STRENGTH-STIFFNESS CORRELATIONS FOR CHEMICALLY TREATED SOILS

by

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ABSTRACT

The central theme of the study is to identify strength-stiffness correlations for chemically treated subgrade soils in Indiana. This was done by conducting Unconfined Compression (UC) tests and resilient modulus tests for soils collected at three different sites, namely : US 31, SR 37 and I-65. At each site, soil samples were obtained from 11 locations at 30 ft spacing. The soils were treated in the laboratory with cement, using the same proportions used for construction, and cured for 7 and 28 days before testing. Results from the UC tests were compared with the resilient modulus results that were available. No direct correlation was found between resilient modulus and UCS parameters for the soils investigated in this study. A brief statistical analysis of the results was conducted, and a simple linear regression model involving the soil characteristics (plasticity index, optimum moisture content and maximum dry density) along with UCS and resilient modulus parameters was proposed.

1. INTRODUCTION

For pavement design, one of the leading soil properties used is the stiffness of the subgrade layer. The Mechanistic-Empirical Pavement Design Guide (MEPDG) relies on the resilient modulus of the subgrade. However, Resilient Modulus (M_R) tests are specialized tests that require expensive equipment and are time consuming. Alternatively, the Resilient Modulus may be estimated from correlations with Falling Weight Deflectometer (FWD) after the construction of pavement for quality assurance (QA) purposes. Chemical stabilization using lime or cement is widely used by INDOT to improve the subgrade. Also, INDOT requires that mix designs for subgrade stabilization have a minimum unconfined compressive strength (UCS). The UCS test is easily performed in the laboratory but is rather difficult in the field requiring extensive equipment for imparting sufficient stress to induce bearing capacity failure. Given that both strength and stiffness affect construction, design, and performance of pavements, the central theme of this study is to establish correlations between strength and stiffness for subgrade soils in Indiana and, more specifically, of chemically treated subgrades.

The report is divided into six chapters. Chapter 2 investigates the past wok done on correlations between resilient modulus and UCS values for untreated as well as chemically treated subgrade soils. The study also looks at resilient modulus and UCS data from a recent JTRP report (Sandoval et al., 2019) to study initial correlations for chemically treated Indiana soils. Chapter 3 provides information on the construction sites where subgrade soils were obtained for testing. The chapter also details the results of laboratory tests, specifically soil characterization and resilient modulus. Chapter 4 focuses on the results of unconfined compressive strength tests performed for all the soils. Chapter 5 highlights the statistical analysis performed to establish correlations for the resilient modulus and UCS test results. The final chapter, Chapter 6, summarizes the report and discusses the major conclusions derived from the study.

2. LITERATURE REVIEW

2.1. Untreated Soils

The MEPGD, for pavement design, relies on the resilient modulus of the subgrade. Resilient Modulus (M_R) tests are specialized tests that require expensive equipment and are time consuming. Past research has focused on using index properties such as percentage of fines (% passing No. 200 sieve), plasticity, compaction, and related properties such as moisture content, dry density, degree of saturation and UCS to develop empirical relationships to estimate the resilient modulus of the soil.

Hossain et. al (2015) performed a comprehensive study of correlations between UCS and other properties derived from UCS curves for fine grained subgrade soils. Figure 1 displays the results of a correlation between UCS and resilient modulus (at 2 psi confining pressure and 6 psi deviatoric strength), for two different types of sample preparation methods for UCS (static and proctor compaction):

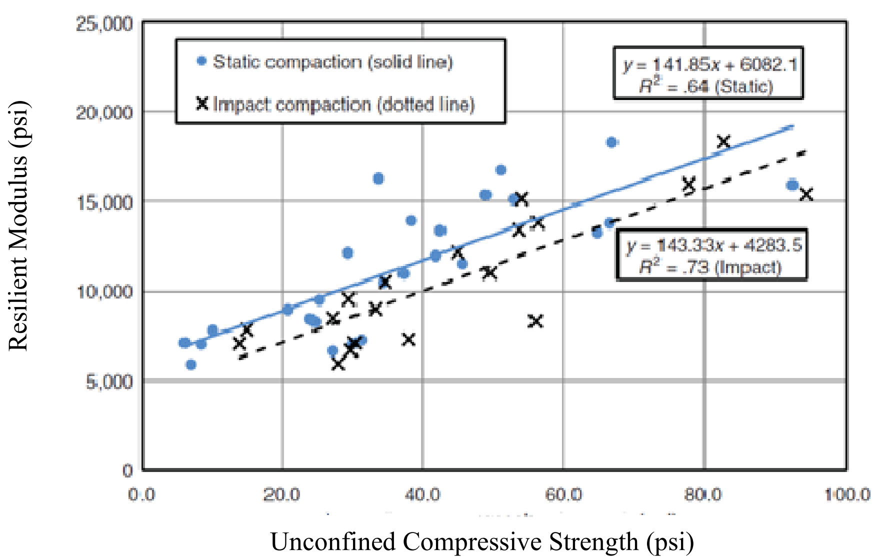


Figure 2.1 Correlation results between UCS and Resilient Modulus adapted from Hossain et. al (2015)

As we can see from the Figure 2.1, there is a fair correlation for the soils investigated. To improve the correlation, Hossain et. al explored a model involving soil index properties along with unconfined compressive strength. They found that the addition of index properties improved the correlations for both sample preparation methods. The models, along with their R^2 values, are:

For static compaction: $M_R = 7{,}884.2 + 99.7 \times (UCS) + 193.1 \times \text{PI} - 47.9 \times P_{200}$; $R^2 = 0.86$

For proctor compaction: $M_R = 6{,}113.0 + 95.1 \times (UCS) + 173.7 \times \text{PI} - 27.8 \times P_{200}$; $R^2 = 0.93$

Where PI : Plasticity Index and P_{200} : % passing No. 200 Sieve

The study also looked at correlations between initial tangent modulus (derived from the UCS stress-displacement plot) and resilient modulus but did not result in good correlations as the values of the initial tangent modulus were not accurately determined due to the initial seating deformations. However, the researchers were able to obtain an excellent correlation ($R^2 = 0.97$) between stress at 1% strain level and resilient modulus.

Lee et al. (1997) found similar results, i.e., a strong correlation between stress at 1% strain level (extracted from UCS curves) and resilient modulus, for three Indiana clayey soils: A-4–A-6 (CL), A-6 (CL), and A-7-6 (CH). The resilient modulus test was conducted on the same sample where the UCS test was performed up to a 1% strain level. The resilient modulus values used were taken at 3 psi confining pressure and 6 psi deviatoric stress. The correlation found was:

$$M_R = 695.4 \times (S_{u1\%}) - 5.93 \times (S_{u1\%})$$

Where, $S_{u1\%}$: Stress at 1% strain level, and $R^2 = 0.93$

Drumm et al. (1990) used 11 different types of fine-grained soils in Tennessee to obtain correlations between UCS, index properties, moduli obtained from UCS curves and resilient modulus. The UCS curve was assumed as hyperbolic and curve fitting parameters were used to find the initial tangent modulus or the small strain modulus. These parameters were then utilized for correlations with resilient modulus. Figure 2.2 shows the hyperbolic representation of the UCS curve:

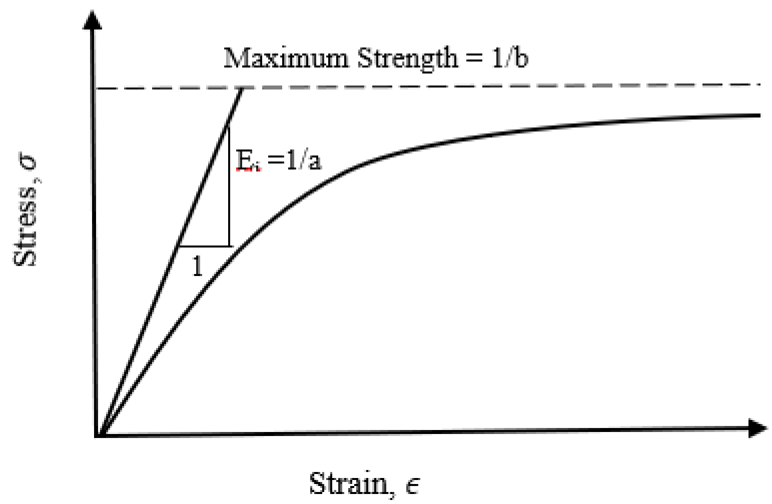


Figure 2.2 Hyperbolic representation of UCS curve, adapted from Drumm et al. (1997)

The parameters a and b are calculated using standard curve fitting techniques, by writing the hyperbola equation in the form :

$$\sigma = \frac{\epsilon}{a + b\epsilon} \rightarrow \frac{\epsilon}{\sigma} = a + b\epsilon$$

The correlation obtained for predicting resilient modulus, for a range of deviatoric stress (2.5 to 25 psi) under no confining pressure, was:

$$M_R = \frac{a' + b'\sigma_d}{\sigma_d}$$

Where,

$R^2 = 0.73$;

$a' = 318.2 + 0.337(q_u) + 0.73(\%\ \text{clay}) + 2.26(\text{PI}) - 0.92(\gamma_d) - 2.19(S) - 0.304(P_{200})$,

$b' = 2.10 + 0.00039(1/a) + 0.104(q_u) + 0.09(\text{LL}) - 0.10(P_{200})$, Where,

% clay = percentage finer than 0.002 mm.

P_{200} = percentage passing No. 200 sieve

LL = liquid limit (%)

σ_d = deviator stress (psi)

q_u = Unconfined compressive strength (psi)

S = degree of saturation (%)

There are additional correlations and models in the literature for predicting resilient modulus similar to those described and based on UCS and soil index properties for untreated subgrade soils. Hossain et al. (2011) developed a relationship between resilient modulus and unconfined compressive strength based on test results of 130 soil samples (A-4, A-6 and A-7-6) from Oklahoma:

$$\frac{M_r}{P_a} = 2494.2 + 0.6(PI) - 8.66(P_{200}) + 16.4(GI) + 165.53(MCR) - 1961(DR) + 185.29\left(\frac{q_u}{P_a}\right)$$

Where,

R^2 = .44,

M_R = resilient modulus at deviator stress of 41.34 kPa (6 psi) and confining stress of 13.78 kPa (2 psi),

P_a = atmospheric pressure (kPa),

GI = group index,

MCR = moisture content ratio (moisture content/optimum moisture content), and

DR = density ratio (dry density/maximum dry density).

The literature reviewed shows fair correlations between UCS and Resilient Modulus for untreated soils. The correlations seem to improve when additional variables/parameters are included such as the index properties of the soil. Other stiffness parameters derived from the UCS curves such as the initial tangent modulus (calculated through curve fitting) have been use for establishing correlations of untreated soils.

2.2. Treated Soils

Thompson's (1966) work from the late 1960's in Illinois is one of the first studies looking into the relationship between resilient modulus and unconfined compressive strength for lime-stabilized subgrade soils. Thompson compared the shear strength (kPa) and secant modulus of elasticity E (MPa), at peak stress, obtained from static, unconsolidated-undrained (UU) triaxial compression tests. The main equation of the correlation is given below:

$$M_R(MPa) = 0.124q_u(kPa) + 68.8$$

Where, q_u : Unconfined Compressive Strength.

CTL/Thompson (1998) performed three sets o resilient modulus and UCS tests on A-7-6 soil mixed with 6% quicklime to verify the applicability of the Thompson's correlation. The results generally agree with Thompson's correlation for UCS values within the range of 1000 to 1400 kPa.

Little et al. (1994) studied subgrade soils in Texas stabilized with lime. They used both laboratory and field data and concluded that Thompson's correlation was conservative for UCS values greater than 1,000 kPa. Little et al. (1994) proposed a relationship between resilient modulus and UCS for lime-stabilized subgrades based on: Thompson's correlation between UCS and flexural modulus (Thompson and Figueroa 1989), and between UCS and resilient modulus back-calculated from falling weight deflectometer (FWD) (Little et al. 1994). Figure 2.3 depicts the comparison between Thompson's correlation and Little et al.'s (1994) proposed relationship for lime stabilized subgrade soils.

Mooney et. al (2013) tested three fine grained soils to try to reproduce the relationship between resilient modulus and UCS recommended by Thompson (1996) and Little et. al (1994,) for lime-stabilized subgrade soils. Table 2.1 summarizes the soil classifications, grain size, and plasticity data for the soils used. Resilient modulus and UCS tests were performed on a total of 15 lime-treated soils (5 per each soil type). Lime-treated specimens with 100 mm diameter and 200 mm height were prepared at OMC and ρ_{dmax} conditions (see Table 2.1). M_R values obtained with confining stresses at 14 kPa and 28 kPa, at a deviator stress of 41 kPa, were used in the analysis. The UCS tests were performed on the same specimens used for the Mr test, and immediately after the M_R test was completed.

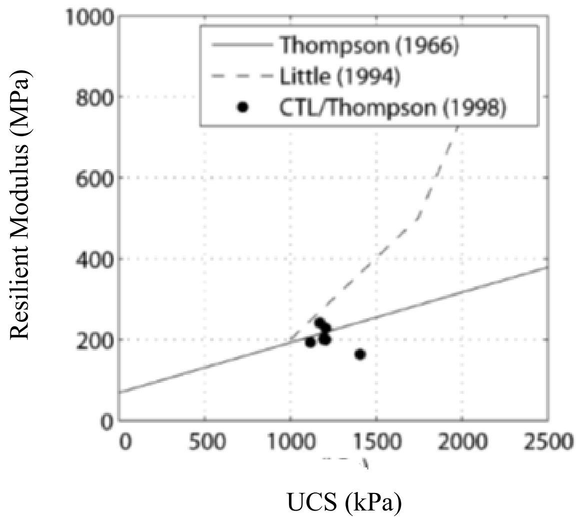


Figure 2.3 Comparison of Thompson's (1966) correlation; CTL/Thompson(1998) results; and Little et al.(1994) proposed relationship for lime stabilized soils

Table 2.1 Soil Properties (Untreated and Treated) for Soils A, B, and C from Mooney et. al (2013)

Untreated								Lime Treated	
Soil	AASHTO Class	USCS Class	Clay (%)	Silt (%)	LL (%)	PL (%)	PI (%)	OMC (%)	$\rho_{dmax}\ (kg/m^3)$
A	A-7-6	CH	29	19	55	18	37	29	1394
B	A-6	CL	12	41	33	16	17	29	1684
C	A-7-6	CL	15	58	43	15	29	25	1554

Note: LL = liquid limit; PI = plasticity index; PL = plastic limit; ρ_{dmax} = maximum unit weight

Figure 2.4 a) and b) are plots of all M_R and UCS test results of A, B, and C soil specimens, at 14 kPa and 28 kPa confining stresses, respectively (both at 41 kPa deviatoric stress). The plots also include the Thomson's (1966) correlation and Little et. al (1991) proposed relations for lime-stabilized subgrades. As observed in Figure 2.4, there is no clear correlation between UCS and M_R values (that is, $R^2 < 0.05$ at both confining stresses).

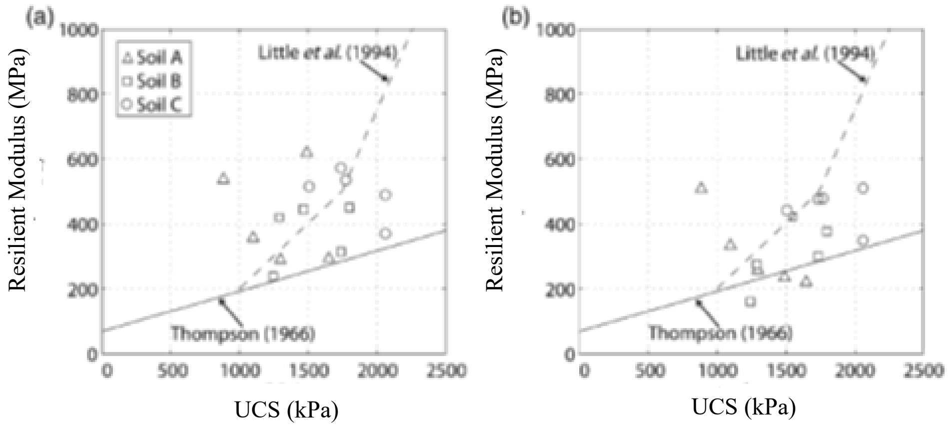


Figure 2.4 Summary of laboratory measured UCS versus (a) MR (Confining stress σc=14 kPa; Deviatoric stress σd=41 kPa) and (b) MR (Confining stress σc=28 kPa; Deviatoric stress σd =41 kPa) adapted from Mooney et. al (2013)

Data from the recent JTRP project: SRP 4107 Subgrade Stabilization Alternatives (Sandoval et. al (2019)), was used to test the correlation between resilient modulus and UCS for fine-grained Indiana subgrade soils. The project investigated soils from three locations in Indiana treated with cement, Lime Kiln Dust (LKD) and a combination of cement and LKD. Details of the soil properties (classification, index properties etc.) are summarized in Table 2.2. Table 2.3 lists the optimum amount of chemical needed, the optimum moisture content (OMC) and the maximum unit weight of the soils.

Table 2.2 Site locations and soil properties from SPR 4107 project (Sandoval et. al (2019))

Site	LL (%)	PL (%)	PI (%)	Passing # 200	AASHTO Class
Hartford City	26.00	11.60	14.40	-	A-6
	37.20	14.20	23.00	88.20	A-6
Bloomington #1	41.20	17.30	23.90	88.40	A-7-6
Fort Wayne	43.00	14.10	28.90	82.00	A-7-6
Bloomington #2	66.00	20.80	45.20	93.50	A-7-6
Bloomington #3	58.60	21.00	37.60	-	A-7-6

Table 2.3 Optimum amount of treatment, maximum unit weight and optimum moisture content for the four soils in SPR 4107 (Sandoval et. al (2019))

Site	Optimum LKD			Optimum Cement			Optimum Cement + LKD		
	Amount (%)	γ_d (pcf)	OMC (%)	Amount (%)	γ_d (pcf)	OMC (%)	Amount (%)	γ_d (pcf)	OMC (%)
Hartford City	6	115.4	16.5	3	121.1	12.3	-	-	-
Bloomington #1	6	103.6	20.8	3	107.3	19.6	2+2	106.1	20.2
Fort Wayne	5	113.6	15.6	3	117.9	14.8	-	-	-
Bloomington #2	5	98.6	26.3	5	101.1	25.7	2+2	99.8	26.4
Bloomington #3	5	101.1	23.1	5	101.8	22.7	-	-	-
Note: OMC – Optimum Moisture Content; γ_d – Maximum Unit Weight									

Resilient modulus and UCS tests were performed at 7-Days and 28-Days curing time for the treated specimens, which were prepared at OMC and at maximum unit weight, as described in Table 2.3. The results of the correlations between UCS and M_R can be found in Figures 2.5 and 2.6. The resilient modulus at 2 psi confinement and 6 psi deviatoric stress was chosen for the comparisons. It is clear from the figures that there is no direct correlation between UCS and resilient modulus for the soils investigated in this study.

