TECHNICAL REPORT STANDARD PAGE

`1. Report No. **FHWA/LA.14/521**	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle **Design Values of Resilient Modulus for Stabilized and Non-Stabilized Base**	5. Report Date July 2015 6. Performing Organization Code LTRC Project Number: 10-3GT State Project Number: 736-99-1727	
7. Author(s) Khalil Hanifa, Murad Y. Abu-Farsakh, Gavin P. Gautreau	8. Performing Organization Report No.	
9. Performing Organization Name and Address Louisiana Transportation Research Center 4101 Gourrier Avenue Baton Rouge, LA 70808	10. Work Unit No. 11. Contract or Grant No.	
12. Sponsoring Agency Name and Address Louisiana Department of Transportation and Development P.O. Box 94245 Baton Rouge, LA 70804-9245	13. Type of Report and Period Covered **Final Report September 2010-September 2013** 14. Sponsoring Agency Code	

15. Supplementary Notes

Conducted in Cooperation with the U.S. Department of Transportation, Federal Highway Administration

16. Abstract

The American Association of State Highway Transportation Officials' (AASHTO) new AASHTOWare pavement design software, Pavement ME Design, has recommended the use of laboratory determined resilient modulus of base, subbase, and subgrade soils in characterizing pavements for their structural analysis and design. Pavement ME Design requires the base course resilient modulus as an input parameter for pavement design. These resilient modulus design values for stabilized (bound) and non-stabilized (unbound) base materials are not well established for Louisiana. The primary objective of this research study was to determine resilient modulus design values for typical base course materials, as allowed by Louisiana Department of Transportation and Development (DOTD) specifications. The study also intended to develop resilient modulus models (k_1, k_2, and k_3) for use to evaluate the resilient modulus for unbound base course materials for use in the MEPDG. To accomplish this objective, typical base course materials specified and constructed as part of Louisiana roadways were evaluated in this research study. Three stabilized soil types (classified as A-2-4, A-4, and A-6, according to AASHTO soil classification) were evaluated as bound base materials. Two field materials (in-place cement stabilized and in-place cement treated base course) were also evaluated as bound base materials. Two aggregate types (Mexican Limestone and Recycled PCC (crushed)) were evaluated as unbound base materials. The basic material properties of the bound and unbound base materials were characterized through laboratory tests; repeated load triaxial tests were also conducted to evaluate their resilient modulus. Resilient modulus design values were recommended for the typical base course materials evaluated.

Three mathematical resilient modulus models, the National Cooperative Highway Research Program (NCHRP Project 1-37A, 2001) model, University of Kentucky Transportation Center (UKTC) model (2002), and Uzan (1985) model were evaluated. Material coefficients k_1, k_2, and k_3 for these models were obtained using multiple regression analysis of all standard testing stresses and corresponding resilient modulus values. These models provide best data "fits" between resilient modulus and testing stresses. Furthermore, using the material coefficients (k_1, k_2, and k_3) for each model, the resilient modulus can be predicted when the stress condition and type of unbound base course material is known. While the NCHRP model, UKTC model, and Uzan model all performed well for estimating the resilient modulus of unbound base materials, the NCHRP model will be recommended and made readily available to the design personnel of DOTD.

17. Key Words Resilient Modulus, Mechanistic-Empirical Pavement Design Guide (MEPDG), Bound, Unbound, Base Course		18. Distribution Statement **Unrestricted. This document is available through the National Technical Information Service, Springfield, VA 21161.**	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 133	22. Price

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Design Values of Resilient Modulus for Stabilized and Non-Stabilized Base

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State Project No. 736-99-1727

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Louisiana Department of Transportation and Development
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July 2015

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Three mathematical resilient modulus models, the National Cooperative Highway Research Program (NCHRP Project 1-37A, 2001) model, University of Kentucky Transportation Center (UKTC) model (2002), and Uzan (1985) model were also evaluated. Material coefficients k_1, k_2, and k_3 for these models were obtained using multiple regression analysis of all standard testing stresses and corresponding resilient modulus values. These models provide best data "fits" between resilient modulus and testing stresses. Furthermore, using the material coefficients (k_1, k_2, and k_3) for each model, the resilient modulus can be predicted when the stress condition and type of unbound base course material is known. While the NCHRP model, UKTC model, and Uzan model all performed well for estimating the resilient modulus of unbound base materials, the NCHRP model will be recommended and made readily available to the design personnel of DOTD.

ACKNOWLEDGMENTS

This research project is funded by the Louisiana Department of Transportation and Development (State Project No. 736-99-1727) and the Louisiana Transportation Research Center (LTRC Project No. 10-3GT). The assistance with report organization, data analysis, comments and suggestions from Zhongjie "Doc" Zhang, Pavement and Geotechnical Administrator of LTRC, are gratefully acknowledged. The authors also appreciated the assistance from the geotechnical research group of LTRC. The authors would like to thank Amar Raghavendra for assisting with resilient modulus testing, subsequent data processing and regression analysis. The authors would also like to thank Benjamin Comeaux for conducting resilient modulus tests.

IMPLEMENTATION STATEMENT

This research established resilient modulus design values for bound and unbound base course materials that can be used as inputs when the DOTD is ready to begin using Pavement ME Design. Also, for unbound base course materials, generalized constitutive models for resilient modulus were evaluated and their corresponding k_1, k_2, and k_3 parameters can be used to predict resilient modulus.

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INTRODUCTION

The American Association of State Highway Transportation Officials' (AASHTO) new AASHTOWare pavement design software, Pavement ME Design, has recommended the use of laboratory determined resilient modulus of base, subbase, and subgrade soils in characterizing pavements for their structural analysis and design. The Louisiana Department of Transportation and Development (DOTD) currently utilizes the 1993 Pavement Design Guide which requires structural coefficient input parameters. The new Pavement ME Design software requires the base course resilient modulus as an input parameter for pavement design. These resilient modulus design values for stabilized and non-stabilized base materials are not well established for Louisiana. Typical base course resilient modulus values need to be established for DOTD to begin implementing the new Pavement ME Design software in the design of pavements in Louisiana. Laboratory testing is therefore required, to establish resilient modulus values.

Current DOTD specifications allow both bound (soil cement, cement stabilized, and cement treated base course) and unbound materials to be utilized as base course materials. Bound materials are controlled by percentage of cement, moisture content and dry density to obtain design strengths and utilize moisture content and dry density (e.g., ± 2% of optimum moisture content, ≥ 95% of maximum dry density and percentage of cement) as a quality control and acceptance criteria in the field. Unbound materials are controlled by moisture content and dry density (e.g., ± 2% optimum moisture content, and ≥ 98% of maximum dry density), which are used as a quality control and acceptance criteria in the field. Resilient modulus testing is not currently a design or quality control parameter. There is a need to determine the design resilient modulus for the different materials at their in-situ acceptable values of moisture content and dry density (including field variation that may occur). These values can then be included in the design of pavement structures.

The use of resilient modulus properties of bases, subbases, and subgrades in the mechanistic design of pavement structures has been increasing among transportation agencies. Some state agencies, such as Kentucky and Missouri, have had success in determining the resilient modulus of aggregates and soils and utilizing this data as input in the new AASHTO mechanistic model [*1, 2*]. Other state transportation agencies, such as Utah and Florida, have realized the importance of establishing resilient modulus values and have initiated research projects to establish resilient modulus values for typical materials to support implementation of the new Pavement ME Design software [*3, 4*].

OBJECTIVE

The primary objective of this research study was to determine resilient modulus design values for typical base course materials, as allowed by DOTD specifications. The study also evaluates generalized constitutive models for resilient modulus and develop material coefficients (k_1, k_2, and k_3) for use to predict the resilient modulus for unbound base course materials.

SCOPE

The bound (stabilized) and unbound (non-stabilized) base course materials evaluated in this research study are typical base course materials specified and constructed as part of Louisiana roadways. Three laboratory cement stabilized soil types (classified as A-2-4, A-4, and A-6, according to the AASHTO soil classification) were evaluated as bound base materials and prepared with 7.4%, 7.3%, and 8.5% cement by volume respectively. In-place cement stabilized (A-4) and in-place cement treated (recycled soil cement base) field base courses were also evaluated as bound base materials and prepared with 6% and 10% cement by volume respectively. Two aggregates types [Mexican limestone and Recycled PCC (crushed)] were evaluated as unbound base materials. The basic material properties of the bound and unbound base materials were characterized through laboratory tests; and then repeated load triaxial tests were also conducted to evaluate their resilient modulus. For each base course material tested samples were made in triplicate for each case (i.e. moisture content and curing period). A total of 84 specimens were tested. An in-house literature review of previous research studies, as related to the scope of this study, was also conducted and includes: Kentucky limestone; ground granulated blast furnace slag (GGBFS)-stabilized blended calcium sulfate (BCS); asphalt base course (AC-30 binder); and asphalt base course (powdered rubber modified).

METHODOLOGY

Laboratory testing was performed on the typical base course materials allowed by DOTD specifications [*5*]. The materials evaluated during this study included the cement stabilized soils (classified as A-2-4, A-4, and A-6 according to AASHTO classification); in-place cement stabilized (A-4) and in-place cement treated (recycled soil cement base (RSCB)) field base course; and base aggregate materials (Mexican limestone and recycled crushed Portland cement concrete).

The laboratory testing program consisted of physical properties tests and repeated loading triaxial (RLT) resilient modulus tests. The materials were evaluated at three moisture contents, which represent the range variation allowed during construction: two percent below optimum, optimum moisture content, and two percent above optimum.

Physical Properties Tests

Physical properties tests were performed in accordance with DOTD standard testing procedures to provide characterization and classification information for the tested materials. Table 1 presents the test procedures conducted on the materials.

Table 1
Soil classification test procedures

Test	DOTD Testing Procedure
Atterberg Limits	TR 428-67
Sieve/Hydrometer Analysis	TR 407-99
Sieve Analysis (Aggregates)	TR 113-11
Classification of Soils	TR 423-99
Moisture-Density Relationship (Standard Proctor)	TR 418-98 Method B (Soils)
Moisture-Density Relationship (Modified Proctor)	TR-418-98 Method G (Aggregates)

Cement Content for Stabilized Base Materials

DOTD utilizes a Class II base course for cement stabilized base course design, as specified by Section 302 of the Louisiana Standard Specifications for Roads and Bridges (2006 edition), with the required cement content (Portland cement: Type I or II, or Portland-Pozzolan cement: Type IP are allowed) to achieve an unconfined compressive strength of 300 psi at seven days (in accordance with standard testing procedure TR 432-02). For each base course material evaluated, samples were molded at three moisture contents (optimum, two percent above optimum, and two percent below optimum), established from the compaction curves, and the cement contents recommended. After curing for seven days in a 100% humidity room, unconfined compressive strength tests were conducted on the samples and the results used to investigate the variation that molding moisture content has on unconfined compressive strength for each base course material. The percentage of cement required to produce an unconfined compressive strength of 300 psi at seven days for each soil cement material were used in preparing samples for other tests.

There are two types of soil cement designs used by DOTD for existing roadbed materials: in-place cement stabilized base course, as specified by Section 303 of the Louisiana Standard Specifications for Roads and Bridges (2006 edition), and in-place cement treated base course, as specified by Section 308 of the Louisiana Standard Specifications for Roads and Bridges (2006 edition). For in-place cement stabilized base course, the current practice is to determine the percentage of cement that produces an unconfined compressive strength of 300 psi at seven days. This cement stabilization is for untreated soils and recycled existing base courses and it is typically 8.5 in. thick. For in-place cement treated base course, the current practice is to determine the percentage of cement that produces an unconfined compressive strength of 150 psi at seven days. This cement treatment is primarily used for recycling existing soil cement base courses for low annual daily traffic (ADT) roads and it is typically 12 in. thick. For both in-place cement stabilized and in-place cement treated base courses, the percentage of cement required to achieve the desired strength is verified by unconfined compressive strength tests (in accordance with standard testing procedure TR 432-02).

Repeated Load Triaxial (RLT) Resilient Modulus Tests

Repeated load triaxial (RLT) tests for resilient modulus were performed in accordance with AASHTO procedure T 307-09 [*6*] standard method for each base course material evaluated as related to the scope of this study.

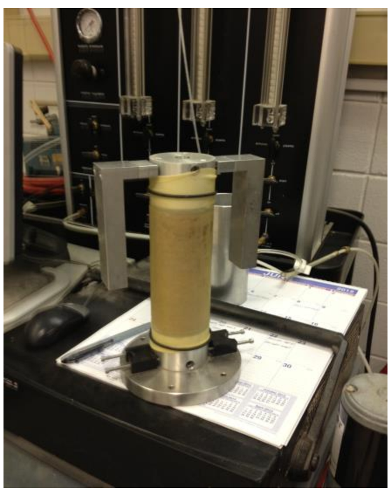
Specimen Preparation

Bound Materials. Samples of stabilized base materials were compacted in a cylindrical mold (2.8 in. by 5.6 in. height) using a standard compaction hammer (5.5-lb. hammer with a 12-in. drop), as shown in Figure 1. Samples were prepared by 5 lifts of approximately 1 in. to achieve uniform compaction throughout the specimen. A predetermined amount of the material at specified moisture content was poured into the mold at each lift and compacted until the specified target density (based on standard Proctor tests) was obtained, as indicated by the distance from the top of the mold to the surface of the compacted layer. Each lift was then slightly scratched to achieve good bonding with the next lift. The specified weight of lift material was compacted into the known volume of the mold to obtain the required sample density. A testing matrix of samples prepared for resilient modulus testing is presented in Table 2. For each bound material tested, the data for the three samples were averaged to generate one summary graph for each test condition (i.e. moisture content and curing period) and the graphs for the three samples are available in Appendices A-C.

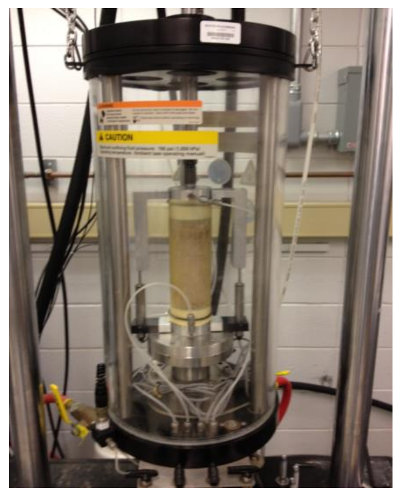
Unbound Materials. Samples of aggregate base materials were compacted in a split mold (6 in. diameter by 13 in. height) using a vibratory compaction device, as shown in Figure 2. Two membranes were used to prevent any damage caused by coarse particles during specimen preparation, with the aid of a vacuum to achieve a good contact with the mold. Samples were prepared by six 2-in. lifts to achieve uniform compaction throughout the specimen. A predetermined amount of the material at specified moisture content was poured into the mold at each lift. Each layer was then compacted until the specified target density (based on modified Proctor tests) was obtained as indicated by the distance from the top of the mold to the surface of the compacted layer. The surface of each lift was then slightly scratched to achieve good bonding with the next lift. The compacted samples were 6 in. x 12 in. (diameter by height) cylinders. For each bound material tested, the data for the three samples were averaged to generate one summary graph for each test condition (i.e. moisture content) and the graphs for the three samples are available in Appendices D-E.

(a) Hammer and Mold

(b) Sample Compaction



(c) Compacted Sample



(d) Sample Being Tested

Figure 1
Bound material specimen preparation

Table 2
Resilient modulus testing matrix

Material	% Cement	Target	7-day curing	28-day curing
Cement Stabilized Base Course (A-2-4)	% to achieve 300 psi	+2%	3 samples	3 samples
		Opt.	3 samples	3 samples
		-2%	3 samples	3 samples
Cement Stabilized Base Course (A-4)	% to achieve 300 psi	+2%	3 samples	3 samples
		Opt.	3 samples	3 samples
		-2%	3 samples	3 samples
Cement Stabilized Base Course (A-6)	% to achieve 300 psi	+2%	3 samples	3 samples
		Opt.	3 samples	3 samples
		-2%	3 samples	3 samples
In-Place Cement Stabilized Base Course (A-4)	% to achieve 300 psi	Field Moisture Content	3 samples	3 samples
In-Place Cement Treated Base Course (RSCB)	% to achieve 150 psi	Field Moisture Content	3 samples	3 samples
Mexican Limestone	N/A	+2%	3 samples	
		Opt.	3 samples	
		-2%	3 samples	
Recycled PCC (Crushed)	N/A	+2%	3 samples	
		Opt.	3 samples	
		-2%	3 samples	

(a) Vibratory Compacter and Mold

(b) Sample Compaction

(c) Compacted Sample

(d) Sample Being Tested

Figure 2
Unbound material specimen preparation

Resilient Modulus Tests

The samples were first conditioned by applying 1,000 load cycles to remove most irregularities on the top and bottom surfaces of the test sample and to suppress most of the initial stage of permanent deformation. The conditioning of the samples was followed by a series of 15 testing sequences, as described in Table 3, consisting of different levels of cyclic deviatoric stress and confining pressure, such that the resilient modulus is measured at varying normal and shear stress levels. For each load sequence, the resilient modulus value is calculated for each of the last five cycles and the values are subsequently averaged. The cyclic loading consists of repeated cycles of a haversine shaped load pulse. These load pulses have a 0.1-second load duration and a 0.9-second rest period. Resilient modulus is a parameter to characterize stiffness of pavement materials under repeated loading, with the consideration of the influence of stress levels (both confining pressure and deviatoric stress) and the nonlinearity induced by traffic loading. Resilient modulus is an essential input parameter in Pavement ME Design. A typical RLT test result is depicted in Figure 3, with marked recoverable axial strain (ε_a) and cumulative permanent axial strain (ε_{pe}) at a certain loading cycle. Resilient modulus is defined as:

$$\boldsymbol{M_r = \frac{\sigma_d}{\varepsilon_r}} \tag{4}$$

Where σ_d = deviatoric stress; and ε_r = recoverable axial strain.

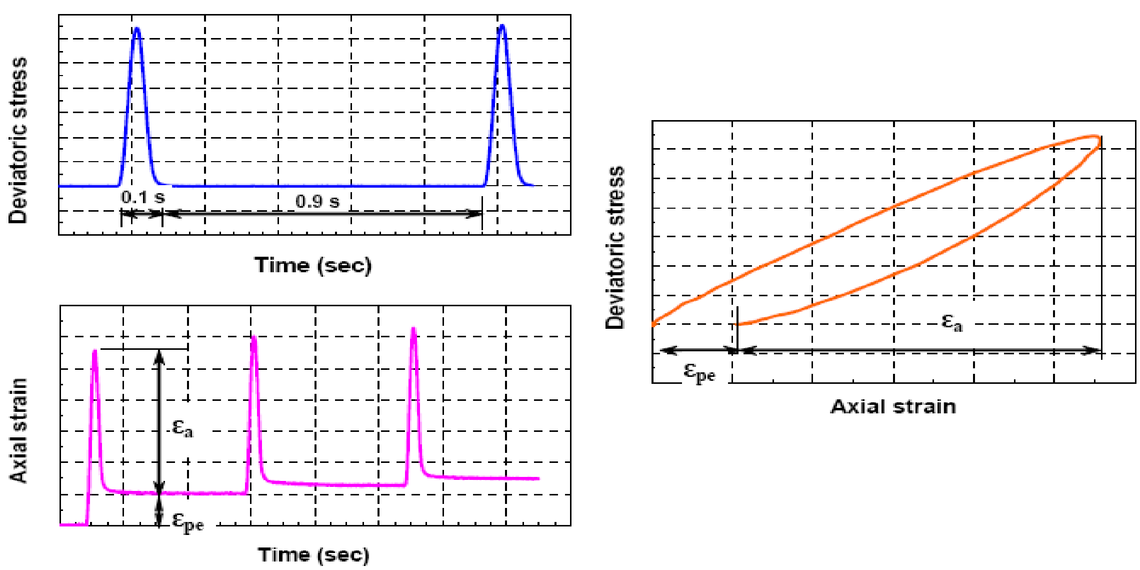


Figure 3
Typical results from a RLT test

Table 3
AASHTO T-307 testing sequences

Sequence Number	Confining Pressure (psi)	Max. Axial Stress (psi)	Cyclic Stress (psi)	Constant Stress (psi)	No. of Load Applications
(Conditioning)	15	15	13.5	1.5	1000
1	3	3	2.7	0.3	100
2	3	6	5.4	0.6	100
3	3	9	8.1	0.9	100
4	5	5	4.5	0.5	100
5	5	10	9.0	1.0	100
6	5	15	13.5	1.5	100
7	10	10	9.0	1.0	100
8	10	20	18.0	2.0	100
9	10	30	27.0	3.0	100
10	15	10	9.0	1.0	100
11	15	15	13.5	1.5	100
12	15	30	27.0	3.0	100
13	20	15 (20*)	13.5 (18.0*)	1.5 (2.0*)	100
14	20	20 (25*)	18.0 (22.5*)	2.0 (2.5*)	100
15	20	40 (45*)	36.0 (40.5*)	4.0 (4.5*)	100

Note: Due to the stiffness of the bound materials, the stresses applied for sequences 13-15 increased compared to AASHTO T 307-09 and are noted in parenthesis. *Bound materials

Review of Generalized Constitutive Models for Resilient Modulus

A number of mathematical models have been proposed for modeling the resilient modulus of soils and aggregates. Some widely published models proposed for characterizing the resilient modulus of soils and aggregates are summarized in Table 4. Most mathematical expressions relate resilient modulus, the dependent variable, to one independent variable: the deviator stress, σ_d, confining stress, σ_3, or bulk stress, θ ($=\sigma_1 + \sigma_2 + \sigma_3$); or the two independent variables: (σ_d and σ_3), (θ and σ_d), or (θ and τ_{oct}). Three mathematical models, including the one recommended by the mechanistic design guide (NCHRP 1-28A), were evaluated for the Mexican Limestone and Recycled PCC (crushed) materials and each is discussed in detail below [*7*]. The models were not evaluated for bound materials because they were developed to characterize raw soils and aggregates. Multiple regression analysis of all standard testing stresses and corresponding resilient modulus values is used to obtain material coefficients k_1, k_2, and k_3. The models provide best data "fits" between resilient modulus and testing stresses. The model proposed by the mechanistic design guide is recommended but not required so all three models were evaluated to determine which provides the best data "fit" between resilient modulus and testing stresses.

Table 4
Proposed resilient modulus models

Reference	Independent Variables	Model Equation
Moossazadeh and Witczak (1981)	σ_d (Deviator Stress)	$M_r = k_1(\frac{\sigma_d}{p_a})^{k_2}$
Dunlap (1963)	σ_3 (Confining Stress)	$M_r = k_1(\frac{\sigma_3}{p_a})^{k_2}$
Seed, Mitry, Monismith and Chan (1967)	θ (Bulk Stress)	$M_r = k_1(\frac{\theta}{p_a})^{k_2}$
Uzan (1985)	θ, σ_d	$M_r = k_1(\frac{\theta}{p_a})^{k_2} \ (\frac{\sigma_d}{p_a})^{k_3}$
UKTC (Ni, Hopkins, and Sun, 2002)	σ_3, σ_d	$M_r = k_1(\frac{\sigma_3}{p_a} + 1)^{k_2} \ (\frac{\sigma_d}{p_a} + 1)^{k_3}$
NCHRP (National Cooperative Highway Research Program) Project 1-28A (Halin, 2001)	θ, τ_{oct} (Octahedral Shear Stress)	$M_r = k_1 p_a(\frac{\theta}{p_a})^{k_2} \ (\frac{\tau_{oct}}{p_a} + 1)^{k_3}$

The generalized constitutive model as described in Part 2 Chapter 2 of the mechanistic design guide, shown in equation (1) and referred to hereafter as Model 1, proposed the following relationship for presenting resilient modulus data [*8*].

$$\mathbf{M_r} = \mathbf{k_1} \ \boldsymbol{P_a}(\frac{\theta}{\mathbf{P_a}})^{\mathbf{k_2}} \ (\frac{\tau_{oct}}{\mathbf{P_a}} + \mathbf{1})^{\mathbf{k_3}} \qquad (1)$$

where,

M_r= resilient modulus,

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

σ_1 = major principal stress,

σ_2 = intermediate principal stress,

σ_3 = minor principal stress/confining pressure,

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

P_a = normalizing stress (atmospheric pressure) = 14.7 psi, and

k_1, k_2, k_3 = material constants.

Coefficient k_1 is proportional to Young's modulus. Thus, the values for k_1 should be positive since M_r can never be negative. Increasing the bulk stress, θ, should produce a stiffening or hardening of the material, which results in a higher M_r. Therefore, the exponent k_2, of the bulk stress term for the above constitutive equation should also be positive. Coefficient k_3 is the exponent of the octahedral shear stress term. The values of k_3 are typically negative since increasing the shear stress should produce a softening of the material (i.e., a lower M_r).

The University of Kentucky Transportation Center (UKTC) resilient modulus model proposed in 2002 (Ni, Hopkins, and Sun), and referred to hereafter as Model 2, is as follows [*9*]:

$$\mathbf{M_r} = \mathbf{k_1}\left(\frac{\boldsymbol{\sigma_3}}{\mathbf{P_a}} + \mathbf{1}\right)^{\mathbf{k_2}} \left(\frac{\boldsymbol{\sigma_d}}{\mathbf{P_a}} + \mathbf{1}\right)^{\mathbf{k_3}} \qquad (2)$$

where,

σ_d= deviator stress.

In this model, resilient modulus increases as the confining pressure increases so the coefficients k_1 and k_2 will always be positive. The modulus will generally decrease with the increase of the deviator stress therefore the coefficient k_3 is typically negative for soils and aggregates.

The model proposed by Uzan (1985), and referred to hereafter as Model 3, is as follows [*10*]:

$$\mathbf{M_r} = \mathbf{k_1}\left(\frac{\boldsymbol{\theta}}{\mathbf{P_a}}\right)^{\mathbf{k_2}} \left(\frac{\boldsymbol{\sigma_d}}{\mathbf{P_a}}\right)^{\mathbf{k_3}} \qquad (3)$$

In this model, increasing the bulk stress, θ, should produce a stiffening or hardening of the material, which results in a higher M_r so coefficients k_1 and k_2 will always be positive. The modulus will generally decrease with the increase of the deviator stress therefore for most situations the coefficient k_3 will be negative.

Regression Analysis

Regression analysis was conducted using SAS Institute Inc. (SAS) software [*11*]. The procedure detailed below was used to analyze the resilient modulus data by use of back-calculation to determine material coefficients (k_1, k_2, and k_3):

- The resilient modulus for each of the three samples was calculated then averaged to generate one set of values for resilient modulus and input with other parameters (i.e. confining pressure, deviatoric stress, etc.).

- SAS software was used to fit the resilient modulus data to nonlinear regression models using the NLIN (nonlinear) procedure [*12*].

- Material coefficients k_1, k_2, and k_3 were determined for each model as well as corresponding Pseudo-R^2 [*12*]. It is important to note that users of linear regression models are accustomed to expressing the quality of fit of a model in terms of the coefficient of determination, also known as R^2. In nonlinear regression analysis, such a measure is unfortunately, not readily defined. One of the problems with the R^2 definition is that it requires the presence of an intercept, which most nonlinear models do not have. A measure relatively closely corresponding to R^2 in the nonlinear case is Pseudo-R^2.

- The Gauss-Newton option was used for fitting algorithm and goodness-of-fit measures were determined for each of the three models.

