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Impact of Curing Time and Curing Stress On the Mechanical Behavior of Cement-Improved and Cement-Fiber-Improved Soft Soil

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IMPACT OF CURING TIME AND CURING STRESS ON THE MECHANICAL BEHAVIOR OF CEMENT-IMPROVED AND CEMENT-FIBER-IMPROVED SOFT SOIL

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ABSTRACT

In order to improve the engineering properties of soft soils, materials, such as cement and fiber, can be introduced to the soil mass. A series of consolidation tests and unconfined compression tests were conducted with special attention being paid to the effects of curing time and vertical curing stress. It is shown that the introduction of cement into soft soils results in decreased compressibility and increased unconfined compressive strength when compared to unimproved soils. Also, the unconfined compressive strength of the cement-soil mixture increases with curing time and with vertical confining stress. The existence of fiber in the cement-soil mixture can significantly improve its ductility in the post-peak strength zone without significantly changing the unconfined compressive strength. When compared to the mixture without curing stress, the elastic moduli of the mixtures were increased by as much as 100% to 1000% when the mixture was cured under vertical confining stress. Strength gain with curing time is modeled by using data from 6 individual studies that provide 23 sets of data. Data was divided into low plasticity clays and high plasticity clays and fitted with logarithmic, power, and linear functions to form a general unconfined compressive strength prediction equation.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

Introduction and Background

Cement soil mixing is an effective ground improvement technique. In order to improve the engineering properties of soft soils, materials, such as cement and fiber, can be introduced to the soil mass. The introduction of cement to soils can effectively increase their shear strength, but at the same time the mixture becomes brittle. To increase the ductility of the mixture, especially after peak strength is reached, fiber can be added to the mixture. Compared to unimproved soils, cement-soil mixtures have lower permeability and compressibility, as well as higher compressive strength (Yang 1997).

Nomenclature for the mixture of cement and native soil are not consistent and has different names for different mixing procedures. For example, Bergado et al. (1999) used “deep mixing method” (DMM) and Dailer and Yang (2005) used CDSM, “Cement Deep Soil Mixing”. Although it seems the name for this technology has “deep”, the inclusion of “deep” could be misleading, especially when only a shallow zone in the field is treated. Therefore, CSM is used in this study and it stands for Cement Soil Mixture or Cement Soil Mixing.

CSM, a ground improvement method invented in 1970s by the Port and Harbor Research Institute of Japanese Ministry of Transportation, has been utilized in many applications throughout the world (Al-Tabbaa and Evans 1999; Maher et al. 2007; Lopez et al. 2009; Rollins et al. 2010). CSM was used to strengthen the embankment of San

Francisco's largest potable water reservoir (Barron et al. 2006), to stabilize the contaminated sediments in Newark Bay, NJ (Maher et al. 2007), and to reinforce a slope to maintain its integrity during seismic events (Dailer and Yang 2005; Yang 2010). Typical applications of CSM include liquefaction mitigation (Wooten and Foreman 2005), soil and foundation stabilization (Bhadriraju 2005), vibration reduction (Arulrajah et al. 2009), and excavation support walls (Rutherford et al. 2007). Recently, special structures, such as high-speed rail tracks and wind turbines, have employed the use of CSM to improve foundations (Woldringh and New 1999; Boehm 2010).

Current design criterion assumes shear strength parameters are obtainable through the measurement of unconfined compressive strength at 28-day curing time, without considering the effects of curing time and curing stress and the simplified design criterion does not reflect the field behavior of cement soil mixtures (Wooten and Foreman 2005; Terashi 2003). For example, during foundation stabilization, failure patterns may dictate the need for triaxial compression tests; during foundation unloading, axial extension triaxial tests may best model the application. When cement and/or fiber are used to strengthen soft soils, some considerations include the curing time or curing stress effect on UCS separately, curing time and curing stress effect on UCS together, changing of the strength or strain at failure by addition of fiber, and the post peak strength behavior of cement-soft soil mixture with included fiber.

To begin the process of fully understanding the mechanical behavior of a cement-soft soil mixture, a series of consolidation tests and unconfined compression tests were conducted with special attention being paid to the effects of curing time and vertical curing stress. Curing times of 7, 14, 28, 56, 90, 120, 182, and 433 days were used to analyze UCS increase due to curing time, while vertical confining pressures of 0, 50, 100, and 200 kPa were used to analyze strength increase due to confining stresses. Next, a model for strength prediction was constructed which may help during the design of CSM. If a better design method becomes available, it should greatly reduce the amount of QA/QC testing required for projects in which CSM is utilized.

CHAPTER 2

LITERATURE REVIEW

It is of importance to fully understand the mechanical behavior of CSM to meet different requirements in different applications. Although CSM has gained popularity in practice, current understanding of the mechanical behavior of cement-soil mixture is limited. The current criterion to evaluate the mechanical properties of cement-soil mixture mainly focuses on one parameter, unconfined compressive strength (UCS), without considering the effects of curing time and curing stress. Sometimes, the friction angle is considered when the Mohr-Coulomb failure criterion is used to design the cement-soil mixture structures. This oversimplified procedure critically needs improvement. Potential problems are associated to the current design criterion. For example, a designed load could be applied to cement-soil mixture at any time after the mixture is placed. Another important consideration is self-weight from the treated CSM mass, as this weight will be present from the time of installation. If loads are applied before 28-day, current design criterion could overestimate the strength of the mixture. For most of the situations, loads will be applied after 28-day strength is reached. Studying the effects of curing time and curing stress on UCS could lead to a more reasonable and economical mixture design.

Significant progress has been made in studying the behavior of cement-sandy soil mixtures (Zhu et al. 1995; Abdulla and Kiousis 1997a&b; Huang and Airey 1998;

Consoli et al. 2000&2007; Schnaid et al. 2001; Sharma and Fahey 2003a&b; Lorenzo and Bergado 2004) and fiber-reinforced cement-sandy soil mixtures (Maher and Ho 1993; Consoli et al. 1998). Current understanding of the mechanical properties of cement-soft soil mixtures is far behind the practice needs and only limited laboratory studies on the mechanical properties of cement-soft soil mixtures are available. The available work for fiber-reinforced cement-soft soil mixture is even scarcer.

Christensen (1969) found that treating soil with cement reduced the plasticity index while increasing the shrinkage limit, unconfined compressive strengths, triaxial compressive strength, and cation exchange capacity. Zhang and Tao (2008) concluded that the water to cement ratio used to improve soil influences UCS and durability. Also, UCS increased with increasing cement content and decreased with increasing water to cement ratio. Molding moisture and dry unit weight also were found to contribute to strength. From Arangol et al. (2001), correlations can be made from UCS to other strength parameters. In this particular study, the dynamic shear strength was taken as 130 percent times the static strength and the elastic modulus was taken as 300 times the unconfined compressive strength

While researching cemented-marine clays, Horpibulsuk (2001) and Horpibulsuk et al. (2004a&b, 2005) found that the compressibility during the post-yield state is governed mainly by the cement content, and the cohesion and the friction angle both tend to increase with cement content. While studying the effects of curing time on the behavior of cement treated marine clay, Xiao and Lee (2009) found that the UCS and isotropic compression strength increase significantly as the curing time increases. In long-term studies, such as in Terashi (2002), strength progression in UCS samples can occur for up to 5 years, with two to three times a strength increase expected ten to twenty years after installation. According to O'Rourke and McGinn (2004), data obtained from field samples may vary too much to assume strength gain with time. This was caused by difficulties surrounding obtaining uniform blends of concrete and clay.

While studying the behavior of cemented marine clay under monotonic and cyclic loading tests, Moses et al. (2003) and Moses and Rao (2009) found that stress-controlled tests are appropriate to evaluate the strength of cement-soft soil mixtures, because the mixture is brittle and failure often occurs at low strains. While studying the effects of curing stress on cemented-sands, Taher et al. (2011) concluded that curing stress increases the stiffness, peak strength, and moduli. Fatahi et al. (2012) has presented UCS results from samples subjected to surcharge applications of between 40 kPa and 120 kPa on kaolin. Specimens displayed higher strengths for higher surcharge applications. Although similar to this study, the range of curing stress covers a smaller stress range and no model for strength gain is discussed.

While the mechanical properties are improved during CSM, the mixture can also help the surrounding environment by chemically binding free liquids, reducing the permeability of waste, encapsulating waste particles, and fixing hazardous materials chemically, by reducing solubility and toxicity (Bone et al. 2005).

According to Lea (1956), the four major strength producing compounds of Type I Portland cement are tricalcium silicate, dicalcium silicate, tricalcium aluminate, and tetracalcium aluminoferrite. When the cement comes into contact with pore water, hydration occurs quickly. The major hydration products are hydrated calcium silicates, hydrated calcium aluminates and hydrated lime. Also, the hydration of this cement increases the pH because of the hydrated lime. This mixture can dissolve silica and alumina from clay minerals and the clay particle surfaces. The hydrous silica and alumina will then react with calcium ions to form secondary cementitious products which harden when cured. Also, deterioration, or loss of strength, can be caused by the leaching of calcium from the boundaries of the treated soil and may also be linear to the logarithm of time. Chew et al. (2004) indicated that behavior of cement-treated clay can be explained by the production of hydrated lime reactions which flocculates illite clay particles, the attack of the calcium ions on kaolinite rather than on illite, the surface deposition, and the cementitious products on clay clusters. While researching leaching from stabilized kaolin, John et al. (2011) found that aluminum and silicon components had minimal leachability, while calcium and sulphur components had higher leachability.

