Resilient moduli characterization of cement-treated silt

Prince Kumar[1], *Anand J.* Puppala[1#], *Surya Sarat Chandra* Congress[2], and *Jeb S.* Tingle[3]

[1]*Zachry Department of Civil and Environmental Engineering, Texas A&M University, College Station, Texas, U.S.A. 77843*
[2]*Department of Civil and Environmental Engineering, Michigan State University, East Lansing, Michigan, U.S.A. 48824*
[3]*U.S. Army Engineer Research and Development Center, Vicksburg, Mississippi, U.S.A. 39180*
[#]*Corresponding author: anandp@tamu.edu*

ABSTRACT

The performance of a flexible pavement depends on the resilient modulus (M_R) of subgrade soil. Thus, M_R is a key design parameter for mechanistic-empirical pavement design of flexible pavements. Generally, the resilient modulus is determined by conducting repeated load triaxial (RLT) tests in the laboratory and has been used to characterize the subgrade soil behavior under repeated traffic loading conditions. The use of cement to stabilize natural subgrade soils is widely accepted by transportation agencies. Several research studies were conducted on the resilient behavior of cement-treated soils. However, limited research studies have been conducted on the resilient behavior of cement-treated silty soil. Therefore, the current research study assessed the resilient moduli properties of cement-treated silt. Cement-stabilized soil specimens were statically compacted and cured in a humid room for a stipulated curing period before conducting RLT tests. RLT tests were conducted on cement-treated specimens at different cement dosages and curing periods to study the effect of the cement dosage and curing time on the resilient modulus. Test results indicated that a significant improvement in performance was observed after cement treatment. The untreated soil specimens exhibited stress-softening behavior with an increase in deviator stress, whereas the cement-treated specimens exhibited stress-hardening behavior. The resilient modulus was increased with an increase in cement dosage. Regression analyses were conducted on RLT test results using three-parameter universal model and model parameters were determined. It was observed that the three-parameter universal model exhibited an excellent fit with experimental data.

Keywords: resilient modulus; silt soil; cement stabilization; resilient strain; permanent strain.

1. Introduction

Generally, natural silty soils do not have enough strength and stiffness to support the pavement structure and traffic loads. Therefore, silt cannot be used directly as a subgrade for pavement and needs treatment to enhance engineering properties. Chemical treatment is an effective method for improving the engineering properties of soils. Several traditional chemical stabilizers such as cement, lime, and fly ash are most widely used in practice to improve the strength and stiffness of soils (Little 1995; Little et al. 2000; Little and Nair 2009; Puppala 2016; 2021).

Cement stabilization is found to be effective in stabilizing different soils such as gravels, sands, silts, and clays (Little et al. 2000; Petry and Little 2002). When water is mixed with the mixture of soil and cement, the following processes occur: cation exchange, flocculation and agglomeration, cementitious hydration, and pozzolanic reaction (Prusinski and Bhattacharja 1999; Little et al. 2000; Firoozi et al. 2017; Puppala 2016). The Portland cement is comprised of calcium-silicates and calcium-aluminates that hydrate after adding water and form cementing compounds of calcium-silicate-hydrate (C-S-H) and calcium-aluminate-hydrate (C-A-H) (Prusinski and Bhattacharja 1999; Firoozi et al. 2017). The C-S-H and C-A-H cementitious compounds bind soil particles and improve the engineering properties of soil after cement stabilization.

In past research studies, researchers studied the use of cement to stabilize silt (Ali and Youssef 1983; Jauberthie et al. 2010; Pu et al. 2020;). An improvement in unconfined compressive strength (UCS) was observed after cement treatment and strength was increased with an increase in dosage at all curing periods.