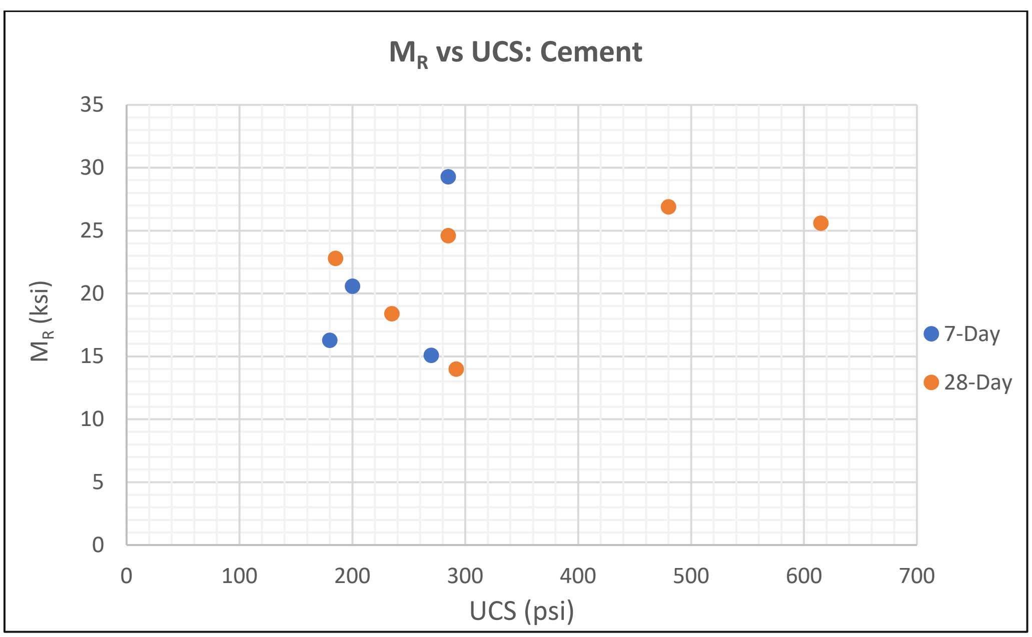


Figure 2.5 Correlation between UCS and resilient modulus for cement-treated samples. Data from Sandoval et. al (2019)

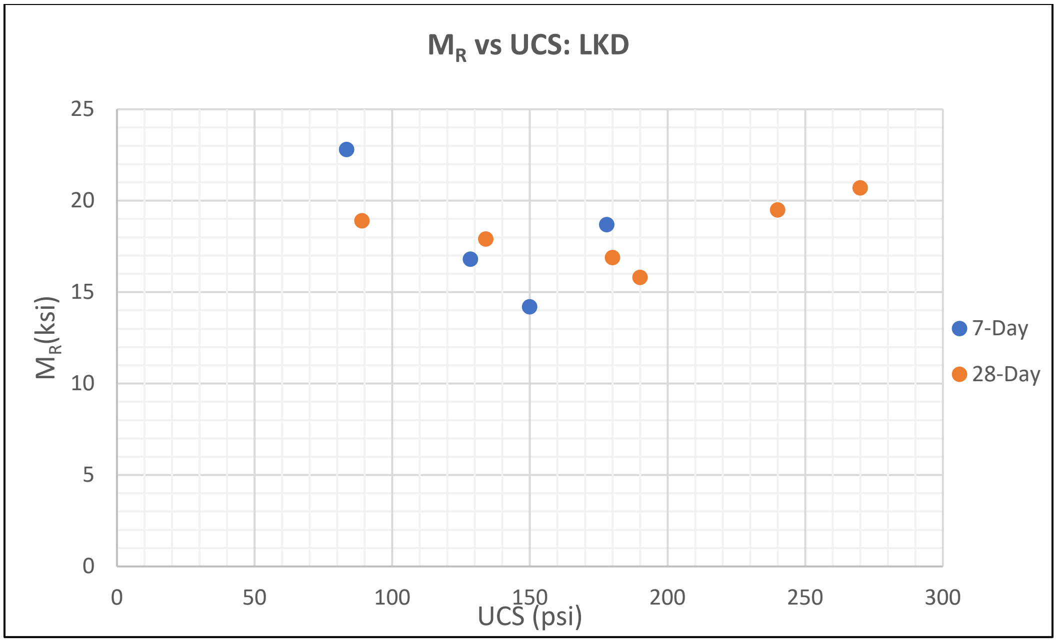


Figure 2.6 Correlation between UCS and resilient modulus for LKD-treated samples. Data from Sandoval et. al (2019)

Becker (2021) developed a correlation between the resilient modulus and the unconfined compression strength for soils encountered on I-69 near Anderson, Indiana. The soil used was primarily fine-grained A-6 soil (CL based on USCS classification). Cement-treated soil specimens at different moisture content, relative compaction and cement content were prepared for resilient modulus and UCS testing. The study resulted in a fair correlation (R^2 = 0.485) between M_r and UCS for cement stabilized subgrade soils, as observed in Figure 2.7. The study proposed that since UCS correlated well with M_R (it also correlated well with LWD deflection), UCS could be well-suited to relate cement-stabilized subgrade performance requirements (pavement design) and acceptance criteria (construction).

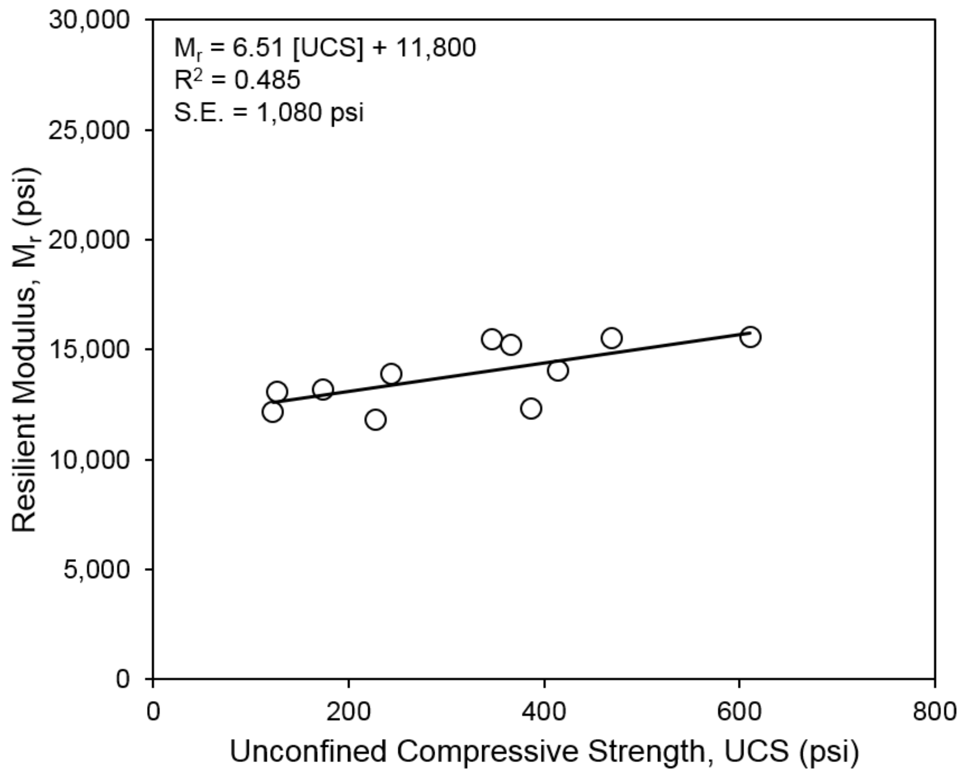


Figure 2.7 Correlation between resilient modulus and unconfined compressive strength for cement stabilized A-6 soil specimens, from Becker (2021) (Note: S.E. = standard error)

3. SOIL CHARACTERISTICS AND RESILIENT MODULUS

3.1. Site Locations and Sample Collections

The key objective of this project is to establish a statistically significant correlation between Resilient Modulus (M_R) and Unconfined Compressive Strength (UCS) for chemically treated subgrade soils in Indiana. In order to achieve this objective, different sites in Indiana were identified to collect soil samples for laboratory testing. Site locations included untreated and treated subgrade soils ranging from A-1 to A-6. Soil samples were collected during the construction of new roads and road reconstruction projects, when the subgrade soils were accessible. At each site, a representative section of 90 m (300 ft) length was selected for sample collection (Figure 3.1). Eleven locations at 9 m (30 ft) intervals were identified at each site, where two bags of soil (approximately 25 Kg each) were collected at each location.

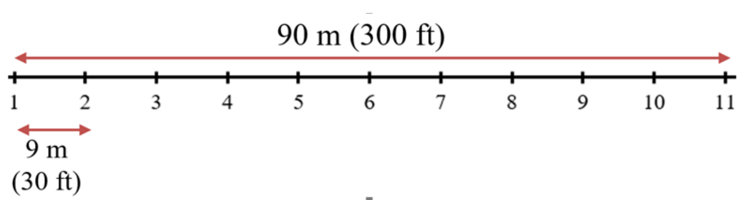


Figure 3.1 Representative section and selected points for sample collection

These are the sites where soil was collected: **US 31, SR 37, and I 65**. The location of the sites is displayed in Figure 3.2.

Site 1 US 31:

This site is located on US 31 in St. Joe county, near South Bend, from station 170+00 to 173+00. Untreated soil samples were collected in July 2020 during road construction under contract no. R-41975. The site has asphalt pavement over a cement stabilized subgrade treated with 4% cement by weight. The water content of the in-situ soil was between 6.0% and 13.1% (average 8.6 %).

Site 2 State Road 37:

This site is located on State Road 37 (SR 37) in Martinsville. Soil samples were collected from RP 349+08 to 346+08 in July 2020, during construction under contract no. R-33493. The road has asphalt pavement over a cement stabilized subgrade treated with 5 % cement by weight. The water content of the in-situ soil was between 9.8% and 13.9%. A sand cone test was performed near station 6 and the in-situ soil unit weight was determined to be 1.98 g/cc (123.3 lb/ft^3).

Site 3 Interstate 65:

This site is located on Interstate road I 65 in West Lafayette, Tippecanoe county. Untreated soil samples were collected in August 2020 on the south-bound section near exit 178 (RP 815+00). The site has a Portland Cement Concrete pavement (PCCP) over a cement stabilized subgrade (5% cement content by weight). Water content of the in-situ soil was between 6.0% and 13.1% (average 8.6 %).

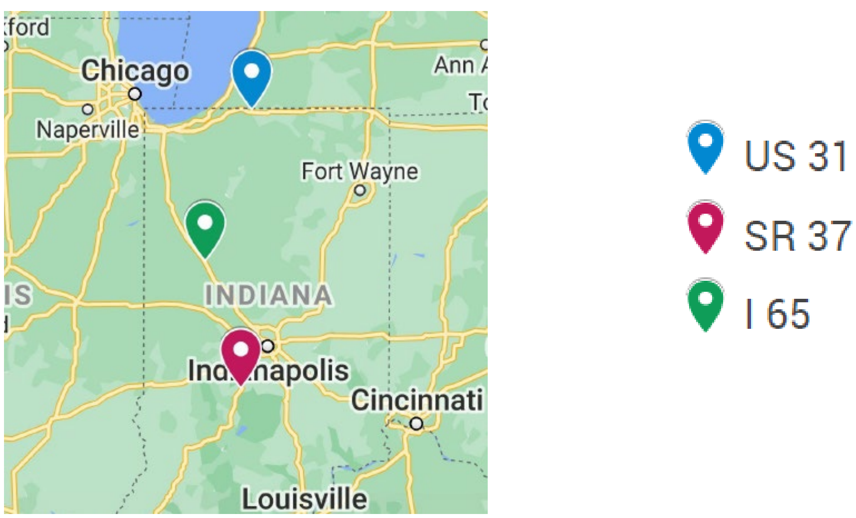


Figure 3.2 Location of the sites for sample collection

3.2. Laboratory Testing: Soil Characterization

The soil samples collected from the selected sites were tested in the laboratory. The tests included Atterberg limits and grain size analysis, following AASHTO T-89/T-90 and ASTM C 136-14 standards, respectively. The soil from each location was crushed and moist samples were washed through the US Standard No. 200 Sieve (75 Microns) prior to sieve analysis to obtain the grain size distribution. Based on the results, the soils were classified as per AASHTO M 145-91. Standard Proctor tests, following AASHTO T-99, were performed on all the soil samples to obtain the Optimum Moisture Content (OMC) and the Maximum Dry Density (MDD) of the soils. All compaction tests were performed with soils passing US Standard Sieve No. 4 (4.75 mm). The results of all classification tests for the sites included in this study were obtained from Gupta (2021).

Site 1 (US 31) results:

The test results of the samples obtained from site 1, US 31, indicate considerable variability. Most of the soils are coarse-grained A-1 (A-1-a and A-1-b) except for Samples 4 and 11, which are classified as A-2-4. The soils exhibited low to no plasticity with a small percentage of fines (11 ~ 22 %). Figures 3.3 and 3.4 present the grain size distribution and compaction curves, respectively, for all 11 locations of the site. Samples 4 and 11 have different gradation curves than the rest of, which is consistent with their different classification (A-2-4). As seen from the results, the soils also exhibited a wide range of MDD values, from 1.83 to 1.99 g/cc (114 to 124 lb/ft^3). The results from classification and compaction tests on all eleven samples are summarized in Table 3.1.

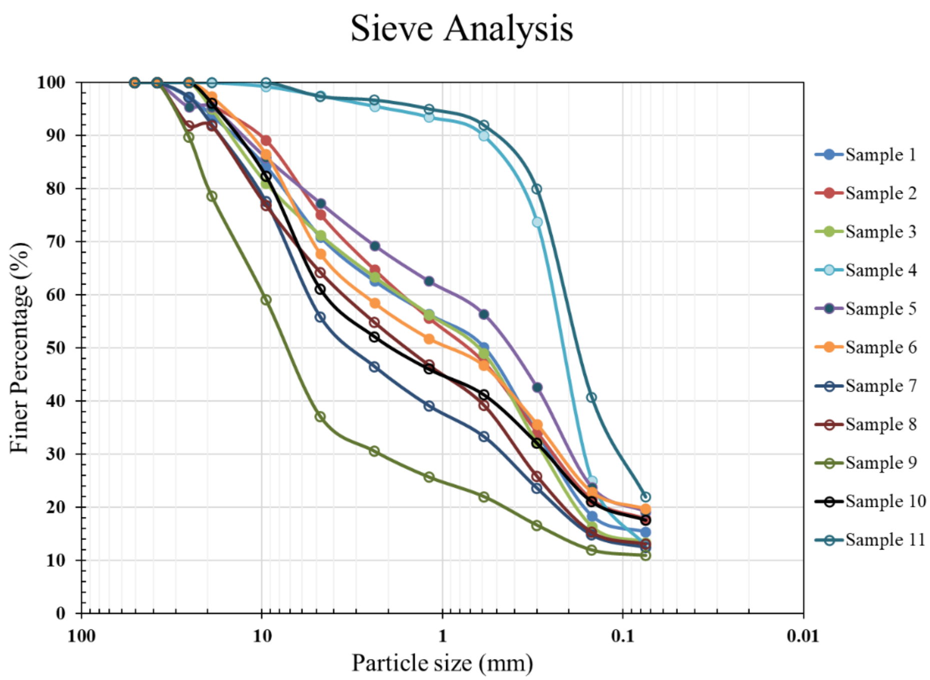


Figure 3.3 Grain size distribution curves for US 31 samples. Data from Gupta(2021)

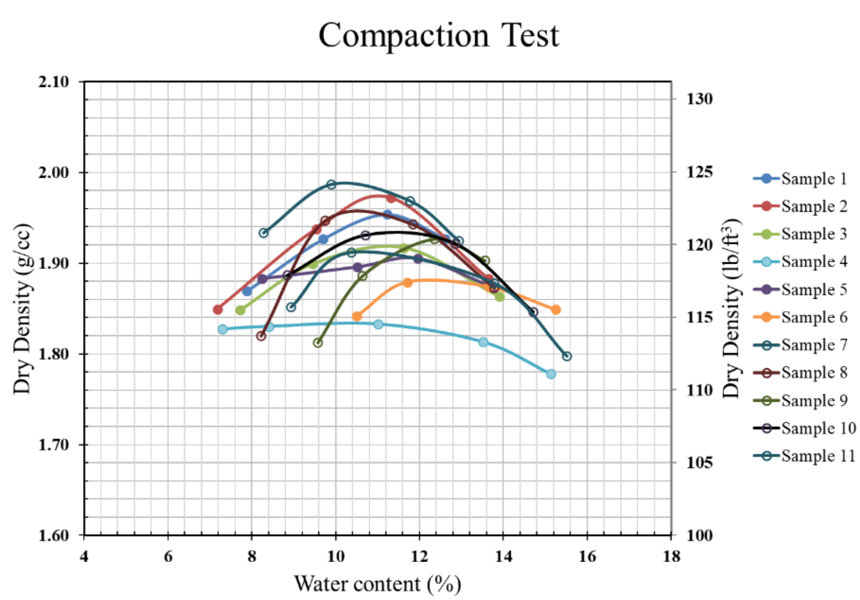


Figure 3.4 Compaction curves for US 31 samples. Data from Gupta (2021)

Table 3.1 Soil classification and compaction results for US 31 samples. Data from Gupta (2021)

Sample	LL	PL	PI	% fines	Classification		OMC	MDD
	%	%	%	%	AASHTO	USCS	**%**	**g/cc (lb/ft^3)**
1	21.4	14.7	6.7	15.4	A-1-b	SC-SM	11.2	1.95
2	18.2	NP	NP	17.7	A-1-b	SM	11.0	1.97
3	18.5	NP	NP	13.6	A-1-b	SM	11.2	1.92
4	NP	NP	NP	12.8	A-2-4	SM	11.0	1.83
5	23.3	NP	NP	19.1	A-1-b	SM	12.0	1.91
6	23.6	17.3	6.3	19.8	A-1-b	GC-GM	12.0	1.88
7	19.1	16.0	3.1	12.4	A-1-a	GM	10.2	1.99
8	19.5	13.1	4.4	13.4	A-1-b	SC-SM	10.8	1.96
9	18.3	14.7	3.6	10.9	A-1-a	GM	12.4	1.93
10	25.9	14.4	11.5	17.4	A-1-b	SC	11.6	1.93
11	23.5	NP	NP	22.0	A-2-4	SM	10.4	1.86
	18~26	**13~17**	**3~11**	**11~22**	**A-1**	**SM**	**10~12**	**1.83~1.99**

Note: NP = Non-Plastic

Site 2 (SR 37) results:

All soils samples collected from this site show little variation in terms of grain size distribution and compaction. The results obtained from classification and compaction tests performed on all eleven samples are summarized in Table 3.2. All soil samples had a high percentage of sand (50 - 60 %), with low liquid limit and plastic limit. The gradation and compaction curves also showed uniform results (Figures 3.5 and 3.6). The average OMC and MDD values were found to be 10% and 2.02 g/cc (126.1 lb/ft3), respectively. Based on the soil properties, the soils were classified as A-2-4 as per AASHTO classification.