The availability of studies that model the behavior of cement-improved soils is limited. The modeling of experiments can be quite complex, as described the research by Chen and Lee (2012) where single- and multi-shaft deep mixing machines were modeled to investigate deep mixing techniques of remediation during centrifuge testing. Important scaling parameters for this study included modeled CSM column size, set times, and binder characteristics. Park and Kutter (2012) have also performed centrifuge testing for artificially cemented sensitive clay slopes to determine slip surfaces. Arroyo et al. (2012) presents research in which a bonded elasto-plastic model is formed and calibrated through analysis of idealized excavation and retaining wall problems.

CHAPTER 3

LABORATORY INVESTIGATION OF STRENGTH GAIN

3.1 METHODS

The soils used for this study include Kaolin clay from Active Minerals International in Aiken, SC and fine Nevada sand from Simplot Silica Products in Overton, NV. When Kaolin and fine Nevada sand are mixed at a 1:1 ratio, the mixture still behaves as a soft soil. Compared with pure Kaolin clay, the mixture has a high permeability, which can save tremendous time when triaxial tests or other boundary value problems are planned. This soil mixing technique may be used to study some boundary value problems in the near future, therefore the permeability of the mixture is a main concern and that is why 50/50 ratio of clay and sand was used to ensure an acceptable permeability. This permeability is also important during specimen saturation when triaxial tests are conducted. If the permeability is too low, it could take a couple of weeks just to saturate the specimen.

In order to study improved soil behavior, these soils were treated with Type I Portland cement, while some were treated with both Portland cement and NyconMM fiber from Nycon Corporation in Fairless Hills, PA. The material properties are shown in Table 3.1. According to Woodward (2005), the typical cement content of cement-soil mixture in practice is around 10% of dry soil weight. It is obvious that cement content has strong effects on the mechanical behavior of the mixture, and mixtures with different cement contents should be treated as different materials. Extreme situations are pure cement or pure soils. Also, if different cement-soil ratios were used, the test matrix would be much larger than what was used. To stay close to the engineering practice, only one, but typical cement content, was used for this work. In order to prepare the cement-soil mixture specimens, cement and deionized water were mixed into a slurry at a 1:1 ratio by weight. This slurry was then introduced to the soil mixture and thoroughly mixed for approximately ten minutes. For specimens that included fiber reinforcement, 0.3% of dry soil weight worth of fiber was added to the soil mixture at the same time as the cement slurry. The recipes for different soil mixtures are given in Table 3.2.

Table 3.1. Properties of Materials

Materials	Properties
Kaolin clay	LL = 75%, PL = 31%, G_s = 2.55, 80% of particles finer than 1.15 µm
Nevada sand	$\rho_{max.}$= 1753 kg/m^3, $\rho_{min.}$= 1378 kg/m^3, G_s = 2.69, D_{50} = 0.115 mm, e_{min} = 0.53, e_{max} = 0.95
Type I Portland cement	Typical properties
NyconMM fiber	G_s = 1.15, fiber length = 19 mm, filament diameter = 36 µm, tensile strength = 303 MPa, E = 1.57 GPa

Table 3.2. Mix Designs for Soil Specimens (Ratios are weight-based)

Unimproved soil mixture	Kaolin clay : Nevada Sand = 1 : 1 Water : dry soil mixture = 1 : 2.5
Cement-improved soil mixture	Cement : dry soil mixture = 1 : 10 Water : Cement = 1 : 1 Water : dry soil mixture = 1 : 2.5
Cement-fiber-improved soil mixture	Cement : dry soil mixture = 1 : 10 Water : Cement = 1 : 1 Water : dry soil mixture = 1 : 2.5 Fiber : dry soil mixture = 0.3%

In order to prepare the specimens, ingredients were added to a 4.5 quart stainless steel mixing bowl in a standing mixer with a 300 watt motor. This mixing device was capable of producing 2.4 to 5.3-N m of torque for mixing of the materials; this is very low compared to typical torque requirements published by Hayward Baker that are in the range of 40,000 to 400,000-N m. This reduction in mixing power allowed for easier mixing procedures in the laboratory because less material became "spoil material" by being thrown from the mixing bowl. While preparing the specimens, Kaolin and fine Nevada sand were always mixed first. A 40% water content was chosen so that these two soils could be mixed uniformly. When water content was 35%, it was difficult to use the mixer to mix the soils uniformly and some dry pockets were observed. However, if a much higher water content, 45%, was used, the mixture became slurry and could not stand stably for UCS tests, even with the added cement. Due to the above-mentioned reasons, 40% water content was selected to ensure that the mixture could be mixed uniformly in an easy manner and also to provide enough water for the hydration reactions when cement was introduced. These two soils were mixed thoroughly together until the appearance of the mixed soil becomes uniform throughout. This was usually indicated by the soil having the same color and moisture content by comparisons through visual inspection. This mixed soil was a mix between the white of Kaolin clay and the light brown color of the fine Nevada sand.

Using a cement slurry greatly improved the efficiency of the mixing process. By adding a cement slurry instead of cement powder, this process effectively models the "Wet Mixing Method", which is typically used in instances where soil water content is below 60%. When improving the soils with cement and fiber, uniformity was of upmost concern. While adding cement slurry, the soil mixture was mixed for approximately 10 minutes or until visual inspection led to the conclusion that uniformity had been reached. Samples prepared in this manner will most likely achieve a higher degree of uniformity than mixtures prepared for use during field applications due to the presence of confining stresses. In general, adding Portland cement to the soil mixture deepened the color to a dark grey color that lightened as curing occurred.

During the addition of fibers, great care was taken to make sure that the individual fibers were well spread out throughout the mixture. This was started by removing the fibers from the storage bag, in which they would become quite entangled. In order to untangle these fibers, the mass of fibers was rubbed against each other and separated within another bag. At this point, the mass of fibers mainly presents itself as a mesh of individual fibers and is added to the soil mixture. During this time, great care has to be taken to ensure that the fibers do not stick to the outside of the mixing bowl, or to the mixer itself. This was done by stopping the mixing machine during the mixing process and continuously scraping the sides of the mixing bucket and mixer towards the bottom of the bucket. In this way, the individual fibers were distributed throughout the mixture. Microscopic analysis using advanced tools, such as SEM, was not used to determine the degree of mixing. However, ingredient distribution was observed carefully and cross-sectional pictures of cured specimens were taken after the specimens failed at the end of UCS tests; an example picture is provided in Figure 3.1. No statistical analysis was performed to determine the mixing efficiency in regard to dispersing the ingredients throughout the mixture. It appears that the fibers were dispersed fairly well throughout the mixture. There were no areas throughout the improved specimens where fibers were not found, nor areas where large “clumps” or aggregations of fibers were present. From the failure surfaces, it was acceptable to say that fiber distribution was uniform. Also, all the fiber reinforced specimens were tested twice for any given curing condition. In that way, the repeatability of the test results was checked.

Figure 3.1. Example Distribution of Nylon Fibers through a Specimen

The curing temperature of the laboratory area varied between 70 and 72 degrees Fahrenheit. The typical humidity for indoors is around 50, but there have been no humidity measurements made; although, the relative humidity of the moisture box would be about 100% and a temperature of 70 degree Farenheit. The difference between laboratory temperature and below ground temperature will affect the strength gain progression when comparing cases from in-situ applications to ones from laboratory studies; this is due to the temperature effect on the reactions resulting from the hardening of concrete in pore water.

METHODS FOR CONSOLIDATION TESTS

ASTM D-2435 was followed to prepare specimens for consolidation tests. For the unimproved soil mixture, the specimens were prepared to maximum dry density at an optimum water content of 16% and trimmed into the consolidation ring from Proctor compacted samples. These samples were inundated from the beginning of the consolidation tests. For both cement-improved soils and cement-fiber-improved soils, specimens were compacted directly into the consolidation ring to minimize disturbances. These improved specimens were then inundated with water and cured for 28 days before consolidation testing. Before the soil mixtures were compacted into the rings, the inside wall of the consolidation ring was greased thoroughly to reduce friction effects. The loading paths for the consolidation tests were: seating load → 8 kPa → 16 kPa → 32 kPa → 64 kPa → 128 kPa → 256 kPa → 512 kPa → 256 kPa → 64 kPa → 16 kPa.

METHODS FOR UNCONFINED COMPRESSION STRENGTH TESTS

UCS tests were conducted according to ASTM D-2166. No unimproved soil specimens were tested due to using 40% water content by weight; this high water content made the unimproved pure soil mixture unsuitable for UCS tests. The UCS testing program can be grouped into two different procedures: one where strength gain is analyzed based on curing time alone and another one where vertical curing stress and curing time are both considered. For each test condition, two specimens were prepared and tested. UCS test specimens that were not subjected to vertical curing stress were tested at 7, 14, 28, 56, 90, 120, 182, and 433 days after preparation in order to determine the effects of curing time on the mechanical behavior of the improved soil mixtures. Strain controlled tests were chosen for this study due to expected low strain values at failure; a strain rate of 0.3 mm/min was used to minimize the loading rate effects. UCS test specimens were prepared so that the height-to-diameter ratio was 2:1 to prevent the Saint-Venant's end effects. PVC pipes with a 50.8 mm inside diameter were cut to a length of 101.6 mm in order to use as molds for forming the improved soil specimens. The cement- or cement-fiber-improved soil mixture were poured into the pipes, carefully compacted to avoid honeycombs and cured in the PVC molds in a moisture closet.