DISCUSSION OF RESULTS

Test results from laboratory studies on the stabilized (bound) and non-stabilized (unbound) base materials will be summarized and discussed in this section.

Physical Properties of Raw Materials

The Atterberg limits, maximum dry density, and optimum moisture content of the tested materials are presented in Table 5. The gradation and moisture-density curves of the tested materials are presented in Figure 4, Figure 5, and Figure 6, respectively.

Table 5
Physical properties of soils tested

Material	Liquid Limit, LL (%)	Plastic Limit, PL (%)	Plasticity Index, PI (%)	Maximum Dry Density, γ_{dmax} (pcf)	Optimum Moisture Content, ω_{opt} (%)
A-2-4[1]	20	12	8	123.0*	10.4*
A-4[1]	23	14	9	121.2*	11.3*
A-6[1]	32	20	12	107.2*	15.9*
A-4[2]	23	19	4	114.1*	14.2*
RSCB[3]	23	17	6	105.2*	19.3*
Mexican Limestone	N/A	N/A	N/A	125.1**	10.1**
Recycled PCC (Crushed)	N/A	N/A	N/A	118.6**	12.0**

Legend: [1]-Soils for Cement Stabilized Base Course, [2]-Soil for In-Place Cement Stabilized Base Course, [3]-Soil for In-Place Cement Treated Base Course (Recycled Soil Cement Base), γ_d- Dry unit weight of the compacted sample, *Based on standard Proctor tests on raw soils, **Based on modified Proctor tests on aggregate materials.

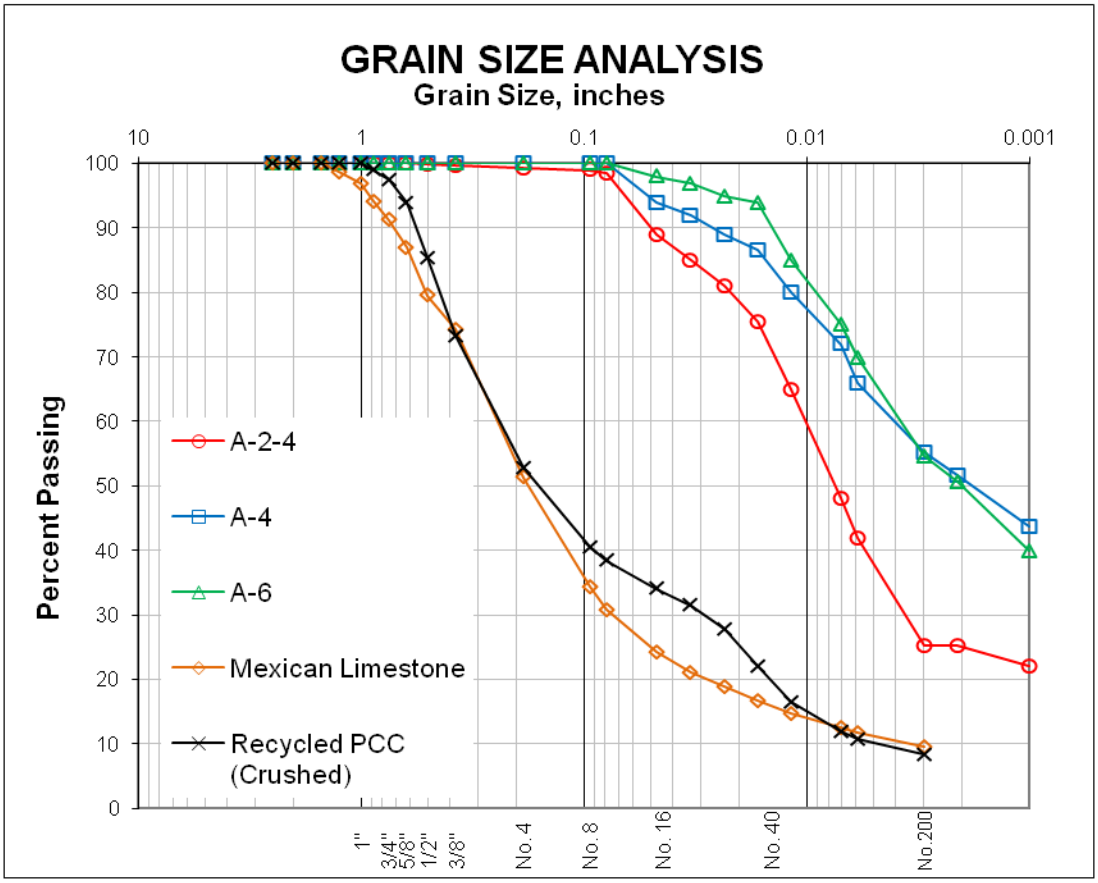


Figure 4
Particle size gradations of tested specimens

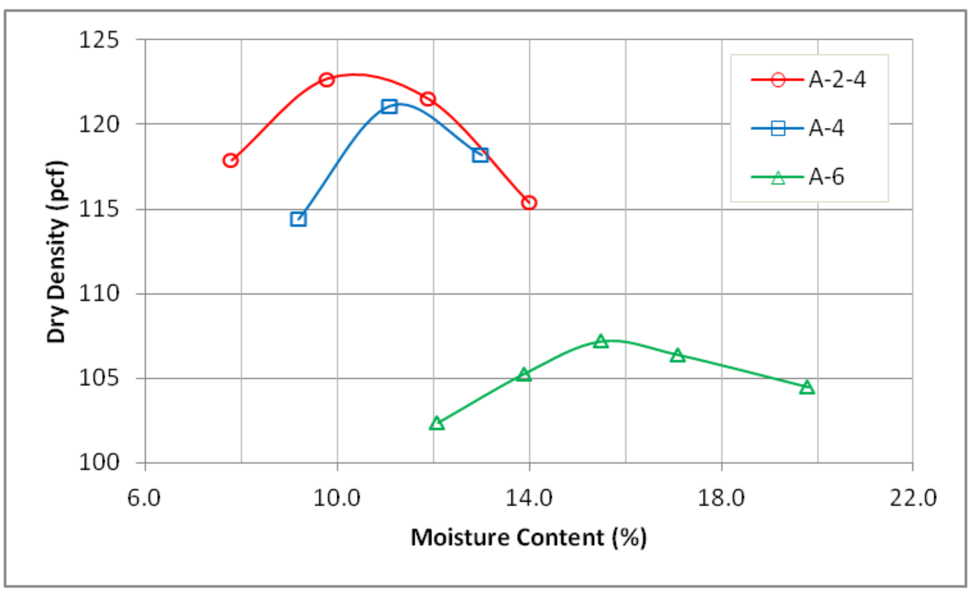


Figure 5
Standard Proctor compaction curves for raw soils

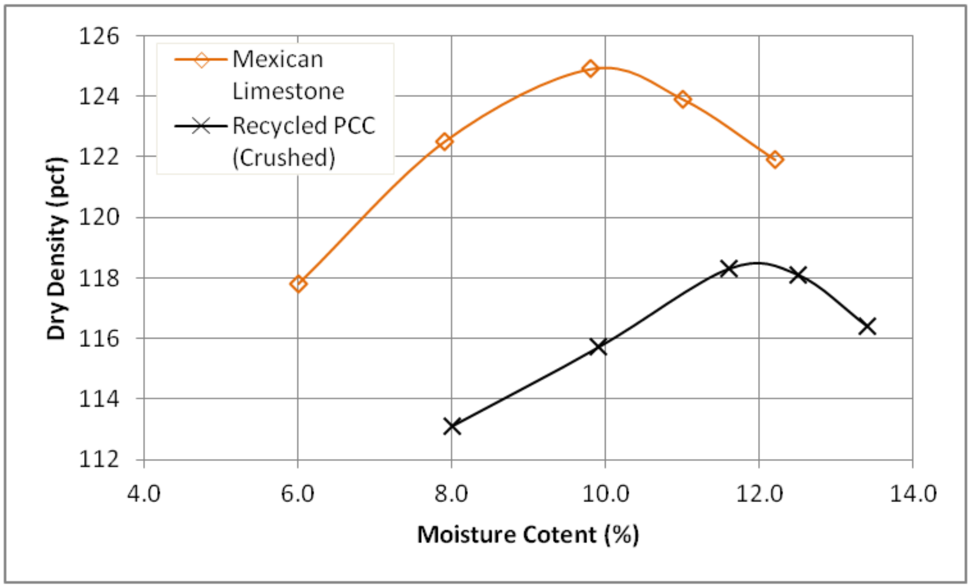


Figure 6
Modified Proctor compaction curves for aggregates

Unconfined Compressive Strength Results

Figure 7 shows the unconfined compressive strength (UCS) results for the cement stabilized soils. The UCS results were used to establish a cement curve from which the minimum percentage of cement required to achieve 7-day strengths of 300 psi for each material was noted. A-2-4 required 6% cement by weight, A-4 required 6% cement by weight, and A-6 required 8% cement by weight. All samples related to the testing scope of the project were produced with the aforementioned percentage of cement by weight.

Figure 8 shows the moisture-density curves of the stabilized base course materials. Compared to the moisture-density curves of the raw soils in Figure 5, the addition of cement caused an increase in optimum moisture content and a decrease in maximum dry density due to the fact that additional moisture is needed for cement hydration. Figure 9 shows the UCS results used to establish a strength curve to determine the effect of molding moisture content on unconfined compressive strength. At optimum moisture content, all three materials reached the required 300 psi UCS at 7-day curing. For all three materials, a variation in molding moisture content affected the UCS. At molding moisture content two percent above optimum, only A-4 was able to reach the target UCS of 300 psi at 7-day curing. At molding moisture content 2% below optimum, all three materials reached the target UCS of 300 psi at 7-day curing. Figure 10 shows the moisture-density curves for the field samples where in-place cement stabilized base course samples were produced with 10% cement by volume and in-place cement treated (recycled soil cement base) base course samples were produced with 6% cement by volume. For field samples, the percentage of cement to be used was determined in accordance with DOTD TR 432 from materials sampled in-place on the project. Figure 11 shows the UCS results for the field samples. For in-place cement treated base course, the required UCS of 150 psi at 7-day curing was achieved. For in-place cement stabilized base course, the required UCS of 300 psi at 7-day curing was achieved.

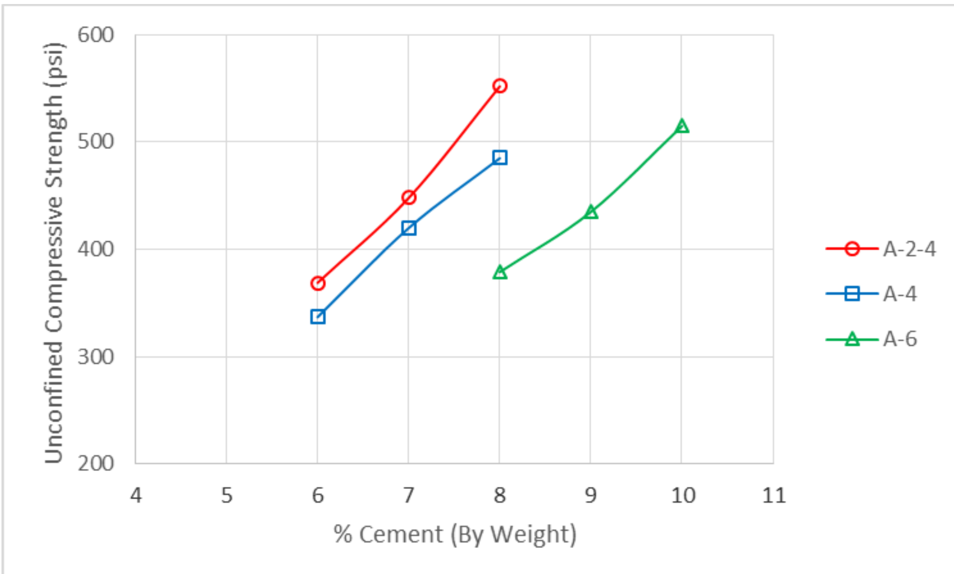


Figure 7
7-Day Cement curves for cement stabilized soils

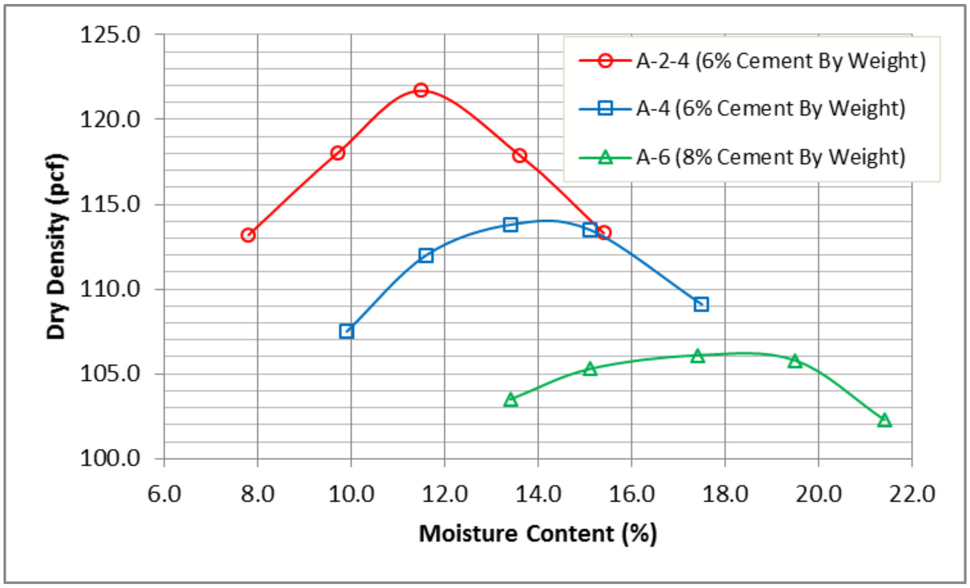


Figure 8
Standard Proctor compaction curves for cement stabilized soils

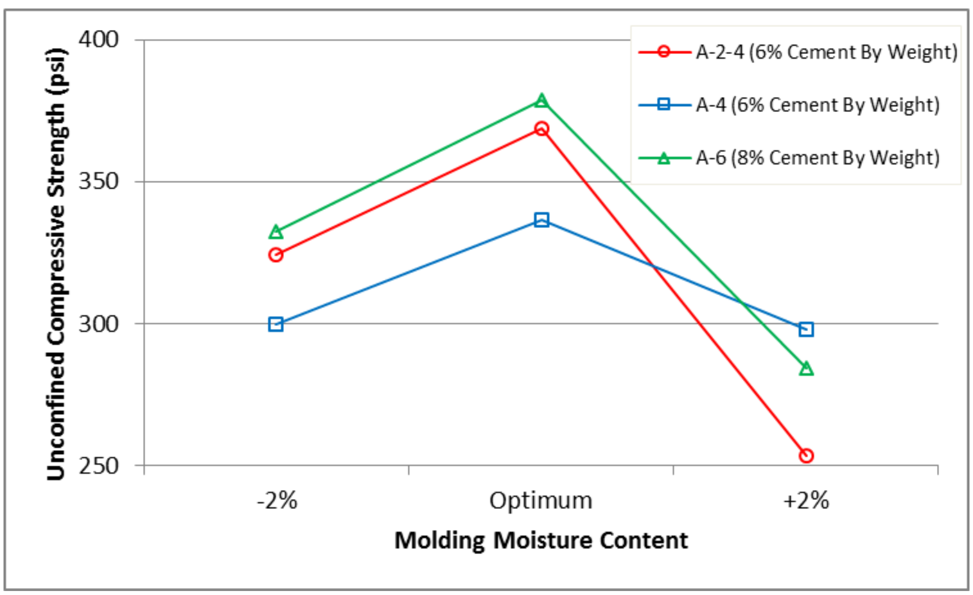


Figure 9
Strength variations with change in moisture content

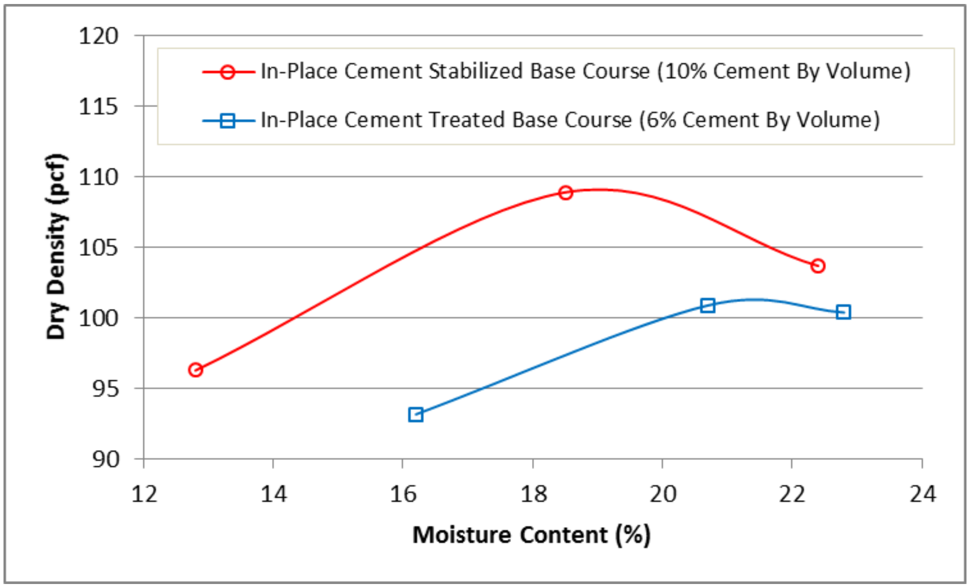


Figure 10
Standard Proctor compaction curves for field samples

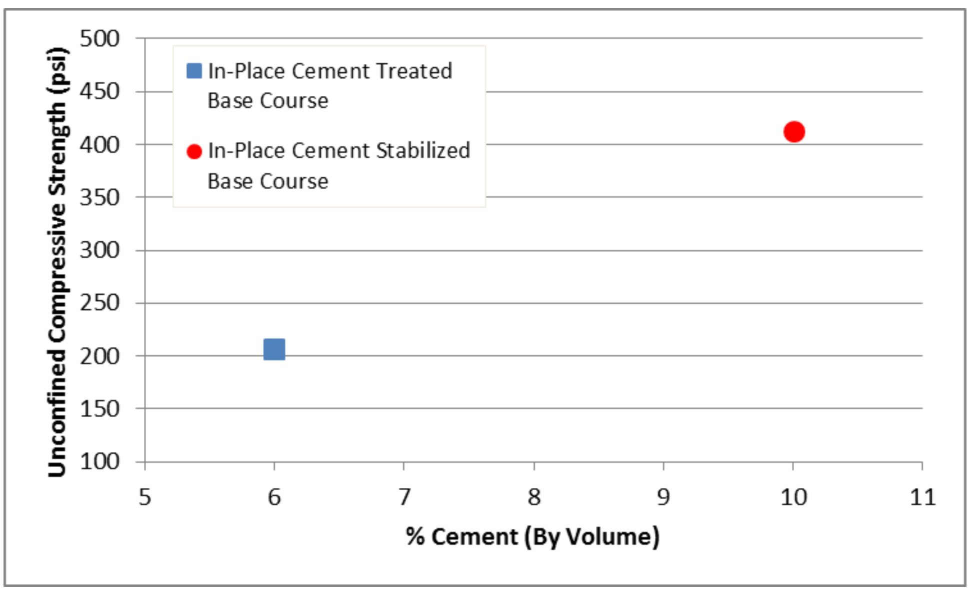


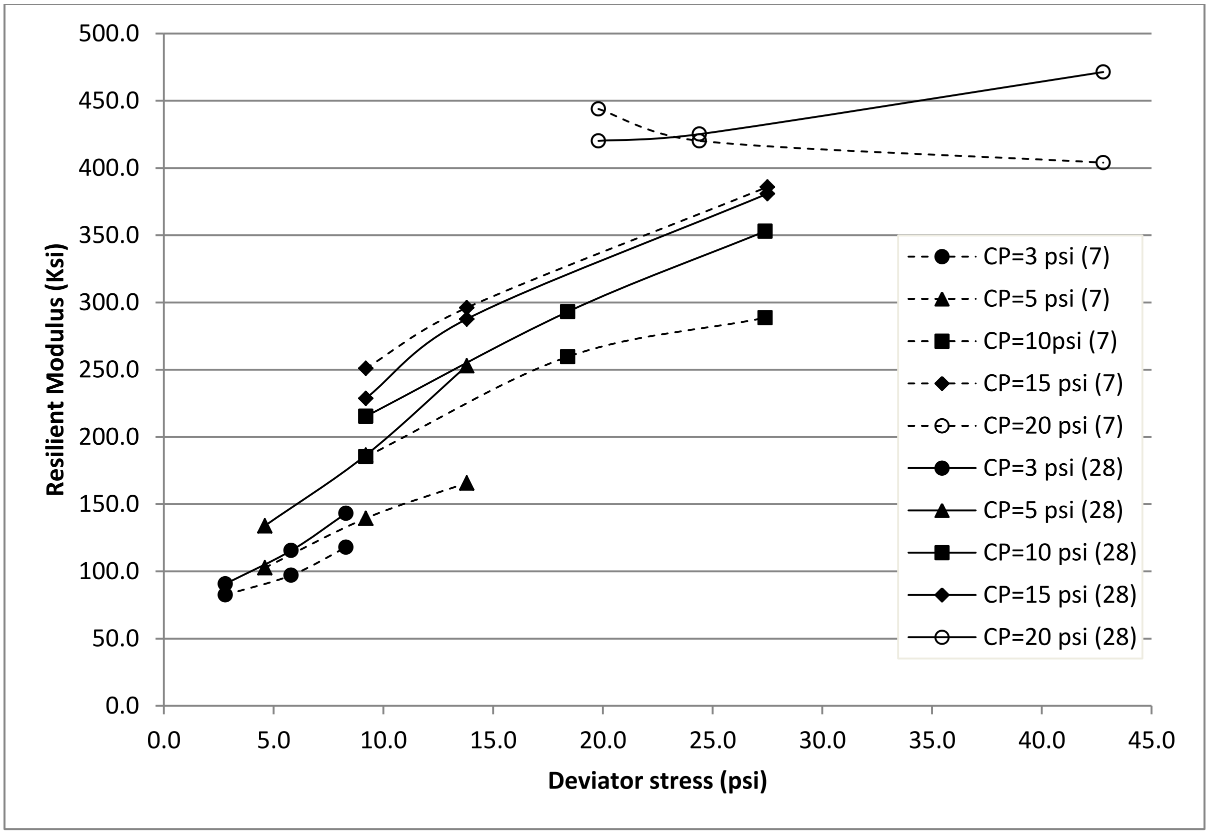
Figure 11
Unconfined compressive strength results for field samples

Resilient Modulus of Cement Stabilized Base Course

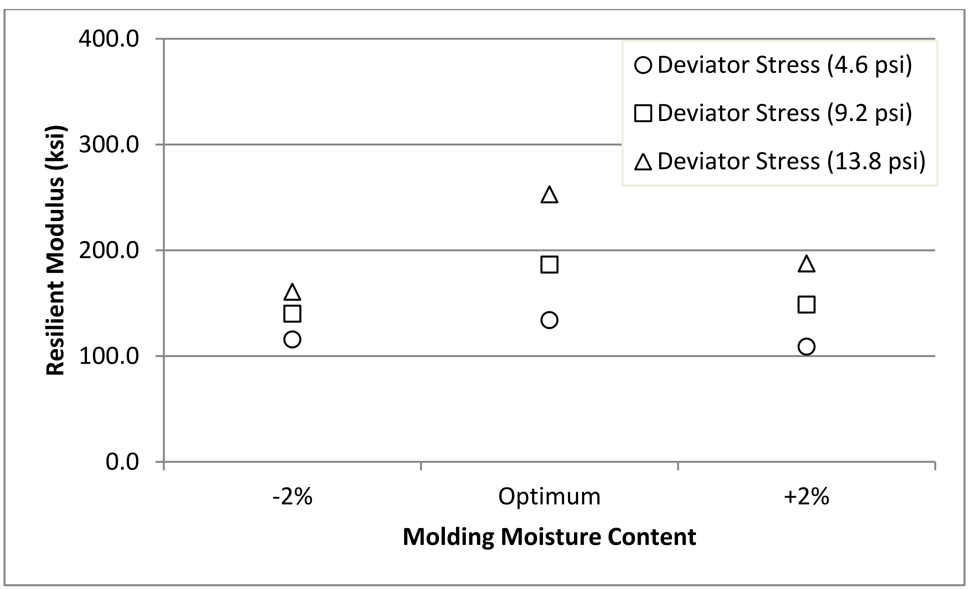
Figure 12 shows the resilient moduli of cement stabilized base course (A-2-4) cured for 7- and 28-day periods at three molded moisture contents (optimum, two percent above optimum, and two percent below optimum) and prepared with 6% cement. As expected, higher confining stresses resulted in higher resilient moduli for all tested materials. Also, each material's resilient modulus increased with curing time and each material generally behaved as a stress-hardening material (i.e., an increase in deviator stress caused an increase in resilient modulus). The effect of molding moisture content caused a decrease in resilient moduli for samples molded at two percent above optimum and two percent below optimum as compared to samples molded at optimum moisture content. Cement stabilized base courses (A-4 and A-6) prepared with 6% and 8% cement respectively, and in-place cement stabilized base course (A-4), prepared with 10% cement, followed these same trends and their results are presented in the Appendix. The effect of variation in field moisture content on resilient moduli could not be investigated for the in-place cement stabilized base course material because samples were only tested at optimum moisture content.

Resilient Modulus of In-Place Cement Treated Base Course

Figure 13 shows the resilient moduli of in-place cement treated base course (recycled soil cement base) cured for 7- and 28-day periods at field moisture content (optimum) and prepared with 6% cement. As expected, higher confining stresses resulted in higher resilient moduli for the in-place cement treated base course material. Also, the material's resilient modulus increased with curing time and each material generally behaved as a stress-softening material (i.e., an increase in deviator stress caused a decrease in resilient modulus.) The effect of variation in field moisture content on resilient moduli could not be investigated for the in-place cement treated base course material because samples were only tested at optimum moisture content.