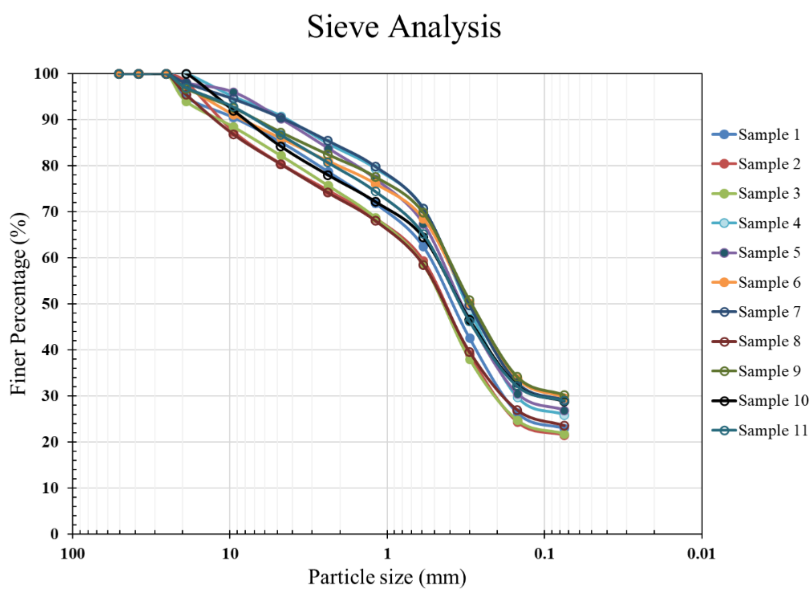


Figure 3.5 Grain size distribution curves for SR 37 samples. Data from Gupta (2021)

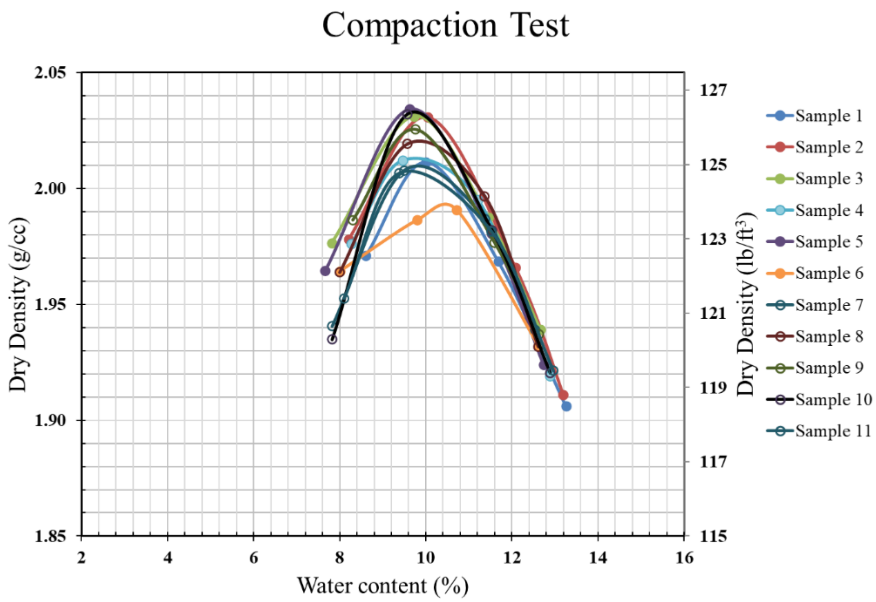


Figure 3.6 Compaction curves for SR 37 samples. Data from Gupta (2021)

Table 3.2 Soil classification and compaction results for SR 37 samples. Data from Gupta (2021)

Sample	**LL**	**PL**	**PI**	**% fines**	**Classification**		**OMC**	**MDD**
	%	%	%	%	AASHTO	USCS	**%**	**g/cc**
1	23.2	12.4	10.8	23.0	A-2-4	SC	10.0	2.01
2	21.4	12.6	8.8	21.5	A-2-4	SC	10.0	2.03
3	23.1	13.7	9.4	21.8	A-2-4	SC	9.7	2.03
4	21.0	12.3	8.7	25.9	A-2-4	SC	9.6	2.01
5	21.0	12.5	8.5	26.9	A-2-4	SC	9.6	2.03
6	21.5	12.7	8.8	29.6	A-2-4	SC	10.4	2.00
7	21.7	12.7	9.0	29.1	A-2-4	SC	9.8	2.01
8	20.1	13.8	6.3	23.5	A-2-4	SC	9.8	2.02
9	20.6	12.5	8.1	30.3	A-2-4	SC	9.8	2.03
10	19.9	12.7	7.2	28.8	A-2-4	SC	9.8	2.03
11	20.4	14.7	5.7	29.0	A-2-4	SC	9.6	2.01
	20 – 23	**14~22**	**6 - 11**	**20 –30**	**A-2-4**	**SC**	**~10.0**	**~2.02**

Site 3 (I-65) Results:

Soil samples collected from the third site (I-65) had considerably higher percentage of fines (50 - 80 %) compared to the previous two sites. Figures 3.7 and 3.8 represent the grain size distribution and compaction test results, respectively, for all the samples. All the soil samples showed high liquid limit but relatively low plasticity. Except for Sample 1, the rest of the samples had high OMC values (14 - 17 %). The samples also showed a wide range of MDD varying from 1.71 – 2.07 g/cc. The results of the classification and compaction tests are summarized in Table 3.3. The soil samples for this site are classified as A-6 (8 out of 11 samples) with 3 samples being A-4, according to the AASHTO classification.

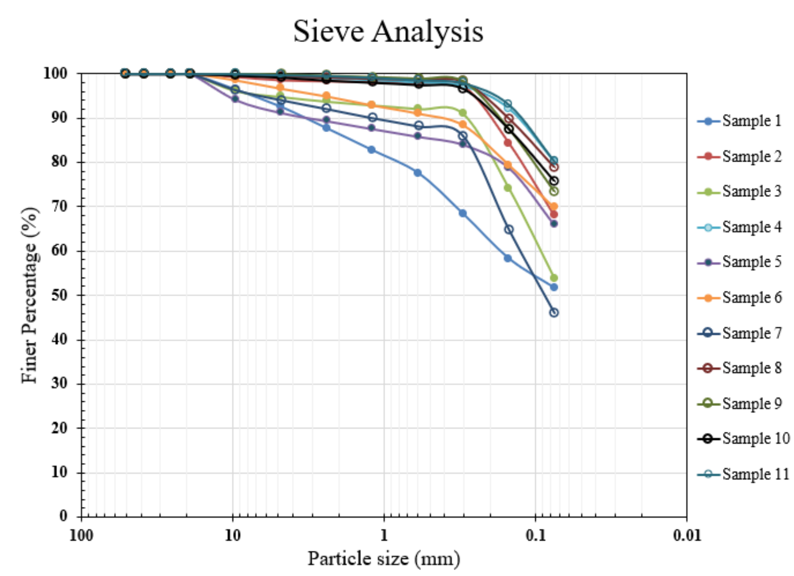


Figure 3.7 Grain size distribution curves for I-65 samples. Data from Gupta (2021)

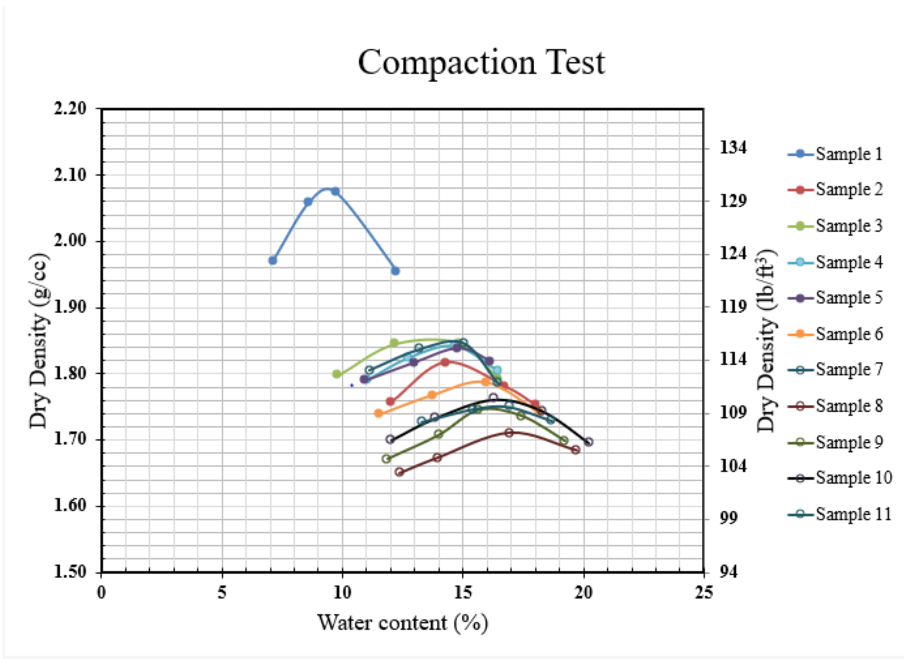


Figure 3.8 Compaction curves for I-65 samples. Data from Gupta (2021)

Table 3.3 Soil classification and compaction results for I-65 samples. Data from Gupta (2021)

Sample	LL	PL	PI	% fines	Classification		OMC	MDD
	%	%	%	%	AASHTO	USCS	**%**	**g/cc**
1	21.5	11.5	10.1	51.7	A-4	CL+ML	9.5	2.07
2	28.5	16.0	12.5	67.9	A-6	CL	14.3	1.82
3	25.4	16.3	9.1	53.7	A-4	CL+ML	14.0	1.84
4	30.1	16.8	13.3	80.1	A-6	CL	14.7	1.84
5	31.4	16.6	14.8	65.9	A-6	CL	14.8	1.84
6	32.7	18.7	13.9	69.8	A-6	CL	16.0	1.79
7	24.1	15.1	9.0	46.0	A-4	CL+ML	15.0	1.85
8	36.2	19.7	16.5	78.9	A-6	CL	17.0	1.71
9	31.0	17.9	13.1	73.3	A-6	CL	16.0	1.75
10	35.1	17.6	17.4	75.8	A-6	CL	16.5	1.76
11	35.3	18.7	16.6	80.2	A-6	CL	16.5	1.75
	21~35	**11~20**	**9 - 17**	**50~80**	**A-6**	**CL**	**9.5~16.5**	**1.71~2.07**

3.3. Resilient Modulus Tests

The resilient modulus tests were performed on samples at all locations, following AASHTO T 307-99 (2007). The M_R test is essentially a cyclic test designed to simulate real life traffic loading in the laboratory. It is comprised of 16 loading sequences with a combination of five deviatoric (2, 4, 6, 8 and 10 psi) and three confining stresses (2, 4 and 6 psi), including a conditioning sequence. The first sequence consists of a conditioning cycle of 750 repetitions to ensure proper contact between the specimen and the loading cap, and to remove any effects of initial loading versus reloading. All other sequences involve 100 cycles of loading and reloading. The average resilient modulus obtained for the last five cycles is reported for each sequence. Each test results in 15 resilient modulus values corresponding to each deviatoric and confining stress. For design purposes, often the resilient modulus value at 6 psi deviatoric stress and 2 psi confining stress is used, as this best represents the loading of a single axle wheel load.

Specimens are prepared for the tests at each location following a modified double plunger method specified in Annex C of AASHTO T 307-99 standard for type 2 subgrade materials (fine-grained soils). The method involves a split mold, spacer disks and a hand press used for static compaction. Remolded specimens are compacted in 5 layers using spacers of different thickness to ensure all layers have equal volume. After compaction, three measurements of height and diameter are taken to obtain the average volume of the sample. The specimens prepared for testing are approximately 2.8 in. (71 mm) in diameter and 5.6 in. (142 mm) in height (2:1 height to diameter ratio). The mass and density of the specimens is also obtained.

For all locations, both untreated and cement-treated M_R test specimens were prepared at OMC and MDD values corresponding to the Standard Proctor test results of the untreated samples. The cement treated samples were cured for 28 days before testing. Curing involved carefully wrapping the samples with clingfilm and storing them in a cooler for the curing period to ensure minimal loss of moisture content. Control specimens of cement treated and untreated specimens were also prepared to determine changes in water content during the curing period. The water content of the treated specimens was measured just after specimen preparation as well as after performing the resilient modulus test. The loss of water content of the treated samples after curing was about 1%, while that of the untreated specimen showed negligible change in water content. The decrease in water content for the treated specimens is attributed to the chemical reaction between the soil and cement during the curing process. The data of resilient modulus tests for all sites included in this study was obtained from Gupta (2021).

US 31 Results:

Resilient Modulus tests were performed on treated as well as on untreated soils at all 11 locations for Site 3 (US 31). The soil specimens were compacted at MDD values obtained from the Standard Proctor tests on untreated samples. The relative compaction for all samples was found to be between 97 % to 99 %. The treated specimens were prepared with 4% cement, by weight, mixed with the natural soil and cured for 28 days. Little variations in M_R values, for untreated specimens, were found for all the soils at the site; however, treated specimens exhibited larger differences. For untreated specimens, the M_R, ranged from 40 – 140 MPa (5800 - 20200 psi), while for treated specimens, the resilient modulus was three times higher, and ranged from 120-470 MPa (18,000 – 68,000 psi). Figures 3.9 and Figure 3.10 provide the resilient modulus test results for all untreated and treated samples, respectively. The variability observed in the treated specimens could be due to differences in gradation and plasticity of the soils. The resilient modulus of the treated specimens showed a slight dependency on confining stress, but little to none on deviatoric stress.

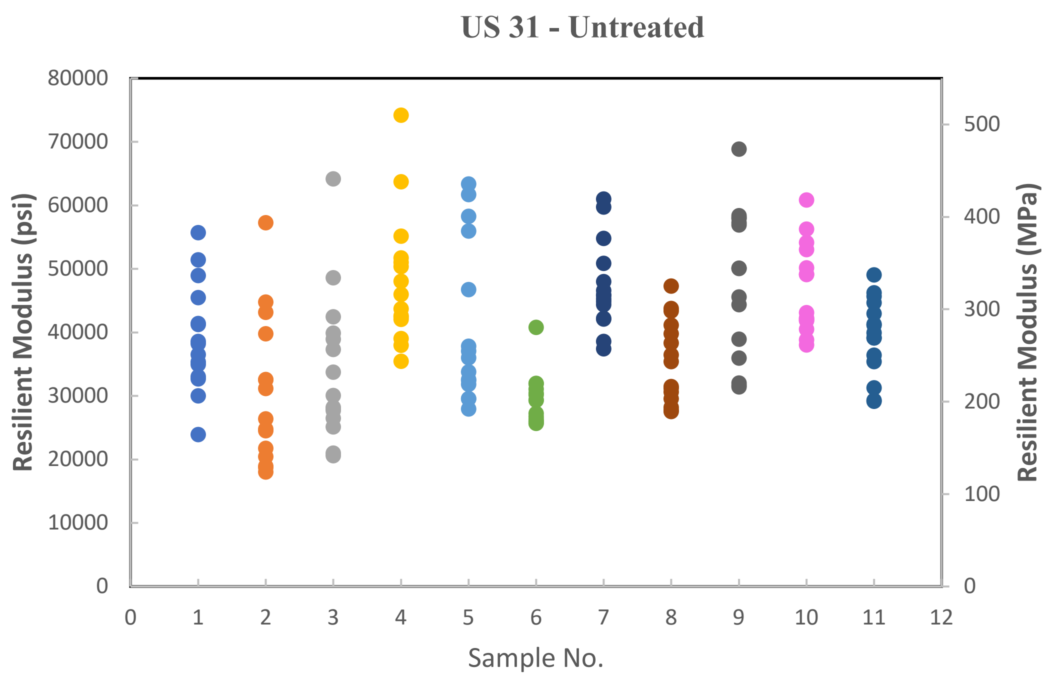


Figure 3.9 Summary of resilient modulus results for untreated samples – US 31. Data from Gupta (2021)

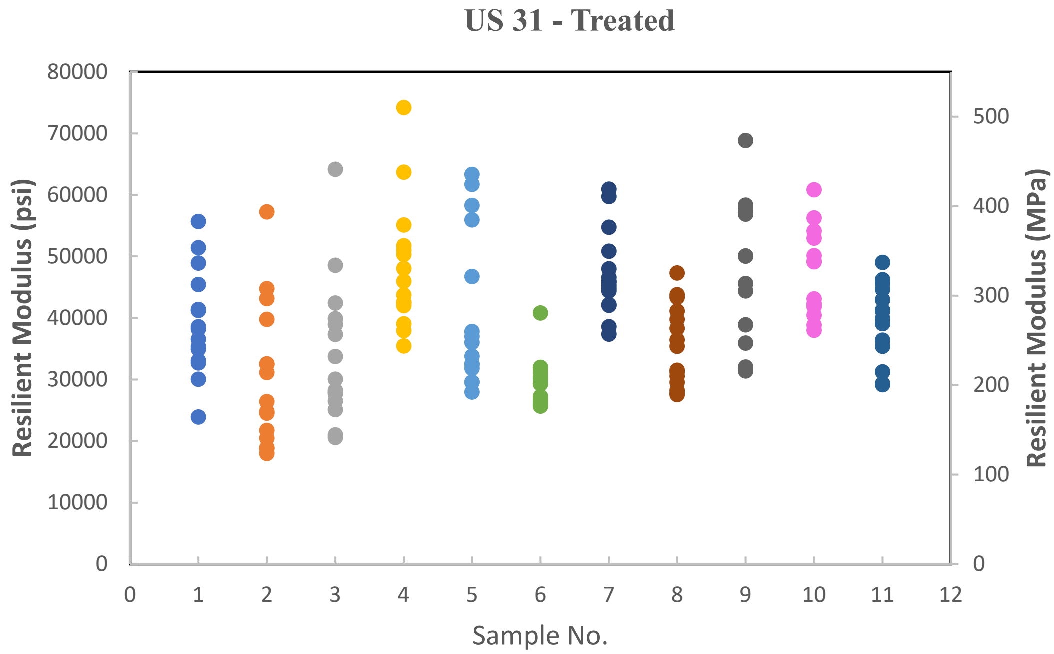


Figure 3.10 Summary of resilient modulus results for treated samples – US 31. Data from Gupta (2021)

SR 37 Results:

For the SR 37 site, Resilient Modulus tests were performed on treated and untreated specimens, which were compacted at the MDD and OMC of the untreated soil. The relative compaction for all samples was found to be, on average, 98 %. The treated specimens were prepared with 5% cement mixed, by weight, and cured for 28 days. The range of M_r values of the untreated specimens were between 48 and 190 MPa (7,000 to 28,000 psi) and of the treated specimens, in the range of 170 to 520 MPa (25,000 to 75,000 psi). Figures 3.11 and 3.12 are plots of the resilient modulus for all untreated and treated samples. The effects of confining stress were observed in the treated as well as in the untreated specimens, with treated specimens exhibiting a large decrease of resilient modulus with increasing confining stress (indicated by the larger spread of values in Figure 3.12). The resilient modulus results are fairly uniform, which indicate uniformity of the soil across all stations. This is expected due to the small differences in soil characteristics at the site (Table 3.2).