The compression device used for conducting unconfined compressive strength testing was a Versa Loader, Model U-905 from ELE International. This equipment supplies only whole numbers in load measurement (1 lb), yet supplies three significant digits in displacement measurements (0.001 in.). In order to construct stress-strain curves, it was assumed that this machine comes into contact with the specimen when the load is equal to a one pound load. A single LVDT was used for taking displacement measurements. Displacement measurements taken from the LVDT were then divided by the total specimen length to compute the vertical strain of the specimen. Inflection points in the initial portion of the stress-strain plots for specimens were thought to come from the specimens being unleveled on either the top or the bottom from curing in a trimmed PVC tube. If these specimens were uneven, the load would essentially be acting only on a small cross-section which would deform faster than the larger area. A 1% strain in this instance corresponds to a displacement of 0.04 inches. So, if a specimen has an inflection point around 1%, it may be assumed that the specimen was not level at the beginning, but comes fully into contact with the loading platen when the 0.04 inches of difference in level is achieved.

Curing stresses of 0 kPa, 50 kPa, 100 kPa, and 200 kPa were used to analyze strength gain due to curing stress. By applying vertical confining loads, overburden stresses that are present during field installation can be simulated. In this instance, these vertical curing stresses can represent soil overburden stresses, which would be present in CSM columns, at depths of 2.8 m, 5.5 m, and 11 m, respectively. The specimens prepared under different vertical curing stresses were tested after being cured for 7, 28, and 56 days. PVC pipes with a 50.8 mm inside diameter were cut to a length of 152.4 mm in length in order to use as molds for test specimens that were subjected to curing stress. This added length allowed for appropriate sample size after consolidation of soil subjected to curing stresses. Drainage during curing was provided to these specimens from both top and bottom. After curing time was reached, these specimens were trimmed to a height of 101.6 mm and tested. In all cases, the inside walls of the PVC molds were greased in order to prevent friction effects during consolidation and extrusion of the soil specimens. The ends of these specimens were also greased before being subjected to UCS tests to minimize end effects.

3.2 RESULTS

CONSOLIDATION TEST RESULTS

The results of the compaction tests for the unimproved soil are shown in Figure 3.2. Two specimens were prepared for each soil mixture and consolidation test results are presented in the form of e-log σ' curves in Figures 3.3-3.5 for each individual soil mixture. Figure 3.6 compares consolidation curves of unimproved, cement-improved, and cement-fiber-improved mixtures and C_c and C_s values are shown in Table 3.3.