The resilient modulus is defined as the ratio of cyclic axial stress to resilient axial strain (Seed et al. 1962). The resilient modulus is a key design parameter for the structural design of flexible pavement systems and it has been used to characterize pavement geomaterials (AASHTO 2004; Puppala 2008; Papagiannakis and Masad 2008). Generally, the repeated load triaxial test is used and recommended by Mechanistic-Empirical Pavement Design Guide (M-EPDG) (Lekarp, Isacsson, and Dawson 2000; Puppala 2008; Ng and Zhou 2014; Han and Vanapalli 2016; AASHTO T 307-99 2017). The RLT test is conducted at different deviator stresses and confining pressures to consider different traffic loads. The AASHTO T 307-99 standard was developed for measuring the resilient modulus of unbound materials, however, several researchers used this standard for measuring the resilient modulus of chemically treated soils (e.g. Puppala, Mohammad, and Allen 1996; Mohammad et al. 1999; Puppala, Ramakrishna, and Hoyos 2003; Solanki, Zaman, and Dean 2010; Pinilla et al. 2011; Puppala, Hoyos, and Potturi 2011; Ardah, Chen, and Abu-Farsakh 2017; Patel et al. 2019; Festugato, Venson, and Consoli 2021; Hu and Solanki 2021; Luo et al. 2021; Jose, Krishnan, and Robinson 2022; Kumar et al. 2022; Yaowarat et al. 2022).

The resilient modulus of unbound materials is affected by several factors including soil type, stress levels, dry density, and moisture content (Seed, Chan, and Lee 1962; Drumm et al. 1997; Lekarp, Isacsson, and Dawson 2000; Puppala 2008; Banerjee et al. 2019; 2020; Kumar et al. 2023). The resilient modulus of chemically stabilized soils depends on all aforementioned factors and also depends on stabilizer type, stabilizer dosage, curing conditions, and curing time (Puppala, Ramakrishna, and Hoyos 2003; Solanki, Zaman, and Dean 2010; Abu-Farsakh, Dhakal, and Chen 2015; Bhuvaneshwari, Robinson, and Gandhi 2019; Kumar et al. 2022).

Researchers developed several characterization models to characterize the resilient modulus of unbound materials (Uzan 1985; Witczak and Uzan 1988; Pezo 1993; Mohammad et al. 1999; Witczak 2003; Ooi, Archilla, and Sandefur 2004; Puppala 2008). The MEPDG recommends a three-parameter universal model that accounts for bulk stress and octahedral shear stresses for characterizing resilient moduli behavior of soils (Witczak 2003; AASHTO 2004). This model was originally developed for characterizing unbound materials, however, several research studies considered this model for characterizing stabilized soils (e.g. Mohammad et al. 1999; Solanki, Zaman, and Dean 2010; Abu-Farsakh, Dhakal, and Chen 2015; Bhuvaneshwari, Robinson, and Gandhi 2019; Patel et al. 2019; Chakraborty, Puppala, and Biswas 2021; Jose, Krishnan, and Robinson 2022; Kumar et al. 2022).

Limited research studies have been conducted on understanding the resilient moduli behavior of cement-treated silty soil using the RLT testing. Therefore, the present study planned a detailed experimental study to understand the resilient behavior of cement-treated silt. The RLT tests were conducted on both untreated and cement-treated silt at three different cement dosages to understand the effect of cement dosages on resilient modulus. Also, resilient moduli were measured after three curing periods to understand the impact of the curing period. Resilient modulus test results were analyzed using the three-parameter universal model.

2. Materials and test program

2.1. Materials

Natural soil was considered in the present study, and it was collected from Mississippi, USA. For basic soil characterization, tests such as sieve analysis, hydrometer analysis, plastic limit, liquid limit, and specific gravity were conducted as per ASTM standards (ASTM 2019). The particle size distribution curve is shown in Fig. 1 and physical properties are presented in Table 1. The soil was classified as low plasticity silt (ML) as per the Unified Soil Classification System (USCS). Modified Proctor compaction tests were conducted on both untreated and cement-treated soil mixtures, and the maximum dry unit weight (MDUW) and optimum moisture content (OMC) were determined. This research study used cement type I for treatment.

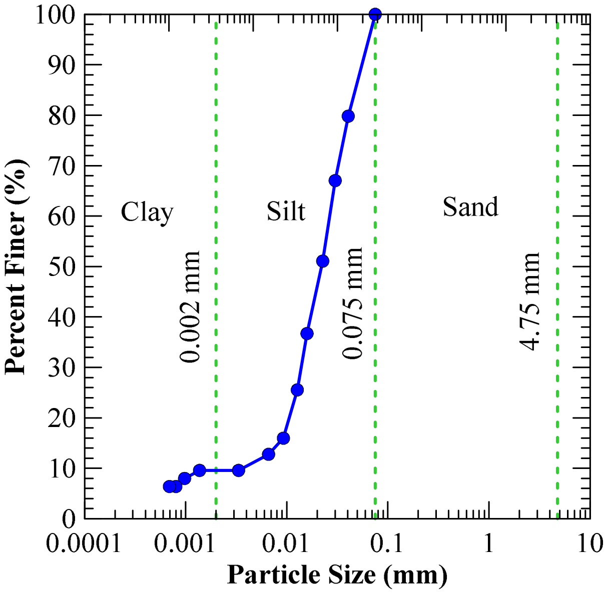


Figure 1. Grain size distribution of soil used in this study.

