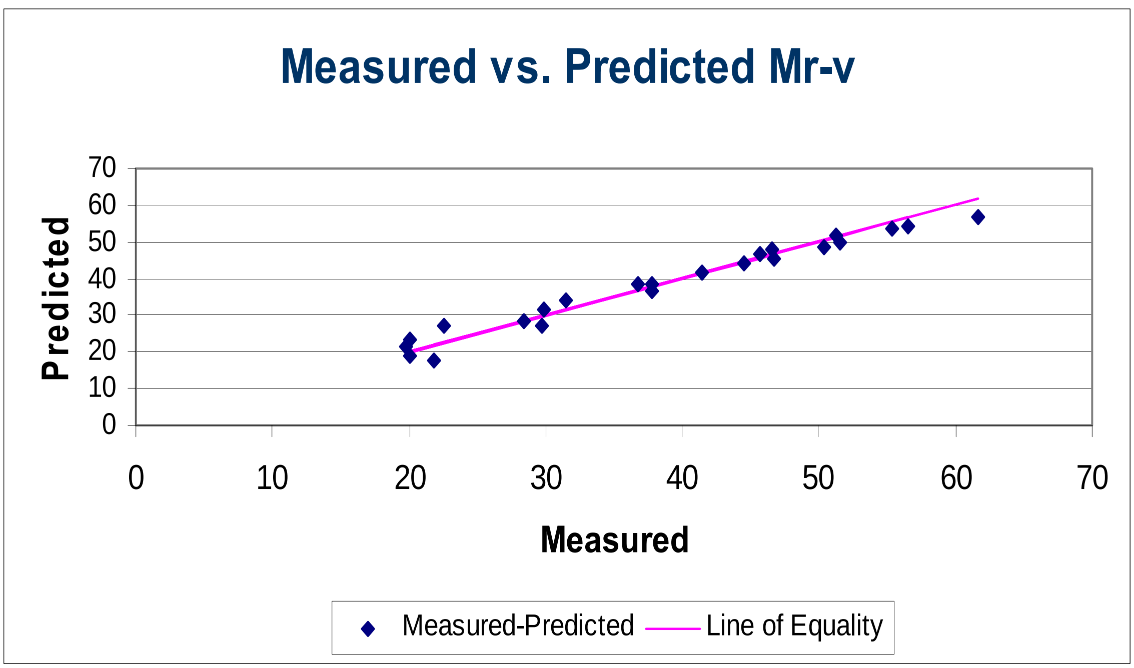


Figure G-3. Measured versus Predicted Resilient Modulus Valve for Sawyer Pit.

Permanent Deformation Test Result for Springdale Material