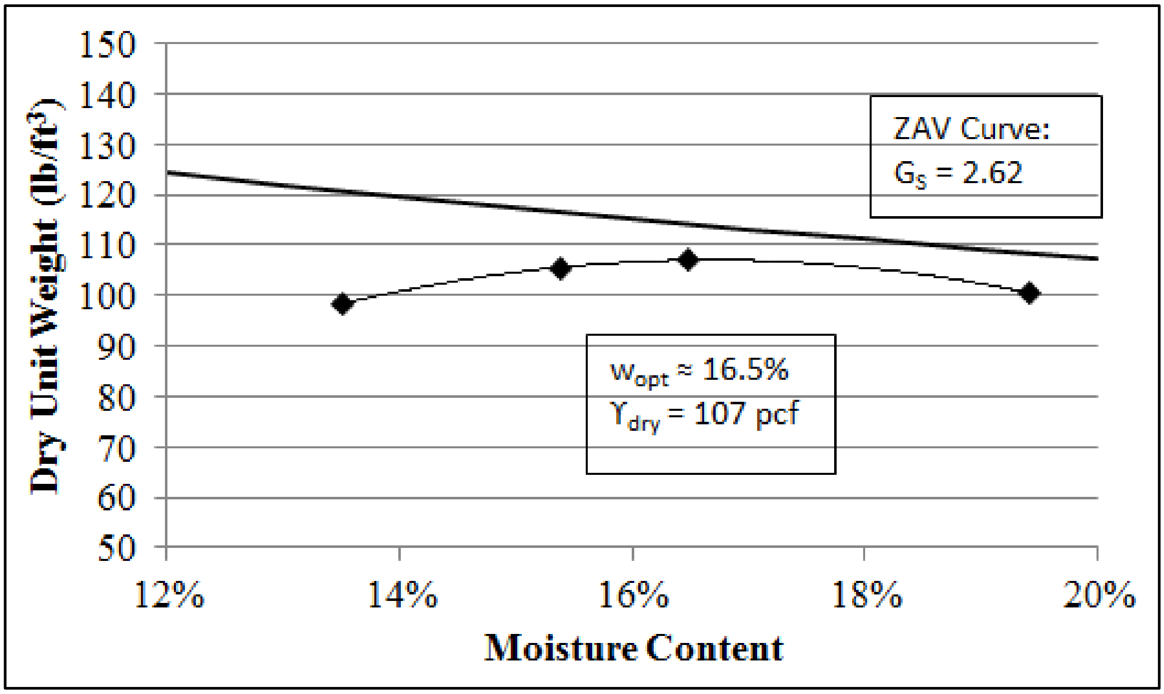

Figure 3.2. Compaction Curve for Unimproved Soil

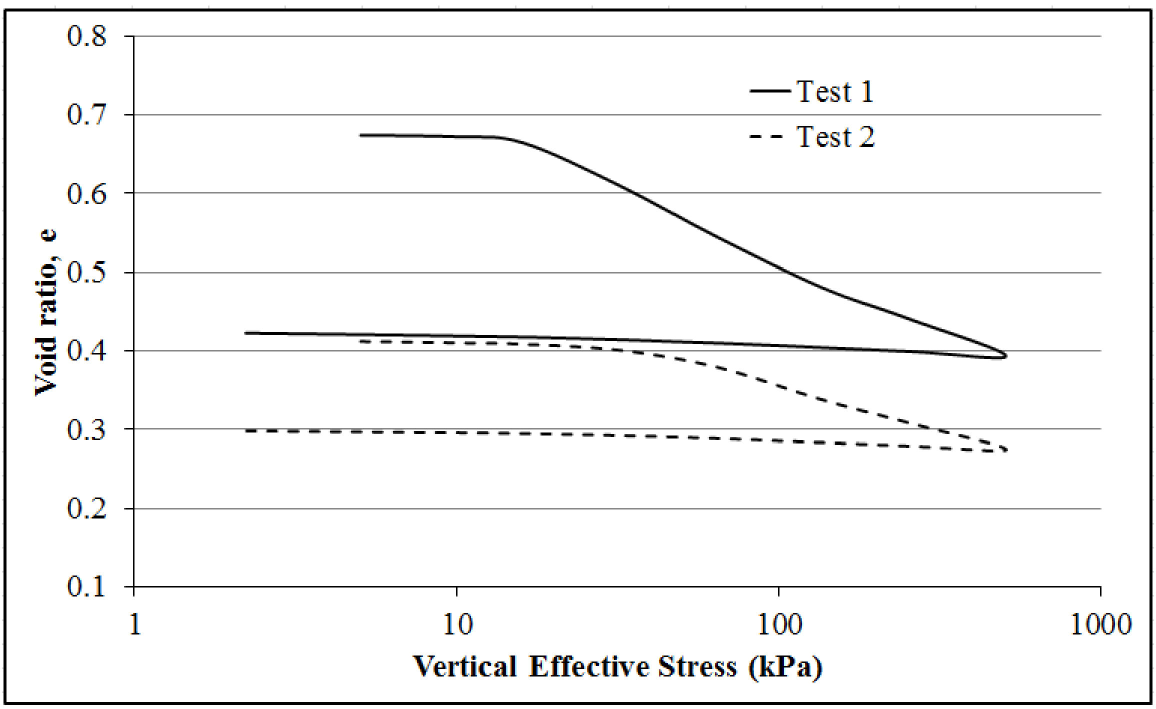

Figure 3.3. Consolidation Results for Unimproved Soil Mixture

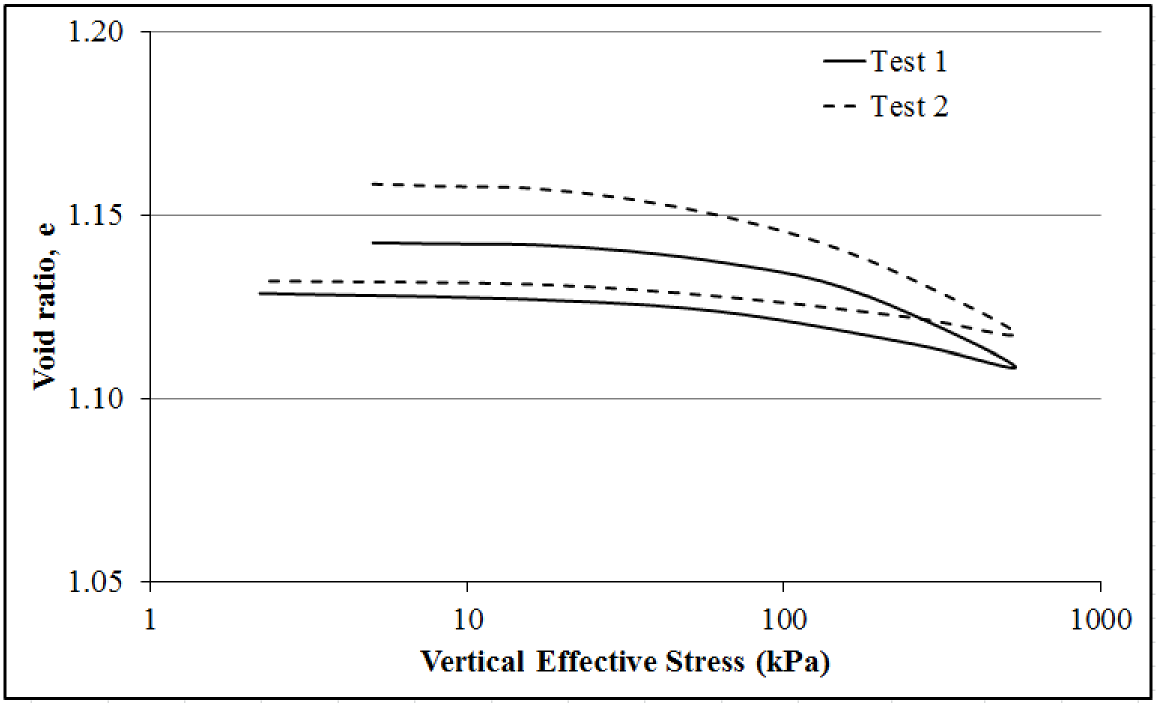

Figure 3.4. Consolidation Results for Cement-Improved Mixture

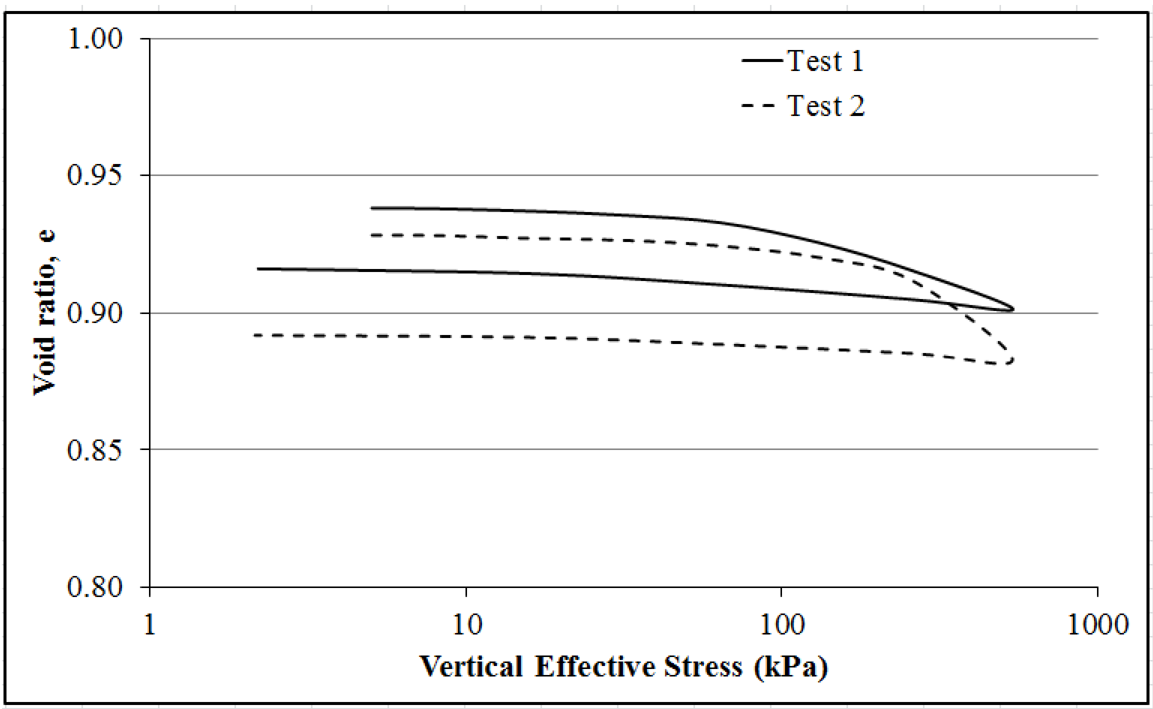

Figure 3.5. Consolidation Results for Cement-Fiber-Improved Mixture

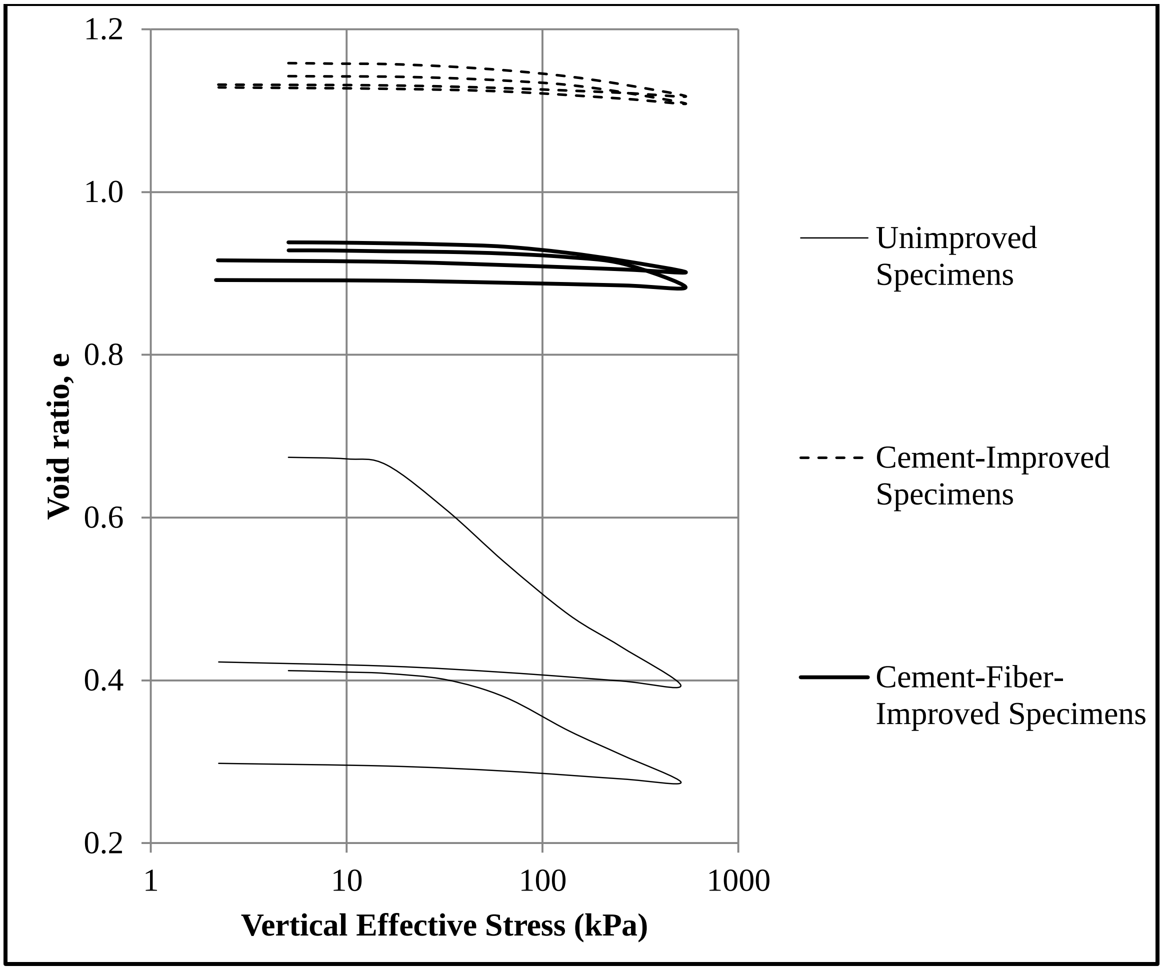

Figure 3.6. Consolidation Results for Unimproved and Improved Soil Specimens

When subjected to same loads, cement-improved specimens deformed the least of the three specimen types, while the unimproved soil deformed the most. The deformation of the unimproved soil was one full order of magnitude higher than the related deformations of the cement-improved and cement-fiber-improved specimens when subjected to higher vertical pressures.

The change in void ratio for improved specimens was much less than that for the unimproved soil mixture for given loadings as can be seen in Figure 3.6. Change in void ratio can be on the order 0.2 for the unimproved soil mixture, while both improved soil mixtures only decreased in void ratio by approximately 0.05. The unimproved soil specimens exhibit different initial void ratios due to the trimming process, and attempts were made to remedy this problem by backfilling the consolidation ring during preparation.

Table 3.3. Consolidation Results for Unimproved and Improved Soil Specimens

Mixture	Specimen	Initial Void Ratio	Final Void Ratio	C_c	C_s
Unimproved Specimens	1	0.676	0.423	0.157	0.018
	2	0.413	0.298	0.117	0.016
Cement-Improved Specimens	1	1.143	1.129	0.044	0.015
	2	1.159	1.132	0.045	0.010
Cement-Fiber-Improved Specimens	1	0.939	0.916	0.044	0.009
	2	0.929	0.892	0.045	0.005

In Table 3.3, consolidation results show that there are improved consolidation properties for cement-improved soils, as well as cement-fiber-improved soils. Improved properties included lower compression and swelling indices and less consolidation settlement. The compression index, C_c, and swelling index, C_s, varied greatly between unimproved and improved soil specimens. The C_c for the unimproved soil mixture was significantly higher than the C_c for both cement-improved and cement-fiber-improved specimens. Cement-improved specimens reduced the C_c by approximately 70% from the C_c for unimproved soil, while cement-fiber-improved specimens reduced the C_c by approximately 30%. The average C_s for the unimproved soil mixture was 0.017 and was also higher than the C_s for both cement-improved and cement-fiber-improved soil mixtures, which reduced the C_s of the unimproved soil by approximately 45% and 60%, respectively. Decreasing the C_c will result in lower overall consolidation settlement for both cement-improved and cement-fiber-improved soil mixtures; decreasing the C_s will result in lower rebound heights after loads are removed.