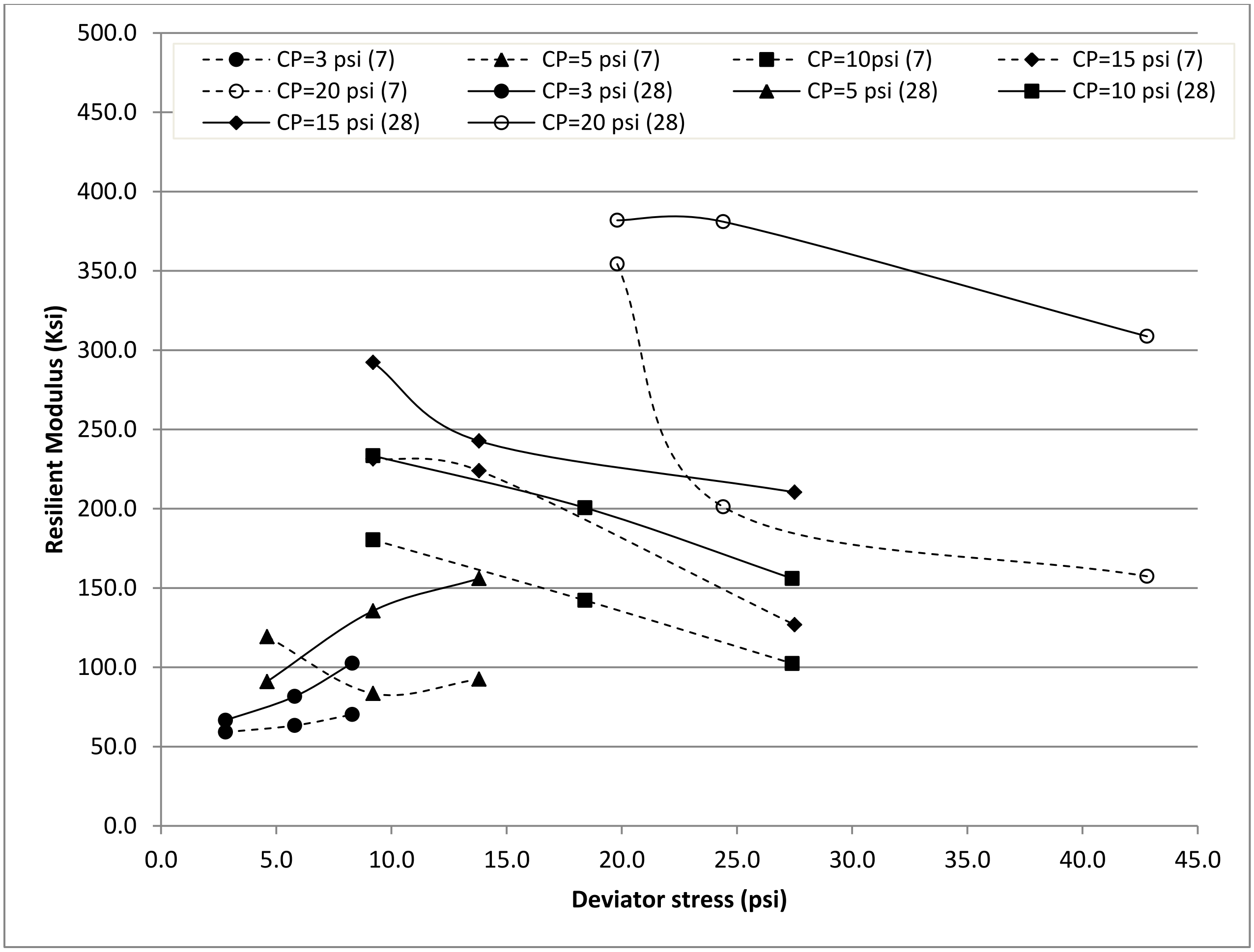


(a) 7-day and 28-day Curing



(b) 5 psi Confining Pressure (28-day Curing)

Figure 12
Resilient moduli of cement stabilized base course (A-2-4)



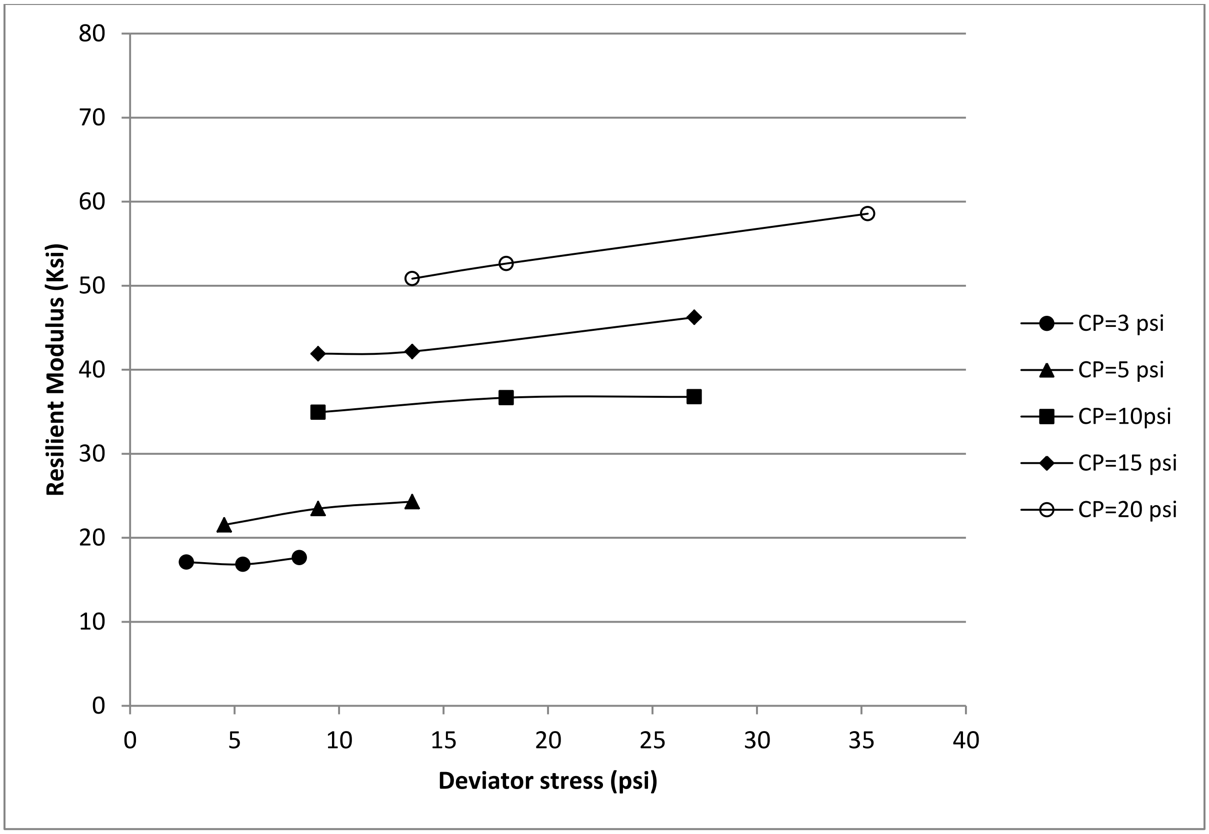
7-day and 28-day Curing

Figure 13
Resilient moduli of in-place cement treated base course (recycled soil cement base)

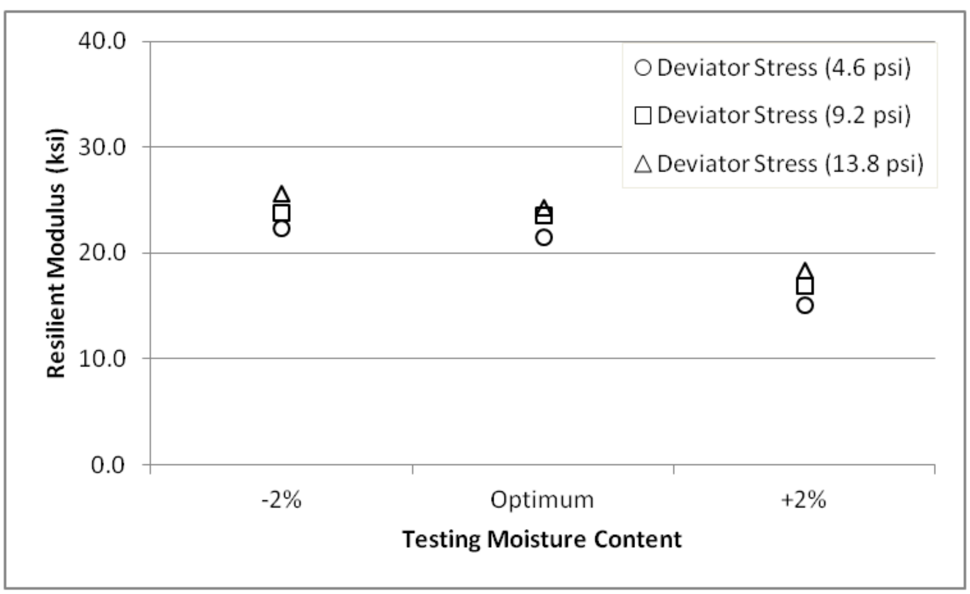
Resilient Modulus of Unbound Materials

The resilient moduli for Mexican limestone samples at optimum testing moisture content, two percent above optimum moisture content, and two percent below optimum moisture content are shown in Figure 14. As expected, the resilient moduli increased with increase in confining pressure. The effect of deviatoric stress on resilient moduli was well defined as an increase in deviatoric stress generally produced an increase in resilient moduli. An increase in testing moisture content (two percent above optimum) produced a decrease in resilient moduli while a decrease in testing moisture content (two percent below optimum) produced an increase in resilient moduli as compared to samples at optimum testing moisture content.

The resilient moduli for Recycled PCC (crushed) samples at optimum testing moisture content, two percent above optimum moisture content, and two percent below optimum moisture content are shown in Figure 15. As expected, the resilient moduli increased with increase confining pressure. The effect of deviatoric stress on resilient moduli was well defined as an increase in deviatoric stress produced an increase in resilient moduli. An increase in testing moisture content (two percent above optimum) produced a decrease in resilient moduli as compared to samples molded at optimum moisture content. A decrease in testing moisture content (two percent below optimum) produced a minimal decrease in resilient moduli as compared to samples at optimum testing moisture content.

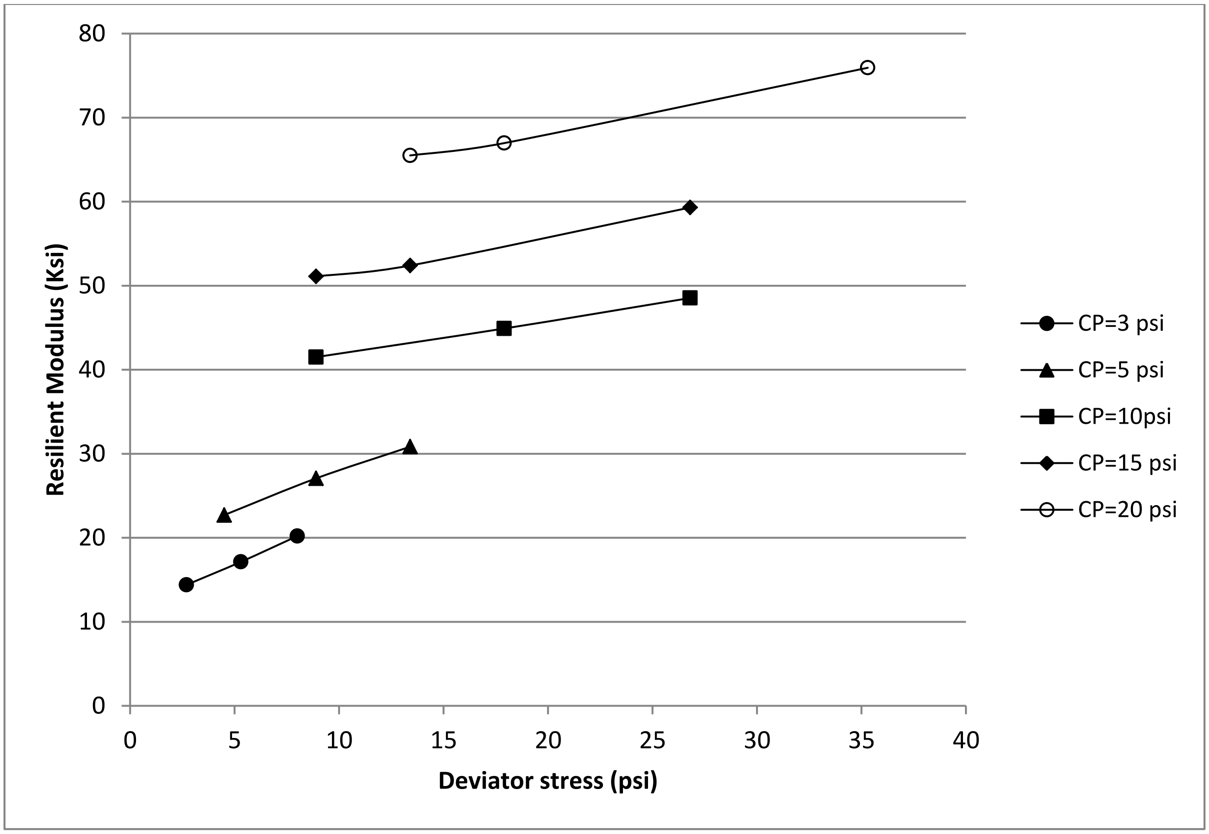


(a) Optimum Moisture Content

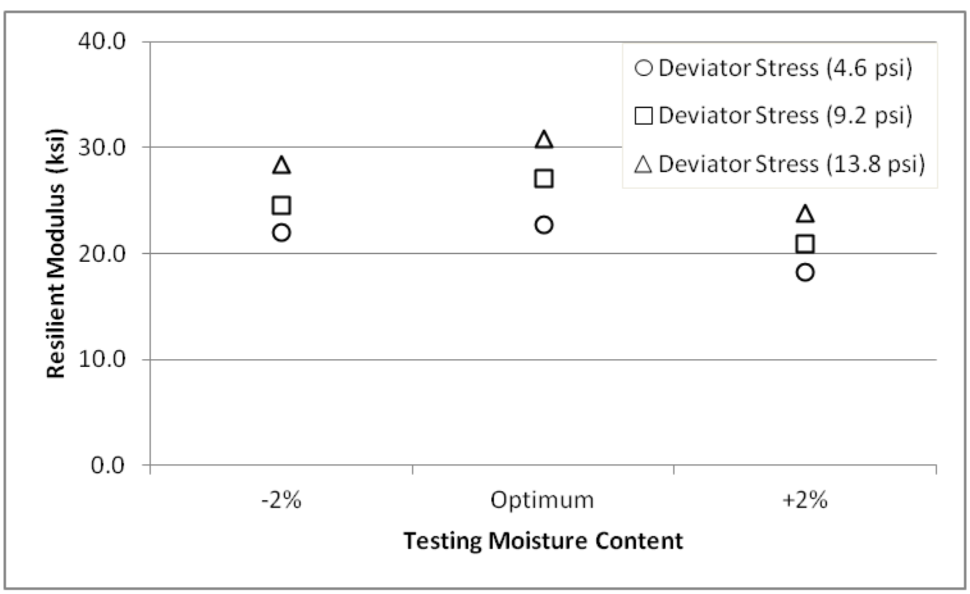


(b) 5 psi Confining Pressure

Figure 14
Resilient moduli of Mexican limestone samples



(a) Optimum Moisture Content



(b) 5 psi Confining Pressure

Figure 15
Resilient moduli of Recycled PCC (crushed) samples

Recommended Resilient Modulus Design Values

Table 6 shows the recommended resilient moduli design values, at the anticipated working stress in pavements (i.e., 5 psi confining pressure and 9 psi deviator stress), for the materials evaluated for this study. For soil cement materials, resilient moduli values are reported at three molding moisture contents (optimum, two percent above optimum, and two percent below optimum), which represent the range of acceptance in the field. The highest resilient moduli values typically occurred at optimum molding moisture content and the lowest resilient moduli value typically occurred at molding moisture content two percent above optimum except for A-6, where the lowest resilient moduli value occurred at molding moisture content two percent below optimum. For the field materials, the resilient moduli values are reported at optimum field moisture content. At 28-day curing, there was a significant increase in resilient moduli. For unbound materials such as Mexican Limestone and Recycled PCC (crushed), resilient moduli values are reported at three testing moisture contents (optimum, two percent above optimum, and two percent below optimum), which represent the range of acceptance in the field. The highest resilient moduli values occurred at optimum testing moisture content while the lowest resilient moduli values occurred at testing moisture content two percent above optimum for both materials. For all materials, resilient modulus design values will be recommended at optimum moisture content.

In order to investigate the anticipated working stress in a pavement, KENPAVE which is a finite element analysis software developed by Huang [*13*] was used in this study. This software analyzes pavements based on the finite-element method, in which the slab is divided into rectangular finite elements. To analyze pavements using KENPAVE software, the inputs required are section geometry, material properties and wheel load. The stresses and deflections of the slab, design life and cracking index are obtained as outputs. The typical sections evaluated are presented in Figure 16. For evaluation, the simulated load is 18,000 lbs applied by a tire with a contact radius of 4.8 inches with a contact pressure of 120 psi. The material properties required as inputs for each layer are elastic modulus and Poisson's ratio. For superpave asphaltic concrete, both wearing and binder course, the elastic modulus was 400,000 psi and the Poisson's ratio was 0.35. For the in-place cement treated base course, the elastic modulus was 80,000 psi and the Poisson's ratio was 0.20. For the soil cement base course, the elastic modulus was 100,000 psi and the Poisson's ratio was 0.20. For the stone base course, the elastic modulus was 27,000 psi and the Poisson's ratio was 0.30. The stress outputs were determined to be a confining pressure of 5 psi and a deviatoric stress of 10.5 psi. The working stress in the pavement will be taken as a confining pressure of 5 psi and a deviatoric stress of 9 psi.

Table 6
Recommended resilient modulus design values

Material	Parameters	Curing Period	Variation in Resilient Modulus (psi)			Design Resilient Modulus (psi)
			Opt.	+2%	-2%	
Cement Stabilized Base Course (A-2-4)	σ_3=5 psi[1] σ_d=9 psi[2]	7-day	130,000	100,000	110,000	130,000
		28-day	180,000	140,000	140,000	180,000
Cement Stabilized Base Course (A-4)		7-day	95,000	90,000	100,000	95,000
		28-day	130,000	120,000	130,000	130,000
Cement Stabilized Base Course (A-6)		7-day	85,000	84,000	85,000	85,000
		28-day	110,000	110,000	100,000	110,000
In-Place Cement Stabilized Base Course (A-4)		7-day	100,000 (Field Optimum Moisture)			100,000
		28-day	140,000 (Field Optimum Moisture)			140,000
In-Place Cement Treated Base Course (RSCB)		7-day	80,000 (Field Optimum Moisture)			80,000
		28-day	135,000 (Field Optimum Moisture)			135,000
Mexican Limestone		N/A	20,000	15,000	20,000	20,000
Recycled PCC (Crushed)		N/A	25,000	20,000	20,000	25,000

Note: Anticipated working stress in pavement: [1](depth), [2] (loading)

2” Superpave Asphaltic Concrete (Wearing Course)
2” Superpave Asphaltic Concrete (Binder Course)
Type E Interlayer Asphaltic Treatment (2 Applications)
12” In-Place Cement Treated Base Course (150 psi design strength)

(a) Cement Treated Base Course

2” Superpave Asphaltic Concrete (Wearing Course)
3” Superpave Asphaltic Concrete (Binder Course)
4” Stone Base Course
8” Soil Cement Base Course (300 psi design strength)

(b) Cement Stabilized Base Course

Figure 16
Typical Sections

Results of Regression Analysis

Table 7 shows an example of the input tables for Mexican Limestone and Recycled PCC (crushed) containing the input parameters that were used as inputs in regression analysis to determine regression constants (k_1, k_2, and k_3). The remaining input parameter tables are available in the Appendices D-E. Table 8 summarizes the regression constants (k_1, k_2, and k_3) for the Mexican Limestone and Recycled PCC (crushed) materials at each test condition (i.e., testing moisture content). All three models performed well in predicting resilient modulus with very high correlations, Pseudo-R^2 values greater than 0.95, for both Mexican Limestone and Recycled PCC (crushed). The authors acknowledge that the Pseudo-R^2 values are high and typically rarely seen in regression analysis and this could be attributed to the fact that the laboratory calculated resilient modulus was averaged to generate one set of values for each material at each test condition.

Verification of Regression Analysis Coefficients

To verify the models and their corresponding coefficients, independent resilient modulus values were used. The resilient modulus values from No. 57 limestone tested by the University of Kentucky Transportation Center (UKTC) [*14*] according to AASHTO T307-99 were used to verify the Mexican Limestone models and their corresponding coefficients. The resilient modulus values of recycled interstate rigid pavement tested by the Mississippi Department of Transportation (MSDOT) [*15*] according to Strategic Highway Research Program (SHRP) Protocol P46 were used to verify the Recycled PCC (crushed) models and their corresponding coefficients. The testing sequences and resilient modulus values of the independent measurements are available in Appendices D and E. Figure 17 shows the model verification for Mexican Limestone at optimum moisture content using the independent measurements. All three models performed well with R^2 values ranging from 0.90-0.93. The remaining model verification graphs are available in Appendix D. Figure 18 shows the model verification for Recycled PCC (crushed) at optimum moisture content using the independent measurements. All three models performed will with R^2 values ranging from 0.90-0.92. The remaining model verification graphs are available in Appendix E. No model performed significantly better than the others in predicting resilient modulus. Model 1 will be recommended for use since it is the general model adopted by AASHTO in the mechanistic design guide.

Table 7
Regression analysis input parameter tables

Sequence Number	σ_d (psi)	σ_3 (psi)	θ (psi)	τ_{oct} (psi)	M_r (psi)
1	2.7	3	11.7	1.2728	17,100
2	5.3	3	14.3	2.5142	16,833
3	8.0	3	17.0	3.7869	17,633
4	4.5	5	19.5	2.1213	21,533
5	8.9	5	23.9	4.2112	23,467
6	13.4	5	28.4	6.3168	24,300
7	8.9	10	38.9	4.2112	34,933
8	17.9	10	47.9	8.4224	36,667
9	26.9	10	56.9	12.6651	36,767
10	8.9	15	53.9	4.2112	41,900
11	13.4	15	58.4	6.3168	42,167
12	26.9	15	71.9	12.6651	46,233
13	13.4	20	73.4	6.3325	50,833
14	17.9	20	77.9	8.4224	52,633
15	35.2	20	95.2	16.5934	58,567

(a) Mexican Limestone (Opt.)

Sequence Number	σ_d (psi)	σ_3 (psi)	θ (psi)	τ_{oct} (psi)	M_r (psi)
1	2.7	3	11.7	1.2728	14,400
2	5.3	3	14.3	2.4984	17,133
3	8.0	3	17.0	3.7712	20,200
4	4.5	5	19.5	2.1213	22,700
5	8.9	5	23.9	4.1955	27,067
6	13.4	5	28.4	6.3168	30,833
7	8.9	10	38.9	4.1955	41,500
8	17.9	10	47.9	8.4381	44,900
9	26.8	10	56.8	12.6336	48,533
10	8.9	15	53.9	4.1955	51,100
11	13.4	15	58.4	6.3168	52,400
12	26.8	15	71.8	12.6336	59,300
13	13.4	20	73.4	6.3168	65,500
14	17.9	20	77.9	8.4381	66,967
15	35.2	20	95.2	16.6092	75,933

(b) Recycled PCC (crushed) (Opt.)

Table 8
Regression analysis coefficients

Material	Moisture Content	Model 1 Coefficients				Model 2 Coefficients				Model 3 Coefficients			
		k_1	k_2	k_3	$^*R^2$	k_1	k_2	k_3	$^*R^2$	k_1	k_2	k_3	$^*R^2$
Recycled PCC (Crushed)	(Opt.)	1,263.0	0.8240	-0.1992	1.00	14,824.7	1.4676	0.3392	0.98	16,829.2	0.8354	-0.0745	1.00
	(+2%)	1,007.9	0.8276	-0.2139	1.00	11,885.8	1.4662	0.3321	0.97	13,352.4	0.8388	-0.0789	1.00
	(-2%)	1,207.5	0.8532	-0.2224	1.00	14,247.1	1.4956	0.3453	0.96	15,991.5	0.8619	-0.0791	1.00
Mexican Limestone	(Opt.)	1,190.0	0.7253	-0.2569	0.99	14,001.4	1.3440	0.2387	0.99	15,043.1	0.7594	-0.1155	0.99
	(+2%)	766.3	0.7361	0.0262	0.99	8,994.7	1.3356	0.4321	0.99	11,269.3	0.7447	-0.0009	0.99
	(-2%)	1,226.1	0.6940	-0.2796	1.00	14,502.7	1.2873	0.2129	0.99	15,477.3	0.7214	-0.1141	1.00

**Pseudo-R^2*

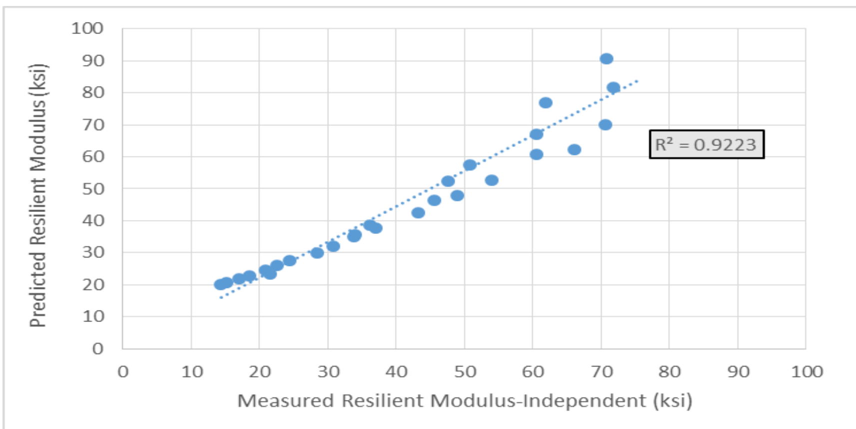
(a) Model 1

(b) Model 2

(c) Model 3

Figure 17
Model verification of Mexican Limestone at optimum moisture content

(a) Model 1



(b) Model 2

(c) Model 3

Figure 18
Model verification of Recycled PCC (crushed) at optimum moisture content

CONCLUSIONS

A laboratory testing program was conducted to determine resilient modulus design values for typical base course materials, as allowed by DOTD specifications and to evaluate generalized constitutive models for resilient modulus based on k_1, k_2, and k_3 parameters for use in predicting resilient modulus of unbound base course materials. Based on the results of this study, the following conclusions can be drawn:

- For soil cement at 7-day curing, moisture content has an effect on resilient moduli as an increase (two percent above optimum) or a decrease (two percent below optimum) in molded moisture content caused a decrease in resilient moduli which can be attributed to the fact that a material will have higher resilient modulus at its maximum dry density.

- For soil cement at 28-day curing, there was a significant increase in resilient moduli as compared to samples at 7-day curing. Resilient moduli design values ranged from 100,000-180,000 psi for the soil cement materials tested in this study. Resilient moduli values varied with molding moisture content for each material and the minimum value was selected.

- For soil cement, the cement content of a base course will enhance its strength characteristics and thus affect its response to loading as observed below:

1) In-place cement treated base course (recycled soil cement base) generally behaved as a stress-softening material (i.e., an increase in deviator stress caused a decrease in resilient moduli).

2) Cement stabilized base course and in-place cement stabilized base course generally behaved as stress-hardening materials (i.e., an increase in deviator stress caused an increase in resilient moduli).

- For unbound materials such as Mexican Limestone and Recycled PCC (crushed), moisture content has an effect on resilient moduli as an increase (two percent above optimum) or a decrease (two percent below optimum) in testing moisture content caused a decrease in resilient moduli which can be attributed to the fact that a material will have higher resilient modulus at its maximum dry density. Resilient moduli design values ranged from 15,000-25,000 psi for the Mexican Limestone and Recycled PCC (crushed) tested in this study. Resilient moduli values varied with testing moisture content for each material and the minimum value was selected.

- The NCHRP Model, UKTC Model, and Uzan Model all performed well in predicting resilient moduli of the Mexican Limestone and Recycled PCC (crushed) tested in this study with the material coefficients (k_1, k_2, and k_3) provided in Table 8.