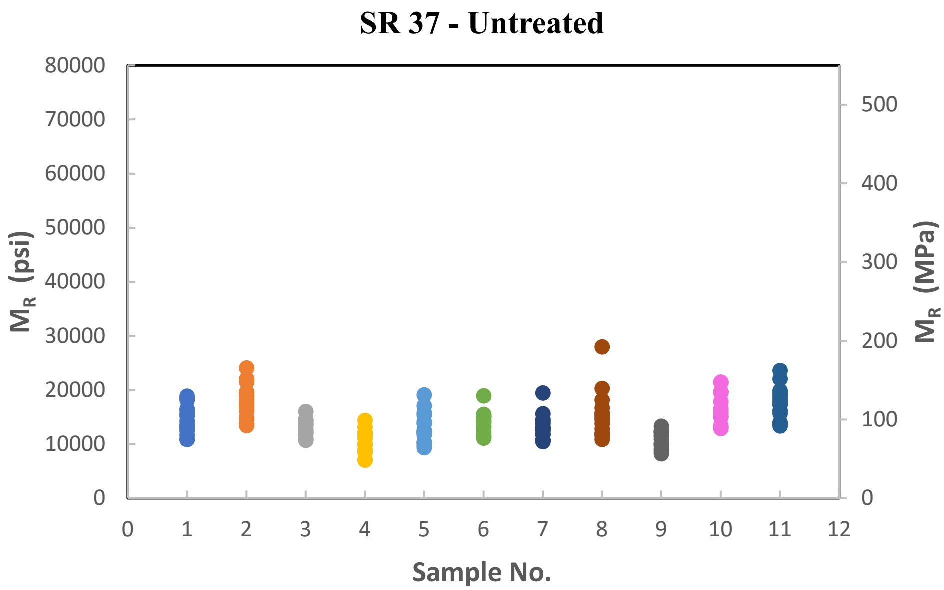


Figure 3.11 Summary of resilient modulus results for untreated samples – SR 37. Data from Gupta (2021)

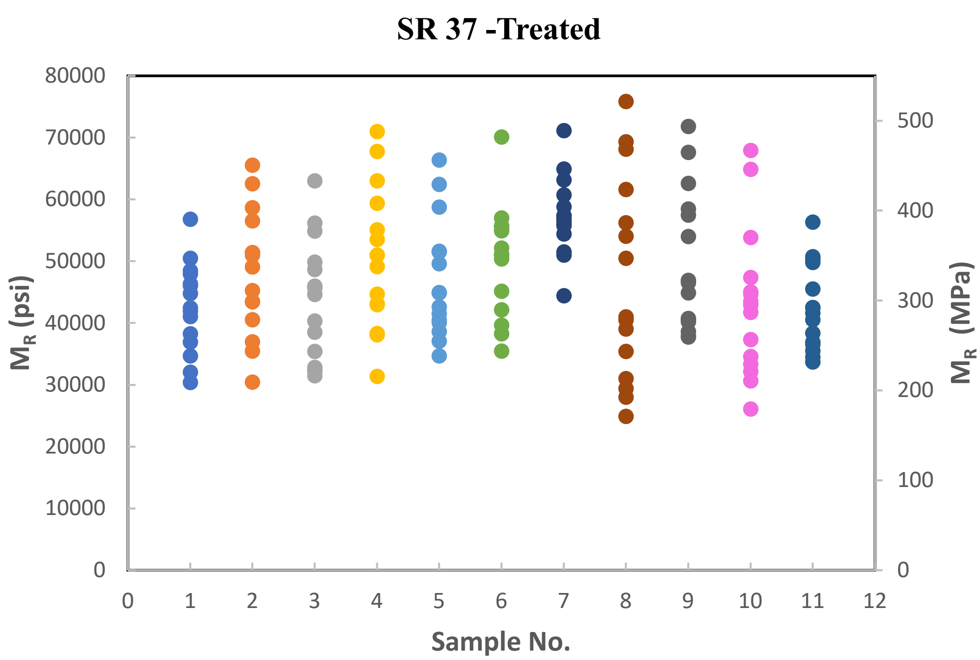


Figure 3.12 Summary of resilient modulus results for treated samples – SR 37. Data from Gupta (2021)

I-65 Results:

At the I-65 site, as with the other sites, Resilient Modulus tests were performed on treated and untreated specimens. All specimens were compacted at the MDD and OMC of the Standard Proctor tests conducted on untreated soil. The relative compaction for all samples was found to be on average between 97 % to 99 %. The treated specimens were prepared with 5% cement mixed, by weight, with the natural soil and cured for 28 days. The M_r values of the untreated specimens were between 34 and 135 MPa (5,000 to 20,000 psi) and of the treated specimens, 82 to 530 MPa (12,000 to 77,000 psi). Figures 3.13 and 3.14 show the resilient modulus of all untreated and treated samples. The effect of confining stress was pronounced in the treated specimens, with values decreasing with decreasing confining. The untreated samples did not exhibit much variation with respect to confining and deviatoric stresses, as indicated by the narrow range of values displayed in Figure 3.13. The variability observed in the resilient modulus values of the treated specimens could be due the wide range of soil properties observed at the site (see Table 3.3)

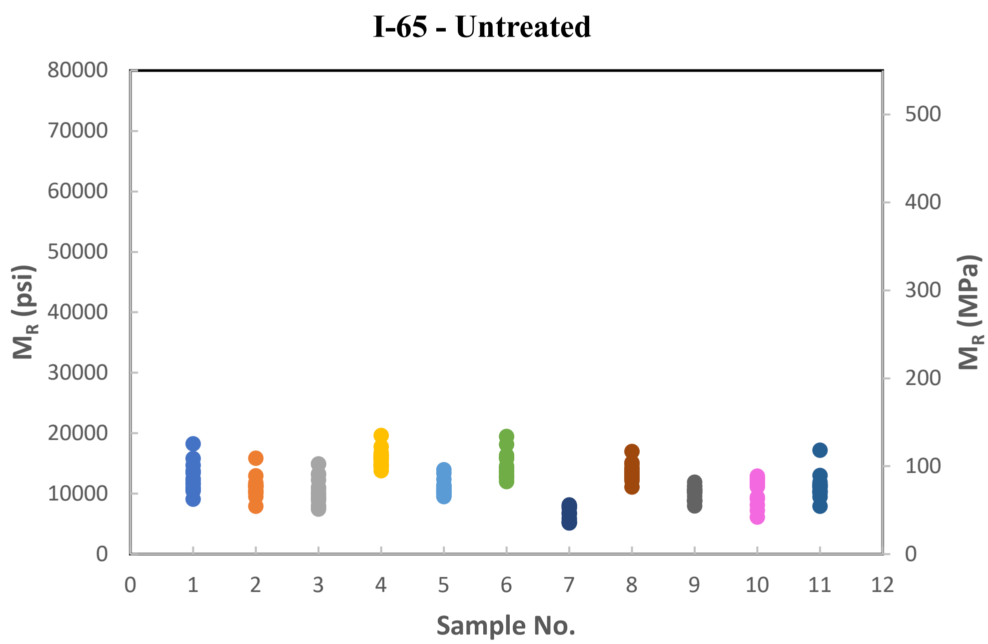


Figure 3.13 Summary of resilient modulus results for untreated samples – I-65. Data from Gupta (2021)

I-65 Treated

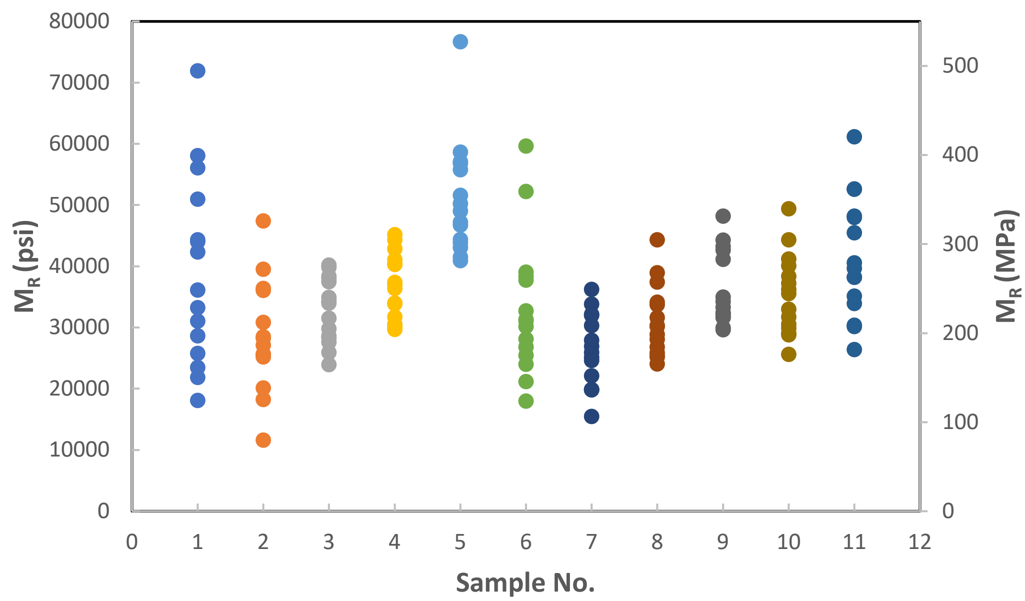


Figure 3.14 Summary of resilient modulus results for treated samples – I-65. Data from Gupta (2021)

4. UNCONFINED COMPRESSIVE STRENGTH TESTS

The Unconfined Compressive Strength (UCS) test is the primary method used to determine the strength of the subgrade. UCS tests were performed on reconstituted treated samples at all locations, as per AASHTO T 208-15. Three tests were performed at each location for all sites to ensure repeatability of results. The sample preparation procedure was kept similar to that for the resilient modulus tests (compacted in 5 layers of equal volume using the double plunger method) to ensure compatibility of results. The specimens prepared were approximately 2.8 in. (71 mm) in diameter and 5.6 in. (142 mm) in height (2:1 height to diameter ratio).

The cement-treated specimens were prepared at OMC and MDD values corresponding to the Standard Proctor test results on untreated samples. The samples were cured for 7 days before testing. Curing involved carefully wrapping the samples with clingfilm and storing them in a cooler for the curing period to ensure minimal loss of moisture content. The water content of the treated specimens was measured just after specimen preparation, as well as after performing the UCS test. The loss of water content of the treated samples after curing was on average about 0.8-1 % which is expected because of the chemical reaction between cement and soil.

The specimens were tested at a 1 % strain rate (0.056 in./min or 0.72 mm/min) and were loaded to failure. The output of the tests was the stress-strain response from which the peak value was identified as the unconfined compressive strength. Additional UCS tests were done on specimens used for the resilient modulus tests. The UCS test, in these cases, was conducted at the end of the M_r tests. Note that these tests were done on specimens 28 days old. Figure 4.1 includes photographs of representative samples loaded to failure.

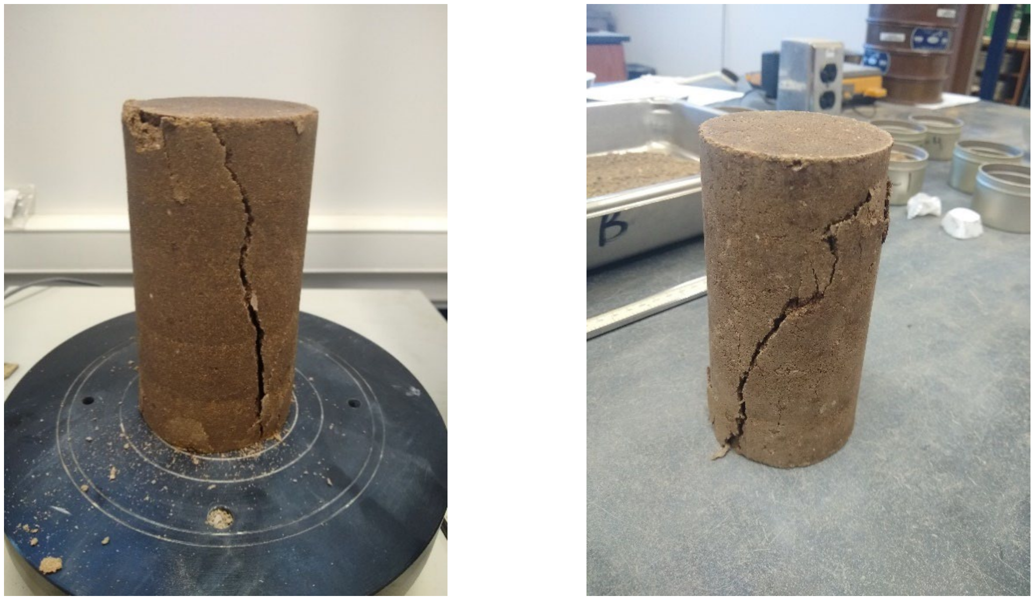


Figure 4.1 Samples post UCS tests.

Three UCS tests were performed on treated soils at each location. The soil specimens were compacted at the OMC and MDD values obtained from Standard Proctor tests on untreated samples. The relative compaction for all samples was found to in the range of 97 % to 99 %.The treated specimens were prepared with 4% cement, by weight, mixed with the natural soil and cured for 7 days. The water content was recorded at the time of sample preparation and after performing the UCS tests. The water content was found to decrease by 1%, on average, among all samples. Figure 4.2 displays the stress-strain plots for UCS tests performed on cement-treated specimens at all locations (except at location no. 4, as the samples were found to have cracks after curing). Figure 4.3 summarizes all the UCS tests. The UCS values range from 220 to 415 psi (1.5 MPa to 2.9 MPa). The variability in the UCS results can be explained by the differences in gradation and plasticity in the soils found at this site (see Table 2.1). The strain at failure is also considerably lower compared to the untreated subgrade soils, as reported in the literature (Hossain et. al (2011), Lee et. al (1997), Sandoval et. al (2019)) and ranges between 0.8 to1.2 %.