Unconfined Compression Strength Test Results

Figures 3.7 and 3.8 contain the stress-strain plots of the UCS tests for cement-improved specimens with no curing stress. Figures 3.9 and 3.10 contain the stress-strain plots of the UCS tests for cement-fiber-improved specimens with no curing stress. Two specimens were tested for each curing time except for the 433-day curing time, where three specimens were tested. By analyzing the stress-strain curves shown in Figures 3.7-3.10, the peak strengths of specimens tend to increase with curing time. Table 3.4 shows peak UCS and corresponding vertical strain. There appears to be little difference between the peak strengths of the cement-improved and cement-fiber-improved specimens at given curing times, although specimens with fiber tended to reach their peak strength at higher strains. This means that the introduction of fiber into the cement-improved soil may not help in strength gain, but will improve the ductility of the cement-soil mixture. Higher ductility in this study resulted in higher values of strain at failure.

A major difference between cement-improved and cement-fiber-improved specimens is the rate of strength degradation after peak strength is reached. For cement-improved specimens, the strength degradation occurs very rapidly (large drop in stress over a small strain range). For cement-fiber-improved specimens, post-peak degradation occurred much more slowly due to the increased ductility of the mixture. By observing the specimens during the UCS tests, it is seen that cement-improved specimens show cracks when vertical strains are very small and these cracks continue to grow until total failure. The cement-fiber-improved specimens developed cracks much slower, as the bond stress between the fiber and cement-soil mixture played a role in postponing the crack development.

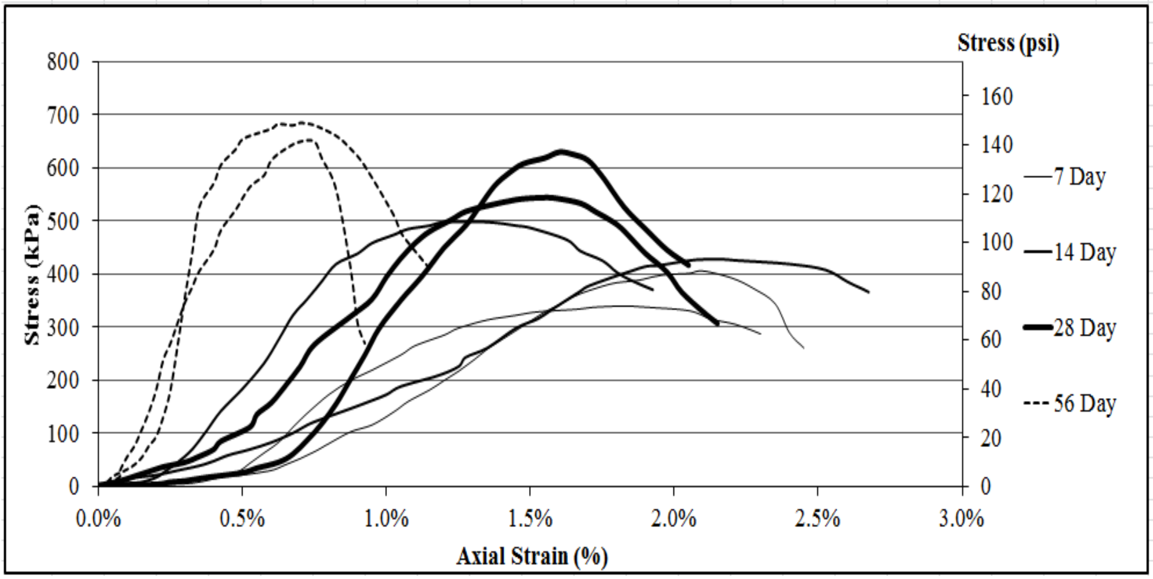

Figure 3.7. Stress-Strain Plots for Cement-Improved Specimens (7-56 Days)

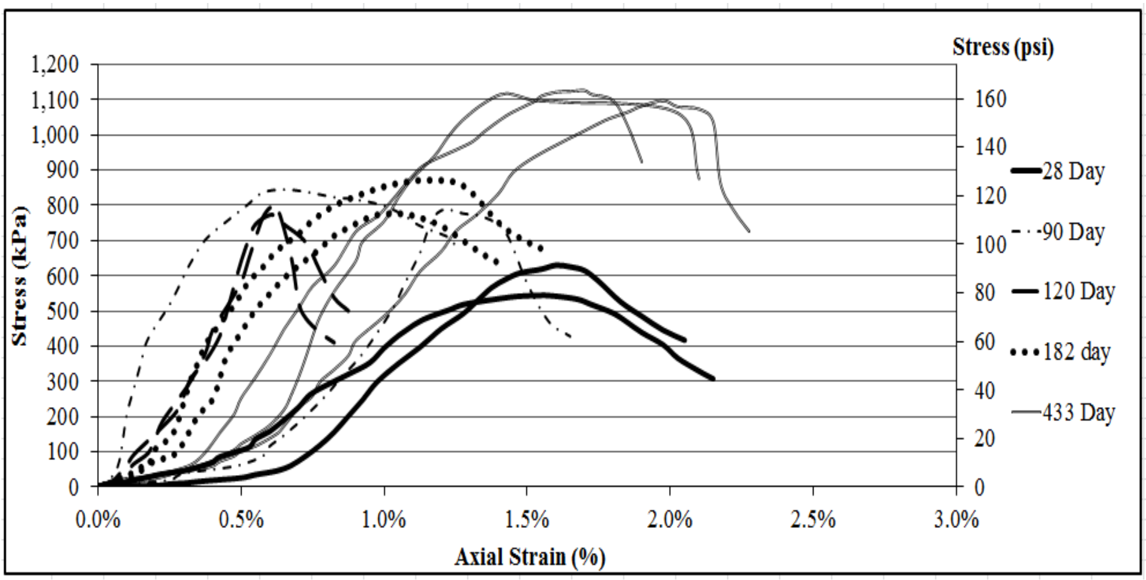

Figure 3.8. Stress-Strain Plots for Cement-Improved Specimens (90-433 Days)

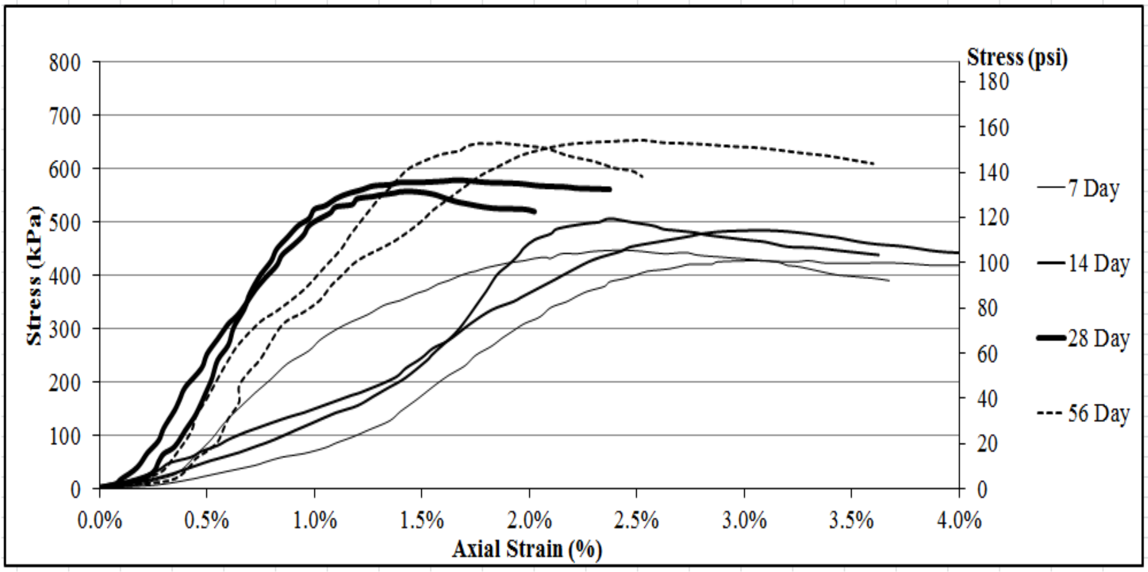

Figure 3.9. Stress-Strain Plots for Cement-Fiber-Improved Specimens (7-56 Days)

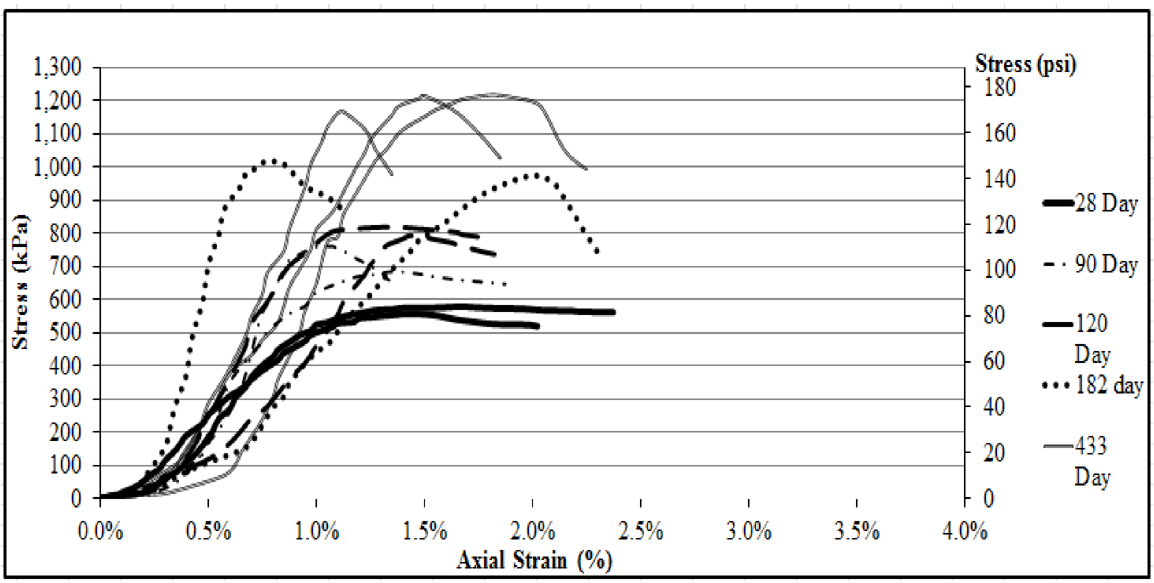

Figure 3.10. Stress-Strain Plots for Cement-Fiber-Improved Specimens (90-433 Days)

Fig. 3.11 presents the relationships between UCS and curing time for cement-improved and cement-fiber-improved specimens without curing stress. It can be seen that shear strength, and UCS, increases even after the 28 day curing time. Therefore, the current design criterion to use 28-day UCS should be on the safe side in terms of compressive strength. However, the cement-soil mixture becomes stiffer as curing time is increased and can reach the peak strength at a much smaller strain, as shown in Figure 3.12. In this case, the post-peak strength degradation also becomes significant.