RECOMMENDATIONS

Based on the conclusions drawn from this study, the following initiatives are recommended in order to facilitate the implementation of this study:

1) For cement stabilized base course (300 psi design strength), as specified by Sections 302 and 303 of the Louisiana Standard Specifications for Roads and Bridges (2006 edition), the following resilient modulus design values are recommended for use as design inputs:

   a. A-2-4 (Cement Stabilized): 180,000 psi

   b. A-4 (Cement Stabilized): 130,000 psi

   c. A-6 (Cement Stabilized): 110,000 psi

   d. A-4 (In-Place Cement Stabilized): 140,000 psi

2) For cement treated base course (150 psi design strength), as specified by Section 308 of the Louisiana Standard Specifications for Roads and Bridges (2006 edition), the following resilient modulus design value is recommended for use as a design input:

   a. In-Place Cement Treated (RSCB): 135,000 psi

3) For cement treated base courses (150 psi design strength), which are typically constructed for low volume roads, design personnel may consider utilizing a cement stabilized base course (300 psi design strength) when the low volume roads are subject to overweight vehicles since cement treated base courses generally behave as a stress-softening material.

4) For Mexican Limestone and Recycled PCC (crushed), as specified by Section 302 of the Louisiana Standard Specifications for Roads and Bridges (2006 edition), the following resilient modulus design values are recommended for use as design inputs:

   a. Mexican Limestone: 20,000 psi

   b. Recycled PCC (crushed): 25,000 psi

5) Model 1 (NCHRP Model) is recommended for use and the material coefficients (k_1, k_2, and k_3) for predicting the resilient moduli of Mexican Limestone and Recycled PCC (crushed) are as follows:

	k_1	k_2	k_3
a. Mexican Limestone:	1,190.0	0.7253	-0.2569
b. Recycled PCC (crushed):	1,263.0	0.8240	-0.1992

ACRONYMS, ABBREVIATIONS, AND SYMBOLS

AASHTO	American Association of State Highway and Transportation Officials
DV	dielectric value
FHWA	Federal Highway Administration
ft.	foot (feet)
in.	inch(es)
DOTD	Louisiana Department of Transportation and Development
LTRC	Louisiana Transportation Research Center
lb.	pound(s)
m	meter(s)
MEPDG	Mechanistic-Empirical Pavement Design Guide
NCHRP	National Cooperative Highway Research Program
PCC	Portland cement concrete
RLT	repeated loaded triaxial
SHRP	Strategic Highway Research Program
UCS	Unconfined Compressive Strength
UKTC	University of Kentucky Transportation Center

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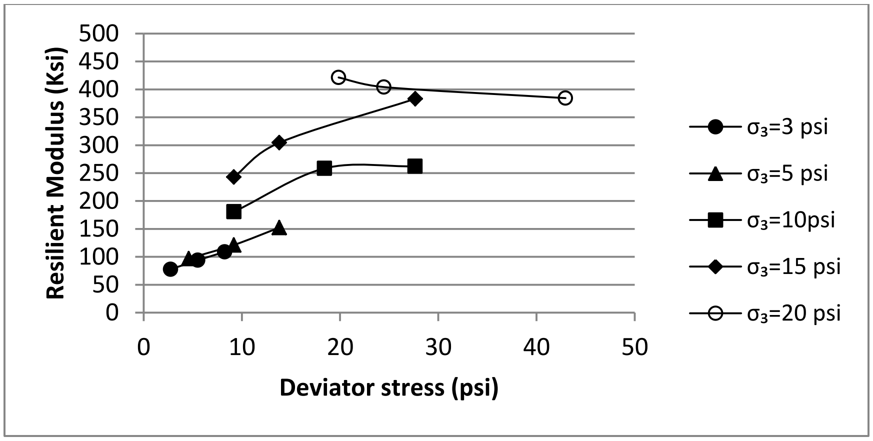
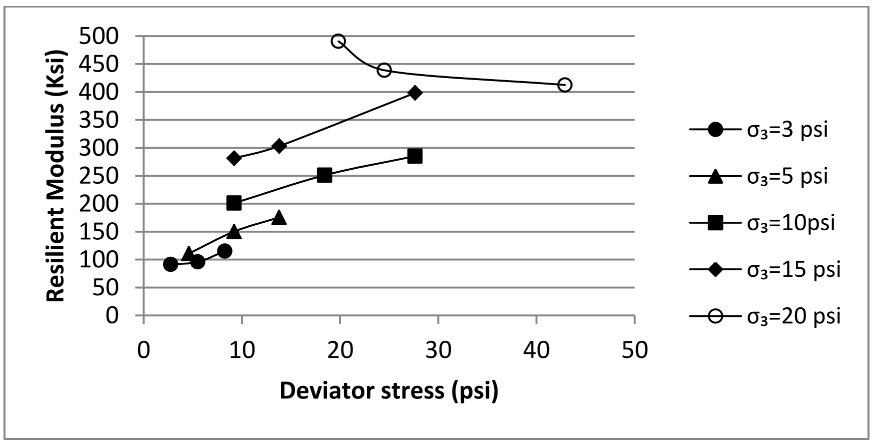
APPENDICES

APPENDIX A

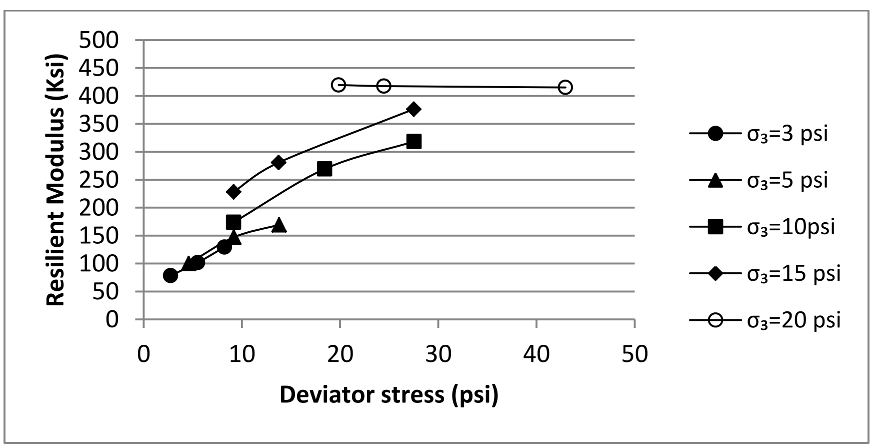
A-2-4 Resilient Modulus Graphs/Data



(a) Sample 1



(b) Sample 2

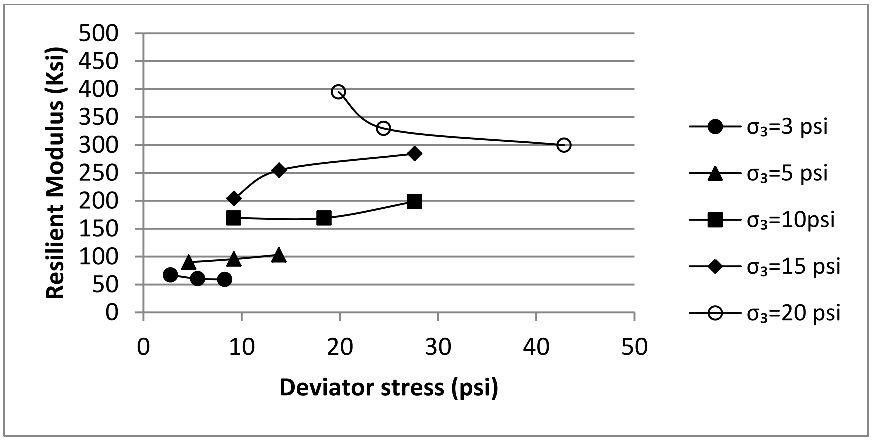


(c) Sample 3

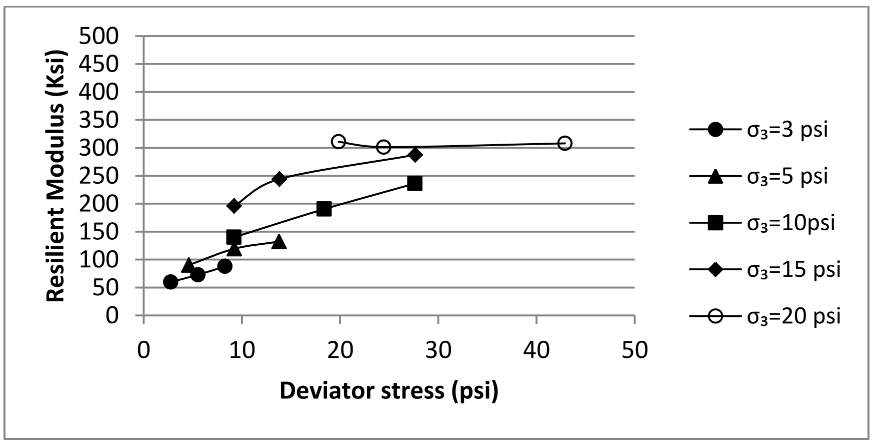
Figure 19
A-2-4 at optimum moisture content and 7-day curing graphs

Table 9
A-2-4 at optimum moisture content and 7-day curing data

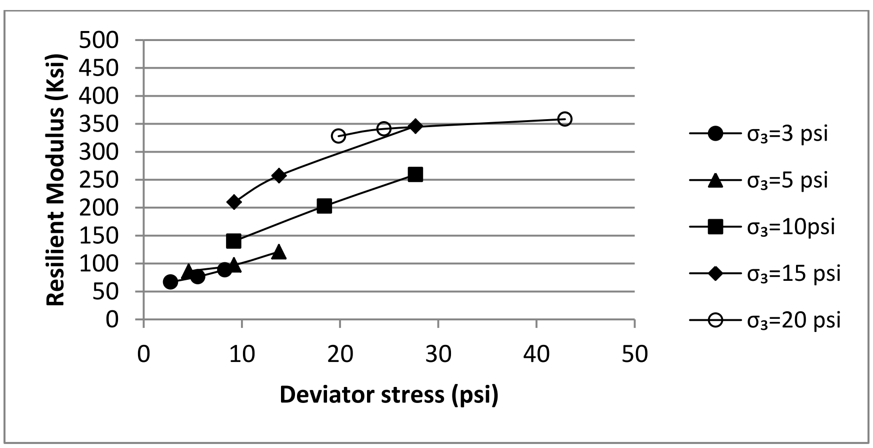
		A-2-4 (Opt.) 7-day Curing					
		Sample Number					
		1	2	3			
σ_3 (psi)	σ_d (psi)	M_r (ksi)			Average	Standard Deviation	Coefficient of Variation (%)
3	2.8	77.7	91.4	78.3	82.5	7.74	9.39
	5.8	93.9	95.8	101.7	97.1	4.07	4.19
	8.3	108.9	115.2	129.6	117.9	10.61	9.00
5	4.6	96.9	110.8	100.3	102.7	7.25	7.06
	9.2	121.2	150.2	147.1	139.5	15.92	11.41
	13.8	152.4	175.6	169.4	165.8	12.01	7.24
10	9.2	180.8	201.0	173.9	185.2	14.08	7.60
	18.4	258.4	251.0	269.4	259.6	9.26	3.57
	27.4	262.2	285.2	318.5	288.6	28.31	9.81
15	9.2	243.0	281.5	228.5	251.0	27.39	10.91
	13.8	304.5	303.3	280.8	296.2	13.35	4.51
	27.5	383.2	398.3	376.3	385.9	11.25	2.92
20	19.8	421.4	490.6	419.6	443.9	40.48	9.12
	24.4	404.2	438.9	417.6	420.2	17.50	4.16
	42.8	384.4	412.5	415.2	404.0	17.06	4.22



(a) Sample 1



(b) Sample 2

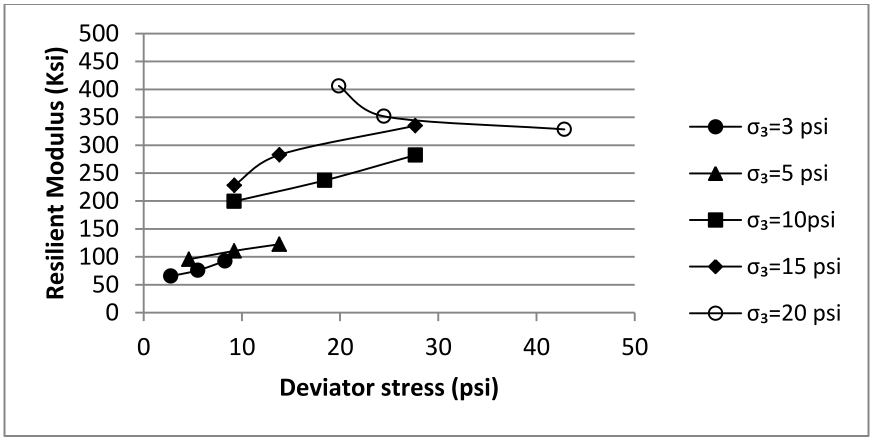


(c) Sample 3

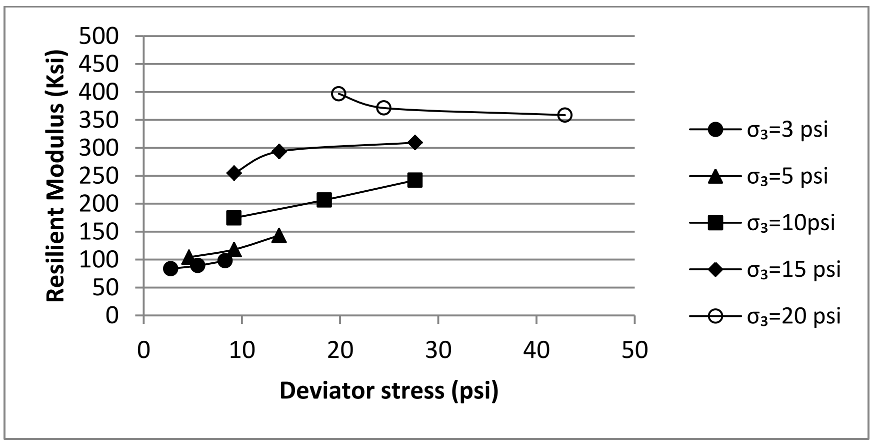
Figure 20
A-2-4 at +2% moisture content and 7-day curing graphs

Table 10
A-2-4 at +2% moisture content and 7-day curing data

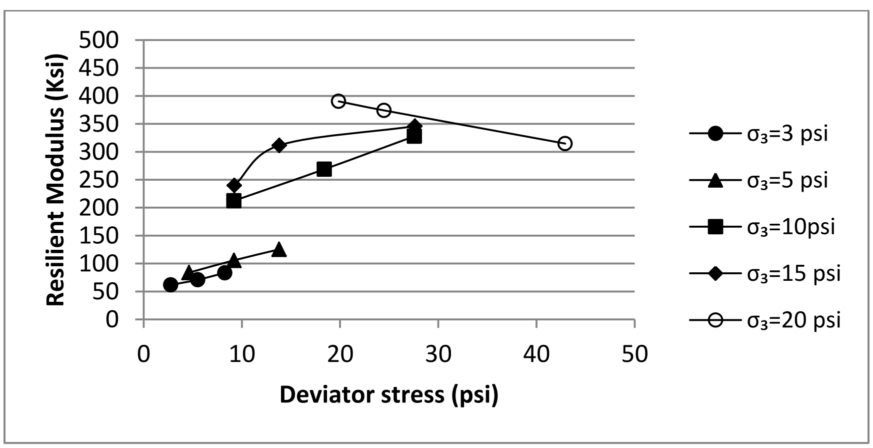
		A-2-4 (+2%) 7-day Curing					
		Sample Number					
		1	2	3			
σ_3 (psi)	σ_d (psi)	M_r (ksi)			Average	Standard Deviation	Coefficient of Variation (%)
3	2.8	66.9	59.9	66.9	64.6	4.04	6.26
	5.8	60.3	72.8	76.5	69.9	8.49	12.15
	8.3	58.9	87.8	88.8	78.5	16.98	21.63
5	4.6	90.0	90.3	86.2	88.8	2.29	2.57
	9.2	95.5	119.4	97.5	104.1	13.26	12.73
	13.8	103.2	132.2	121.2	118.9	14.64	12.32
10	9.2	169.0	140.0	140.0	149.7	16.74	11.19
	18.4	169.0	190.4	202.8	187.4	17.10	9.12
	27.4	198.5	236.2	259.2	231.3	30.65	13.25
15	9.2	204.4	195.9	210.0	203.4	7.10	3.49
	13.8	254.8	244.2	257.4	252.1	6.99	2.77
	27.5	284.5	287.5	346.0	306.0	34.67	11.33
20	19.8	394.8	310.8	328.0	344.5	44.37	12.88
	24.4	329.6	301.3	341.0	324.0	20.44	6.31
	42.8	299.6	308.0	358.4	322.0	31.80	9.88



(a) Sample 1



(b) Sample 2

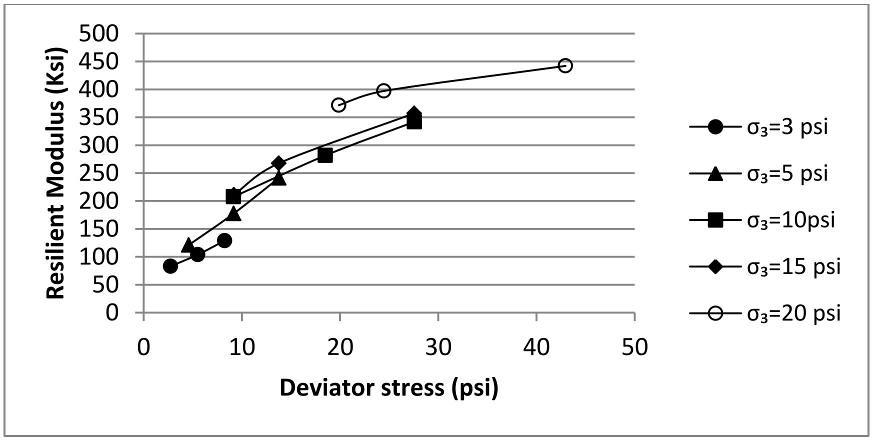


(c) Sample 3

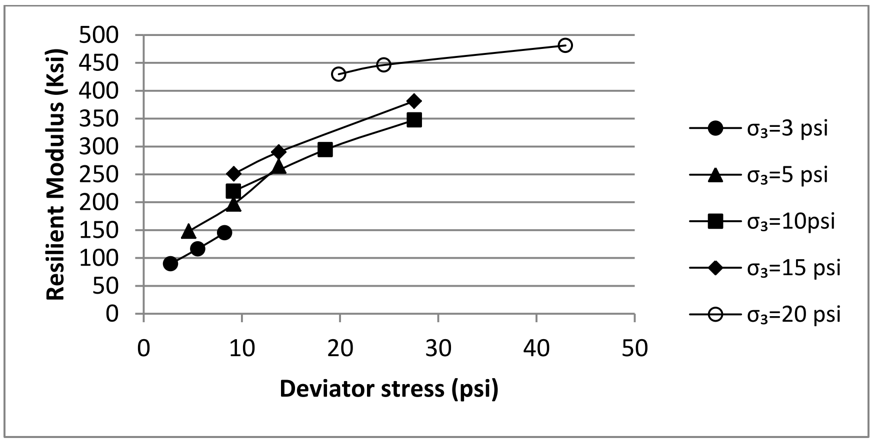
Figure 21
A-2-4 at -2% moisture content and 7-day curing graphs

Table 11
A-2-4 at -2% moisture content and 7-day curing data

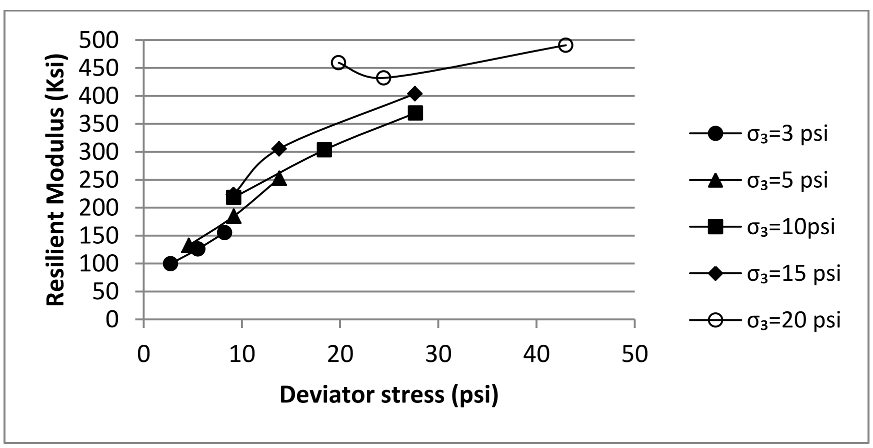
		A-2-4 (-2%) 7-day Curing					
		Sample Number					
		1	2	3			
σ_3 (psi)	σ_d (psi)	M_r (ksi)			Average	Standard Deviation	Coefficient of Variation (%)
3	2.8	65.4	83.6	61.8	70.3	11.69	16.63
	5.8	75.8	89.2	71.0	78.7	9.43	11.99
	8.3	92.6	97.8	83.4	91.3	7.29	7.99
5	4.6	95.6	104.2	83.8	94.5	10.24	10.83
	9.2	110.6	118.0	105.8	111.5	6.15	5.51
	13.8	122.6	143.2	125.4	130.4	11.17	8.57
10	9.2	199.5	174.5	212.4	195.5	19.27	9.86
	18.4	237.0	206.6	268.8	237.5	31.10	13.10
	27.4	282.3	242.0	327.9	284.1	42.98	15.13
15	9.2	228.2	254.7	239.9	240.9	13.28	5.51
	13.8	282.8	293.5	311.4	295.9	14.45	4.88
	27.5	335.0	309.4	345.9	330.1	18.74	5.68
20	19.8	406.2	396.8	390.3	397.8	7.99	2.01
	24.4	351.8	371.3	374.1	365.7	12.15	3.32
	42.8	328.4	358.6	314.7	333.9	22.46	6.73



(a) Sample 1



(b) Sample 2

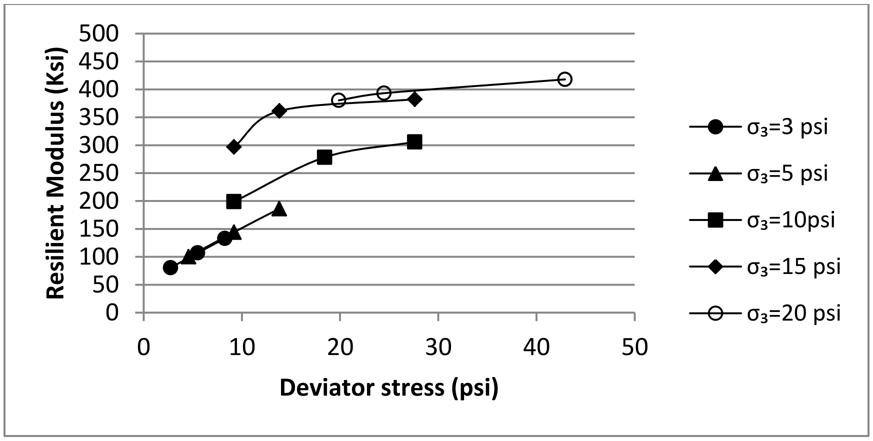


(c) Sample 3

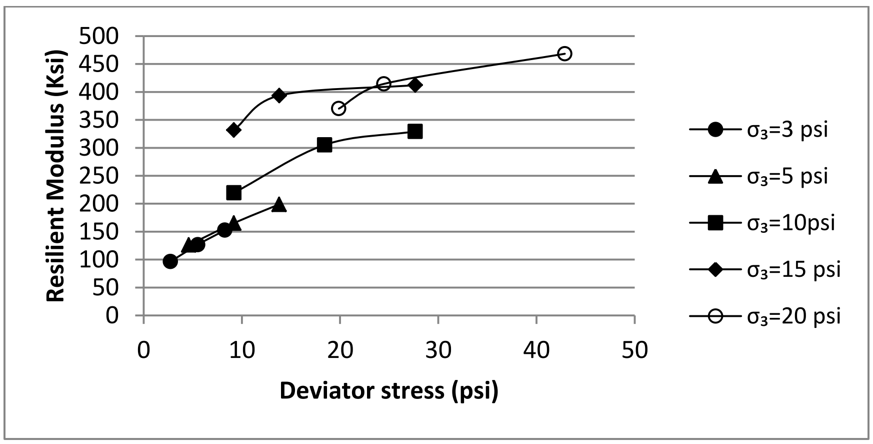
Figure 22
A-2-4 at optimum moisture content and 28-day curing graphs

Table 12
A-2-4 at optimum moisture content and 28-day curing data

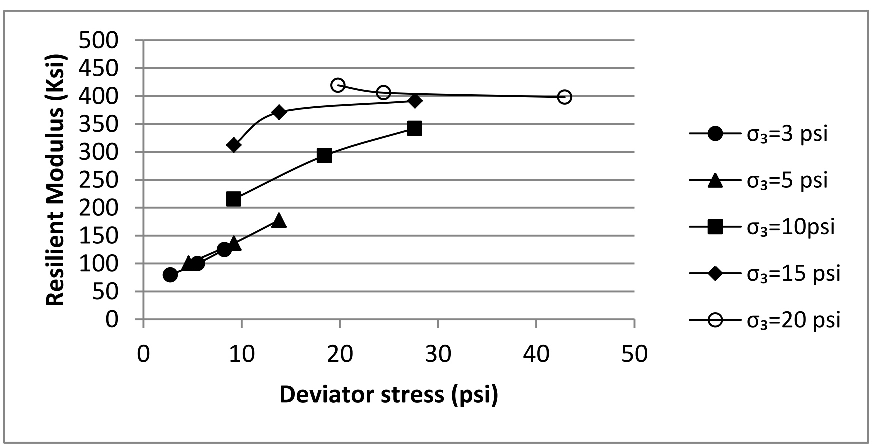
		A-2-4 (Opt.) 28-day Curing					
		Sample Number					
		1	2	3			
σ_3 (psi)	σ_d (psi)	M_r (ksi)			Average	Standard Deviation	Coefficient of Variation (%)
3	2.8	83.0	89.6	99.6	90.7	8.36	9.21
	5.8	104.0	116.4	126.0	115.5	11.03	9.55
	8.3	129.0	145.2	155.4	143.2	13.31	9.30
5	4.6	121.2	148.0	132.6	133.9	13.45	10.04
	9.2	177.6	196.8	184.8	186.4	9.70	5.20
	13.8	241.2	264.9	252.6	252.9	11.85	4.69
10	9.2	207.6	219.8	218.4	215.3	6.68	3.10
	18.4	281.6	294.2	303.5	293.1	10.99	3.75
	27.4	342.0	347.6	369.5	353.0	14.53	4.12
15	9.2	211.2	251.0	223.8	228.7	20.34	8.90
	13.8	267.6	290.1	305.4	287.7	19.01	6.61
	27.5	357.2	381.4	404.1	380.9	23.45	6.16
20	19.8	371.6	429.7	459.4	420.5	44.66	10.63
	24.4	397.2	446.2	432.2	425.2	25.24	5.94
	42.8	442.1	481.3	490.8	471.4	25.82	5.48