Table 1. Properties of soil used in this study

Parameters	Soil
Sand (%)	0.0
Silt (%)	90.4
Clay (%)	9.6
USCS classification	ML
Specific gravity, Gs	2.72
Maximum dry unit weight (MDUW) kN/m^3	17.5
Optimum moisture content (OMC) (%)	14.8

2.2. Specimen preparation

Soil specimens were prepared as per the U.S. Department of Defence protocol and AASHTO T307 standard (AASHTO T 307-99 2017; UFC 3-250-11 2004; 2020). Initial estimated cement content was selected as 9% of the dry weight of soil as per UFC 3-250-11 (2004; 2020) for ML soil and cement contents 2% above and below were also considered. Therefore, cement dosages of 7%, 9%, and 11% were used for preparing cement-treated specimens. The predetermined amount of cement was homogeneously mixed with dry soil until a uniform color was obtained and then water was added to the mixture. The mixtures were then statically compacted into a cylindrical mold having a height of 142 mm and a diameter of 71 mm at respective optimum moisture contents and maximum dry unit weights. All specimens were compacted within half an hour after mixing soil and cement to prevent the initial set of soil mixtures. All cement-treated soil specimens were prepared at the dry unit weight of 17.3 kN/m^3 and moisture content of 14.2% obtained from the modified Proctor compaction test. The same values of MDUW and OMC were considered for all three cement dosages to make the same initial strength at all dosages. These specimens were cured in a moist room for 7, 14, and 28 days.