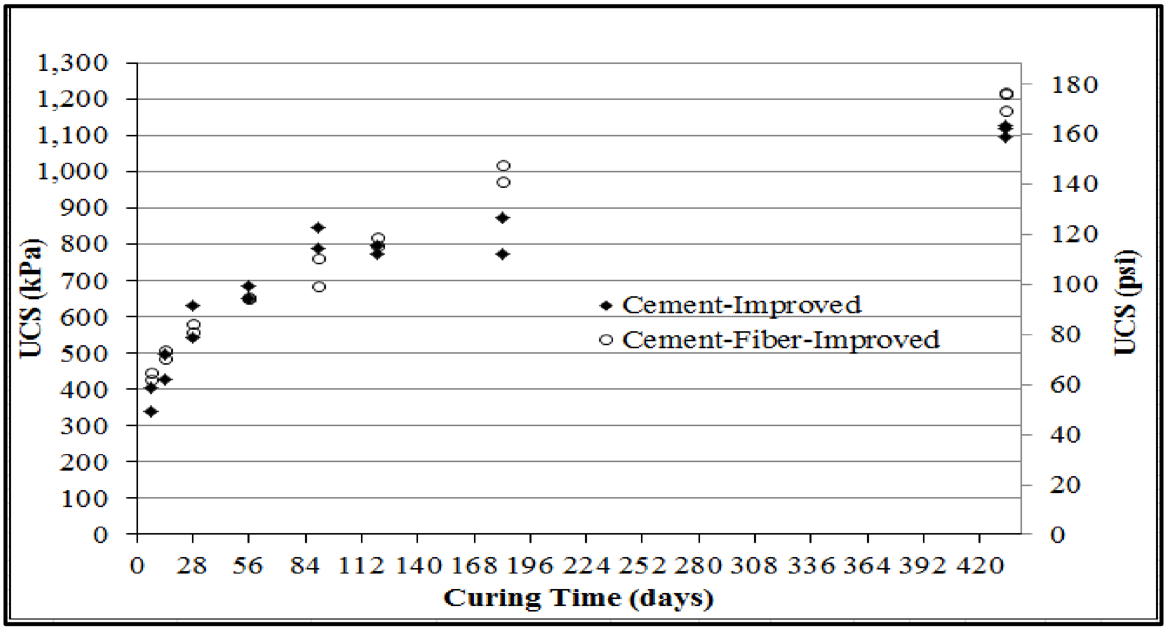

Figure 3.11. Tracking UCS Increase over Curing Time

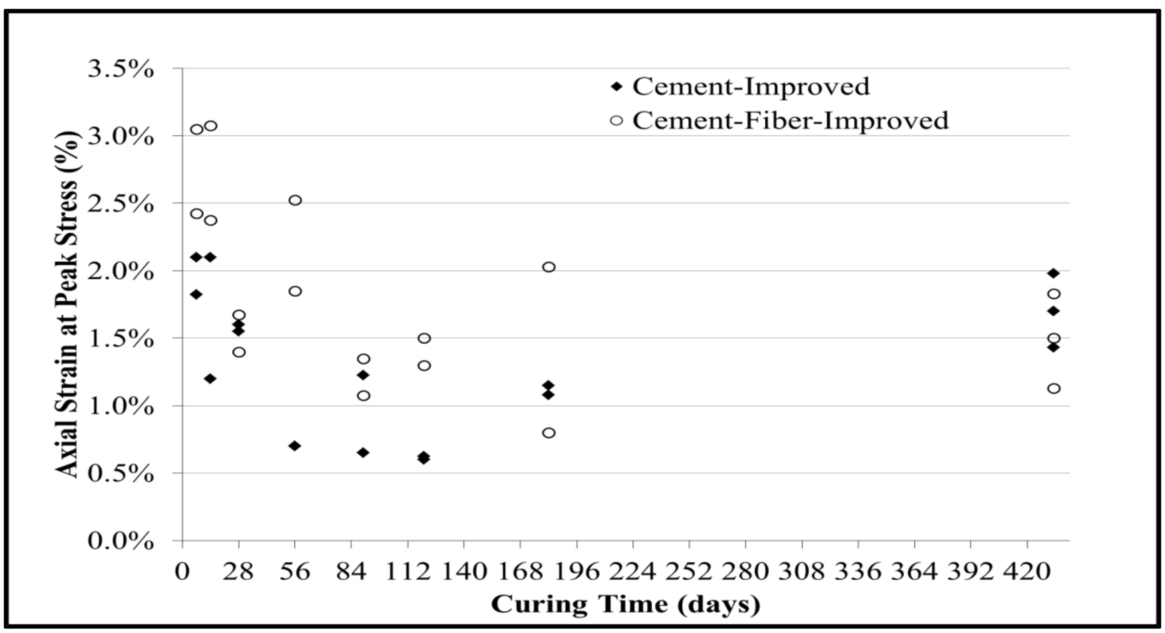

Figure 3.12. Tracking Strain Values at Failure over Curing Time

Table 3.4. Peak UCS and Corresponding Strain Values

	Curing Time (days)	Peak Strength (kPa)	Peak Strength (psi)	Strain at Peak Strength (%)
Cement-Improved	7	340	49.3	1.83%
	7	406	58.9	2.10%
	14	498	72.3	1.20%
	14	428	62.1	2.10%
	28	630	91.4	1.60%
	28	544	78.9	1.55%
	56	650	94.2	0.70%
	56	685	99.3	0.70%
	90	788	114.3	1.23%
	90	845	122.6	0.65%
	120	797	115.6	0.63%
	120	773	112.0	0.60%
	182	775	112.4	1.08%
	182	871	126.4	1.15%
	433	1097	159.1	1.98%
	433	1117	162.0	1.43%
	433	1126	163.3	1.70%
Cement-Fiber-Improved	7	428	62.1	3.05%
	7	448	64.9	2.43%
	14	507	73.5	2.38%
	14	485	70.4	3.08%
	28	557	80.9	1.40%
	28	579	84.0	1.68%
	56	654	94.9	2.53%
	56	650	94.2	1.85%
	90	762	110.5	1.08%
	90	685	99.3	1.35%
	120	819	118.7	1.30%
	120	797	115.6	1.50%
	182	1018	147.7	0.80%
	182	974	141.3	2.03%
	433	1216	176.3	1.50%
	433	1168	169.3	1.13%
	433	1218	176.7	2.00%

Other properties, such as initial tangent modulus, chord modulus, and toughness, are calculated from the stress-strain plots and are included in Table 3.5. These properties were calculated by using exact data points from the stress strain plots and a visual example for each calculation is shown in Figure 3.13 and 3.14. For estimations of initial tangent modulus, slopes were obtained by using the origin and the first obtained data point of the stress-strain plot. Chord moduli were estimated by using data points that gave slopes that best represented the actual slope of the stress-strain plot. These data points were not chosen at a constant stress level for all specimens, instead using the data points that best represented each individual specimen's data. The measurements for initial tangent modulus appear to be unstable and non-representative of the elastic modulus; this is due to the fact that inflection points are seen in some stress-strain plots.