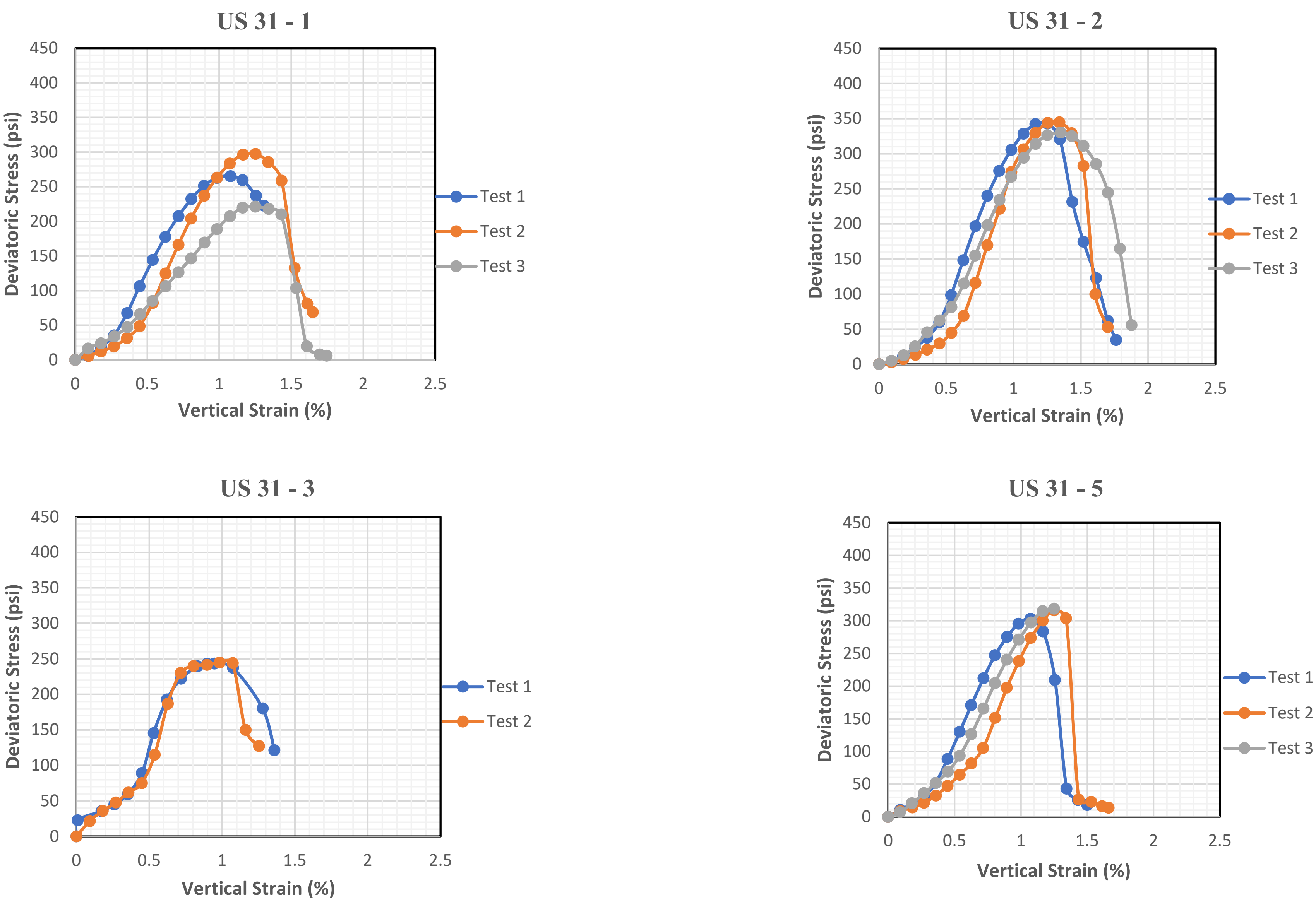


Figure 4.2 Stress-Strain plots of 7-Day UCS tests for site US 31

Figure 4.2 continued

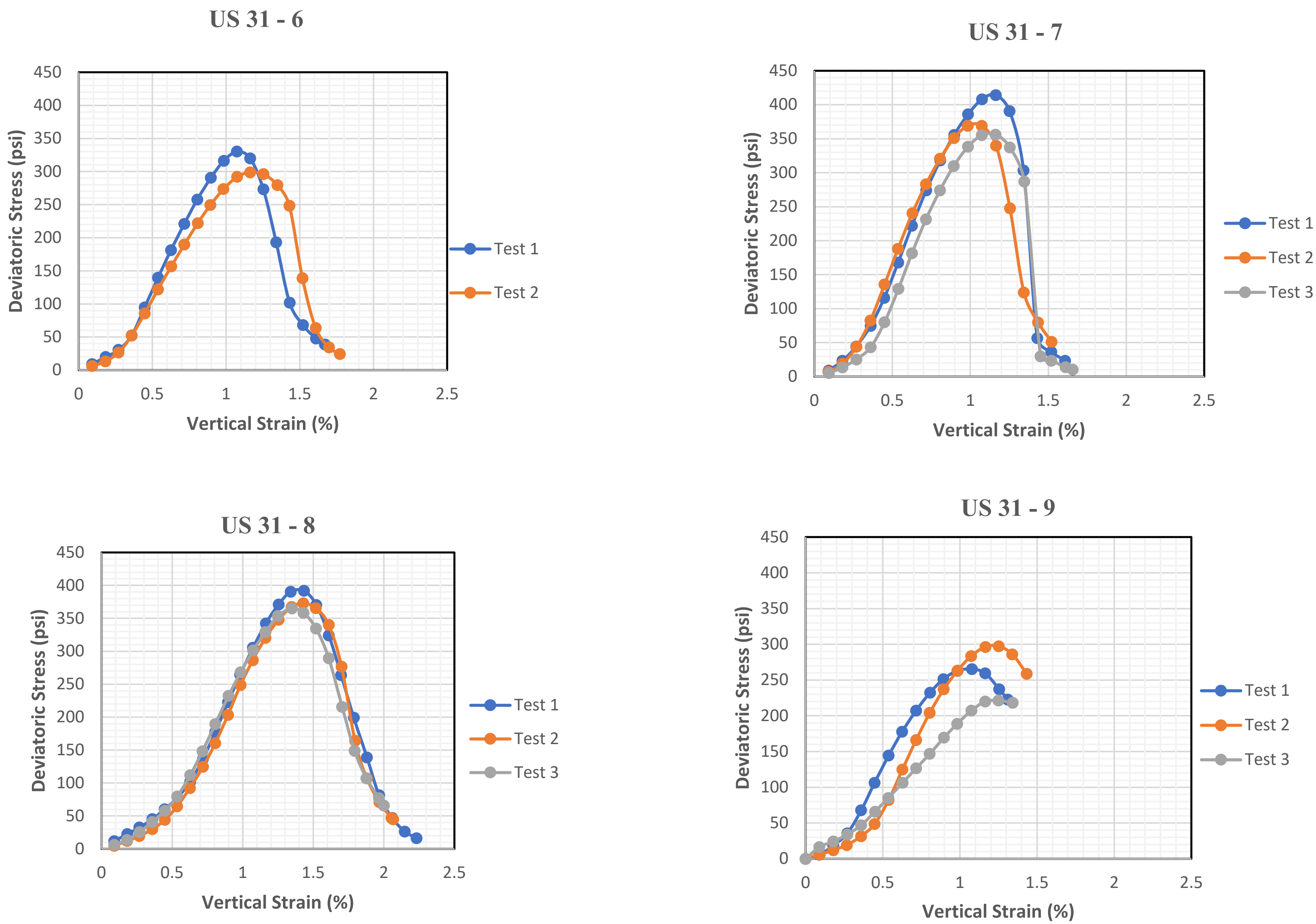
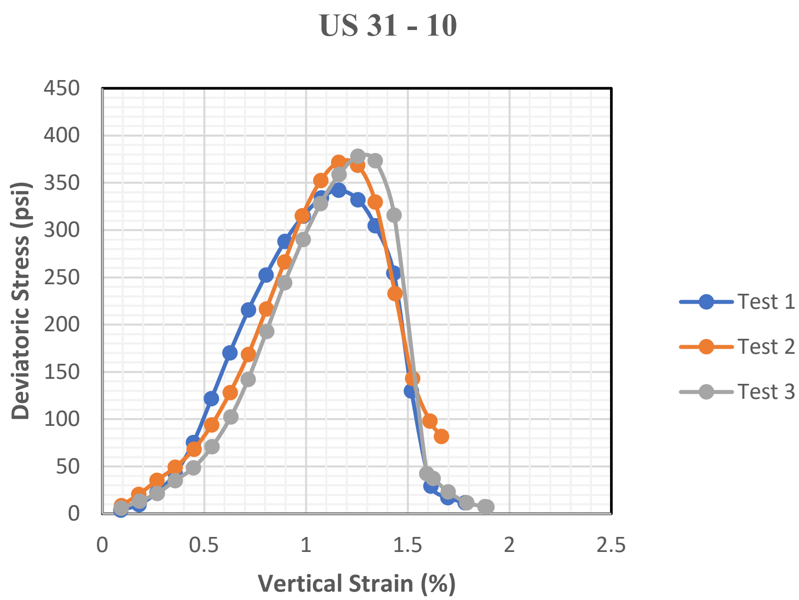
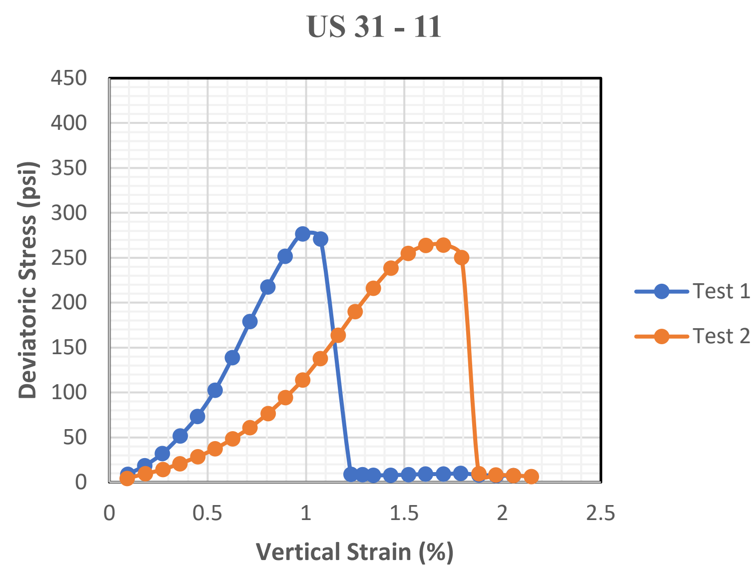


Figure 4.2 continued





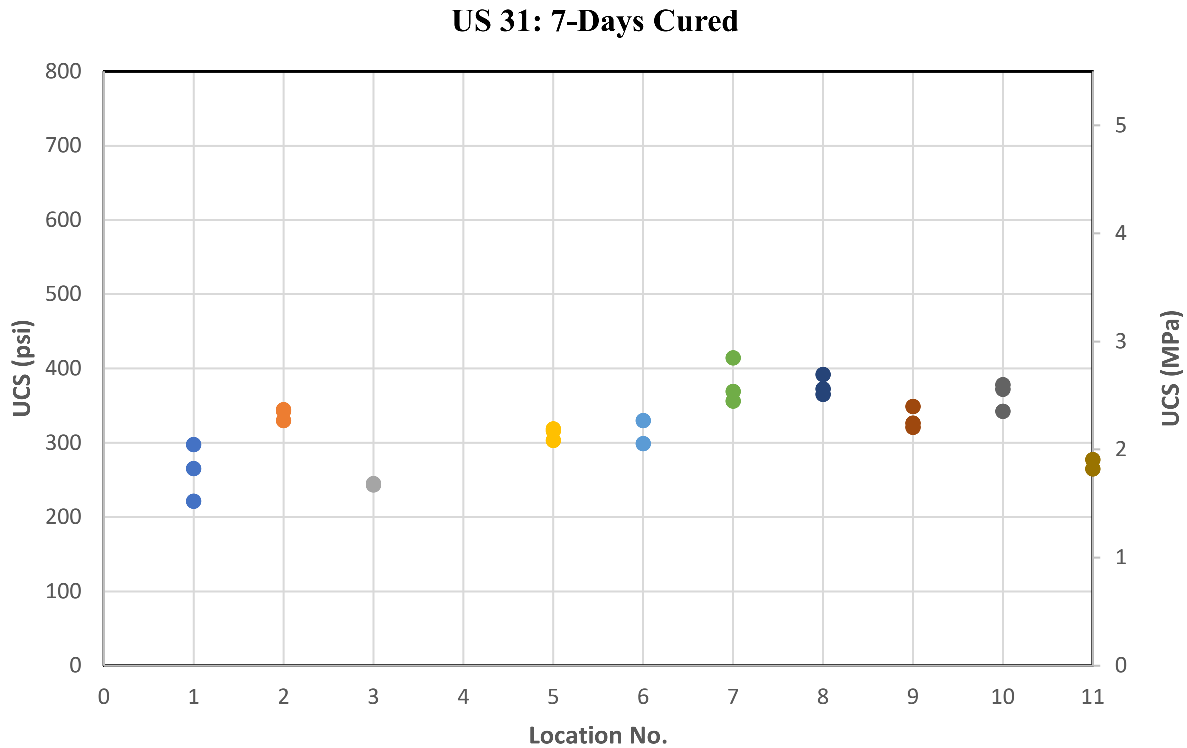


Figure 4.3 Summary of 7-Days cured UCS values for all locations at US 31 site

UCS tests were also performed on 28 days cured cement-treated samples. These tests were done on the same specimens used for resilient modulus testing. Figure 4.4 is a plot of the UCS test results for the 28 days cured samples. The results range from 255 to 470 psi (1.75 MPa to 3.2 MPa) and are on average about 1.2 times larger than the UCS at 7-Days.

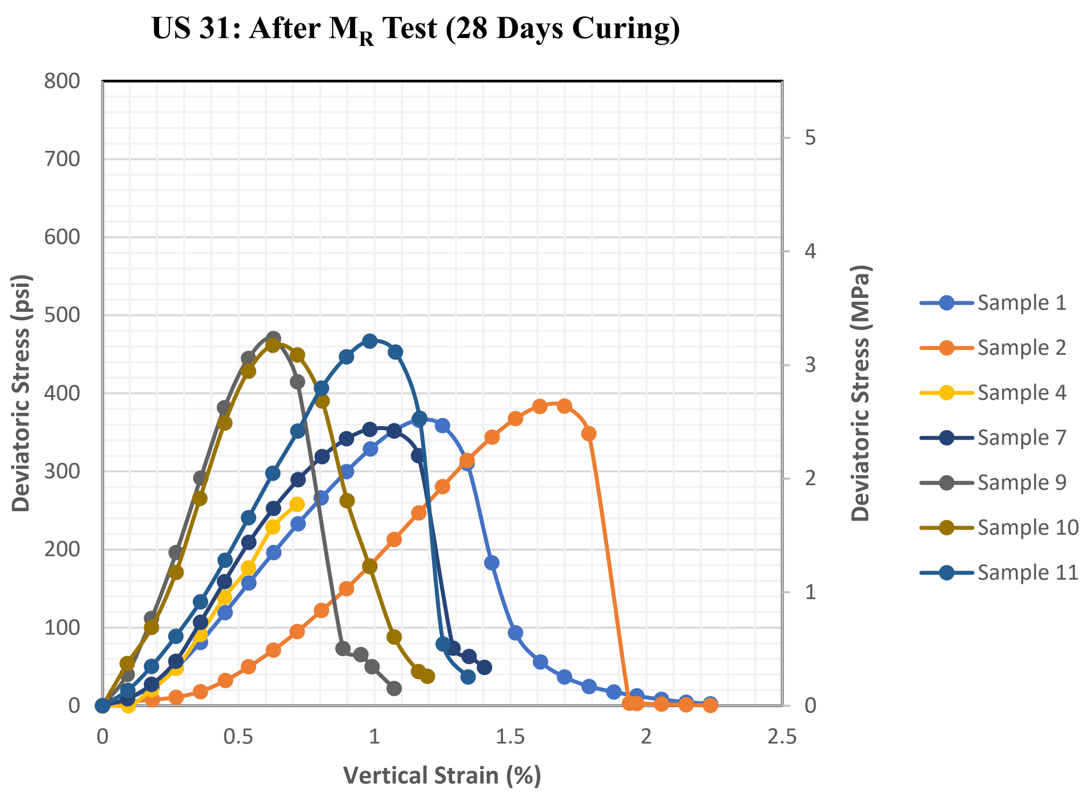


Figure 4.4 UCS test results for the 28 days cured samples performed after MR test – US 31

SR 37 Results:

Three UCS tests were performed on treated soils at each location at the SR 37 site. The soil specimens were compacted at the OMC and MDD values obtained from the Standard Proctor tests on untreated samples. The relative compaction for all the prepared samples was found to be on average 98 %. The treated specimens were prepared with 5% cement, by weight, mixed with the natural soil and cured for 7 days.

Figure 4.5 displays the stress-strain plots of UCS tests performed on cement-treated specimens at all locations. The plots include a large number of data points because the tests were performed with the new UCS load frame (Humboldt Master Loader), capable of recording data at frequent intervals.