2.3. Resilient modulus test methodology

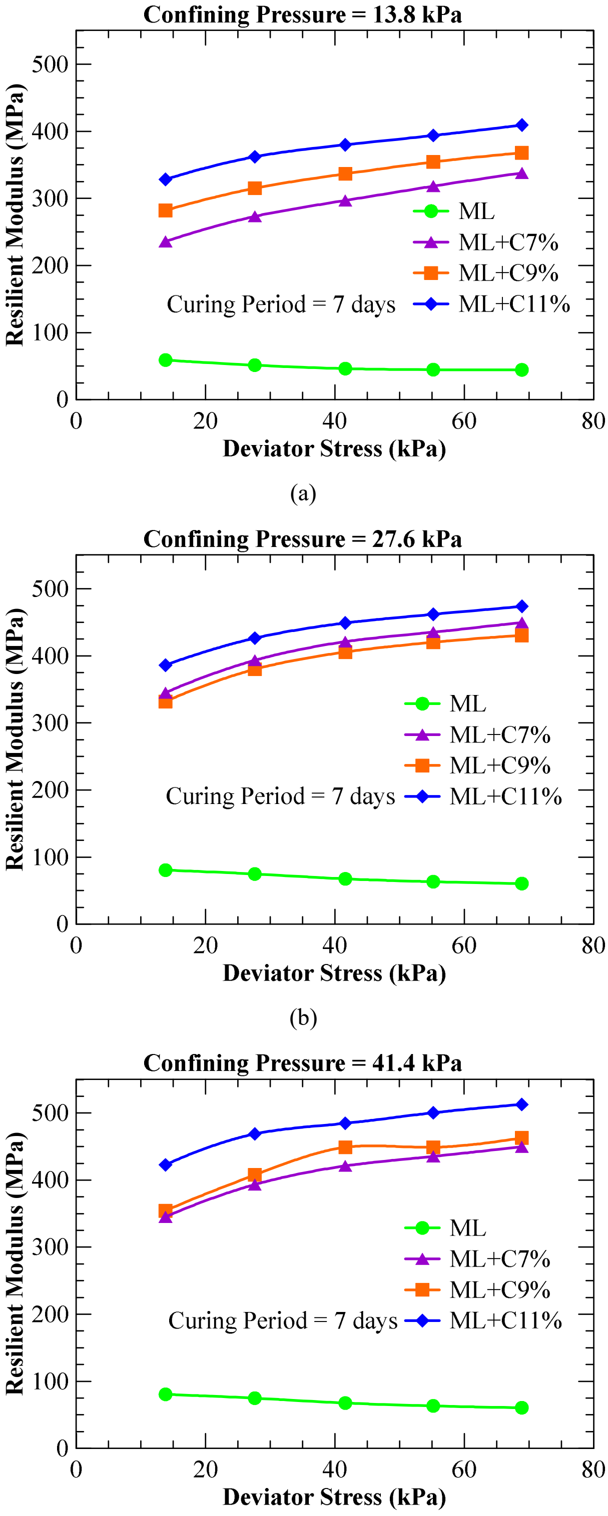
The repeated load triaxial test was conducted as per the AASHTO T307 standard method (AASHTO T 307-99 2017). The RLT test equipment is designed to simulate different traffic loadings on in-situ subgrade soil by applying cyclic loading on the specimens and the load was applied as a haversine-shaped cyclic load. The cyclic load was applied for 0.1 seconds, followed by a 0.9-second relaxation period. The RLT test determines resilient modulus at three confining pressures (41.4 kPa, 27.6 kPa, and 13.8 kPa) and five deviatoric stresses (13.8 kPa, 27.6 kPa, 41.4 kPa, 55.2 kPa, and 68.9 kPa). The load response was measured using a submersible load cell, and axial deformations were recorded using two linear variable differential transducers (LVDT). In this study, specimens were preconditioned by applying 500 load cycles with cyclic stress of 24.8 kPa and confining pressure of 41.4 kPa. The preconditioning sequence was applied to reduce irregularities between the top platen and soil specimen. Moreover, it helped in eliminating the effects of the time interval between compaction and loading (AASHTO T 307-99 2017). After the completion of the preconditioning sequence, RLT tests were conducted using 15 loading sequences. Each loading sequence consists of 100 loading cycles and is conducted at different combinations of deviator and confining stresses. The final resilient modulus was calculated by averaging the last five cycles' resilient modulus.

Untreated soil specimens were prepared and tested immediately for resilient modulus measurements. Cement-treated soil specimens were prepared at three different dosages such as 7, 9, and 11%. In this study, three curing periods including 7, 14, and 28 days were considered to evaluate the effect of curing time. After the completion of the curing period, RLT tests were conducted on cement-treated specimens. To consider variability, triplicate specimens were prepared, and average results are presented in the results and discussion section.

3. Test results and discussion

3.1. Resilient modulus test results

Extensive repeated load triaxial tests were performed on untreated and cement-treated silt specimens. Resilient moduli of untreated soil and cement-treated soil specimens at different cement dosages, cured for 7 days are shown in Fig. 2. Results show that the stress conditions affect the resilient moduli behavior of both untreated and cement-treated silty soil. Untreated soil specimens showed a reduction in resilient modulus with an increase in deviator stress, which shows stress-softening behavior. Under stress-softening behavior, specimens tend to soften when subjected to higher axial loading. On the other hand, cement-treated soil specimens displayed an increase in resilient modulus with an increase in deviator stress, which indicates stress-hardening behavior. Under higher axial loading, specimens tend to get hardened which showed stress-hardening behavior. As expected, resilient moduli increased with an increase in confining pressure for both untreated and cement-treated silt. Cement stabilization improved the resilient modulus significantly after stabilization at all cement dosages; and the increment percentages varied from 299% to 661%, 340% to 729%, and 374% to 780% for 7%, 9%, and 11% cement dosages, respectively. Similar to 7 days curing period, a great increase in resilient modulus was observed after cement stabilization at other curing periods.



(a)

(b)

(c)

Figure 2. Variation of resilient modulus with deviator stress at confining pressures (a) 13.8 kPa, (b) 27.6 kPa, and (c) 41.4 kPa.