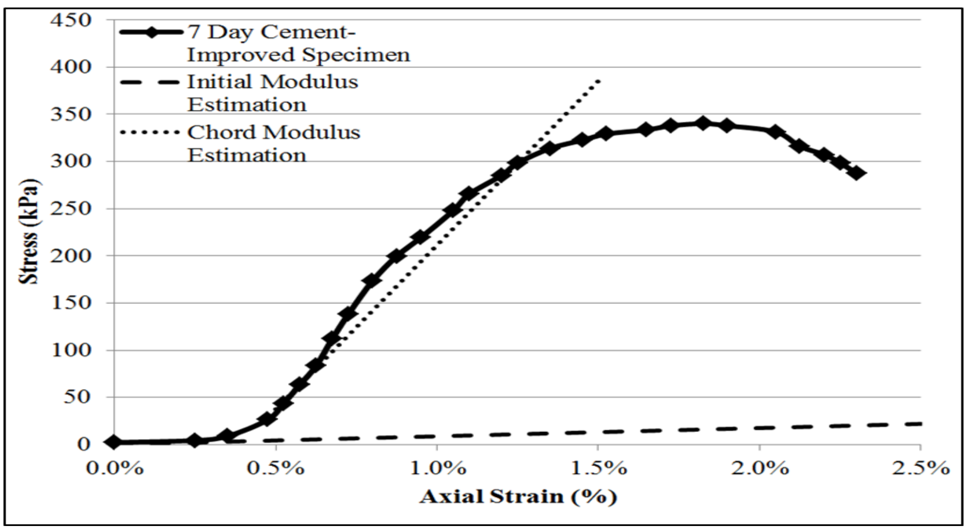

Figure 3.13. Visual Example of Calculations of Moduli

Toughness values were estimated by constructing basic shapes from specific data points for each specimen. For example, in Figure 3.14, the toughness was estimated by using five shapes, two rectangles and three triangles. In other cases, more or less shapes were used to get the best fit for the toughness measurement. As seen from the stress-strain plots in Figures 3.7-3.10, the specimens were not tested until the stress level reached zero stress. This was due to the time challenge of completing a large experimental test matrix with a slow strain rate. For instance, UCS tests of ductile specimens with fiber included could run for as long as fifteen minutes. Clear failures were not easily visible in fiber specimens which lead to the shapes of the stress-strain plots where values of stress remain near peak stress for a large strain range after reaching peak stress. An example of this is shown in Figure 3.15, where a cement-fiber-improved specimen developed many small cracks and the stress level remained close to the peak stress. In the case of the cement-improved specimen shown, the stress level dropped significantly after reaching peak stress. For these reasons, the toughness calculations can be considered conservative for both types of prepared specimens. Chord moduli values and toughness calculation values are plotted against curing time and are shown in Figures 3.16 and 3.17, respectively.

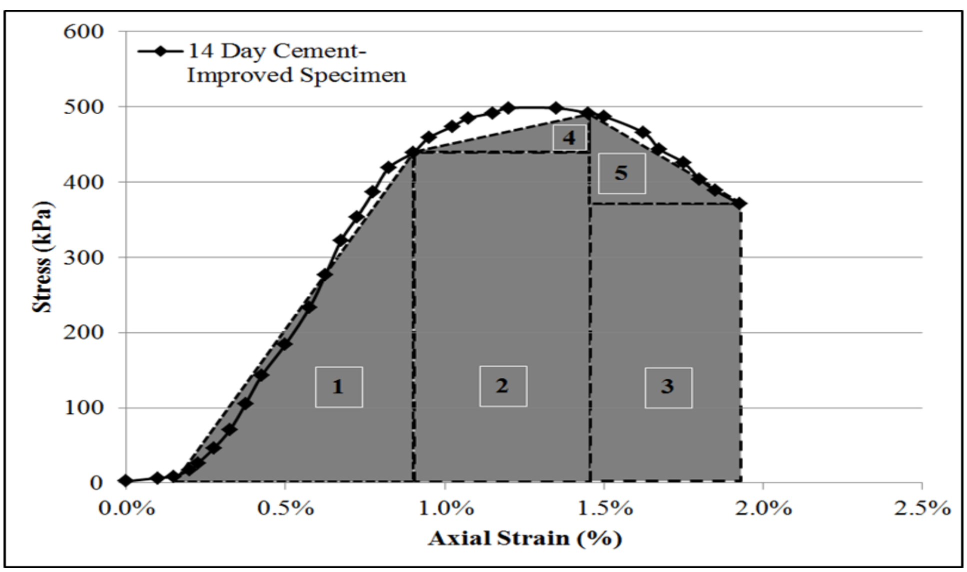

Figure 3.14. Visual Example of Calculation of Toughness

Table 3.5. Properties Obtained from Stress-Strain Curves

	Curing Time (days)	Initial Tangent Modulus (kPa)	Chord Modulus (kPa)	Toughness (kPa)
Cement-Improved	7	900	34800	4.5
	7	2200	32800	5.2
	14	4400	55200	5.4
	14	11700	23200	6.7
	28	1100	74600	6.9
	28	11700	60100	6.9
	56	17600	106900	3.5
	56	17600	144500	4.7
	90	8800	125700	7.3
	90	56700	181200	7.4
	120	22000	147800	3.5
	120	30700	170800	3.9
	182	20500	123500	6.4
	182	15400	119100	9.0
	433	5900	89300	13.4
	433	30700	126000	15.1
	433	16700	80300	11.4
Cement-Fiber-Improved	7	1300	26600	12.5
	7	2200	36900	10.7
	14	2200	32500	11.3
	14	8800	20000	12.5
	28	8800	45100	7.3
	28	7500	51900	8.8
	56	3500	40000	15.0
	56	2900	42500	10.2
	90	4400	123400	6.2
	90	4400	64900	8.1
	120	8800	54700	9.2
	120	17600	70200	8.4
	182	8800	218700	7.4
	182	8800	77800	12.5
	433	4400	107700	13.1
	433	8800	156300	9.1
	433	3900	150000	16.0