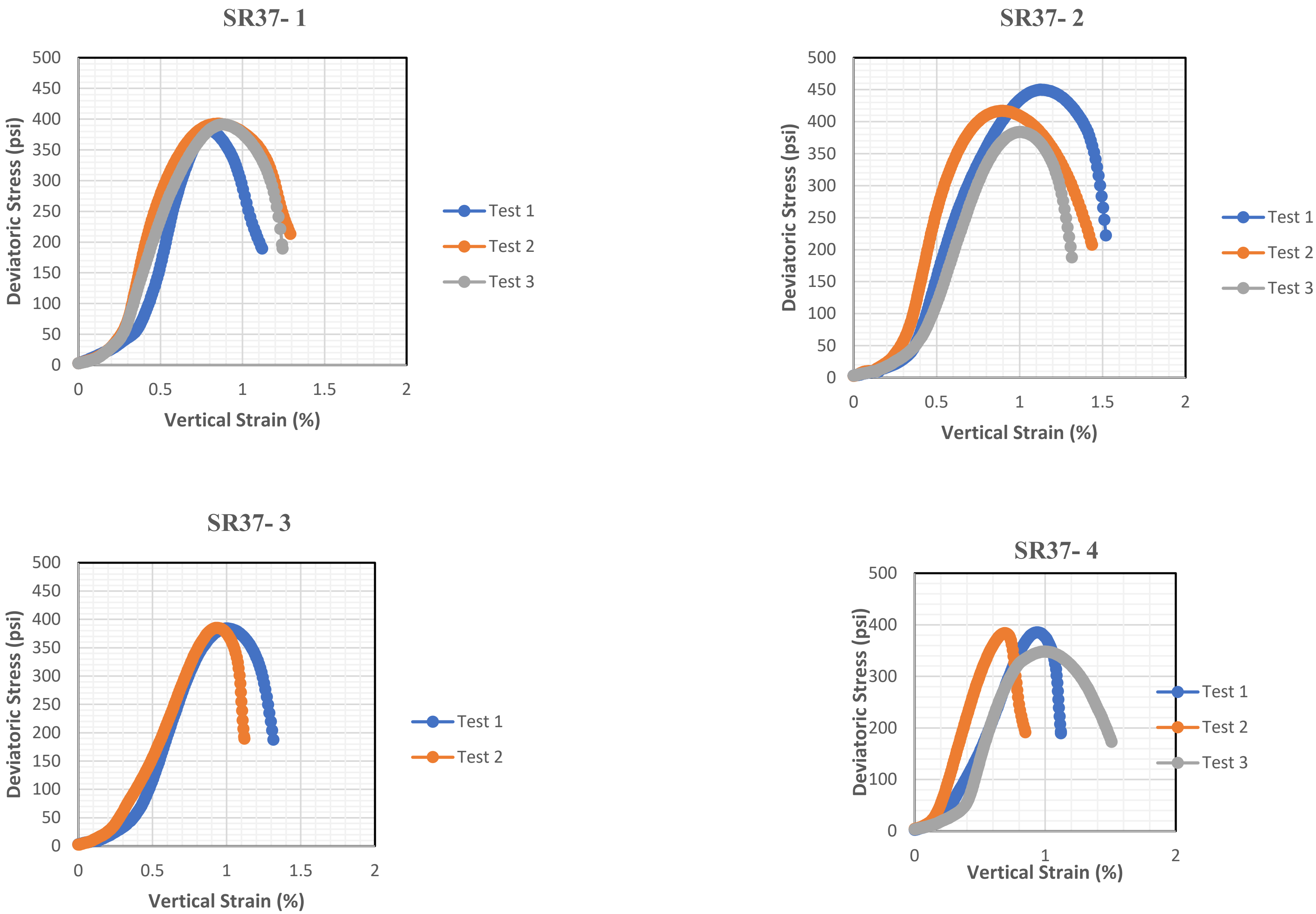


Figure 4.5 Stress-Strain plots of 7-Day UCS tests for site SR 37

Figure 4.5 continued

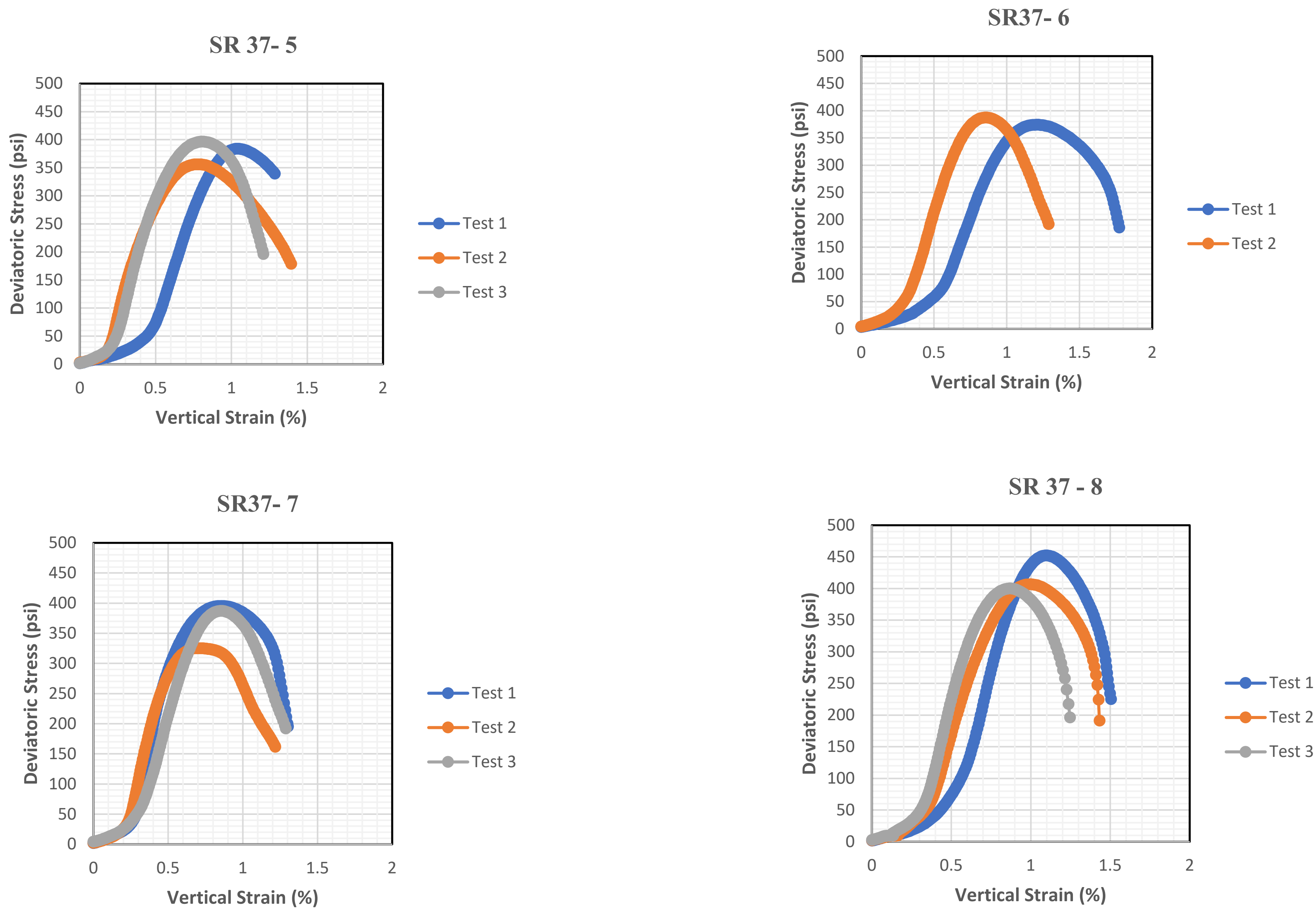
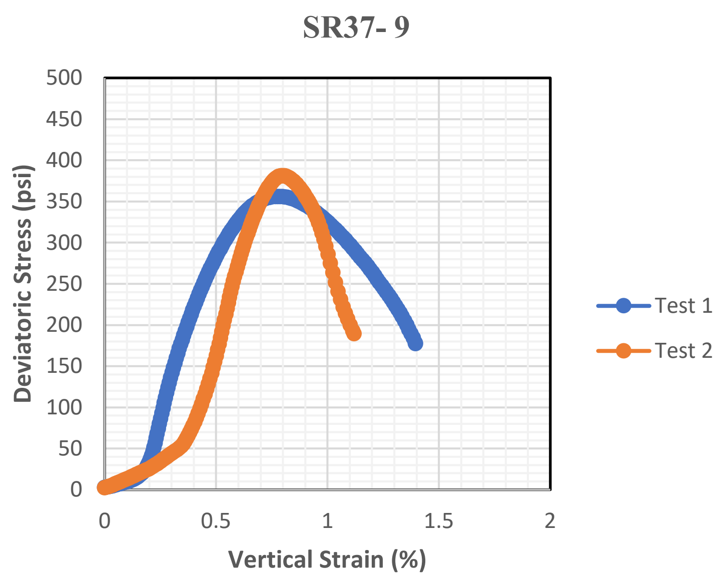
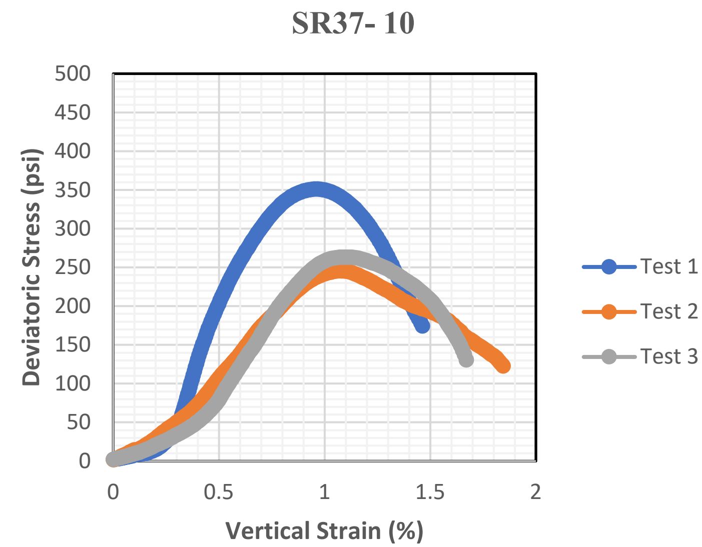


Figure 4.5 continued





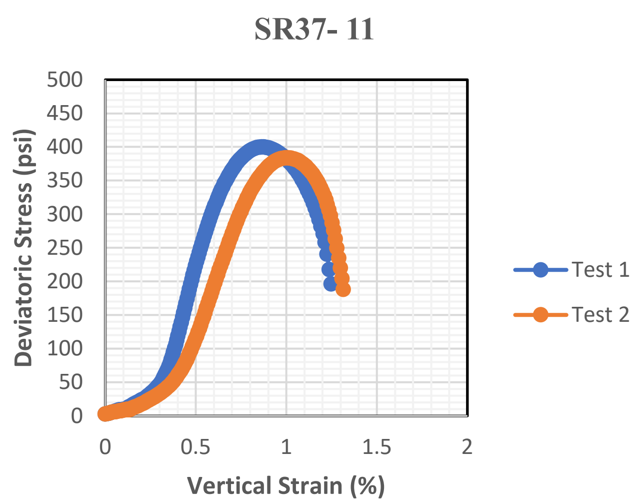


Figure 4.6 summarizes the UCS test results done at the site. The majority of UCS values lie in the range of 350 psi to 450 psi (2.4 MPa to 3.1 MPa). The similarity of the stress-strain plots and the narrow range of UCS values can be explained by the uniform nature of the soils found at this site (see Table 3.2).

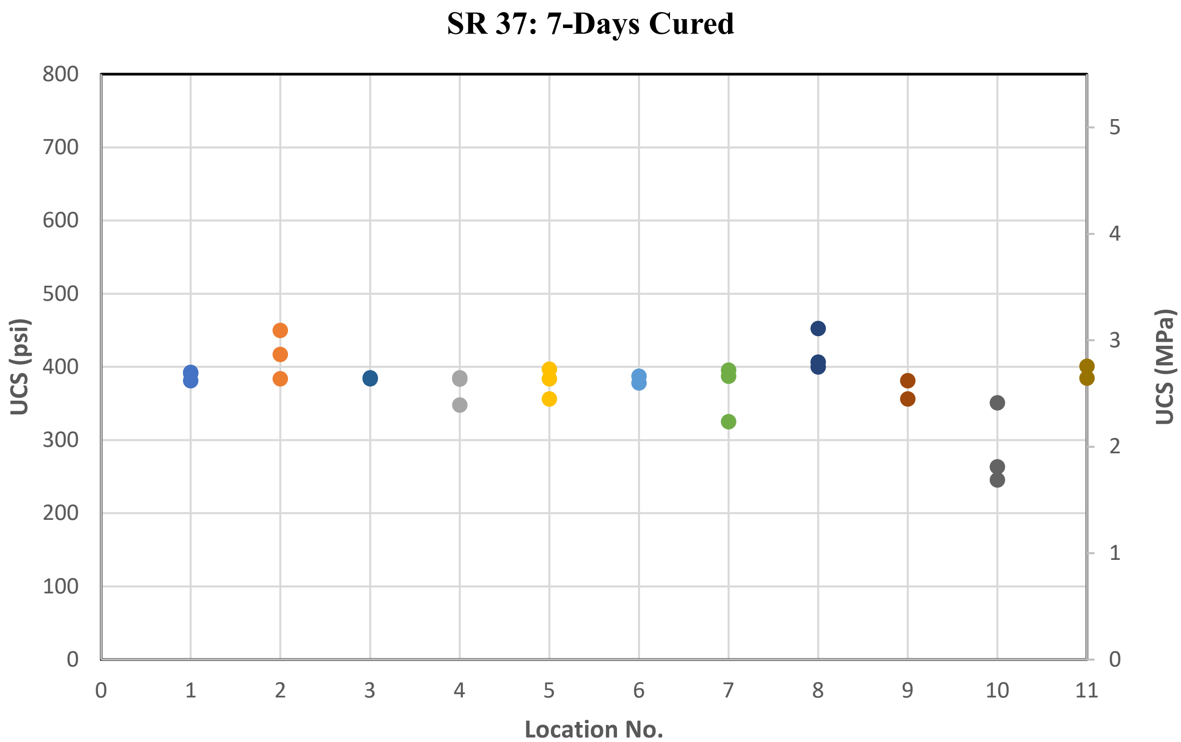


Figure 4.6 Summary of 7-Days cured UCS values for all locations at SR 37 site

UCS tests were also performed on 28 days cured cement-treated samples at all 11 locations. These tests were done on the same sample after the resilient modulus test. Figure 4.7 displays the UCS test results for the 28 days cured samples. The UCS values range from 410 to 575 psi (2.8 to 4 MPa) and are, on average, about 1.4 times the UCS at 7-Days.

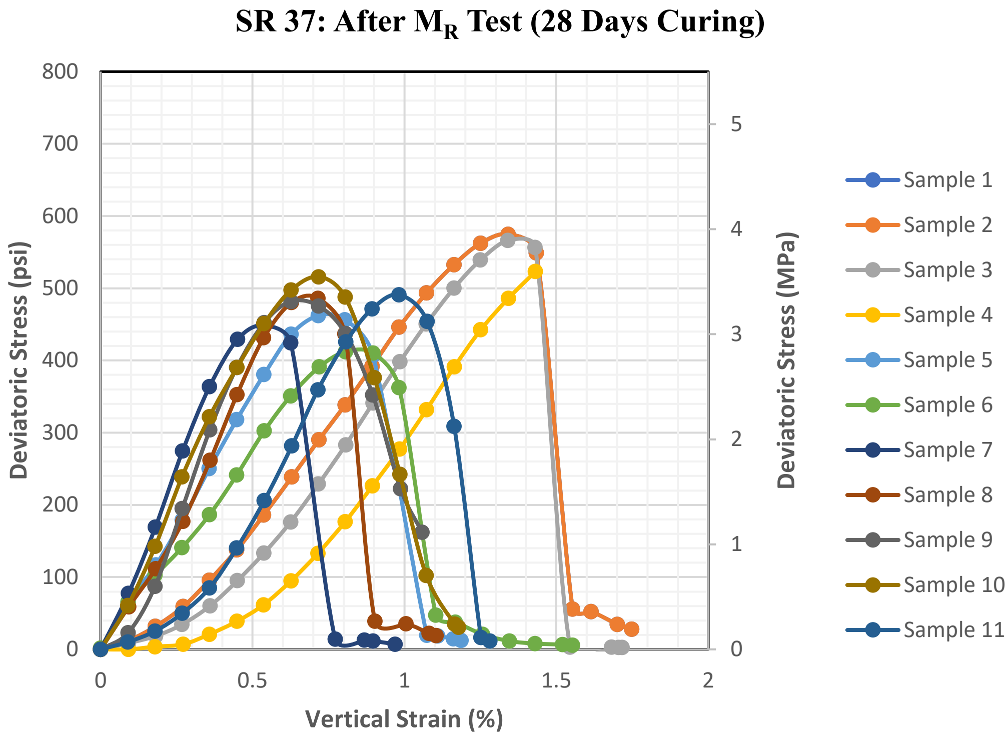


Figure 4.7 UCS test results for the 28 days cured samples performed after MR test – SR 37

I-65 Test Results:

Three UCS tests were performed on treated soils at each location, at the I-65 site. The soil specimens were compacted at the OMC and MDD values obtained from the Standard Proctor tests on untreated samples. The relative compaction for the prepared samples was found to be on average 97 % to 98 %. The treated specimens were prepared with 5% cement, by weight, mixed with the natural soil and cured for 7 days. Figure 4.8 shows the results of 7-Days cured specimens tested at all locations of I-65.

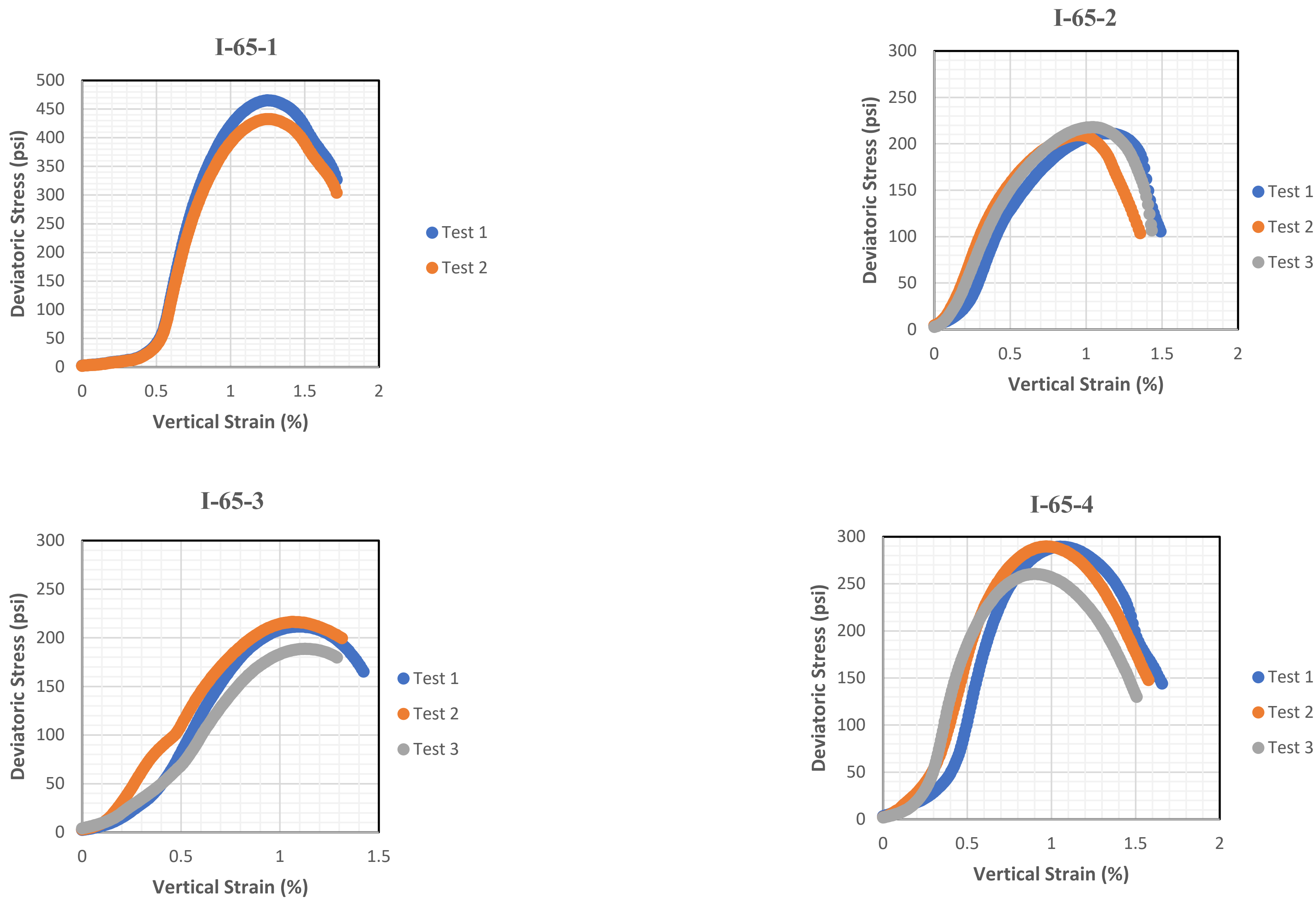
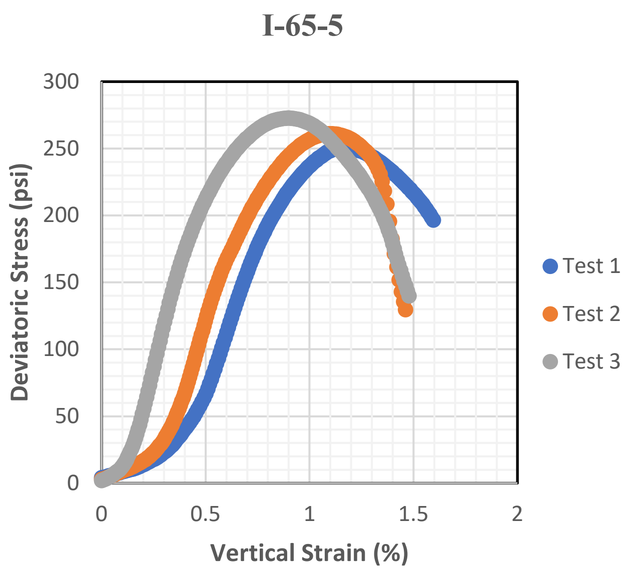
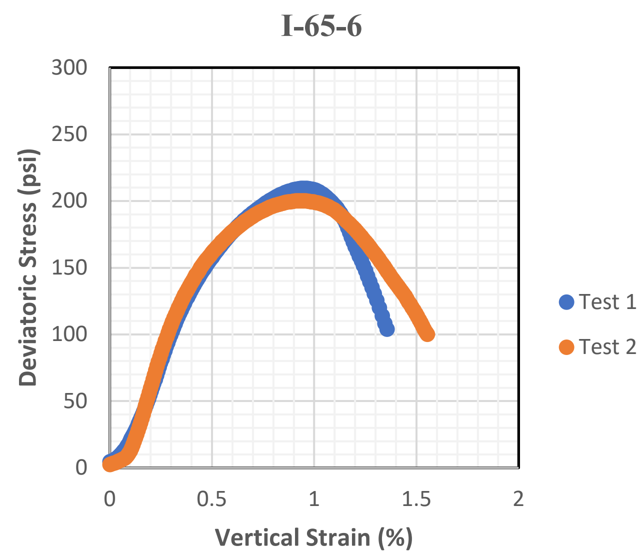
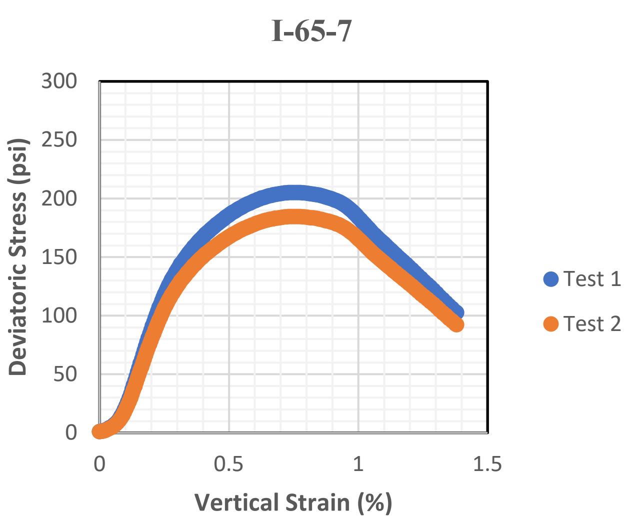