3.2. Effect of cement dosage on resilient modulus

The resilient modulus is determined at 15 loading sequences for both untreated and treated specimens, and all 15 resilient modulus values were not used in this comparison study. For comparison, only one resilient modulus value i.e., design value was considered for each case. Several past studies recommended determining design resilient modulus value for flexible pavement at deviatoric stress of 41.4 kPa and confining pressure of 13.8 kPa (Jones and Witczak 1977; Solanki, Zaman, and Dean 2010). Therefore, the resilient modulus values corresponding to deviatoric stress of 41.4 kPa and confining pressure of 13.8 kPa were considered in this section and the following sections. Variation of resilient modulus with cement dosage is shown in Fig. 3. The resilient modulus of cement-stabilized soil cured for 7 days was only shown in Fig. 3. Results showed that the resilient modulus increased non-linearly with an increase in cement dosage. The rate of increase was reduced with an increase in cement dosage. This increment in resilient modulus with an increase in cement dosage was provided due to the increased formation of cementitious products.

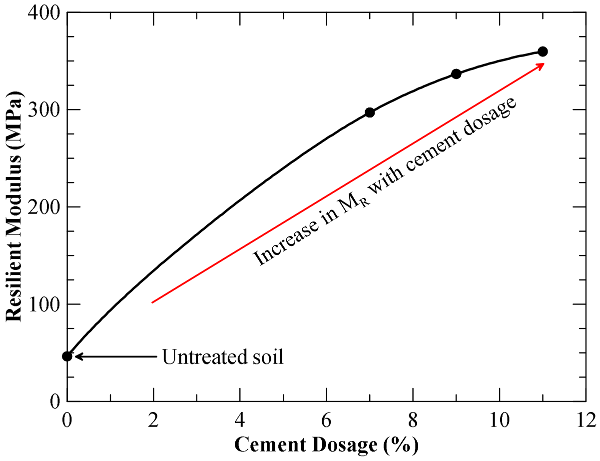


Figure 3. Variation of resilient modulus with cement dosage.

3.3. Effect of water-cement ratio on resilient modulus

Similar to the previous section, the resilient modulus values corresponding to deviatoric stress of 41.4 kPa and confining pressure of 13.8 kPa were considered for this analysis. Fig. 4 shows the variation of resilient modulus with water cement ratio for cement-treated silt cured for 7 days. Results showed that resilient modulus reduced with an increase in water-cement ratio and varied linearly. An increase in the water-cement ratio means a reduction in cement dosage. Therefore, this reduction in resilient modulus was due to the reduction in cement dosage.

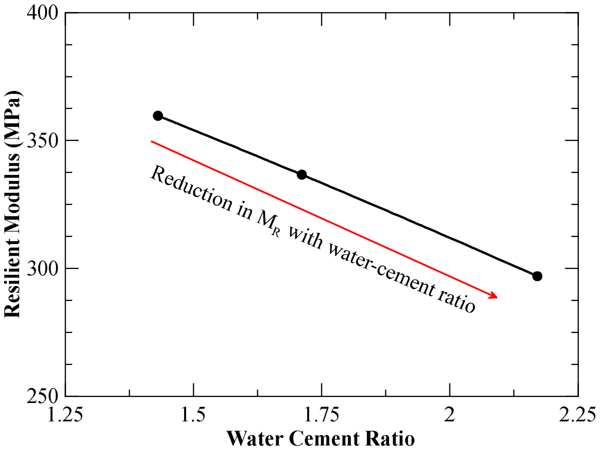


Figure 4. Variation of resilient modulus with water cement ratio.

3.4. Effect of curing time on resilient modulus

The resilient modulus values corresponding to deviatoric stress of 41.4 kPa and confining pressure of 13.8 kPa were considered for this comparison. Fig. 5 shows the variation of resilient modulus with the curing period at all cement dosages. Results showed a slight reduction in resilient modulus with an increase in the curing period at all cement dosages. The reason for this observation might be due to the development of micro-cracks on specimen surfaces during the curing period. The difference between resilient modulus at different curing periods for all cement dosages is not significant, and considering the standard deviations, the difference can be considered negligible for practical purposes.