(a) Sample 1



(b) Sample 2

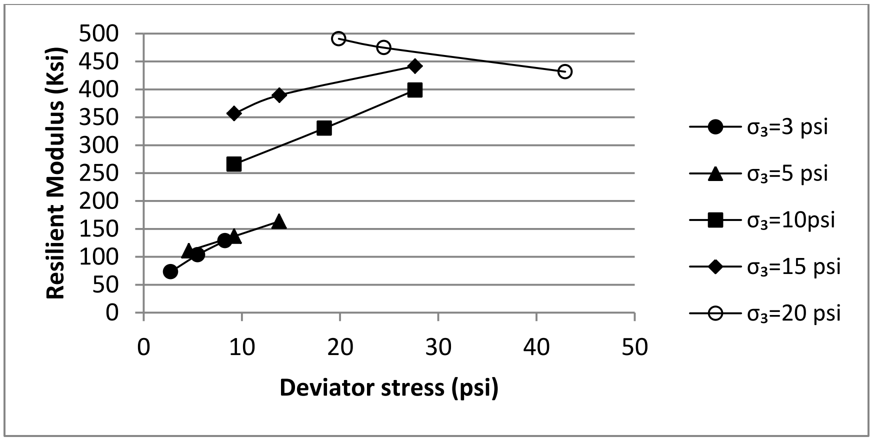


(c) Sample 3

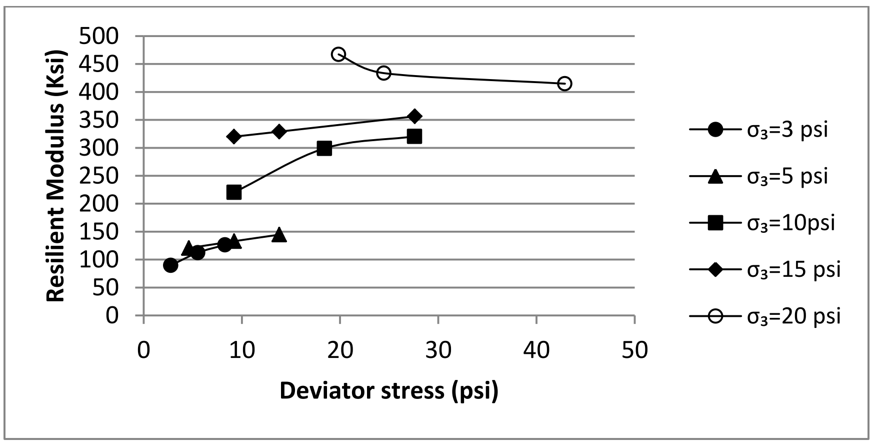
Figure 23
A-2-4 at +2% moisture content and 28-day curing graphs

Table 13
A-2-4 at +2% moisture content and 28-day curing data

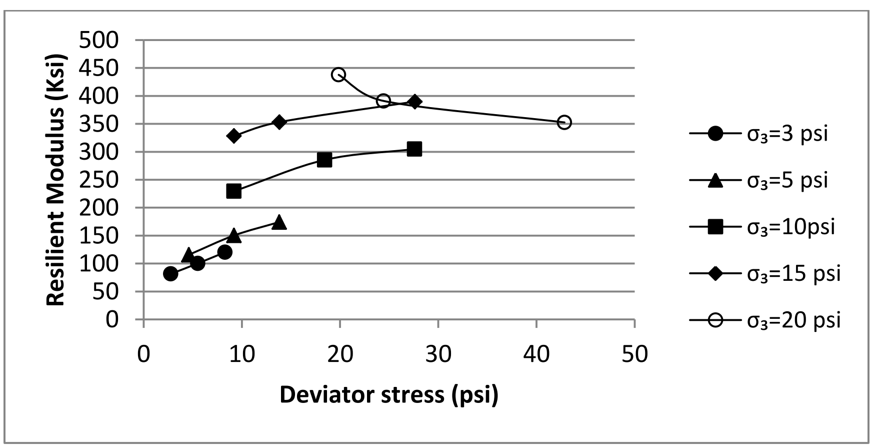
		A-2-4 (+2%) 28-day Curing					
		Sample Number					
		1	2	3			
σ_3 (psi)	σ_d (psi)	M_r (ksi)			Average	Standard Deviation	Coefficient of Variation (%)
3	2.8	80.5	96.6	79.5	85.5	9.60	11.22
	5.8	107.0	126.7	100.0	111.2	13.84	12.45
	8.3	133.0	152.6	125.0	136.9	14.20	10.38
5	4.6	100.1	126.2	100.4	108.9	14.98	13.76
	9.2	144.2	165.2	136.4	148.6	14.90	10.02
	13.8	186.2	198.9	177.6	187.6	10.72	5.71
10	9.2	198.9	219.6	215.6	211.4	10.98	5.19
	18.4	278.3	305.3	293.4	292.3	13.53	4.63
	27.4	305.9	329.4	342.3	325.9	18.46	5.66
15	9.2	296.8	331.8	312.5	313.7	17.53	5.59
	13.8	361.4	393.6	371.0	375.3	16.53	4.40
	27.5	382.4	412.3	391.4	395.4	15.34	3.88
20	19.8	380.4	370.2	419.3	390.0	25.91	6.64
	24.4	393.2	414.5	406.0	404.6	10.72	2.65
	42.8	417.9	468.4	398.1	428.1	36.25	8.47



(a) Sample 1



(b) Sample 2



(c) Sample 3

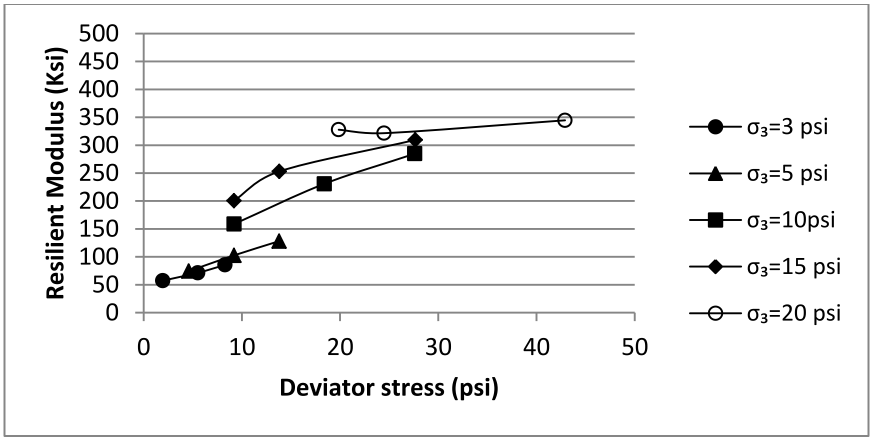
Figure 24
A-2-4 at -2% moisture content and 28-day curing graphs

Table 14
A-2-4 at -2% moisture content and 28-day curing data

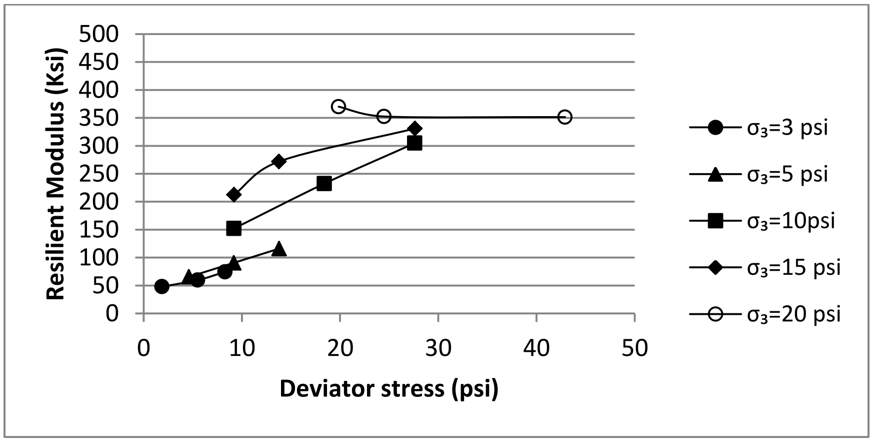
		A-2-4 (-2%) 28-day Curing					
		Sample Number					
		1	2	3			
σ_3 (psi)	σ_d (psi)	M_r (ksi)			Average	Standard Deviation	Coefficient of Variation (%)
3	2.8	73.2	89.6	81.5	81.4	8.20	10.07
	5.8	103.6	112.4	100.3	105.4	6.25	5.93
	8.3	128.8	126.4	120.3	125.2	4.38	3.50
5	4.6	110.7	120.6	115.8	115.7	4.95	4.28
	9.2	136.8	132.9	150.3	140.0	9.13	6.52
	13.8	163.5	144.6	174.3	160.8	15.03	9.35
10	9.2	266.0	220.4	229.5	238.6	24.13	10.11
	18.4	330.4	299.0	285.5	305.0	23.04	7.55
	27.4	398.8	320.5	304.9	341.4	50.32	14.74
15	9.2	356.8	320.0	328.5	335.1	19.27	5.75
	13.8	389.6	329.0	353.2	357.3	30.50	8.54
	27.5	441.7	356.4	389.9	396.0	42.98	10.85
20	19.8	490.7	467.3	437.8	465.3	26.51	5.70
	24.4	474.8	433.7	391.0	433.2	41.90	9.67
	42.8	431.7	414.8	352.6	399.7	41.66	10.42

APPENDIX B

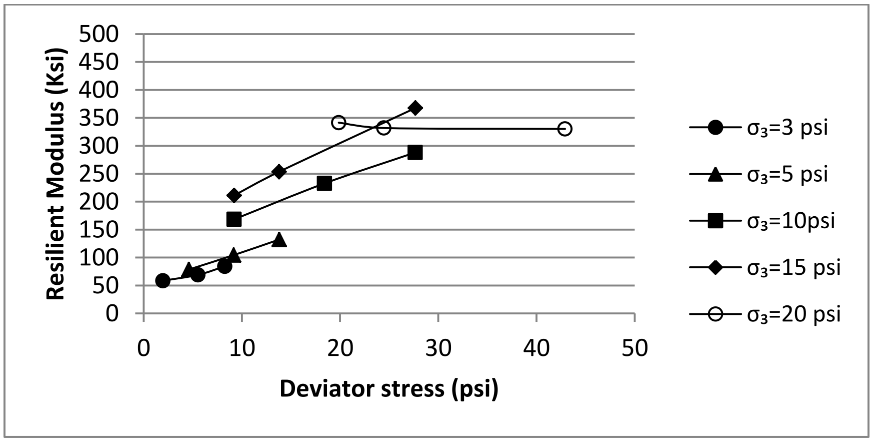
A-4 Resilient Modulus Graphs/Data



(a) Sample 1



(b) Sample 2

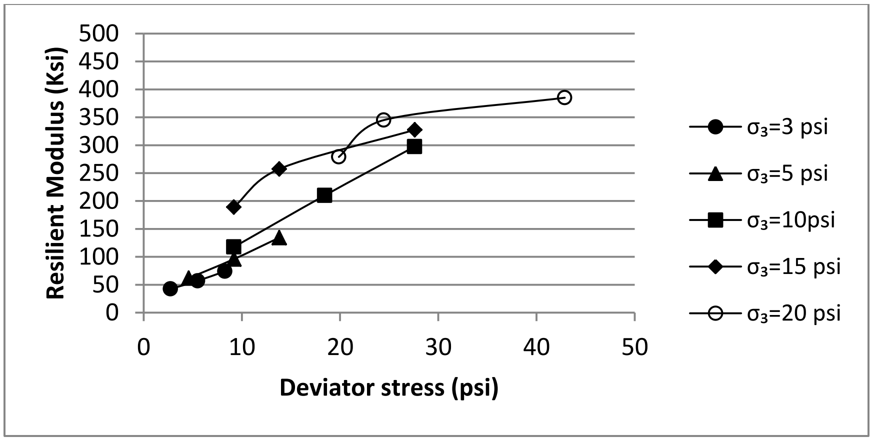


(c) Sample 3

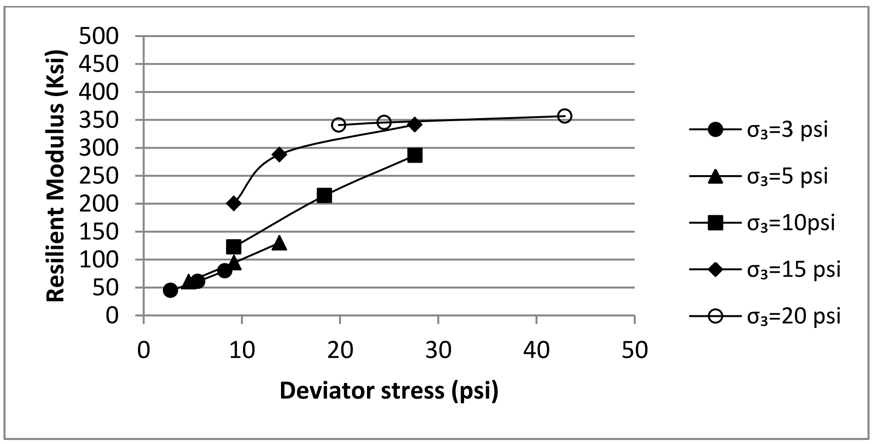
Figure 25
A-4 at optimum moisture content and 7-day curing graphs

Table 15
A-4 at optimum moisture content and 7-day curing data

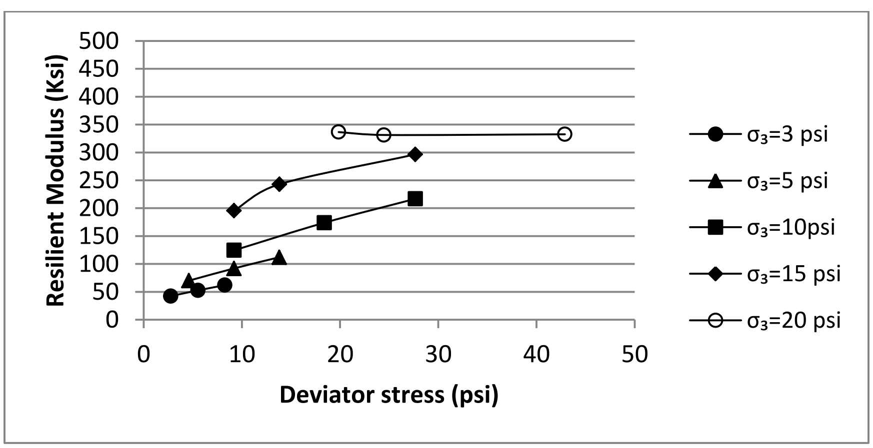
		A-4 (Opt.) 7-day Curing					
		Sample Number					
		1	2	3			
σ_3 (psi)	σ_d (psi)	M_r (ksi)			Average	Standard Deviation	Coefficient of Variation (%)
3	2.8	57.3	48.0	58.5	54.6	5.75	10.53
	5.8	71.4	59.7	69.0	66.7	6.18	9.27
	8.3	85.5	74.4	84.3	81.4	6.09	7.48
5	4.6	74.4	65.4	78.6	72.8	6.74	9.26
	9.2	102.6	90.6	104.4	99.2	7.50	7.56
	13.8	128.1	116.1	132.3	125.5	8.41	6.70
10	9.2	158.8	152.0	168.4	159.7	8.24	5.16
	18.4	230.8	232.4	232.7	232.0	1.02	0.44
	27.4	284.8	304.8	288.1	292.6	10.72	3.66
15	9.2	200.5	212.5	211.2	208.1	6.59	3.16
	13.8	253.0	272.0	253.6	259.5	10.80	4.16
	27.5	309.5	331.0	367.6	336.0	29.38	8.74
20	19.8	327.8	370.1	341.4	346.4	21.59	6.23
	24.4	321.6	352.5	331.8	335.3	15.74	4.70
	42.8	344.6	351.5	330.2	342.1	10.87	3.18



(a) Sample 1



(b) Sample 2

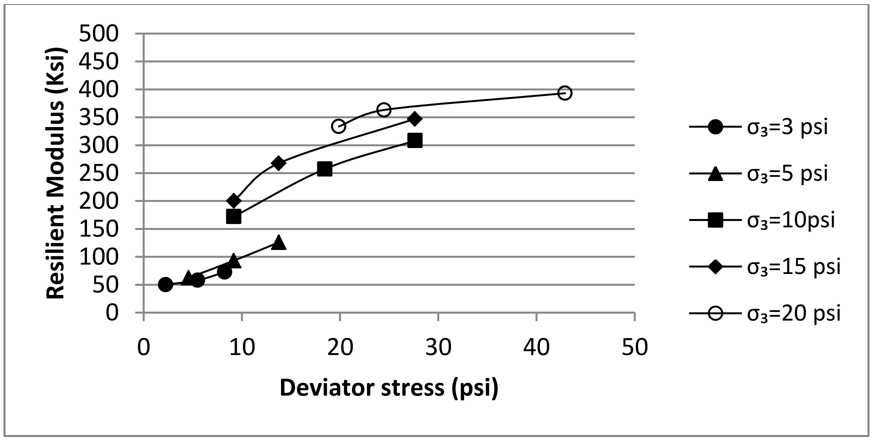


(c) Sample 3

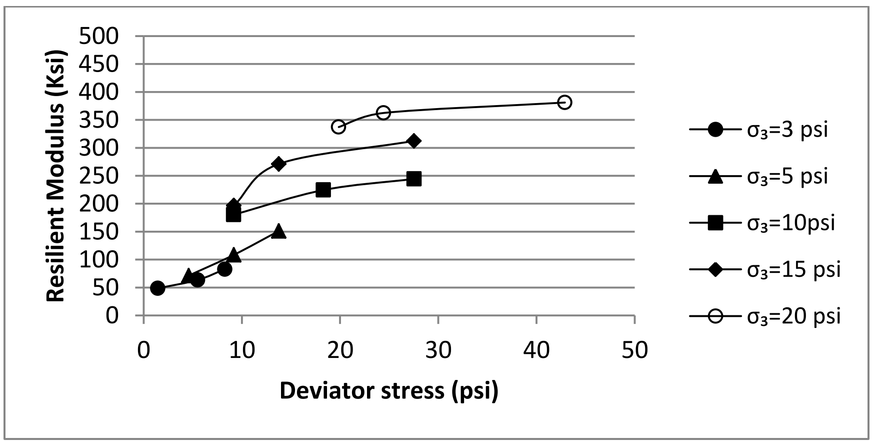
Figure 26
A-4 at +2% moisture content and 7-day curing graphs

Table 16
A-4 at +2% moisture content and 7-day curing data

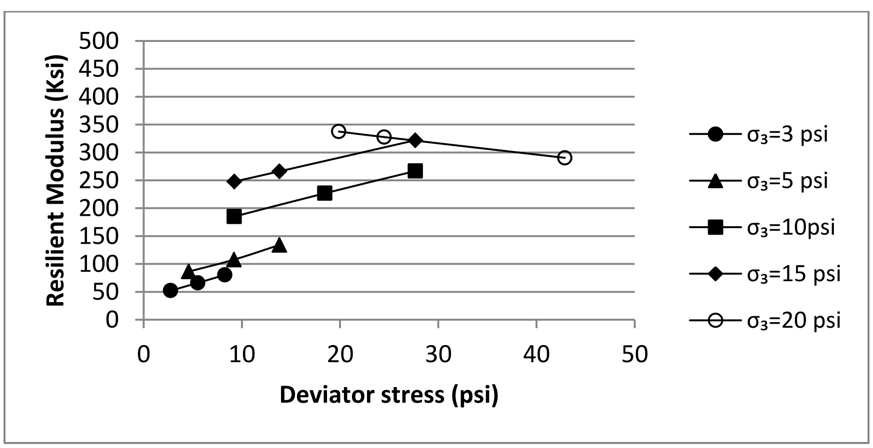
		A-4 (+2%) 7-day Curing					
		Sample Number					
		1	2	3			
σ_3 (psi)	σ_d (psi)	M_r (ksi)			Average	Standard Deviation	Coefficient of Variation (%)
3	2.8	42.5	44.8	42.4	43.2	1.36	3.14
	5.8	57.0	60.9	52.6	56.8	4.15	7.31
	8.3	74.0	79.8	62.0	71.9	9.08	12.62
5	4.6	61.8	60.4	70.0	64.1	5.19	8.09
	9.2	96.0	94.4	92.0	94.1	2.01	2.14
	13.8	134.4	130.0	112.0	125.5	11.87	9.46
10	9.2	117.6	122.5	124.5	121.5	3.55	2.92
	18.4	210.0	214.5	174.0	199.5	22.20	11.13
	27.4	297.5	286.5	216.9	267.0	43.71	16.37
15	9.2	189.2	200.7	195.8	195.2	5.77	2.96
	13.8	257.4	288.0	243.0	262.8	22.98	8.74
	27.5	327.6	341.6	296.5	321.9	23.08	7.17
20	19.8	279.0	340.7	336.6	318.8	34.50	10.82
	24.4	345.0	345.3	331.4	340.6	7.94	2.33
	42.8	385.1	356.7	332.6	358.1	26.28	7.34



(a) Sample 1



(b) Sample 2

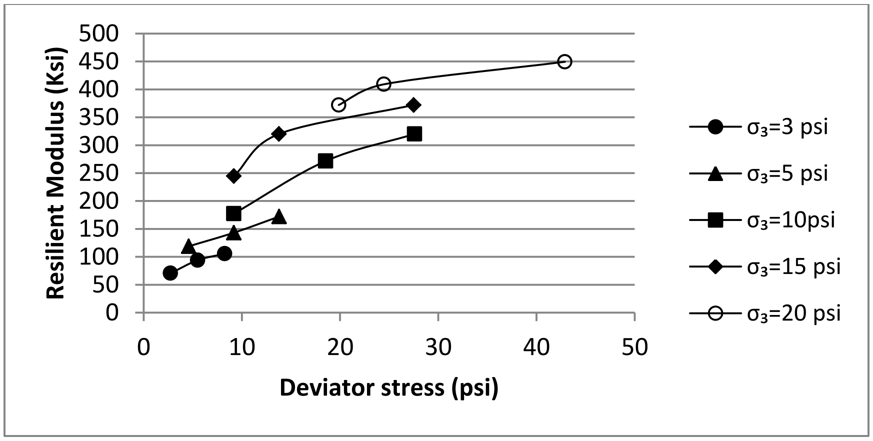


(c) Sample 3

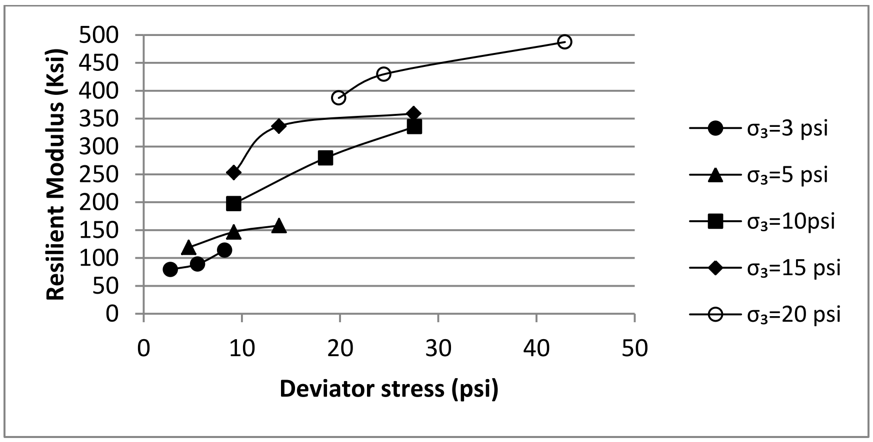
Figure 27
A-4 at -2% moisture content and 7-day curing graphs

Table 17
A-4 at -2% moisture content and 7-day curing data

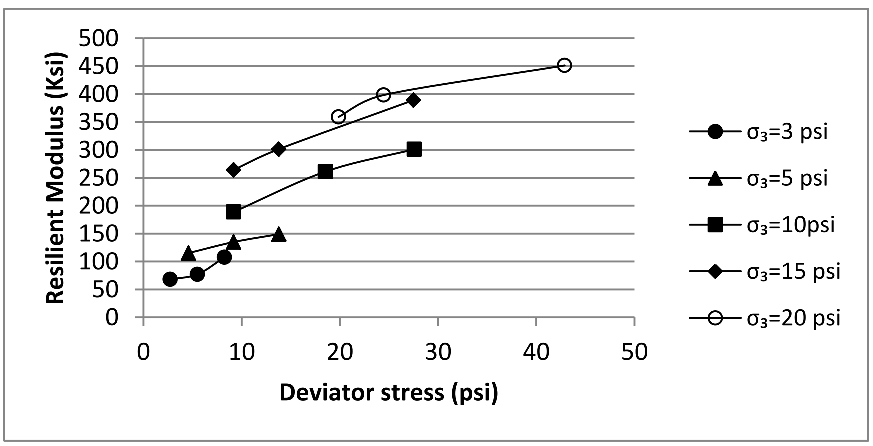
		A-4 (-2%) 7-day Curing					
		Sample Number					
		1	2	3			
σ_3 (psi)	σ_d (psi)	M_r (ksi)			Average	Standard Deviation	Coefficient of Variation (%)
3	2.8	50.1	48.6	52.2	50.3	1.81	3.60
	5.8	58.0	63.6	66.0	62.5	4.11	6.56
	8.3	72.6	82.8	80.4	78.6	5.33	6.78
5	4.6	62.4	71.4	86.4	73.4	12.12	16.52
	9.2	93.0	108.5	107.7	103.1	8.73	8.47
	13.8	126.0	151.2	134.1	137.1	12.87	9.38
10	9.2	172.2	180.4	185.1	179.2	6.53	3.64
	18.4	257.4	224.5	226.8	236.2	18.37	7.77
	27.4	308.3	244.4	266.7	273.1	32.43	11.87
15	9.2	200.4	196.8	247.8	215.0	28.46	13.24
	13.8	267.6	271.2	266.1	268.3	2.62	0.98
	27.5	347.2	312.4	321.9	327.2	17.99	5.50
20	19.8	333.6	337.2	337.5	336.1	2.17	0.65
	24.4	363.2	362.4	327.6	351.1	20.33	5.79
	42.8	393.1	381.1	290.4	354.9	56.15	15.82



(a) Sample 1



(b) Sample 2

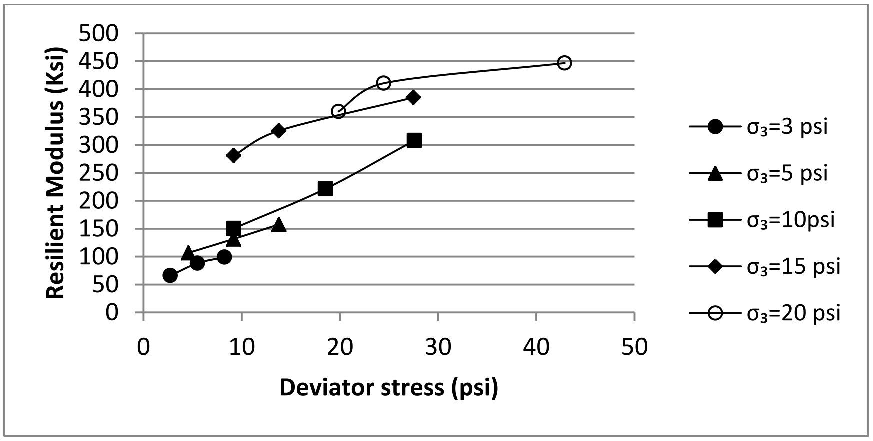


(c) Sample 3

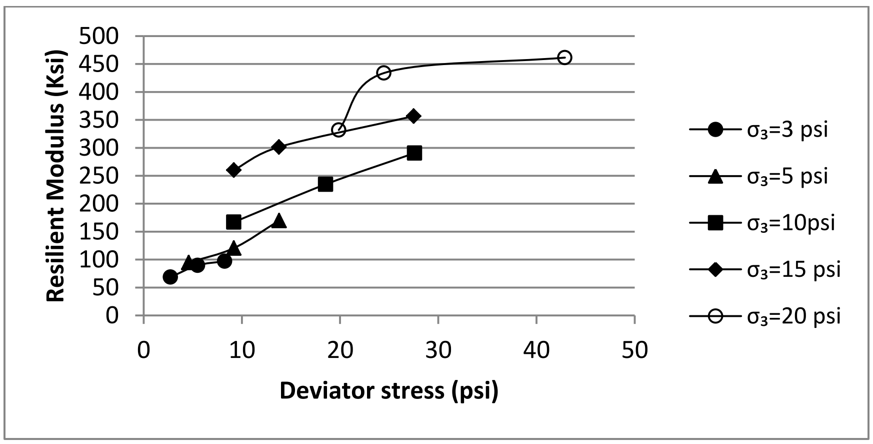
Figure 28
A-4 at optimum moisture content and 28-day curing graphs