Figure 4.8 Stress-Strain plots for 7-Day UCS tests for site I-65

Figure 4.8 continued







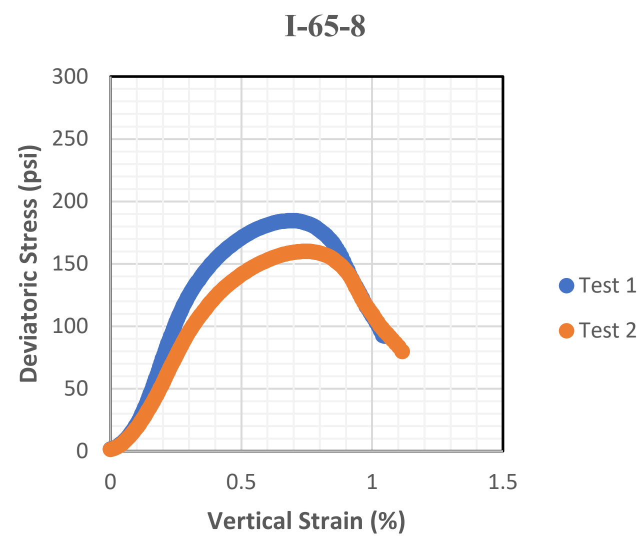


Figure 4.8 continued

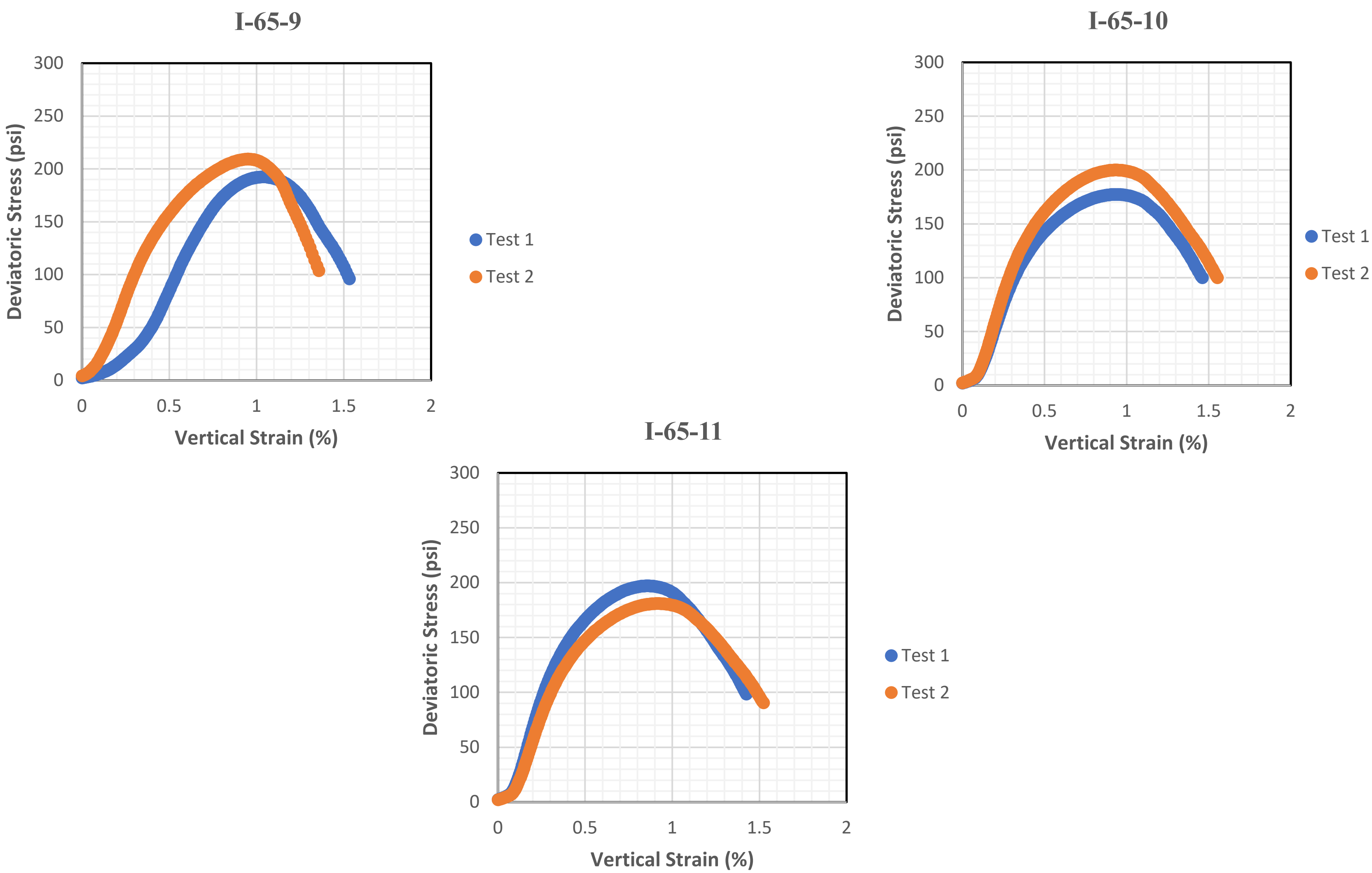


Figure 4.9 summarizes the UCS test results done at the site. The majority of the UCS values for this site lie in the range of 180 to 290 psi (1.2 to 2 MPa) (except for location 1). The UCS value at location 1 is distinctly higher compared to the rest due to a considerably lower OMC value and higher MDD at this location (see Table 3.2).

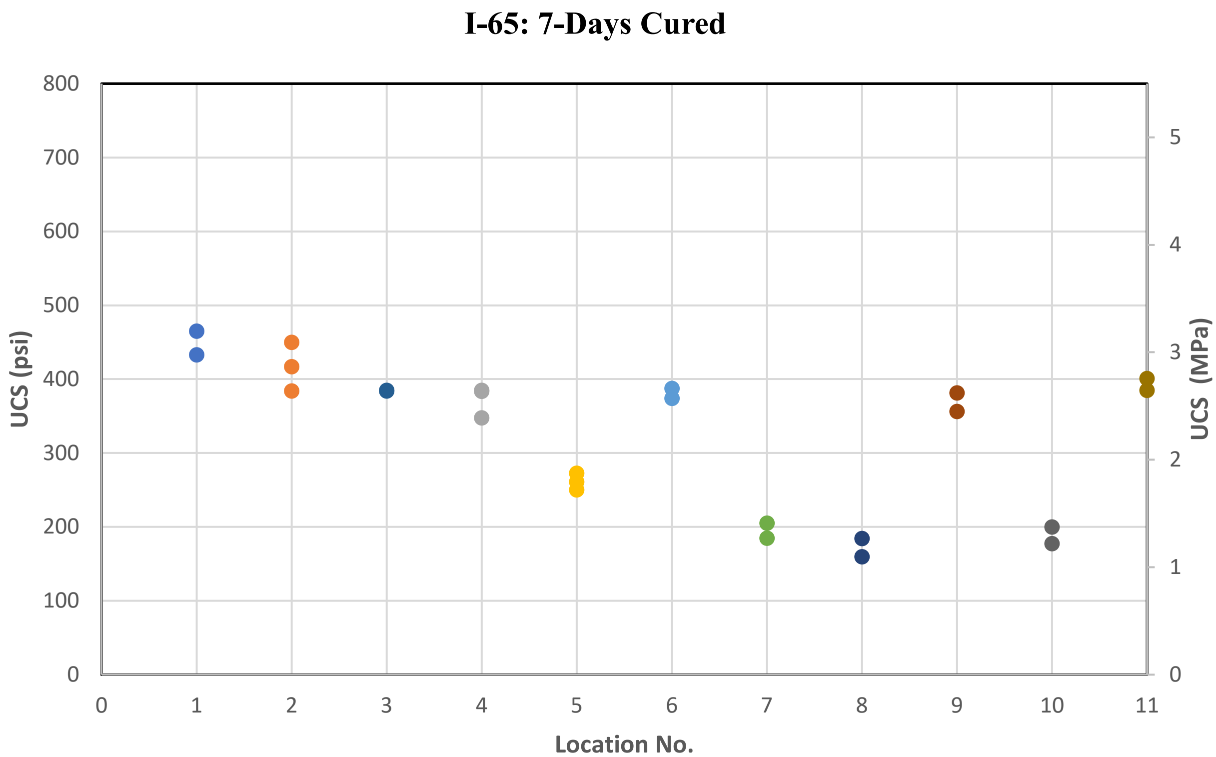


Figure 4.9 Summary of 7-Days cured UCS values for all locations at I-65 site

Figure 4.10 includes plots of the UCS test results for the 28 days cured samples. The UCS values range from 240 to 745 psi (1.7 to 5.1 MPa). The UCS at location 1 is distinctly higher than the rest, which is most likely due to the high MDD and low OMC of the soil (see Table 3.3). The UCS values at 28-days curing are on average 1.4 to 1.5 times the UCS values at 7-days curing for this site, consistent with the results from the other sites.

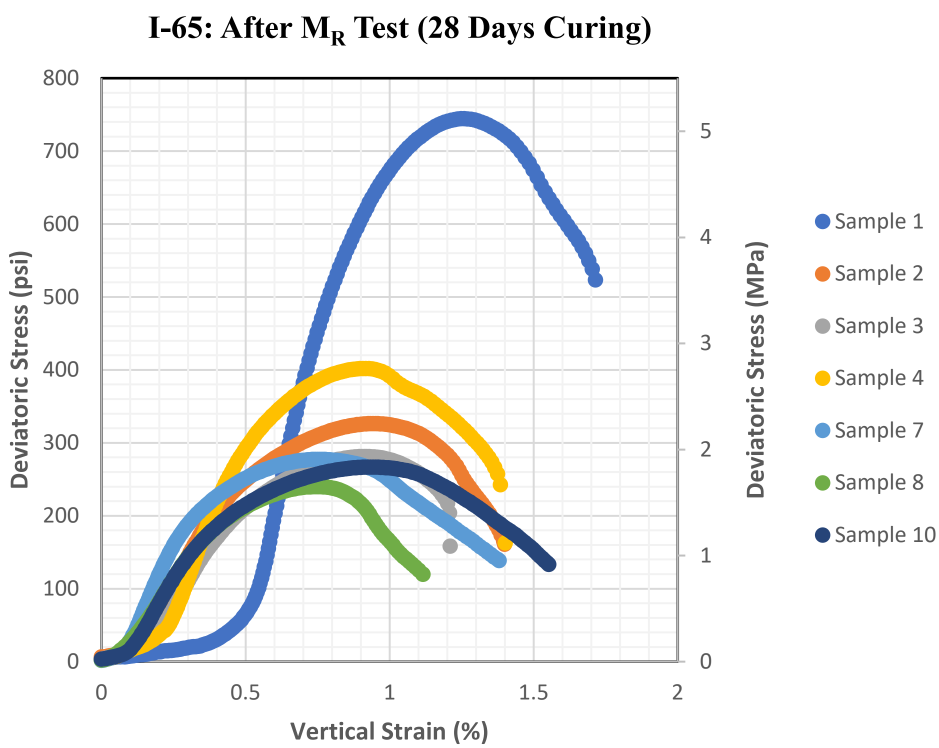


Figure 4.10 UCS test results for the 28 days cured samples performed after MR test – I-65

5. CORRELATIONS BETWEEN RESILIENT MODULUS AND UCS

The discussion and data presented in chapter 2 (literature review) suggests that it is unlikely to get a statistically significant or direct correlation between the resilient modulus and unconfined compressive strength parameters in the case of treated soils. The approach in this study is to try to establish a range of values for the resilient modulus and UCS test results across the three sites used for this project. Data representing the resilient modulus and UCS test results were taken to represent the strength-stiffness test results. The resilient modulus values corresponding to 6 psi deviatoric stress, and 2 psi (low confinement) and 6 psi (high confinement) confining stress were selected from all the tests. For the UCS tests, the data selected were the average UCS values at the 7-Days and 28-days cured samples.

Figures 5.1 and 5.2 display the plots of resilient modulus versus 7-Day and 28-Day cured UCS, respectively, for all the sites. As evident from the plots there is a wide range of values in terms of both resilient modulus and UCS results for the soils used in this project. The degree of scatter in the plots also indicates that there is no direct statistically significant correlation between the resilient modulus and UCS for the treated soils considered in this study.

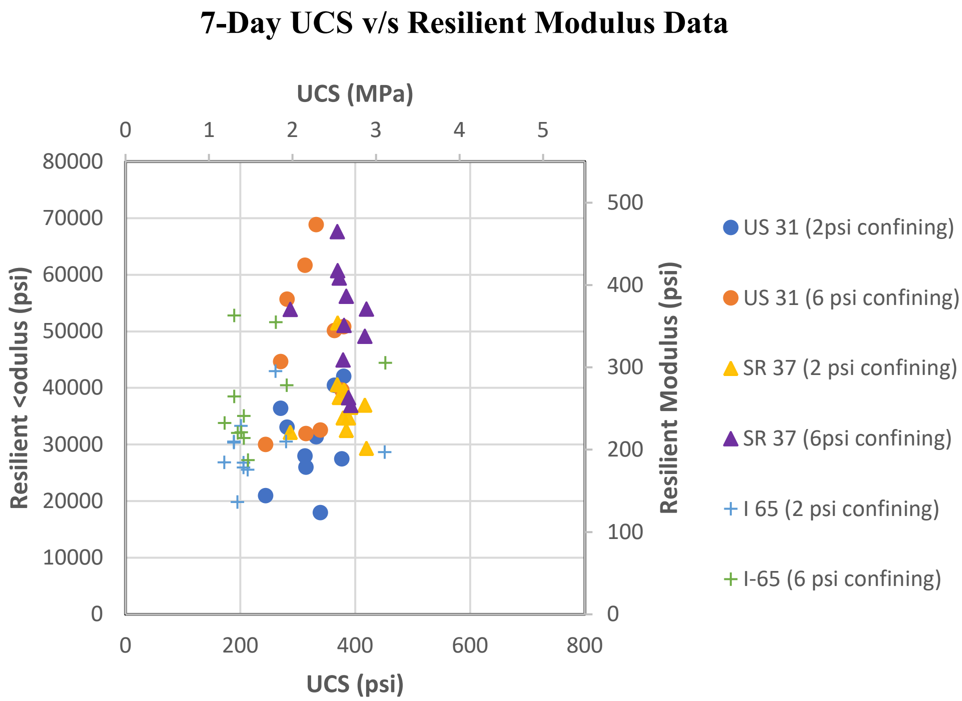


Figure 5.1 Resilient Modulus versus 7-Days cured UCS results for all sites

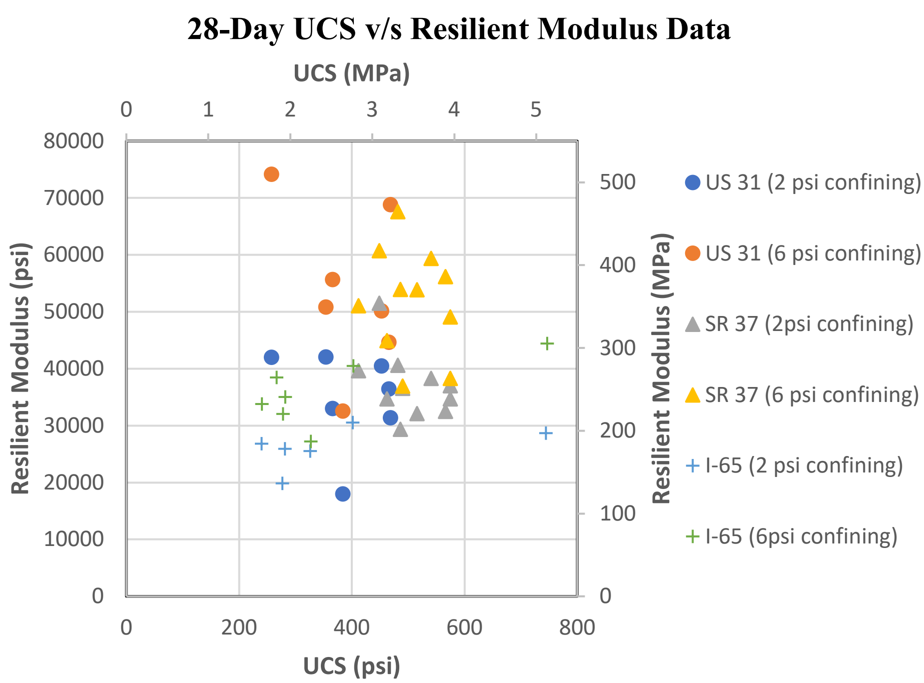


Figure 5.2 Resilient Modulus versus 28-Days cured UCS results for all sites

An alternate way to plot the resilient modulus and UCS data for all the sites is to sort them with respect to the type of soil. The MPEGD, for pavement design relies on the use of the resilient modulus of the subgrade at 2 psi confinement and 6 psi deviatoric stress. A plot combining the resilient modulus, UCS and soil type data can prove useful for estimating the expected range of values of the resilient modulus. Figures 5.3 and 5.4 are plots of the resilient modulus (6 psi deviatoric stress and 2 psi confinement) versus the 7-Day and 28-Day UCS, respectively, including the type of soil.