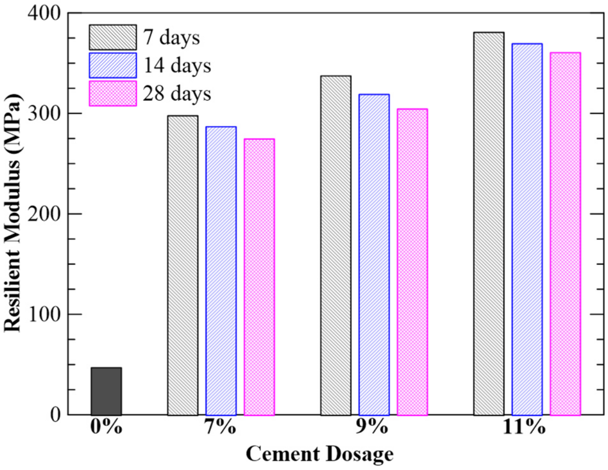


Figure 5. Resilient modulus at different curing periods.

3.5. Resilient strain

Resilient strains were determined using the axial deformation readings for all loading cycles for both untreated and cement-treated soil. For all 15 loading sequences, the final resilient strain was calculated by averaging the last five cycles' resilient strains. Variation of resilient strain with cyclic deviator stress at different confining pressures for both untreated and cement-treated soil is shown in Fig. 6. For comparison purposes, resilient strains of the 7% cement dosage-stabilized specimen are shown in the below figure and compared with untreated soil. Resilient strains were determined at other cement dosages also and similar results were observed. With an increase in deviator stress, the resilient strain increased at all confining pressures. A significant reduction in the resilient strain was observed after cement stabilization, hence, the resilient modulus increased after cement stabilization. Results showed that the resilient strain reduced with an increase in confining pressure.

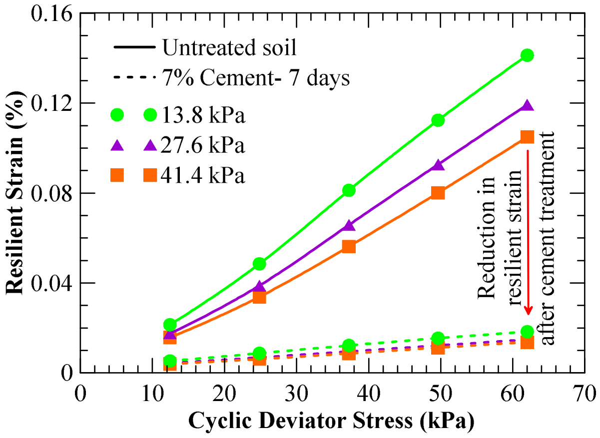


Figure 6. Variation of resilient strain with cyclic deviator stress.

4. Modeling of resilient modulus test results

The mathematical equation of the three-parameter universal model is provided in Eq. (1).

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

Where,
M_R = resilient modulus
k_1, k_2, and k_3 = model constants
θ = bulk stress
τ_{oct} = octahedral shear stress
For triaxial condition, $\sigma_2 = \sigma_3$ and $\sigma_1 - \sigma_3 = \sigma_d$, therefore the octahedral shear stress is:

$$\tau_{oct} = \frac{\sqrt{2}}{3}\sigma_d \quad (2)$$

To conduct regression analysis on resilient modulus test results, Eq. (1) was transformed to logarithmic form and expressed as follows:

$$\log\left(\frac{M_R}{P_a}\right) = log k_5 + k_6 \times log\left(\frac{\theta}{P_a}\right) + k_7 \times log\left[\left(\frac{\tau_{oct}}{P_a}\right) + 1\right] \quad (3)$$

Multiple-linear regression analyses were conducted on resilient modulus test results of both untreated and cement-treated silty soil, and the model constants are presented in Table 2. Regression analysis results showed that the coefficient of determination (R^2) for the three-parameter universal model varied from 0.93 to 0.98, which indicates an excellent fit.

The model constant k_1, which is an indicator of M_R magnitudes, increased after cement stabilization at all cement dosages and curing periods. This increase was observed due to the development of cementitious compounds after treatment. Cement dosages increased the value of the parameter at all curing periods. Results showed a slight decrease in the model constant k_1 with an increase in the curing period at all cement dosages.

The model parameter k_2, which illustrates the stiffening of the soil with an increase in bulk stress, was less than 1, which indicates that the effect of bulk stress decreased with an increase in the resilient modulus. Model constant k_2 decreased after cement stabilization at all cement dosage and curing periods except for 7% cement dosage. A reduction in the model parameter was observed with an increase in cement dosage at all curing periods. With an increase in the curing period, the model constant k_2 value remained almost the same for all cement dosages except 9% dosage.