Table 18
A-4 at optimum moisture content and 28-day curing data

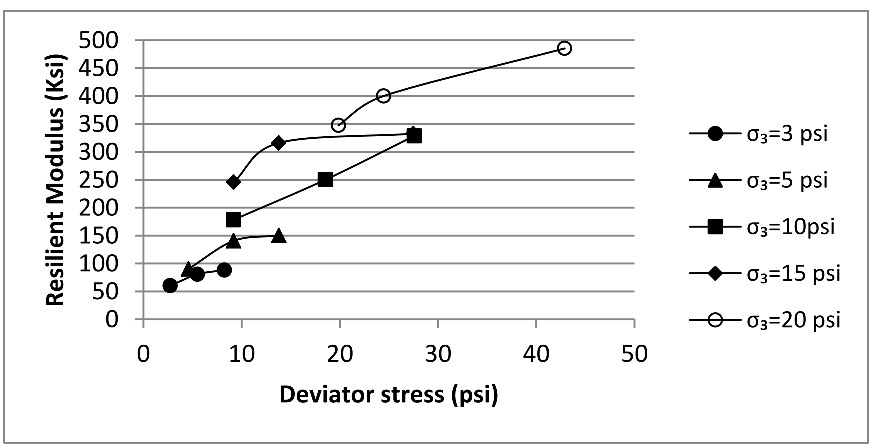
		A-4 (Opt.) 28-day Curing					
		Sample Number					
		1	2	3			
σ_3 (psi)	σ_d (psi)	M_r (ksi)			Average	Standard Deviation	Coefficient of Variation (%)
3	2.8	70.6	79.4	68.1	72.7	5.94	8.16
	5.8	94.0	89.0	77.0	86.7	8.74	10.08
	8.3	105.6	114.0	107.6	109.1	4.39	4.02
5	4.6	118.9	119.0	115.1	117.7	2.22	1.89
	9.2	143.2	146.6	134.9	141.6	6.02	4.25
	13.8	172.1	158.2	149.0	159.8	11.63	7.28
10	9.2	177.3	197.5	188.8	187.9	10.13	5.39
	18.4	271.6	279.5	261.1	270.7	9.23	3.41
	27.4	320.1	335.6	301.3	319.0	17.18	5.38
15	9.2	244.6	253.4	264.1	254.0	9.77	3.84
	13.8	320.1	336.5	301.3	319.3	17.61	5.52
	27.5	372.1	359.2	389.1	373.5	15.00	4.02
20	19.8	372.1	387.1	359.1	372.8	14.01	3.76
	24.4	409.2	429.7	398.3	412.4	15.94	3.87
	42.8	449.5	487.4	451.3	462.7	21.38	4.62



(a) Sample 1



(b) Sample 2

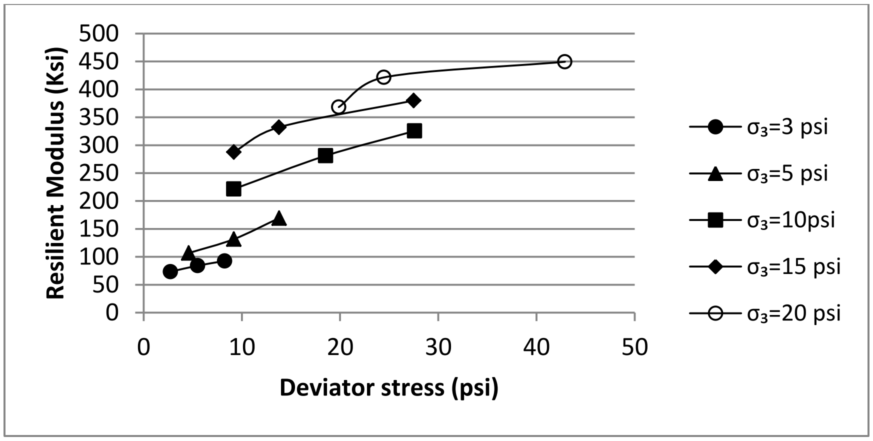


(c) Sample 3

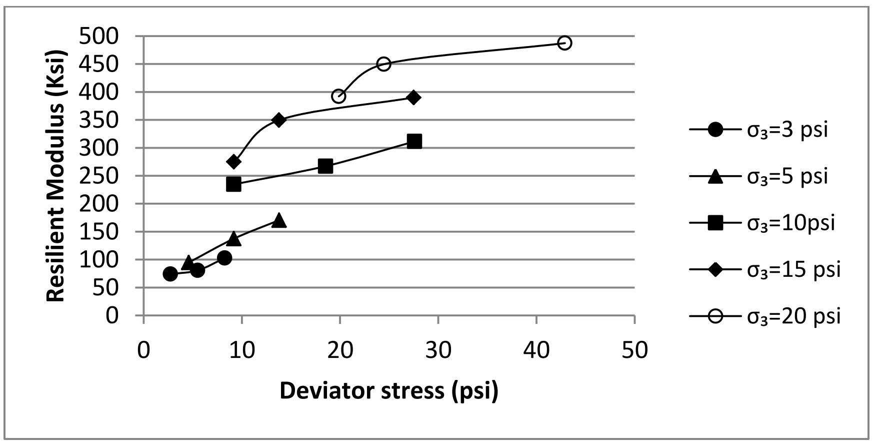
Figure 29
A-4 at +2% moisture content and 28-day curing graphs

Table 19
A-4 at +2% moisture content and 28-day curing data

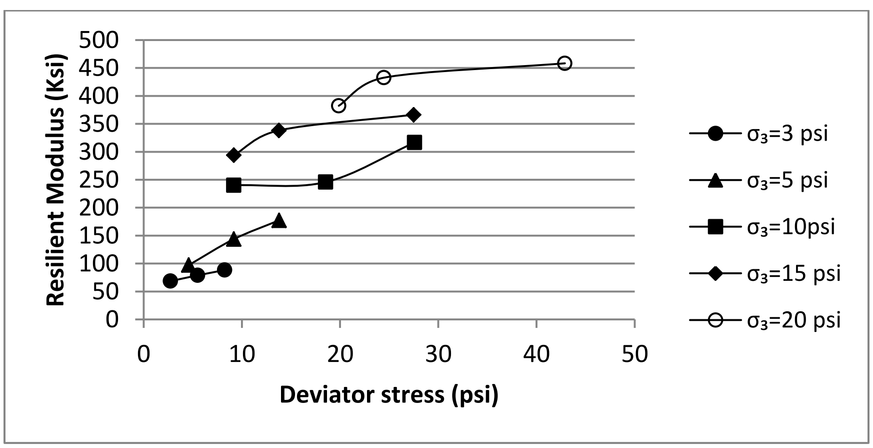
		A-4 (+2%) 28-day Curing					
		Sample Number					
σ_3 (psi)	σ_d (psi)	1	2	3	Average	Standard Deviation	Coefficient of Variation (%)
		M_r (ksi)					
3	2.8	66.0	68.7	60.4	65.0	4.23	6.51
	5.8	88.1	89.7	80.6	86.1	4.86	5.64
	8.3	99.1	97.1	88.3	94.8	5.75	6.06
5	4.6	106.8	94.8	90.3	97.3	8.53	8.77
	9.2	131.6	120.5	140.6	130.9	10.07	7.69
	13.8	157.6	169.8	150.1	159.2	9.94	6.25
10	9.2	150.4	167.0	178.3	165.2	14.03	8.49
	18.4	221.5	234.7	250.1	235.4	14.31	6.08
	27.4	308.2	290.7	328.7	309.2	19.02	6.15
15	9.2	281.0	260.2	245.8	262.3	17.70	6.75
	13.8	325.5	301.5	316.0	314.3	12.09	3.85
	27.5	385.1	356.7	332.6	358.1	26.28	7.34
20	19.8	360.0	332.0	347.6	346.5	14.03	4.05
	24.4	410.6	433.9	400.2	414.9	17.26	4.16
	42.8	446.8	461.5	485.4	464.6	19.48	4.19



(a) Sample 1



(b) Sample 2



(c) Sample 3

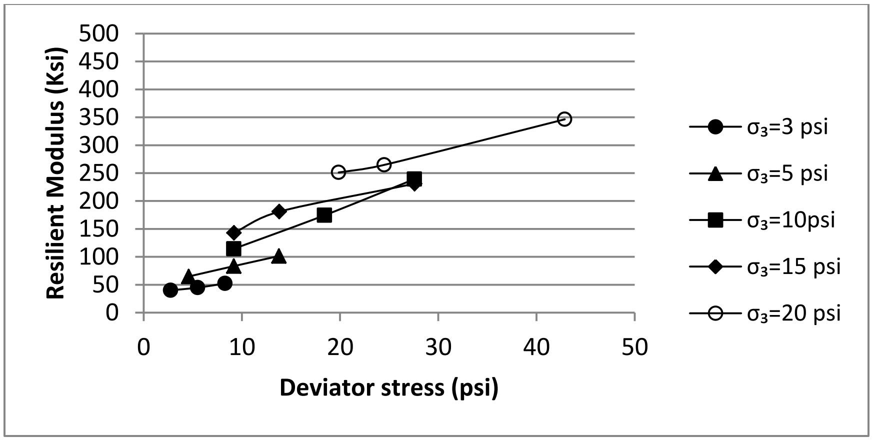
Figure 30
A-4 at -2% moisture content and 28-day curing graphs

Table 20
A-4 at -2% moisture content and 28-day curing data

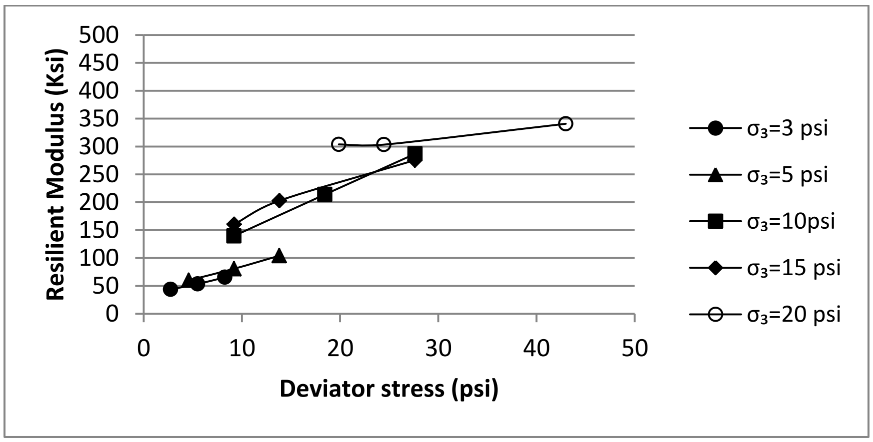
		A-4 (-2%) 28-day Curing					
		Sample Number					
σ_3 (psi)	σ_d (psi)	1	2	3	Average	Standard Deviation	Coefficient of Variation (%)
		M_r (ksi)					
3	2.8	73.4	74.0	68.6	72.0	2.96	4.11
	5.8	84.2	80.7	78.9	81.3	2.70	3.32
	8.3	92.6	102.8	88.4	94.6	7.41	7.83
5	4.6	106.8	94.8	97.3	99.6	6.33	6.35
	9.2	131.7	137.4	143.7	137.6	6.00	4.36
	13.8	169.4	170.5	177.4	172.4	4.34	2.51
10	9.2	221.5	234.7	240.1	232.1	9.57	4.12
	18.4	281.1	267.2	245.8	264.7	17.78	6.72
	27.4	325.5	311.5	316.6	317.9	7.09	2.23
15	9.2	287.8	275.1	294.1	285.7	9.68	3.39
	13.8	332.2	349.5	338.3	340.0	8.77	2.58
	27.5	380.0	390.1	366.4	378.8	11.89	3.14
20	19.8	368.3	392.1	382.4	380.9	11.97	3.14
	24.4	421.5	449.7	432.7	434.6	14.20	3.27
	42.8	449.5	487.4	458.4	465.1	19.82	4.26

APPENDIX C

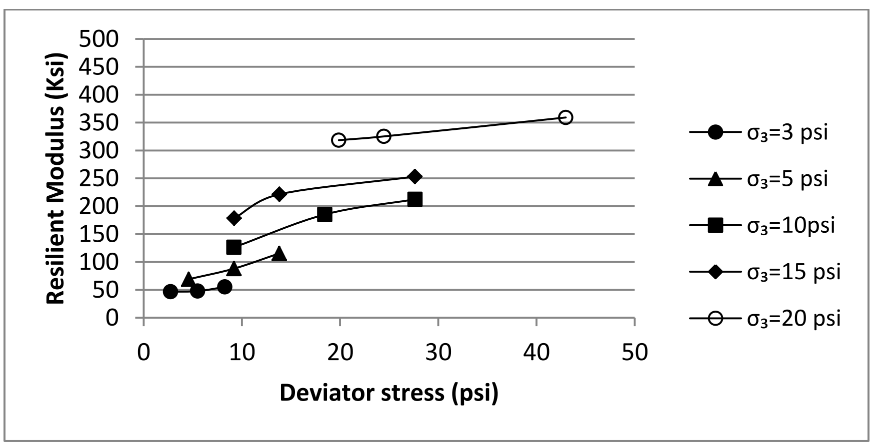
A-6 Resilient Modulus Graphs/Data



(a) Sample 1



(b) Sample 2

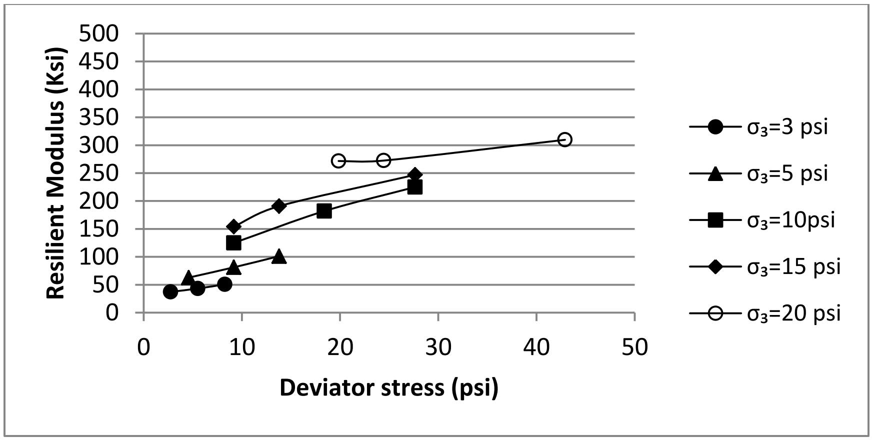


(c) Sample 3

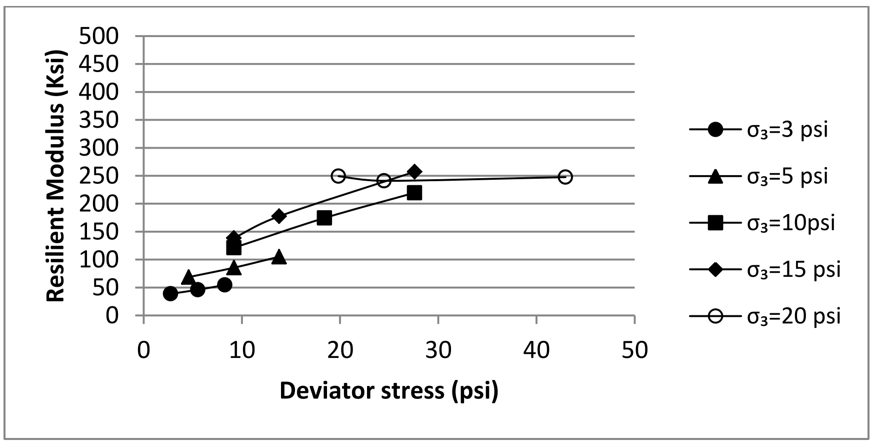
Figure 31
A-6 at optimum moisture content and 7-day curing graphs

Table 21
A-6 at optimum moisture content and 7-day curing data

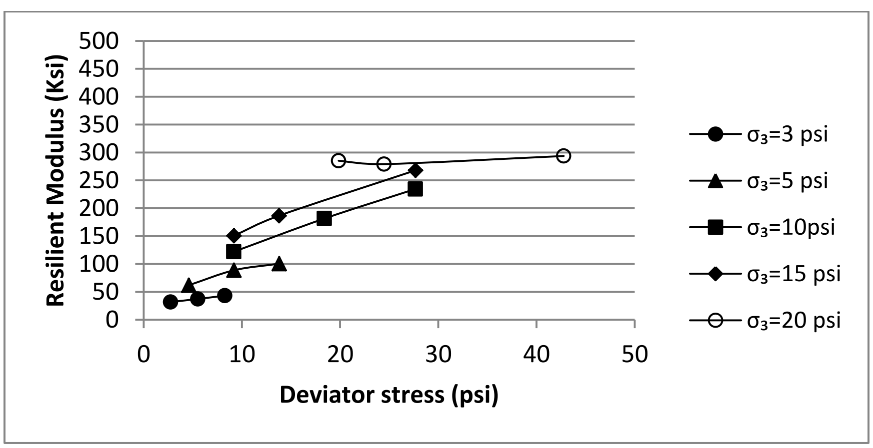
		A-6 (Opt.) 7-day Curing					
		Sample Number					
σ_3 (psi)	σ_d (psi)	1	2	3	Average	Standard Deviation	Coefficient of Variation (%)
		M_r (ksi)					
3	2.8	40.0	43.8	46.6	43.5	3.31	7.62
	5.8	44.8	53.4	47.7	48.6	4.38	9.00
	8.3	52.4	65.4	55.2	57.7	6.84	11.86
5	4.6	64.8	60.0	69.1	64.6	4.55	7.04
	9.2	83.4	80.7	88.1	84.1	3.74	4.45
	13.8	101.4	104.1	115.4	107.0	7.43	6.94
10	9.2	114.4	139.6	126.3	126.8	12.61	9.94
	18.4	174.4	214.0	185.2	191.2	20.47	10.71
	27.4	239.2	286.8	212.4	246.1	37.68	15.31
15	9.2	143.0	160.4	178.5	160.6	17.75	11.05
	13.8	181.0	202.8	221.4	201.7	20.22	10.02
	27.5	231.0	275.5	253.2	253.2	22.25	8.79
20	19.8	251.2	303.8	318.5	291.2	35.38	12.15
	24.4	264.8	303.4	325.2	297.8	30.59	10.27
	42.8	346.4	340.8	359.2	348.8	9.43	2.70



(a) Sample 1



(b) Sample 2

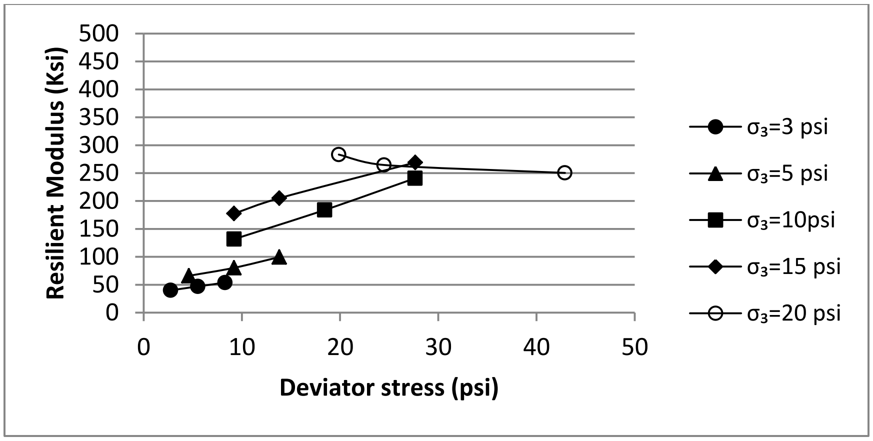


(c) Sample 3

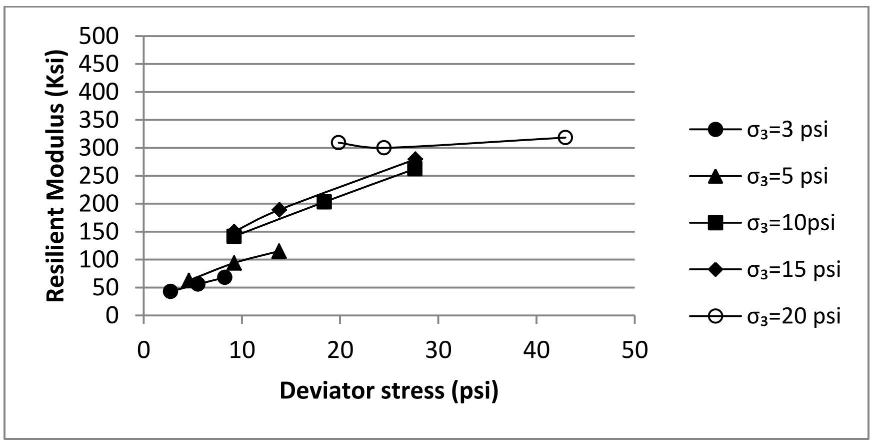
Figure 32
A-6 at +2% moisture content and 7-day curing graphs

Table 22
A-6 at +2% moisture content and 7-day curing data

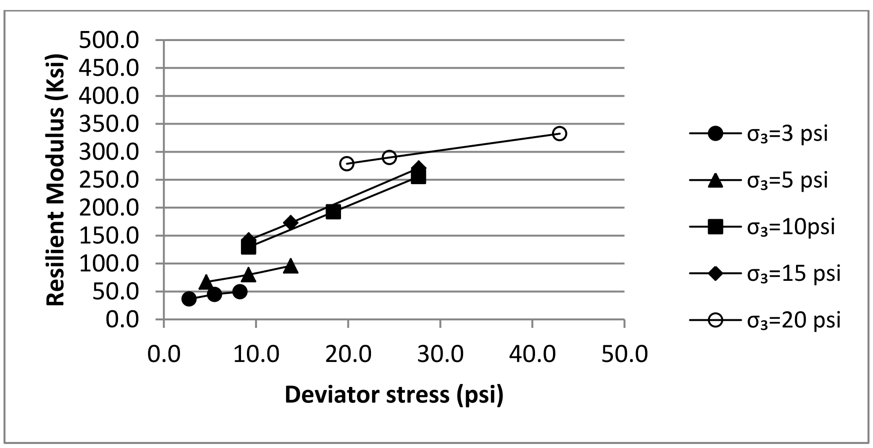
		A-6 (+2%) 7-day Curing Sample Number					
σ_3 (psi)	σ_d (psi)	1	2	3	Average	Standard Deviation	Coefficient of Variation (%)
		M_r (ksi)					
3	2.8	37.2	38.8	31.8	35.9	3.67	10.21
	5.8	43.2	46.0	37.2	42.1	4.50	10.67
	8.3	50.7	54.6	43.2	49.5	5.79	11.70
5	4.6	62.8	68.7	61.9	64.5	3.69	5.73
	9.2	81.2	85.5	88.7	85.1	3.76	4.42
	13.8	101.2	105.1	100.5	102.3	2.48	2.42
10	9.2	125.0	121.2	122.0	122.7	2.00	1.63
	18.4	182.0	174.4	181.5	179.3	4.25	2.37
	27.4	225.0	219.6	234.5	226.4	7.54	3.33
15	9.2	154.2	138.5	150.6	147.8	8.22	5.57
	13.8	190.8	177.5	186.6	185.0	6.80	3.68
	27.5	246.9	257.2	268.0	257.4	10.55	4.10
20	19.8	271.7	249.2	285.2	268.7	18.19	6.77
	24.4	272.5	241.0	279.1	264.2	20.36	7.71
	42.8	309.7	247.6	293.7	283.7	32.24	11.37



(a) Sample 1



(b) Sample 2

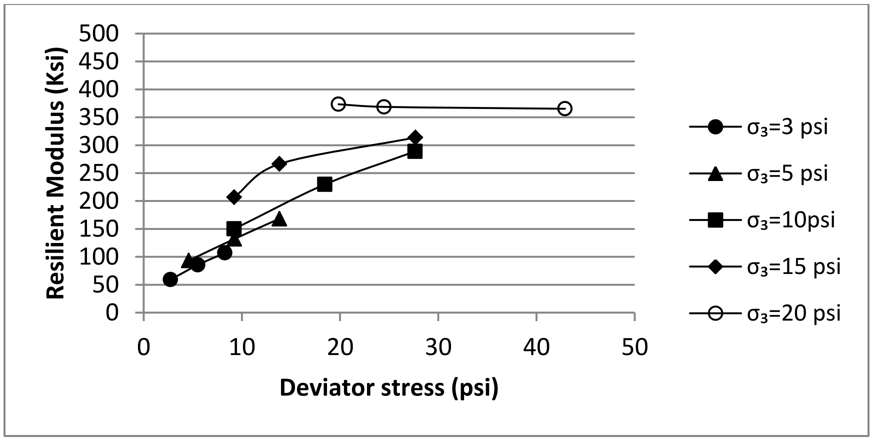


(c) Sample 3

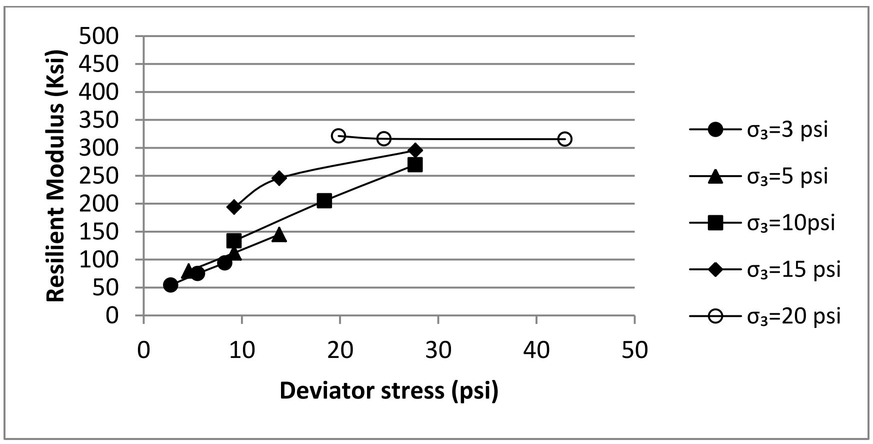
Figure 33
A-6 at -2% moisture content and 7-day curing graphs