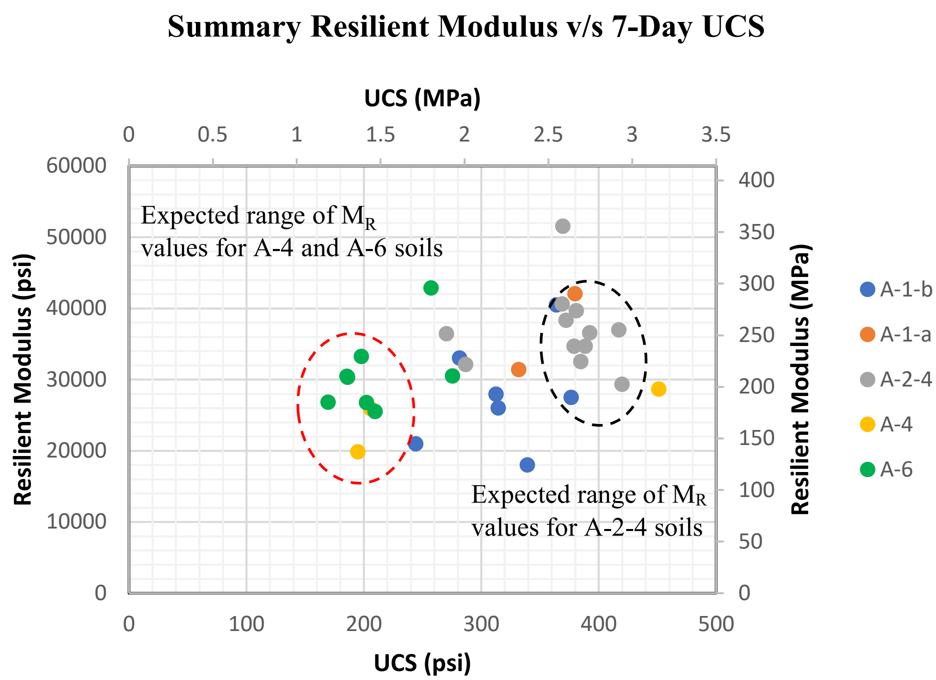


Figure 5.3 Resilient Modulus versus 7-Days cured UCS results with soil type

Summary Resilient Modulus v/s 28-Day UCS

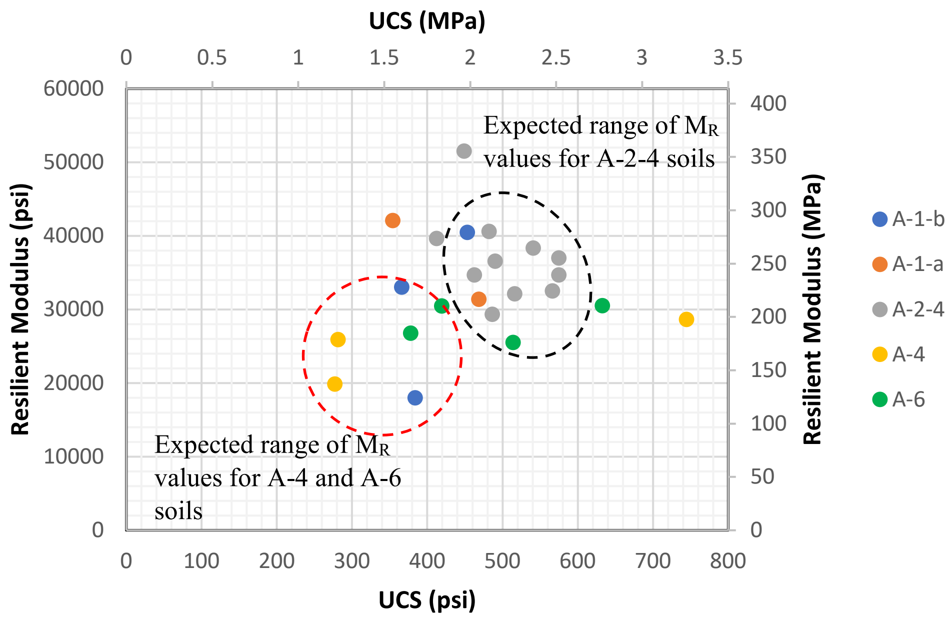


Figure 5.4 Resilient Modulus versus 28-Days cured UCS results with soil type

From figures 5.3 and 5.4 it can be observed that the expected range of resilient modulus values for cement-treated A-2-4, A-4 and A-6 soils can be estimated from the 7-Day or 28-Day cured UCS values with a fair degree of confidence. The majority of resilient modulus values fall in the range of 30,000 to 40,000 psi (210 to 275 MPa) for cement-treated A-2-4 soils. Most of the resilient modulus values for cement-treated A-4 and A-6 soils (fine-grained/clayey soils) fall in the range of 20,000 to 35,000 psi (135 to 240 MPa). The resilient modulus values of A-1 soils exhibit a large degree of scatter. The reason may be the non-uniform properties of the soils at US 31, i.e. different Atterberg limits, OMC and MDD; see Table 3.1. This calls for including all soil properties, in addition to OMC and MDD, to improve estimates of resilient modulus values.

A statistical analysis was conducted to build a correlation model for the dataset. A multi-variate linear regression was performed that included the following parameters: Resilient Modulus, UCS (7 days and 28 days cured), percentage of fines, plasticity index, optimum moisture content (OMC) and maximum dry density (MDD). The values of the resilient modulus and UCS were normalized for the analysis. The normalization utilized was:

$$Normalized\ M_R = \frac{M_R - \min(M_R)}{\max(M_R) - \min(M_R)}\ ;\ Normalized\ UCS = \frac{UCS - \min(UCS)}{\max(UCS) - \min(UCS)}$$

Where,

Min M_R, Max M_R : minimum and maximum resilient modulus values across all sites respectively

Min UCS, Max UCS: minimum and maximum UCS values across all sites respectively

The generalized model utilized for the analysis was:

$$Normalized\ M_R = X_1 * (\%\ of\ fines) + X_2 * (PI) + X_3 * (OMC) + X_4 * (MDD) + X_5 * (Normalized\ UCS)$$

Where,

$X_1 - X_5$: Coefficients (estimated from the linear regression analysis)

PI: Plasticity Index (%)

OMC: Optimal Moisture Content (%)

MDD: Maximum dry density (g/cc)

The coefficients X_1-X_5 for the 28 days cured UCS values are presented in Table 5.1:

Table 5.1 Linear regression analysis results for correlation between resilient modulus and 28 days cured UCS including all five parameters.

Parameter	Coefficients	Estimate	Std. Error	t-value	p-value
% of fines	X_1	-0.00236	0.003849	-0.612	0.54774
PI	X_2	0.038135	0.020857	1.828	0.08323
OMC	X_3	-0.0756	0.037209	-2.032	0.0564
MDD	X_4	0.632981	0.219603	2.882	0.00954
28-Day Normalized UCS	X_5	-0.44307	0.323901	-1.368	0.1873

The p-value represents the significance of the variable with respect to the regression analysis. If the p-value is less than a certain significance level, then the parameter has a statistically significant relationship with the response variable (in our case the resilient modulus. The results in Table 5.1 show that the p-value of the percentage of fines is the highest, meaning it is the least statistically significant parameter in the model. Because of that, a new trial was attempted without the percentage of fines. The new model used for analysis is:

$$\boldsymbol{Normalized\ M_R} = \boldsymbol{X_1} * (\boldsymbol{PI}) + \boldsymbol{X_2} * (\boldsymbol{OMC}) + \boldsymbol{X_3} * (\boldsymbol{MDD}) + \boldsymbol{X_4} * (\boldsymbol{Normalized\ UCS})$$

The results of the model, using the 28-days cured UCS values, are presented in Table 5.2. The table shows that the MDD and OMC parameters are the most statistically significant (lowest p – values).

Table 5.2 Linear regression analysis results for correlation between resilient modulus and 28 days cured UCS.

Parameter	Coefficients	Estimate	Std. Error	t-value	p-value
PI	X_1	0.03159	0.01763	1.792	0.08824
OMC	X_2	-0.0867	0.03198	-2.711	0.01345
MDD	X_3	0.69546	0.19137	3.634	0.00165
28-Day Normalized UCS	X_4	-0.48531	0.31148	-1.558	0.1349

The predicted resilient modulus values, using the regression analysis with the values in Table 5.2, are then compared with the measured resilient modulus values, to verify the accuracy of the model. Figure 5.5 plots the predicted and the measured resilient modulus values for the all the soils tested. The model does a fairly good job of predicting the resilient modulus with a multi-variate $R^2 = 0.86$.

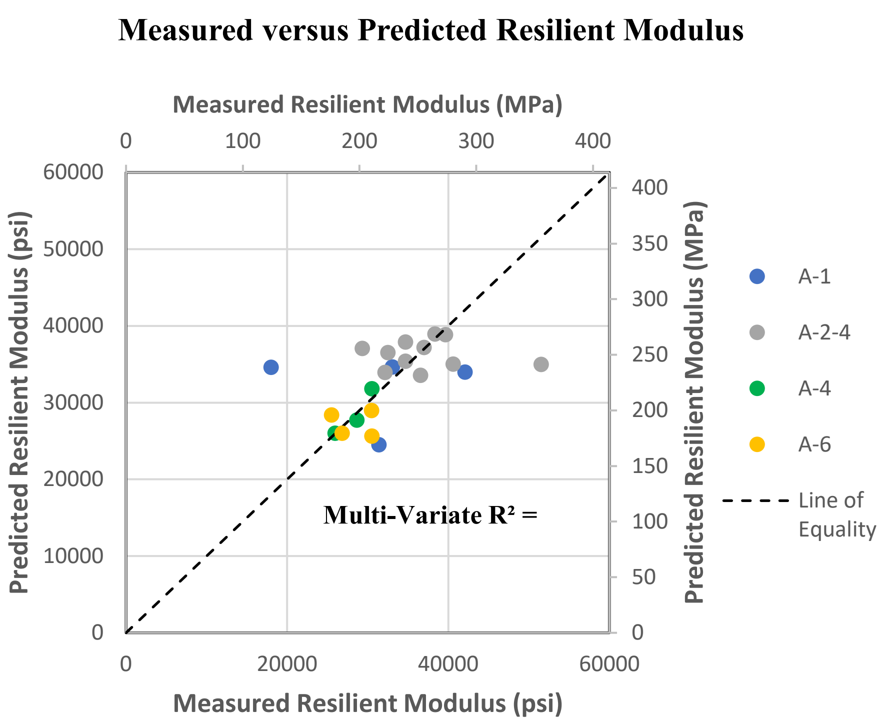


Figure 5.5 Measured versus predicted resilient modulus from 28-days cured UCS

Table 5.3 presents the results of the statistical analysis following the same process discussed, but for the 7-days cured UCS values. The table shows that the PI and OMC are the most statistically significant parameters (lowest p – values) for the model.

Table 5.3 Linear regression analysis results for correlation between resilient modulus and 7- days cured UCS.

Parameter	Coefficients	Estimate	Std. Error	t-value	p-value
PI	X_1	-0.03987	0.01305	-3.056	0.00489
OMC	X_2	0.06429	0.02967	2.167	0.0389
MDD	X_3	0.05832	0.10203	0.572	0.57215
7-Day Normalized UCS	X_4	0.12174	0.23005	0.529	0.60083

Similar to what was done with the 28 days cured UCS values in Figure 5.5, Figure 5.6 plots the predicted resilient modulus using the 7-days cured UCS and provides a comparison with the measured resilient modulus. The model for the 7-days does perform reasonably well, with a multi-variate $R^2 = 0.91$.

It should be noted that although these simple linear regression models do a reasonable job relating stiffness with strength, the dataset used, albeit of high quality, is limited. Thus, the applicability of the model should be limited to the range of soils used in the study. The accuracy of the model should be tested with a large number of cases taken from different sites.

Measured versus Predicted Resilient Modulus

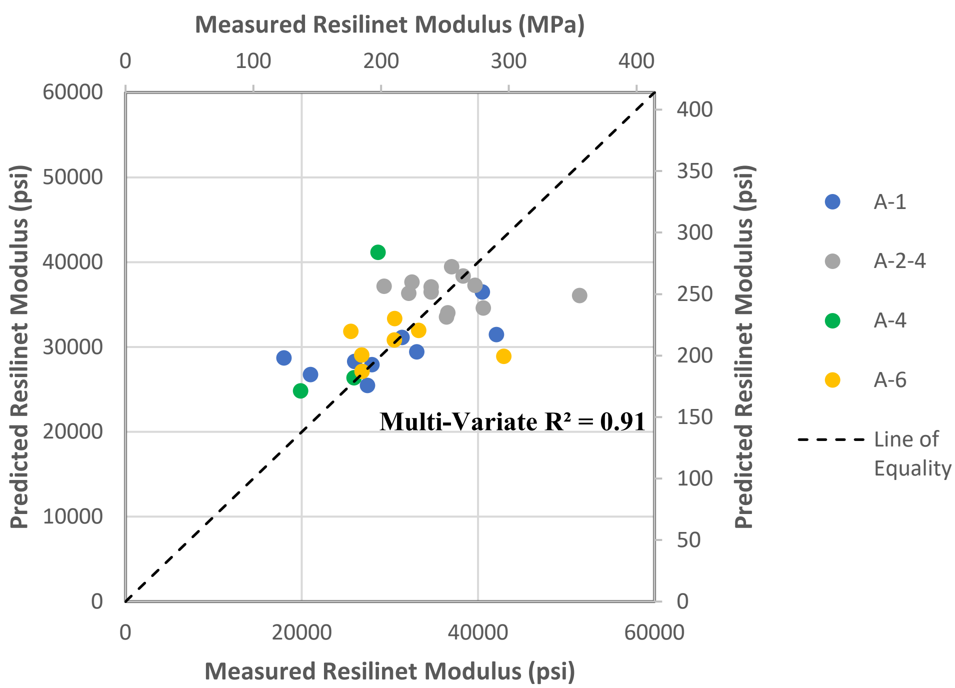


Figure 5.5 Measured versus predicted resilient modulus from 7-days cured UCS

6. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

6.1. Summary

The study presents data from 3 different sites in Indiana, identified with the help of INDOT, for sample collection and laboratory testing of subgrade soils. The sites selected, namely US 31, SR 37 and I-65 were all projects involving stabilization of subgrade soils with cement. Soil characterization tests indicated that the soils collected from site US 31 were primarily A-1 (SM) soils, those collected from site SR 37 were A-2-4 (SC) soils and the soils collected from the I-65 site were A-6 (CL+CM) soils and A-4 (CL) soils. The Atterberg limits and the compaction tests indicated that the soils found in the US 31 and I-65 sites were highly variable in terms of Plasticity Index, Optimum Moisture Content (OMC) and Maximum Dry Density (MDD), across the 11 locations where the samples were collected. The soils from site SR 37 were uniform across the 11 locations.

Resilient modulus tests were performed on untreated and cement-treated samples for all locations in all the three sites. The samples from site US 31 were treated with 4 % cement by weight and the samples from sites SR 37 and I-65 with 5 % cement by weight. All samples were prepared at OMC and MDD and cured for 28 days prior to testing. The resilient modulus values for cement treated samples was found to be more sensitive to the deviatoric stress and confining stress compared to untreated samples across all three sites.

Unconfined compressive strength testing was also performed on the cement treated samples. Similar to what was done for the resilient modulus, the samples were prepared at OMC and MDD and cured for 7 days prior to testing. The sample preparation and curing process was kept identical to that of the resilient modulus tests to ensure compatibility of results. The UCS results ranged from 170 psi to 450 psi (1.2 MPa to 3.1 MPa) for all the soils studied in this project. The considerable range in the UCS test results is attributed to soil variability and different soil types across the sites. Additional tests were also performed on the 28 day cured samples after the resilient modulus test was completed. The UCS values of the28-days cured samples was found to be 1.2 to 1.5 times the 7-day cured UCS values. The average UCS values for the 7- and 28-days cured specimens were used for the correlations.

6.2. Conclusions

The major conclusion of the study is that there is no direct statistically significant correlation between the resilient modulus and UCS parameters. Such correlation has not been found in the technical literature, nor from the tests performed in this study. However, it seems that the resilient modulus falls within a certain range of values depending on the soil type. The majority of the resilient modulus of cement-treated A-2-4 soils investigated in this study ranged from 30,000 to 40,000 psi (210 to 275 MPa). The majority of the resilient modulus values for cement-treated A-4 and A-6 soils fell in the range of 20,000 to 35,000 psi (135 to 240 MPa). These range of values can prove useful to get a sense of expected stiffness of cement stabilized subgrades for typical Indiana soils. A linear regression analysis involving the soil properties (plasticity index, OMC and MDD) along with resilient modulus and UCS results was also performed, to establish a simple model for predicting the resilient modulus values for the soils investigated. The linear regression models perform at R^2 values of 0.85 and 0.91 using 28-days cured and 7-days cured UCS data, respectively. The drawback of these models is that they are derived from and tested on limited high-quality laboratory data. Thus, the applicability of the model is limited to the range of soils used in the study.

6.3. Recommendations

The laboratory tests and analyses performed in this study, as well as those found in the literature, indicate limited potential for accurate correlations between resilient modulus and unconfined compressive strength for treated subgrade soils. One possible explanation for this is that the current resilient modulus testing sequence leads to initial overconsolidation of the sample (as it goes from high confining to low confining pressure). Other possible explanation is that, because of the disparity of the tests, i.e. UCS tests strength while the resilient modulus tests stiffness, such correlations do not exist. However, given the complexity of the resilient modulus test and that it is a test widely used and its results employed for pavement design, further investigation on the test seems warranted. Future work could focus on a more in-depth study of the resilient modulus testing procedure and exploring a possible modification of the test sequence to see the effects on correlations, both with UCS and with FWD tests. Future testing could also be performed to find stiffness to stiffness correlations in terms seismic modulus or small-strain modulus derived from shear wave velocity as an alternative approach for estimating resilient modulus of treated subgrade soils.

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