It was observed that the model parameter k_3 was negative for untreated soil and it was positive for all cement-treated soil specimens. After cement stabilization, the value of the model constant increased. No definite pattern was observed for the model parameter with an increase in cement dosage and curing time.

Table 2. Three-parameter model constants for control and treated soil

Specimen Group	Cement Dosage	Curing Period (days)	k_1	k_2	k_3	R^2
ML	0	0	829.8	0.4667	-2.4725	0.95
ML+C7%	7%	7	3147.4	0.4846	0.1762	0.98
		14	2987.5	0.4825	0.2565	0.97
		28	2901.2	0.4905	0.2279	0.95
ML+C9%	9%	7	3318.9	0.3424	0.4055	0.94
		14	3300.1	0.3807	0.2370	0.93
		28	3304.0	0.4524	0.0254	0.97
ML+C11%	11%	7	3913.8	0.3367	0.1456	0.97
		14	3838.3	0.3485	0.1059	0.98
		28	3688.7	0.3327	0.1844	0.97

A comparison between measured resilient modulus values and predicted resilient modulus values obtained from the three-parameter universal model is shown in Fig. 7. Line of equality was also drawn to see the scattering of resilient modulus data. Fig. 7 shows that the three-parameter universal model reasonably predicts the resilient modulus values for both untreated and cement-treated silt.

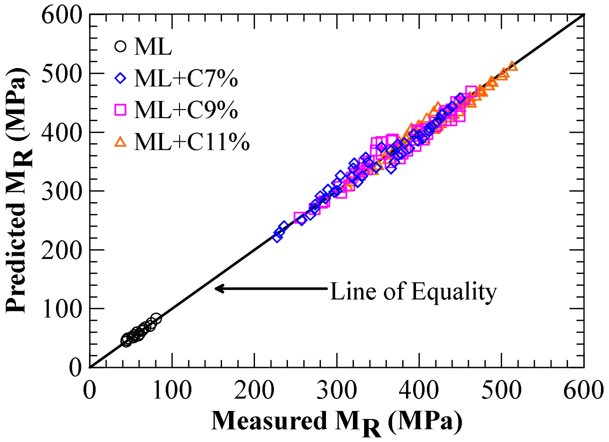


Figure 7. Measured M_R versus predicted M_R using the three-parameter universal model for untreated and cement-treated soil.

Regression analyses showed that the three-parameter universal model provided an excellent fit for both untreated and cement-treated silt. Hence, the three-parameter universal model is recommended for silty soil considered in the present research study.

5. Summary and Conclusions

The objective of this research study was to understand the resilient moduli response of cement-treated silt under repeated loading. Extensive repeated load triaxial tests were conducted on both untreated and cement-stabilized silt soil specimens. This study considered three cement dosages and three curing periods to study the effect of dosages and curing time on the resilient modulus of cement-treated silt. Three-parameter universal model was used to characterize the resilient modulus and model constants were determined using regression analysis. Based on the above results, the following conclusions were drawn:

1. The untreated silt showed a decrease in resilient modulus with an increase in deviator stress, which showed stress-softening behavior. On the other hand, cement-treated silt specimens showed stress-hardening behavior. Cement treatment increased the resilient modulus of silt which shows an improvement in the resilient property after cement treatment. As expected, resilient modulus increased with an increase in confining pressure.
2. An increase in resilient modulus was observed with an increase in cement dosage. This shows that an increase in cement dosage increased the formation of cementitious products, which increased the resilient modulus of the soil. The rate of increase of resilient modulus reduced with an increase in cement dosage.
3. The resilient strain reduced significantly after cement treatment, therefore, the resilient modulus increased after cement treatment. The resilient strain increased with an increase in deviator stress and reduced with an increase in confining pressure. Moreover, the rate of increase of resilient strain with deviator stress reduced after cement treatment.
4. Regression analysis results showed a higher coefficient of determination for the three-parameter universal model that provides an excellent fit for both untreated and cement-treated silt considered in the present research study. Therefore, it is recommended to use the three-parameter universal model for silt soil examined in the study.

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