Table 23
A-6 at -2% moisture content and 7-day curing data

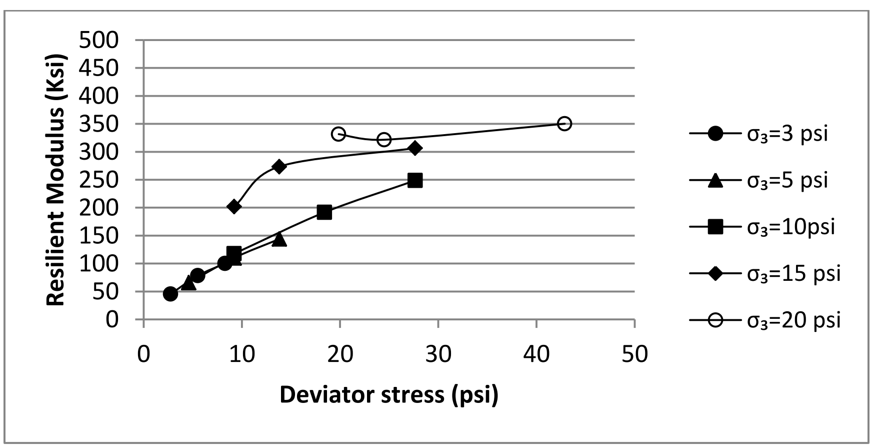
		A-6 (-2%) 7-day Curing					
		Sample Number					
		1	2	3			
σ_3 (psi)	σ_d (psi)	M_r (ksi)			Average	Standard Deviation	Coefficient of Variation (%)
3	2.8	40.0	43.0	36.6	39.9	3.20	8.03
	5.8	47.0	56.0	44.7	49.2	5.97	12.13
	8.3	53.8	68.0	49.5	57.1	9.68	16.96
5	4.6	66.0	62.7	67.1	65.3	2.29	3.51
	9.2	80.3	93.9	80.1	84.8	7.91	9.33
	13.8	99.5	115.2	95.9	103.5	10.26	9.91
10	9.2	131.7	141.6	129.5	134.3	6.45	4.80
	18.4	184.0	203.2	192.5	193.2	9.62	4.98
	27.4	240.8	262.4	255.5	252.9	11.03	4.36
15	9.2	177.5	150.0	142.1	156.5	18.58	11.87
	13.8	205.1	189.2	172.9	189.1	16.10	8.52
	27.5	269.1	279.6	270.9	273.2	5.62	2.06
20	19.8	283.2	309.2	278.6	290.3	16.50	5.68
	24.4	264.6	300.0	289.8	284.8	18.22	6.40
	42.8	250.4	318.4	332.5	300.4	43.90	14.61



(a) Sample 1



(b) Sample 2

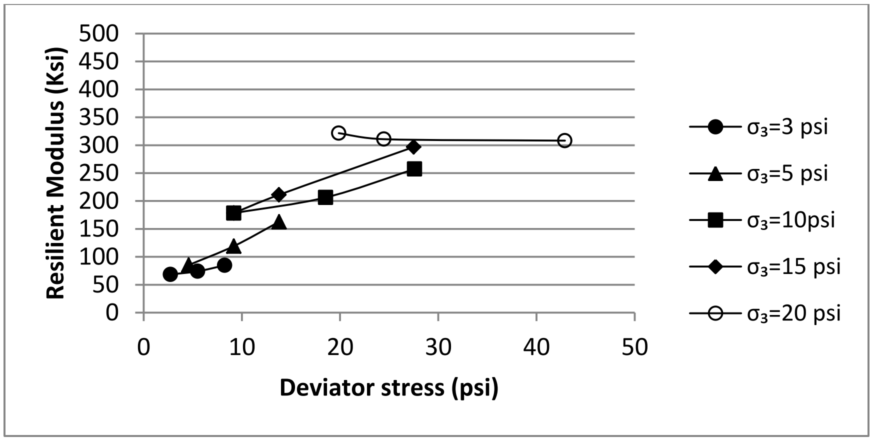


(c) Sample 3

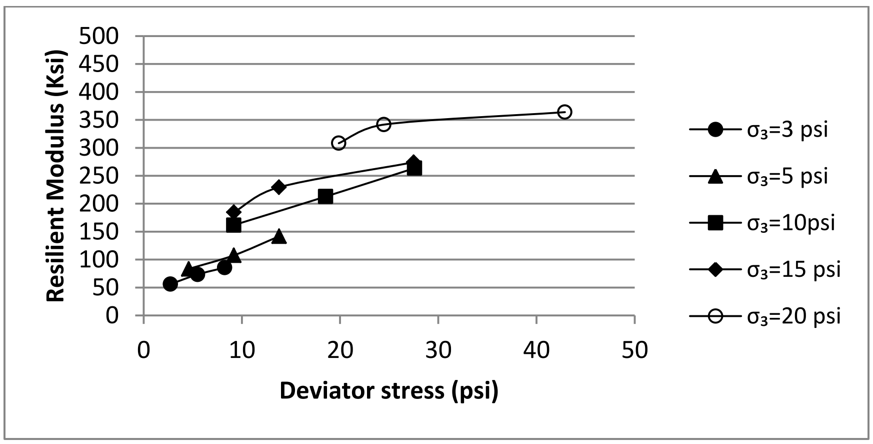
Figure 34
A-6 at optimum moisture content and 28-day curing graphs

Table 24
A-6 at optimum moisture content and 28-day curing data

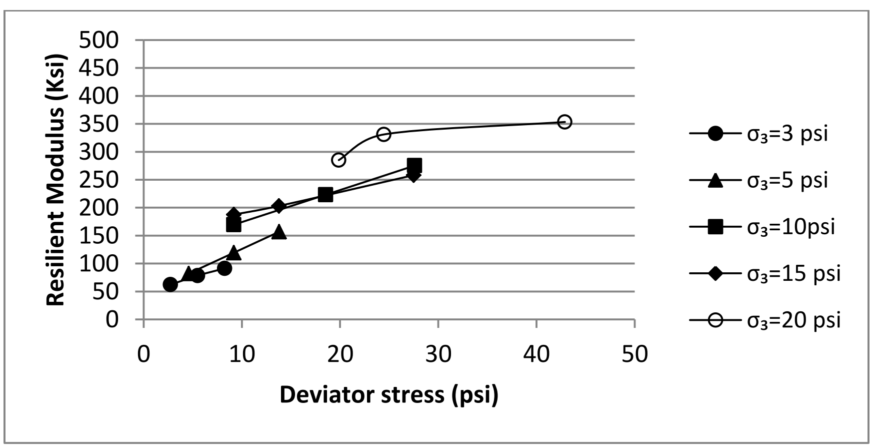
		A-6 (Opt.) 28-day Curing					
		Sample Number					
σ_3 (psi)	σ_d (psi)	1	2	3	Average	Standard Deviation	Coefficient of Variation (%)
		M_r (ksi)					
3	2.8	59.1	54.3	45.6	53.0	6.84	12.91
	5.8	85.5	75.0	78.3	79.6	5.37	6.75
	8.3	107.1	93.9	100.2	100.4	6.60	6.58
5	4.6	93.3	79.5	65.7	79.5	13.80	17.36
	9.2	132.0	111.9	110.1	118.0	12.16	10.30
	13.8	168.3	144.9	144.0	152.4	13.78	9.04
10	9.2	150.0	133.5	117.6	133.7	16.20	12.12
	18.4	229.8	205.2	191.7	208.9	19.32	9.25
	27.4	288.9	269.7	248.7	269.1	20.11	7.47
15	9.2	206.8	194.0	202.0	200.9	6.47	3.22
	13.8	266.4	245.6	273.5	261.8	14.50	5.54
	27.5	313.8	295.5	306.6	305.3	9.22	3.02
20	19.8	373.4	321.2	331.6	342.1	27.63	8.08
	24.4	368.7	316.2	321.6	335.5	28.88	8.61
	42.8	365.3	315.5	350.2	343.7	25.53	7.43



(a) Sample 1



(b) Sample 2

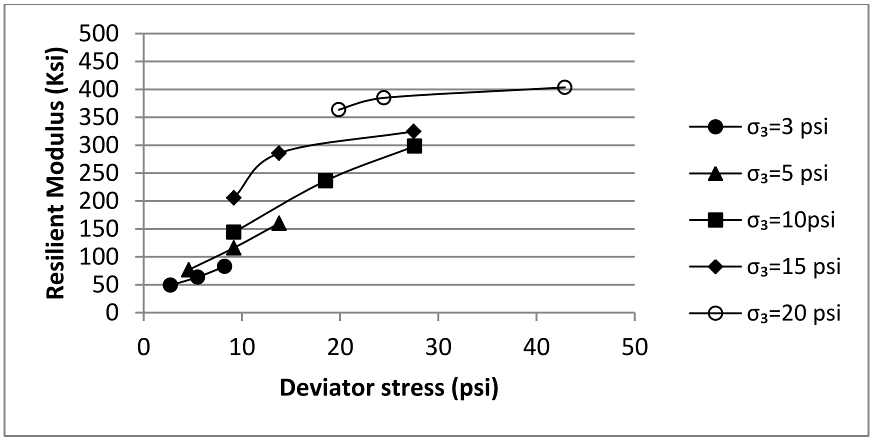


(c) Sample 3

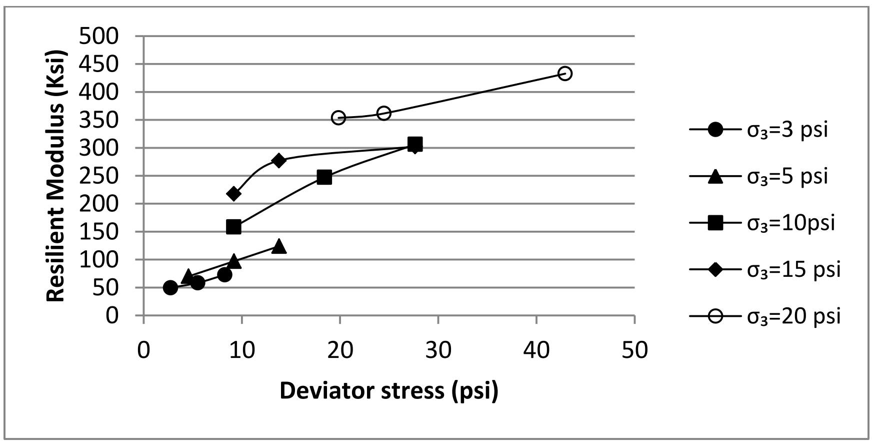
Figure 35
A-6 at +2% moisture content and 28-day curing graphs

Table 25
A-6 at +2% moisture content and 28-day curing data

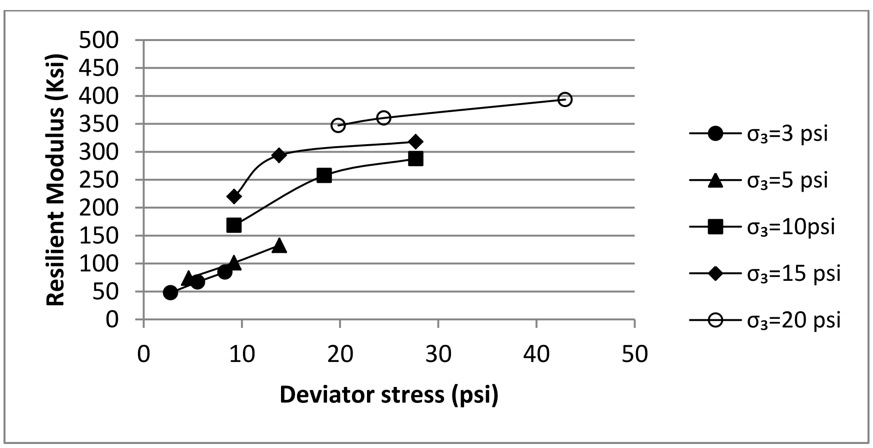
		A-6 (+2%) 28-day Curing					
		Sample Number					
		1	2	3			
σ_3 (psi)	σ_d (psi)	M_r (ksi)			Average	Standard Deviation	Coefficient of Variation (%)
3	2.8	68.5	56.2	62.3	62.3	6.15	9.87
	5.8	74.1	73.4	78.5	75.3	2.76	3.67
	8.3	84.8	85.7	91.4	87.3	3.58	4.10
5	4.6	85.4	83.4	82.2	83.7	1.62	1.93
	9.2	119.2	107.6	119.4	115.4	6.76	5.85
	13.8	162.7	141.7	156.9	153.8	10.84	7.05
10	9.2	178.3	161.7	169.5	169.8	8.31	4.89
	18.4	206.4	212.8	223.1	214.1	8.43	3.94
	27.4	257.3	263.7	275.3	265.4	9.12	3.44
15	9.2	178.5	184.8	187.6	183.6	4.66	2.54
	13.8	211.1	229.4	203.1	214.5	13.48	6.28
	27.5	296.8	274.2	258.2	276.4	19.39	7.02
20	19.8	321.6	308.3	285.2	305.0	18.42	6.04
	24.4	310.8	341.6	331.1	327.8	15.66	4.78
	42.8	308.2	363.9	353.4	341.8	29.60	8.66



(a) Sample 1



(b) Sample 2



(c) Sample 3

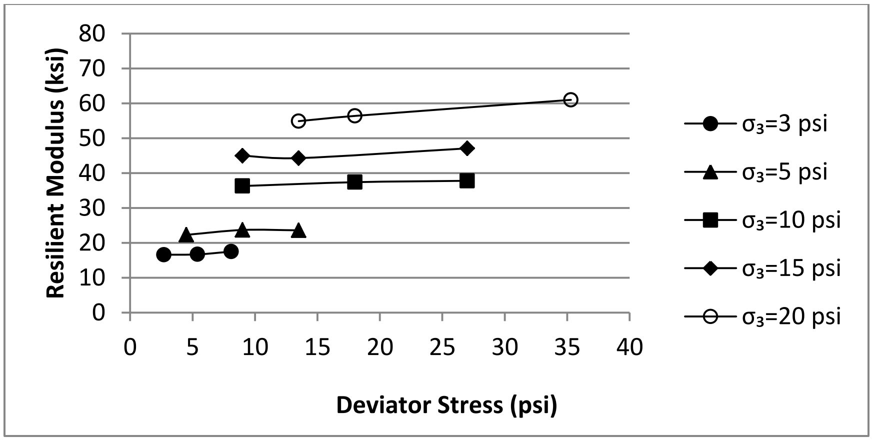
Figure 36
A-6 at -2% moisture content and 28-day curing graphs

Table 26
A-6 at -2% moisture content and 28-day curing data

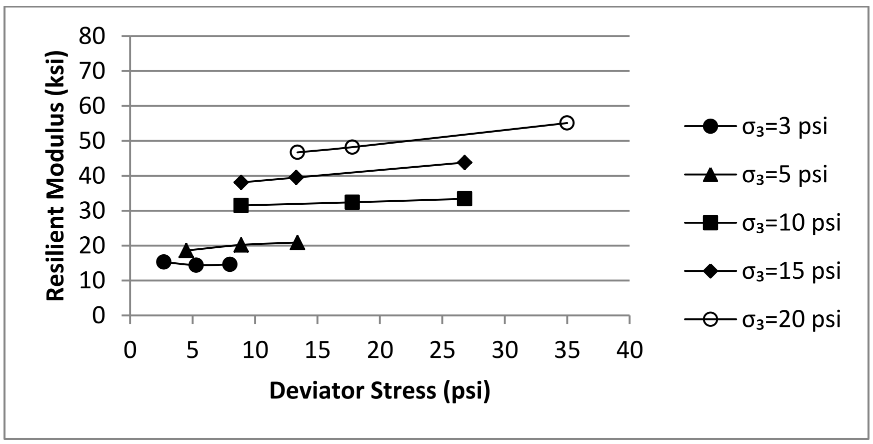
		A-6 (-2%) 28-day Curing					
		Sample Number					
σ_3 (psi)	σ_d (psi)	1	2	3	Average	Standard Deviation	Coefficient of Variation (%)
		M_r (ksi)					
3	2.8	49.2	49.6	47.7	48.8	1.00	2.05
	5.8	63.6	58.4	66.9	63.0	4.29	6.81
	8.3	82.8	72.8	84.6	80.1	6.36	7.94
5	4.6	76.8	70.0	73.8	73.5	3.41	4.63
	9.2	116.0	97.0	101.4	104.8	9.95	9.49
	13.8	160.0	124.0	132.6	138.9	18.80	13.54
10	9.2	144.0	158.4	168.4	156.9	12.27	7.82
	18.4	236.2	247.2	257.6	247.0	10.70	4.33
	27.4	298.3	306.3	287.7	297.4	9.33	3.14
15	9.2	205.8	217.8	220.0	214.5	7.64	3.56
	13.8	285.6	277.2	293.8	285.5	8.30	2.91
	27.5	324.8	302.4	318.2	315.1	11.51	3.65
20	19.8	363.6	353.6	347.1	354.8	8.31	2.34
	24.4	384.8	361.6	360.5	369.0	13.72	3.72
	42.8	403.6	432.8	393.5	410.0	20.41	4.98

APPENDIX D

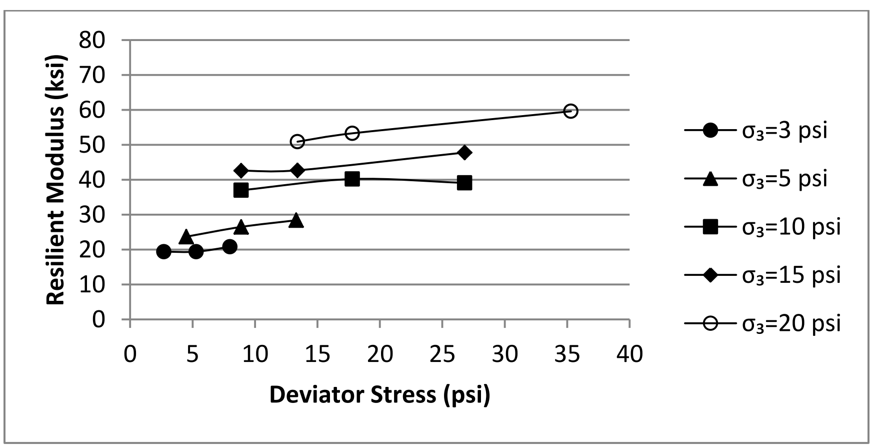
Mexican Limestone Resilient Modulus Graphs/Data



(a) Sample 1



(b) Sample 2

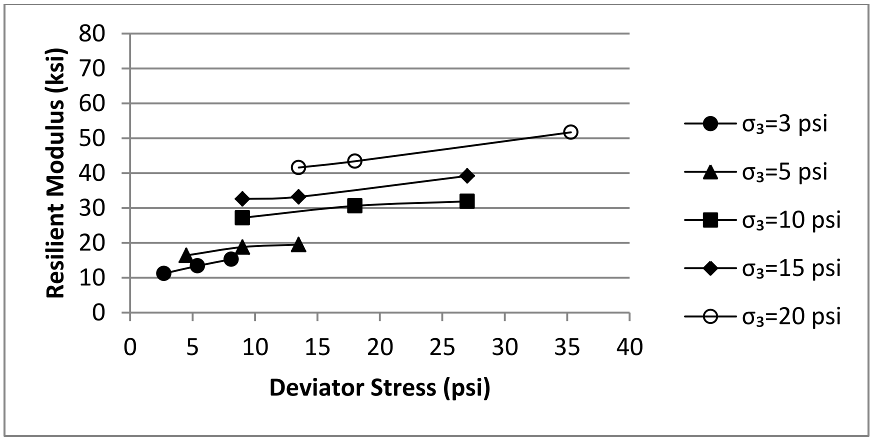


(c) Sample 3

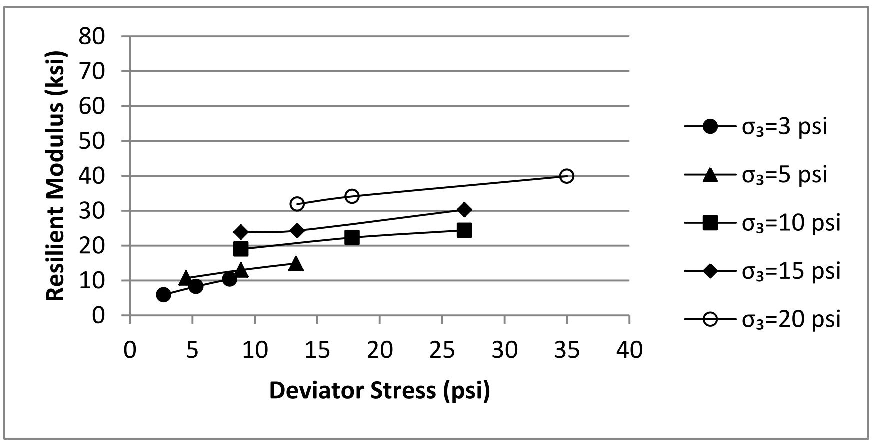
Figure 37
Mexican limestone at optimum moisture content graphs

Table 27
Mexican limestone at optimum moisture content data

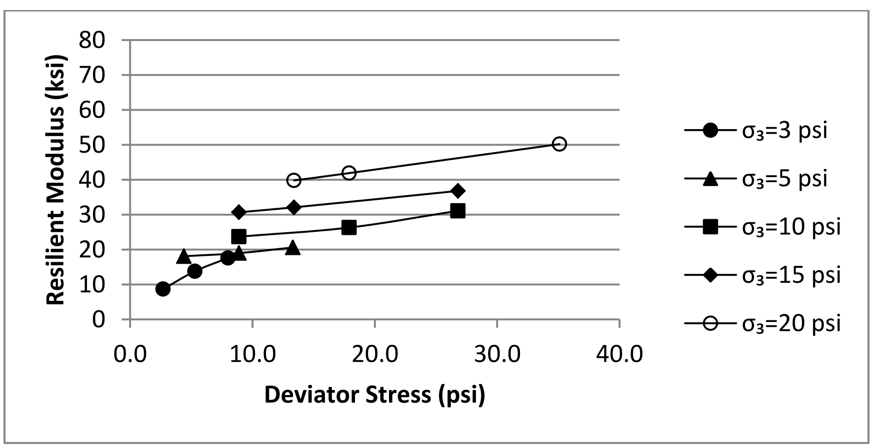
		Mexican Limestone (Opt.)					
		Sample Number					
		1	2	3			
σ_3 (psi)	σ_d (psi)	M_r (ksi)			Average	Standard Deviation	Coefficient of Variation (%)
3	2.8	16.6	15.3	19.4	17.1	2.10	12.25
	5.8	16.7	14.4	19.4	16.8	2.50	14.87
	8.3	17.5	14.6	20.8	17.6	3.10	17.59
5	4.6	22.3	18.6	23.7	21.5	2.64	12.24
	9.2	23.7	20.2	26.5	23.5	3.16	13.45
	13.8	23.6	20.9	28.4	24.3	3.80	15.63
10	9.2	36.3	31.5	37.0	34.9	2.99	8.57
	18.4	37.4	32.4	40.2	36.7	3.95	10.78
	27.4	37.8	33.4	39.1	36.8	2.99	8.12
15	9.2	45.0	38.1	42.6	41.9	3.50	8.36
	13.8	44.3	39.5	42.7	42.2	2.44	5.80
	27.5	47.1	43.8	47.8	46.2	2.14	4.62
20	13.4	54.9	46.7	50.9	50.8	4.10	8.07
	17.9	56.4	48.2	53.3	52.6	4.14	7.87
	35.2	61.0	55.1	59.6	58.6	3.08	5.26



(a) Sample 1



(b) Sample 2

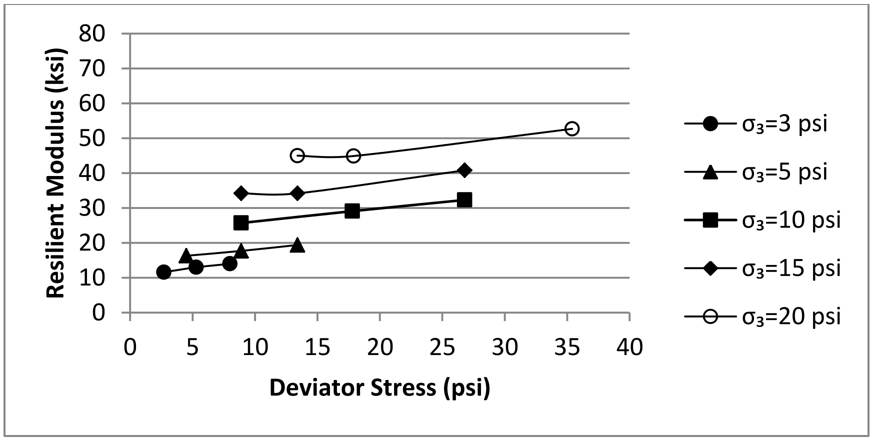


(c) Sample 3

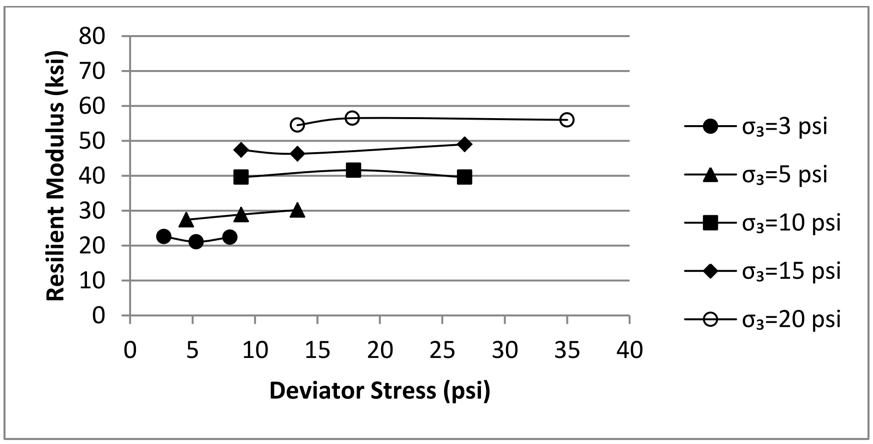
Figure 38
Mexican limestone at +2% moisture content graphs

Table 28
Mexican limestone at +2% moisture content data

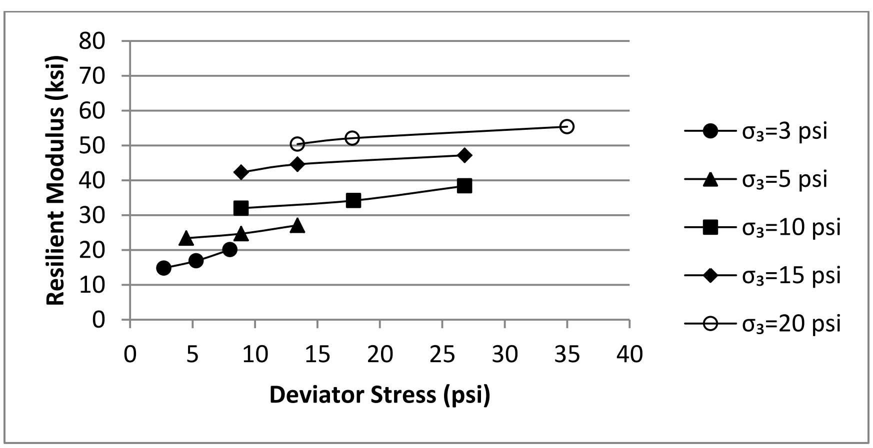
		Mexican Limestone (+2%)					
		Sample Number					
σ_3 (psi)	σ_d (psi)	1	2	3	Average	Standard Deviation	Coefficient of Variation (%)
		M_r (ksi)					
3	2.8	11.2	5.9	8.7	8.6	2.65	30.83
	5.8	13.4	8.3	13.8	11.8	3.07	25.91
	8.3	15.3	10.4	17.6	14.4	3.68	25.48
5	4.6	16.4	10.7	18.1	15.1	3.88	25.73
	9.2	18.8	13.0	19.0	16.9	3.41	20.13
	13.8	19.5	14.9	20.6	18.3	3.02	16.49
10	9.2	27.2	19.0	23.7	23.3	4.11	17.66
	18.4	30.6	22.3	26.3	26.4	4.15	15.72
	27.4	31.9	24.4	31.1	29.1	4.12	14.14
15	9.2	32.6	23.9	30.7	29.1	4.57	15.74
	13.8	33.2	24.3	32.1	29.9	4.85	16.25
	27.5	39.2	30.3	36.8	35.4	4.60	13.00
20	13.4	41.6	31.9	39.8	37.8	5.16	13.66
	17.9	43.4	34.1	41.9	39.8	4.99	12.55
	35.2	51.7	39.9	50.2	47.3	6.42	13.59



(a) Sample 1



(b) Sample 2



(c) Sample 3

Figure 39
Mexican limestone at -2% moisture content graphs

Table 29
Mexican limestone at -2% moisture content data

		Mexican Limestone (-2%) Sample Number					
		1	2	3			
σ_3 (psi)	σ_d (psi)	M_r (ksi)			Average	Standard Deviation	Coefficient of Variation (%)
3	2.8	11.6	22.6	14.8	16.3	5.66	34.64
	5.8	13.0	21.1	16.9	17.0	4.05	23.83
	8.3	14.0	22.4	20.1	18.8	4.34	23.05
5	4.6	16.3	27.4	23.4	22.4	5.62	25.13
	9.2	17.7	28.9	24.7	23.8	5.66	23.81
	13.8	19.4	30.2	27.1	25.6	5.56	21.75
10	9.2	25.7	39.6	32.0	32.4	6.96	21.46
	18.4	29.1	41.6	34.2	35.0	6.29	17.97
	27.4	32.3	39.6	38.4	36.8	3.91	10.65
15	9.2	34.2	47.4	42.3	41.3	6.66	16.12
	13.8	34.2	46.3	44.6	41.7	6.55	15.71
	27.5	40.8	49.0	47.2	45.7	4.31	9.44
20	13.4	45.0	54.5	50.4	50.0	4.76	9.54
	17.9	44.9	56.5	52.1	51.2	5.86	11.45
	35.2	52.7	56.0	55.4	54.7	1.76	3.21

Table 30
Regression analysis input parameter tables

Sequence Number	σ_d (psi)	σ_3 (psi)	θ (psi)	τ_{oct} (psi)	M_r (psi)
1	2.7	3	11.7	1.2728	6,600
2	5.3	3	14.3	2.5142	11,833
3	8.0	3	17.0	3.7869	14,433
4	4.5	5	19.5	2.1056	15,067
5	8.9	5	23.9	4.2112	16,933
6	13.4	5	28.4	6.3011	18,333
7	8.9	10	38.9	4.2112	23,300
8	17.9	10	47.9	8.4381	26,400
9	26.9	10	56.9	12.6651	29,133
10	8.9	15	53.9	4.2112	29,067
11	13.4	15	58.4	6.3325	29,867
12	26.9	15	71.9	12.6651	35,433
13	13.4	20	73.4	6.3325	37,767
14	17.9	20	77.9	8.4381	39,800
15	35.1	20	95.1	16.5620	47,267

(a) Mexican Limestone (+2%)

Sequence Number	σ_d (psi)	σ_3 (psi)	θ (psi)	τ_{oct} (psi)	M_r (psi)
1	2.7	3	11.7	1.2728	16,333
2	5.3	3	14.3	2.4984	17,000
3	8.0	3	17.0	3.7712	18,833
4	4.5	5	19.5	2.1213	22,367
5	8.9	5	23.9	4.1955	23,767
6	13.4	5	28.4	6.3168	25,567
7	8.9	10	38.9	4.1955	32,433
8	17.9	10	47.9	8.4224	34,967
9	26.8	10	56.8	12.6336	36,767
10	8.9	15	53.9	4.1955	41,300
11	13.4	15	58.4	6.3168	41,700
12	26.8	15	71.8	12.6336	45,667
13	13.4	20	73.4	6.3168	49,967
14	17.8	20	77.9	8.4067	51,167
15	35.1	20	95.1	16.5620	54,700

(b) Mexican Limestone (-2%)

(a) Model 1

(b) Model 2

(c) Model 3

Figure 40
Model verification of Mexican Limestone at +2% moisture content

(a) Model 1

(b) Model 2

(c) Model 3

Figure 41
Model verification of Mexican Limestone at -2% moisture content

Table 31
AASHTO T 307 Testing Sequences

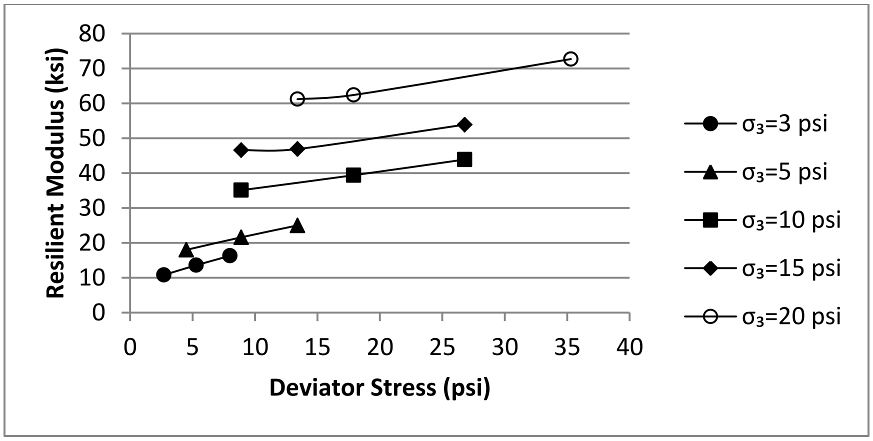
Sequence	Confining Pressure (psi)	Deviator Stress (psi)	Major Principle Stress (psi)	Sum of Principle Stresses (psi)	Number of Cycles
0	15.0	15.0	30.0	60.0	200
1	3.0	3.0	6.0	12.0	100
2	3.0	6.0	9.0	15.0	100
3	3.0	9.0	12.0	18.0	100
4	5.0	5.0	10.0	20.0	100
5	5.0	10.0	15.0	25.0	100
6	5.0	15.0	20.0	30.0	100
7	10.0	10.0	20.0	40.0	100
8	10.0	20.0	30.0	50.0	100
9	10.0	30.0	40.0	60.0	100
10	15.0	10.0	25.0	55.0	100
11	15.0	15.0	30.0	60.0	100
12	15.0	30.0	45.0	75.0	100
13	20.0	15.0	35.0	75.0	100
14	20.0	20.0	40.0	80.0	100
15	20.0	40.0	60.0	100.0	100

Table 32
University of Kentucky Transportation Center Resilient Moduli Values

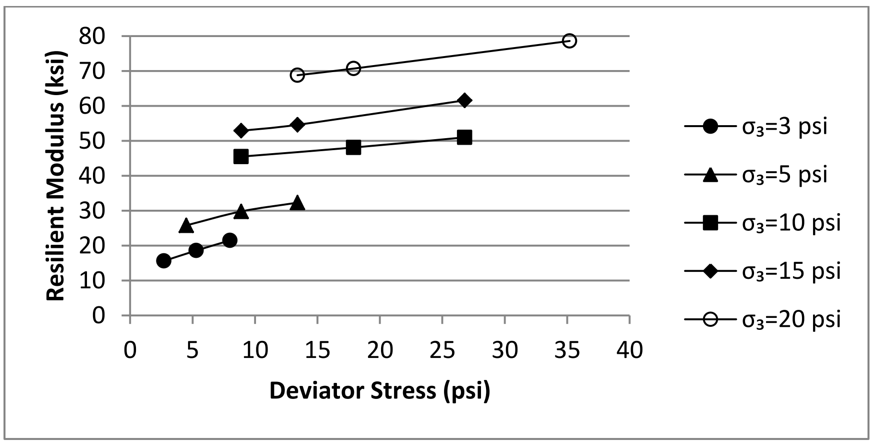
Sequence	Sample 1 (psi)	Sample 2 (psi)	Sample 3 (psi)	Average (psi)
1	21,447	21,023	24,391	22,287
2	22,440	20,391	23,562	22,131
3	24,795	20,573	24,496	23,288
4	30,097	29,734	34,476	31,436
5	31,419	26,900	31,631	29,983
6	33,149	27,840	31,510	30,833
7	47,134	42,705	46,383	45,407
8	44,008	38,672	43,203	41,961
9	42,674	39,121	42,538	41,444
10	57,205	55,112	60,956	57,758
11	53,932	51,119	56,518	53,856
12	51,928	49,697	52,912	51,512
13	63,729	59,712	65,045	62,829
14	58,304	58,684	61,553	59,514
15	63,524	59,177	58,141	60,281

APPENDIX E

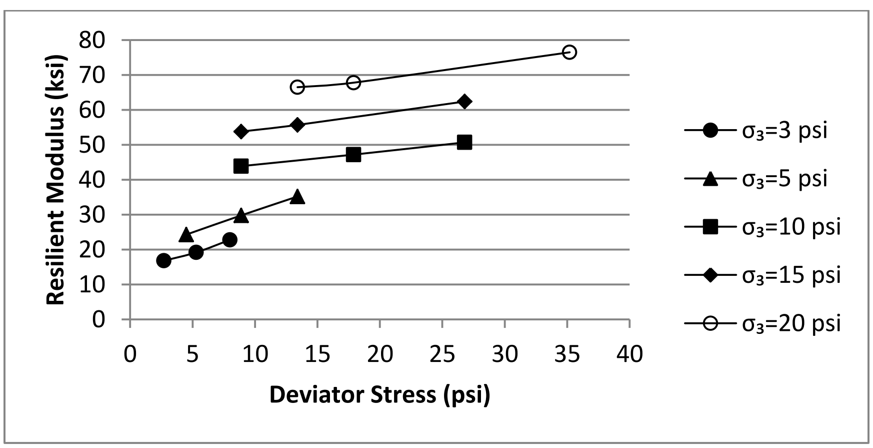
Recycled PCC (Crushed) Resilient Modulus Graphs/Data



(a) Sample 1



(b) Sample 2

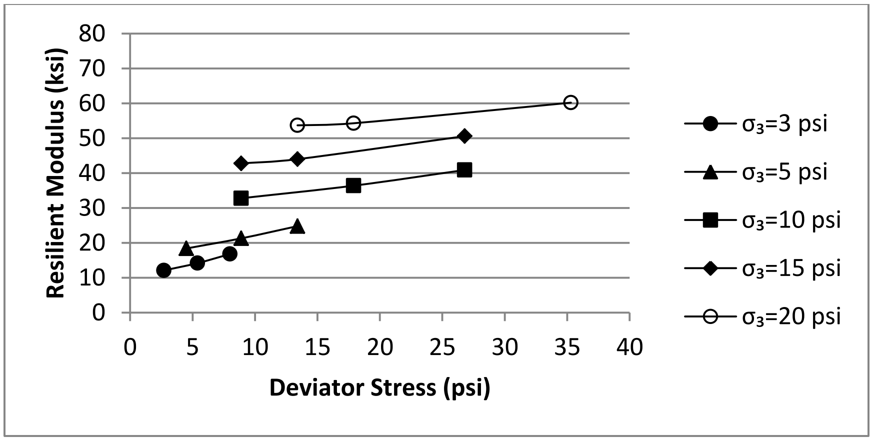


(c) Sample 3

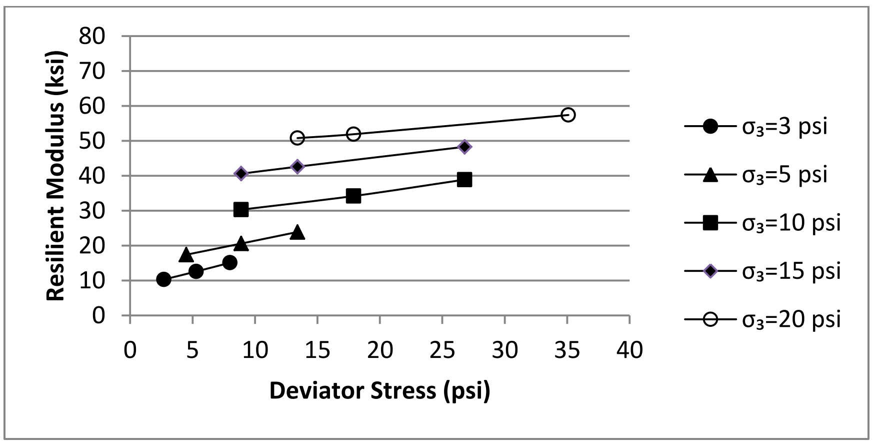
Figure 42
Recycled PCC (crushed) at optimum moisture content graphs

Table 33
Recycled PCC (crushed) at optimum moisture content data

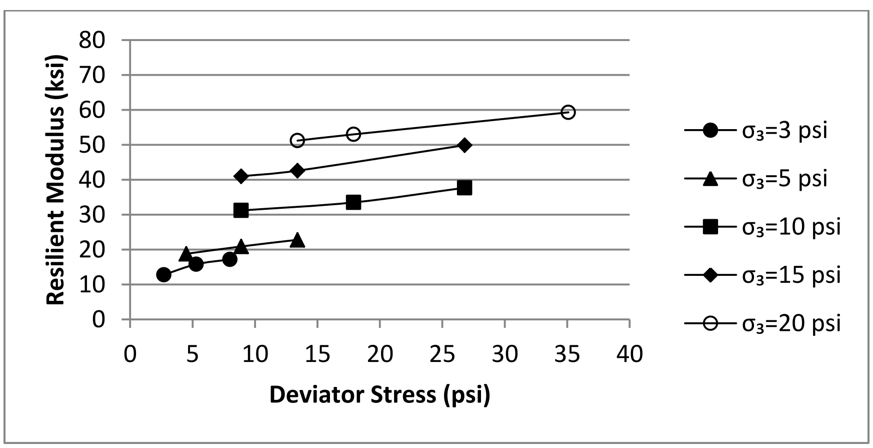
		Recycled PCC (Opt.)					
		Sample Number					
σ_3 (psi)	σ_d (psi)	1	2	3	Average	Standard Deviation	Coefficient of Variation (%)
		M_r (ksi)					
3	2.8	10.8	15.6	16.8	14.4	3.17	22.05
	5.8	13.6	18.6	19.2	17.1	3.07	17.95
	8.3	16.3	21.5	22.8	20.2	3.44	17.03
5	4.6	18.0	25.8	24.3	22.7	4.14	18.23
	9.2	21.6	29.8	29.8	27.1	4.73	17.49
	13.8	25.0	32.3	35.2	30.8	5.26	17.05
10	9.2	35.1	45.5	43.9	41.5	5.60	13.49
	18.4	39.4	48.1	47.2	44.9	4.78	10.66
	27.4	43.9	51.0	50.7	48.5	4.02	8.27
15	9.2	46.6	52.9	53.8	51.1	3.92	7.68
	13.8	46.9	54.6	55.7	52.4	4.79	9.15
	27.5	53.9	61.6	62.4	59.3	4.69	7.92
20	13.4	61.2	68.8	66.5	65.5	3.90	5.95
	17.9	62.4	70.7	67.8	67.0	4.21	6.29
	35.2	72.7	78.6	76.5	75.9	2.99	3.94



(a) Sample 1



(b) Sample 2

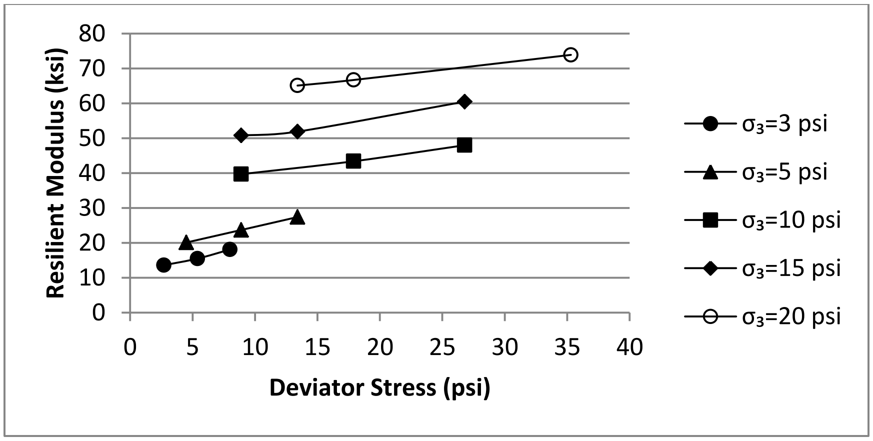


(c) Sample 3

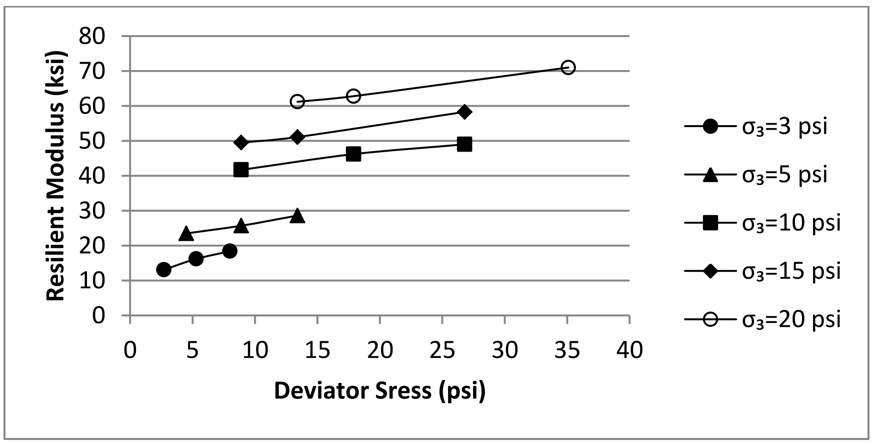
Figure 43
Recycled PCC (crushed) at +2% moisture content graphs

Table 34
Recycled PCC (crushed) at +2% moisture content data

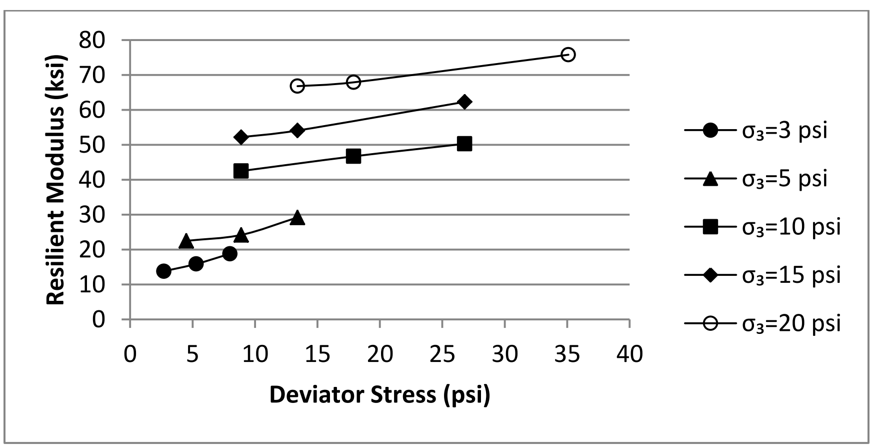
		Recycled PCC (+2%)					
		Sample Number					
σ_3 (psi)	σ_d (psi)	1	2	3	Average	Standard Deviation	Coefficient of Variation (%)
		M_r (ksi)					
3	2.8	12.1	10.3	12.8	11.7	1.29	10.99
	5.8	14.2	12.6	15.8	14.2	1.60	11.27
	8.3	16.8	15.1	17.2	16.4	1.125	6.81
5	4.6	18.4	17.4	18.8	18.2	0.72	3.96
	9.2	21.3	20.6	20.9	20.9	0.35	1.68
	13.8	24.8	23.9	22.8	23.8	1.00	4.20
10	9.2	32.8	30.3	31.2	31.4	1.27	4.03
	18.4	36.4	34.2	33.5	34.7	1.51	4.36
	27.4	40.9	38.9	37.7	39.2	1.62	4.13
15	9.2	42.8	40.6	41.0	41.5	1.17	2.83
	13.8	44.0	42.6	42.6	43.1	0.81	1.88
	27.5	50.6	48.3	49.9	49.6	1.18	2.38
20	13.4	53.7	50.8	51.2	51.9	1.57	3.03
	17.9	54.3	51.9	53.0	53.1	1.20	2.26
	35.2	60.2	57.4	59.3	59.0	1.43	2.42



(a) Sample 1



(b) Sample 2



(c) Sample 3

Figure 44
Recycled PCC (crushed) at -2% moisture content graphs

Table 35
Recycled PCC (crushed) at -2% moisture content data

		Recycled PCC (-2%)					
		Sample Number					
σ_3 (psi)	σ_d (psi)	1	2	3	Average	Standard Deviation	Coefficient of Variation (%)
		M_r (ksi)					
3	2.8	13.6	13.1	13.8	13.5	0.36	2.67
	5.8	15.5	16.2	15.9	15.9	0.35	2.21
	8.3	18.1	18.4	18.8	18.4	0.35	1.91
5	4.6	20.1	23.5	22.5	22.0	1.75	7.93
	9.2	23.7	25.7	24.2	24.5	1.04	4.24
	13.8	27.4	28.6	29.2	28.4	0.92	3.23
10	9.2	39.7	41.7	42.5	41.3	1.44	3.49
	18.4	43.4	46.2	46.7	45.4	1.78	3.91
	27.4	48.0	49.0	50.3	49.1	1.15	2.35
15	9.2	50.8	49.5	52.2	50.8	1.35	2.66
	13.8	51.9	51.1	54.1	52.4	1.55	2.97
	27.5	60.5	58.3	62.3	60.4	2.00	3.32
20	13.4	65.1	61.2	66.8	64.4	2.87	4.46
	17.9	66.7	62.8	67.9	65.8	2.67	4.05
	35.2	73.9	71.0	75.8	73.6	2.42	3.29

Table 36
Regression analysis input parameter tables

Sequence Number	σ_d (psi)	σ_3 (psi)	θ (psi)	τ_{oct} (psi)	M_r (psi)
1	2.7	3	11.7	1.2728	11,733
2	5.3	3	14.3	2.5142	14,200
3	8.0	3	17.0	3.7712	16,367
4	4.5	5	19.5	2.1213	18,200
5	8.9	5	23.9	4.1955	20,933
6	13.4	5	28.4	6.3168	23,833
7	8.9	10	38.9	4.1955	31,433
8	17.9	10	47.9	8.4381	34,700
9	26.8	10	56.8	12.6336	39,167
10	8.9	15	53.9	4.1955	41,467
11	13.4	15	58.4	6.3168	43,067
12	26.8	15	71.8	12.6336	49,600
13	13.4	20	73.4	6.3168	51,900
14	17.9	20	77.9	8.4381	53,067
15	35.2	20	95.2	16.5777	58,967

(a) Recycled PCC (crushed) (+2%)

Sequence Number	σ_d (psi)	σ_3 (psi)	θ (psi)	τ_{oct} (psi)	M_r (psi)
1	2.7	3	11.7	1.2728	13,500
2	5.3	3	14.3	2.5142	15,867
3	8.0	3	17.0	3.7712	18,433
4	4.5	5	19.5	2.1213	22,033
5	8.9	5	23.9	4.1955	24,533
6	13.4	5	28.4	6.3168	28,400
7	8.9	10	38.9	4.1955	41,300
8	17.9	10	47.9	8.4381	45,433
9	26.8	10	56.8	12.6336	49,100
10	8.9	15	53.9	4.1955	50,833
11	13.4	15	58.4	6.3168	52,367
12	26.8	15	71.8	12.6336	60,367
13	13.4	20	73.4	6.3168	64,367
14	17.9	20	77.9	8.4381	65,800
15	35.2	20	95.2	16.5777	73,567

(b) Recycled PCC (crushed) (-2%)

(a) Model 1

(b) Model 2

(c) Model 3

Figure 45
Model verification of Recycled PCC (crushed) at +2% moisture content

(a) Model 1

(b) Model 2

(c) Model 3

Figure 46
Model verification of Recycled PCC (crushed) at -2% moisture content

Table 37
SHRP Protocol P46 Testing Sequences

Sequence	Confining Pressure (psi)	Contact Stress (psi)	Cyclic Stress (psi)	Maximum Stress (psi)	Number of Cycles
0	15.0	3.0	30.0	33.0	1000
1	3.0	0.6	1.5	2.1	100
2	6.0	1.2	3.0	4.2	100
3	10.0	2.0	5.0	7.0	100
4	15.0	3.0	7.5	10.5	100
5	20.0	4.0	10.0	14.0	100
6	3.0	0.6	3.0	3.6	100
7	6.0	1.2	6.0	7.2	100
8	10.0	2.0	10.0	12.0	100
9	15.0	3.0	15.0	18.0	100
10	20.0	4.0	20.0	24.0	100
11	3.0	0.6	6.0	6.6	100
12	6.0	1.2	12.0	13.2	100
13	10.0	2.0	20.0	22.0	100
14	15.0	3.0	30.0	33.0	100
15	20.0	4.0	40.0	44.0	100
16	3.0	0.6	9.0	9.6	100
17	6.0	1.2	18.0	19.2	100
18	10.0	2.0	30.0	32.0	100
19	15.0	3.0	45.0	48.0	100
20	20.0	4.0	60.0	64.0	100
21	3.0	0.6	15.0	15.6	100
22	6.0	1.2	30.0	31.2	100
23	10.0	2.0	50.0	52.0	100
24	15.0	3.0	75.0	78.0	100
25	20.0	4.0	100.0	104.0	100
26	3.0	0.6	21.0	21.6	100
27	6.0	1.2	42.0	43.2	100
28	10.0	2.0	70.0	72.0	100
29	15.0	3.0	105.0	108.0	100
30	20.0	4.0	140.0	144.0	100

Table 38
Mississippi Department of Transportation resilient moduli values

Sequence	Sample 1 (psi)	Sample 2 (psi)	Sample 3 (psi)	Average (psi)
1	14,393	14,302	14,342	14,346
2	21,573	22,144	23,839	22,519
3	31,598	33,530	36,368	33,832
4	45,971	48,115	52,947	49,011
5	62,681	64,257	71,176	66,038
6	15,081	14,815	15,516	15,137
7	23,447	23,771	25,883	24,367
8	34,740	36,382	39,797	36,973
9	50,951	52,784	58,048	53,928
10	67,842	68,818	75,409	70,690
11	16,893	16,591	17,723	17,069
12	26,997	27,816	30,302	28,372
13	40,632	42,593	46,406	43,210
14	57,802	59,288	64,549	60,546
15	69,420	69,992	75,955	71,789
16	18,275	18,035	19,334	18,548
17	29,441	30,141	32,777	30,786
18	43,210	45,295	48,456	45,654
19	58,240	59,811	63,596	60,549
20	68,837	69,526	73,895	70,753
21	20,321	20,816	21,465	20,867
22	32,494	34,043	35,435	33,991
23	45,543	47,698	49,691	47,644
24	59,347	62,021	64,150	61,839
25	73,618	75,220	78,468	75,769
26	20,748	22,050	22,033	21,610
27	34,450	36,653	37,166	36,090
28	48,487	51,445	52,227	50,720
29	63,956	66,311	0	0
30	0	0	0	0