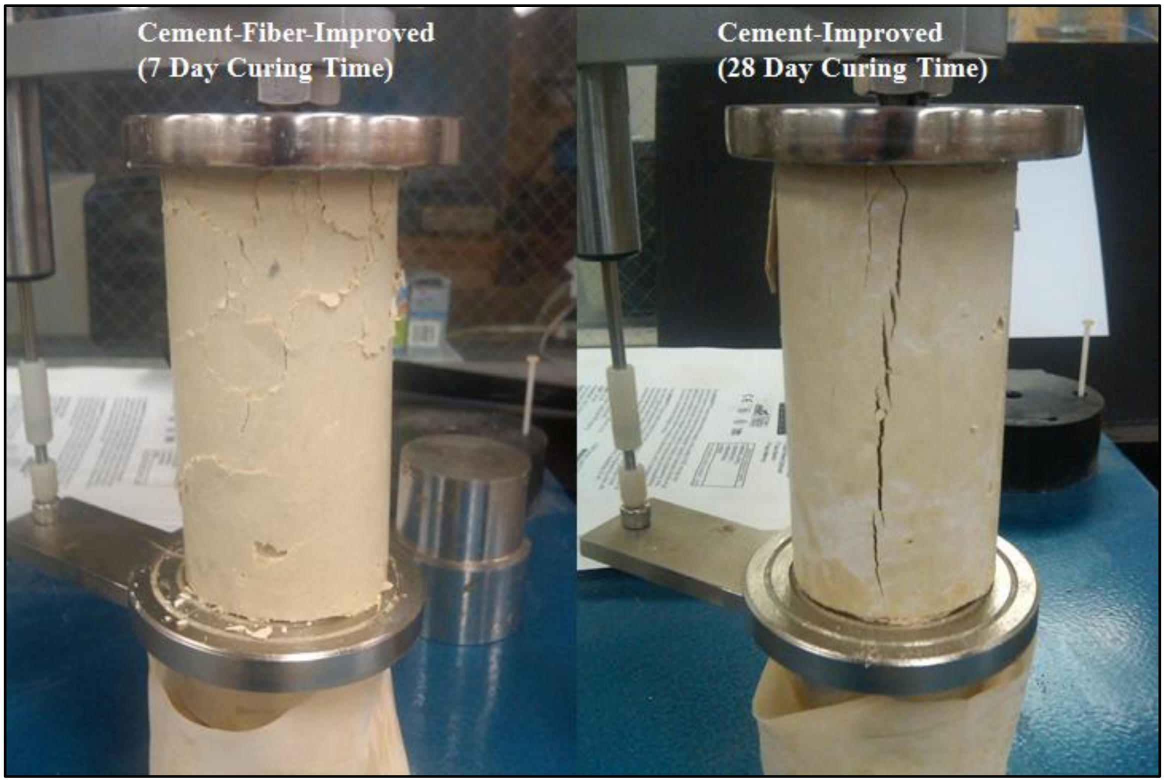

Figure 3.15. Specimens at End of UCS Tests

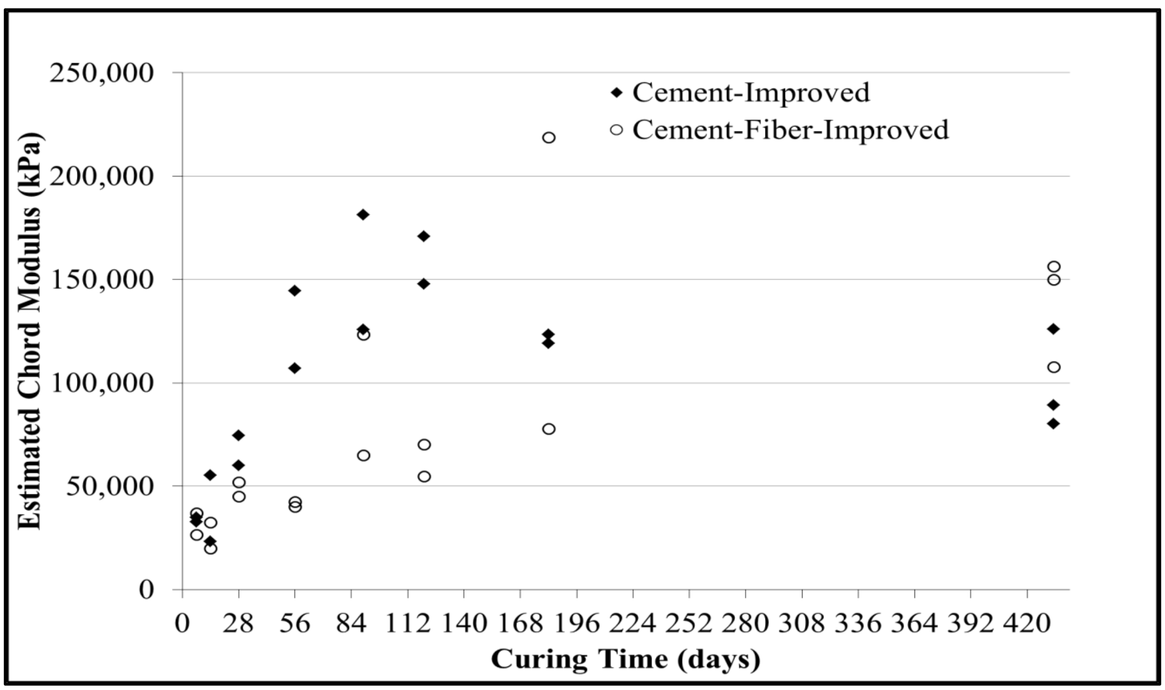

Figure 3.16. Tracking Chord Moduli over Curing Time

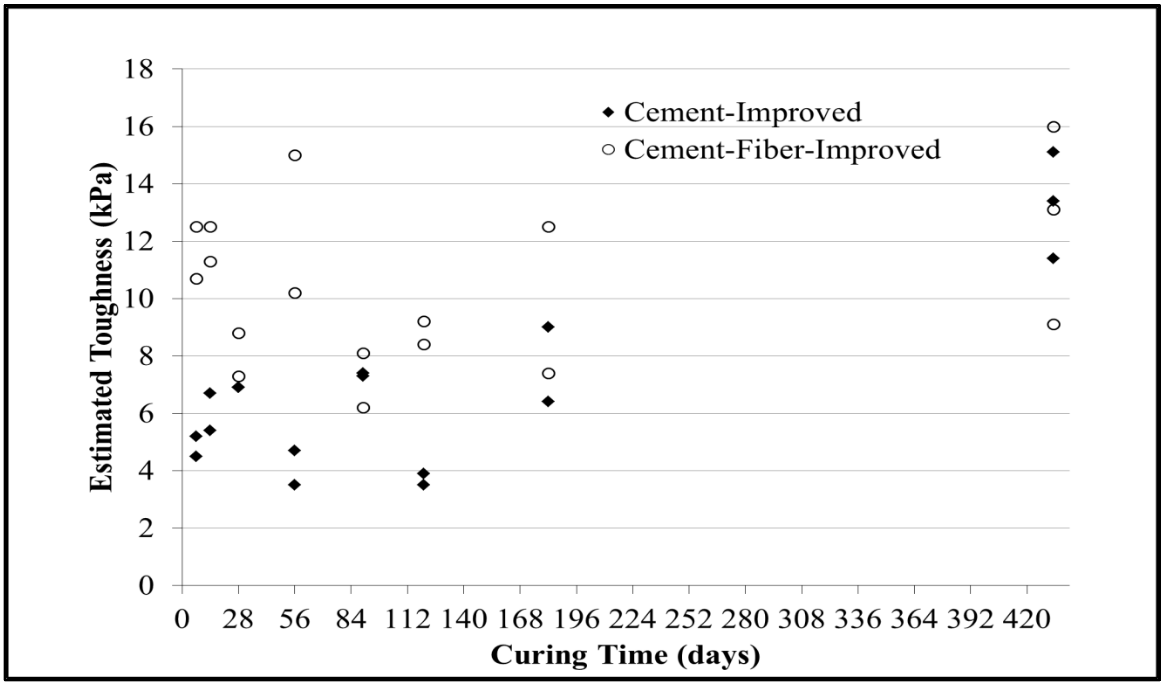

Figure 3.17. Tracking Toughness over Curing Time

The elastic modulus, as estimated by a chord modulus, increases with curing time up to 120-day curing time for cement-improved specimens, while increases in modulus occurs for cement-fiber-improved specimens up through the 433-day curing time. The estimated modulus appears to become slightly smaller for curing times of 182 and 433 days in cement-improved specimens. From Figure 3.17, there is no discernable pattern for the progression of toughness over curing time for cement-fiber-improved specimens, although, higher toughness estimations were found in cement-fiber-improved specimens compared to cement-improved specimens because larger values of strain were used when calculating the area under the stress-strain curve. Although the pattern of toughness increase for cement-improved specimens is not clear, there is a general upward progression of toughness for those specimens up through the 433 day curing time.

UNCONFINED COMPRESSION STRENGTH TESTS WITH CURING STRESS

The UCS of installed CSM will be affected by both curing time and curing stress. In Figures 3.18, 3.19, and 3.20, the stress vs. vertical strain curves from UCS tests for cement-improved and cement-fiber-improved specimens after 7, 28, and 56 day curing time with curing stress are presented, respectively. The relationships between UCS and curing stress for cement-improved and cement-fiber-improved specimens are included in Figure 3.21, while the relationships between strain values at peak stress and curing stress and shown in Figure 3.22. Peak UCS and corresponding strain values for specimens subject to curing stress are included in Table 3.6, while parameters calculated from the stress-strain plot are included in Table 3.7.

As seen in Figures 3.18-3.21, the application of curing stress during specimen preparation can greatly increase UCS for both cement-improved and cement-fiber-improved specimens. For example, at 7 day curing time with no confining stress, cement-improved specimens display an average UCS of 373 kPa. Under 50 kPa, 100 kPa, and 200 kPa curing stress, cement-improved specimens displayed an increased average UCS of 630 kPa, 760 kPa, and 970 kPa, respectively. For cement-improved specimens cured 7 days, 50 kPa curing stress resulted in a 68% increase in UCS, 100 kPa curing stress resulted in a 103% increase in UCS, and a 200 kPa curing stress resulted in a 160% increase in UCS from the 7 day UCS of cement-improved specimens with no curing stress. For cement-fiber-improved specimens cured 7 days, 50 kPa curing stress resulted in a 37% increase in UCS, 100 kPa curing stress resulted in a 74% increase in UCS, and a 200 kPa curing stress resulted in a 124% increase in UCS from the 7 day UCS of cement-fiber-improved specimens with no curing stress.

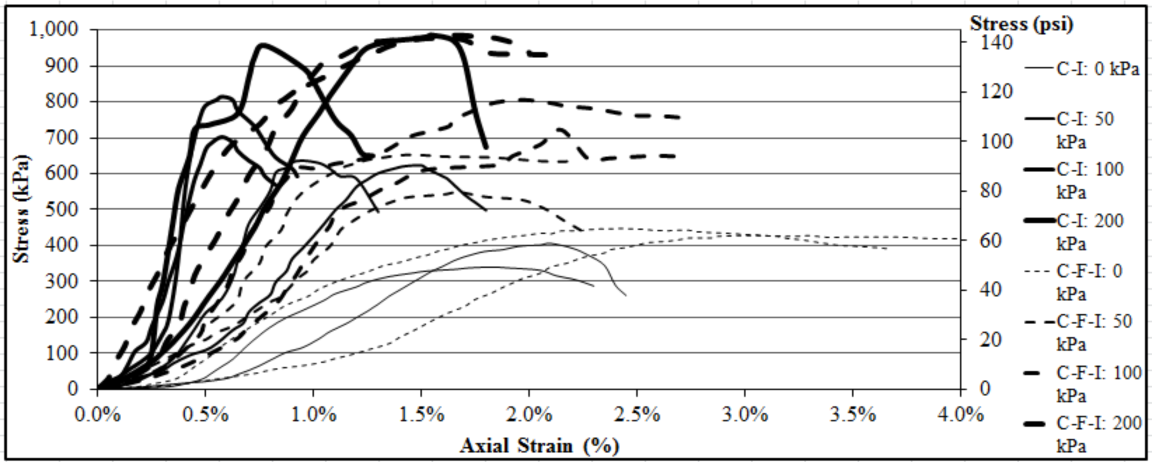

Figure 3.18. Stress-Strain Plots of Specimens Under Curing Stress (7 Day)

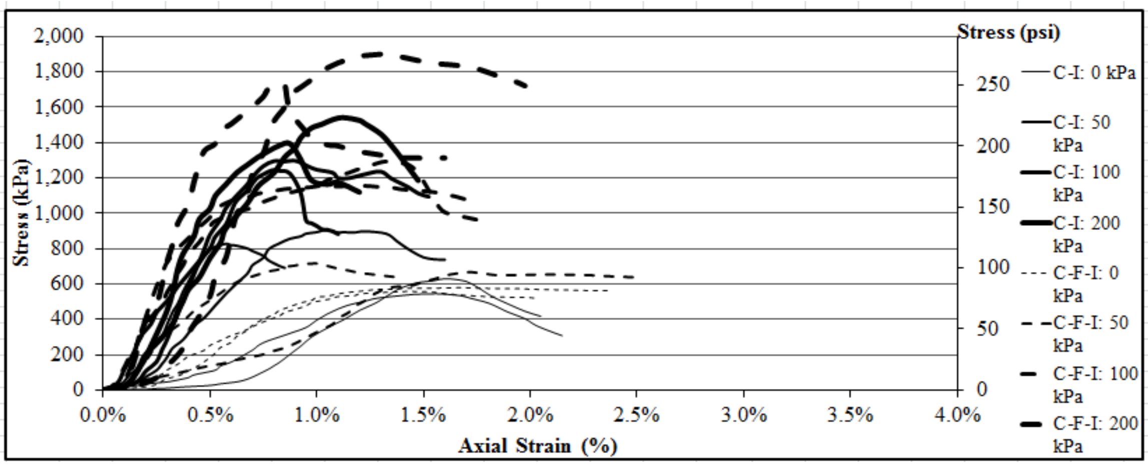

Figure 3.19. Stress-Strain Plots of Specimens Under Curing Stress (28 Day)

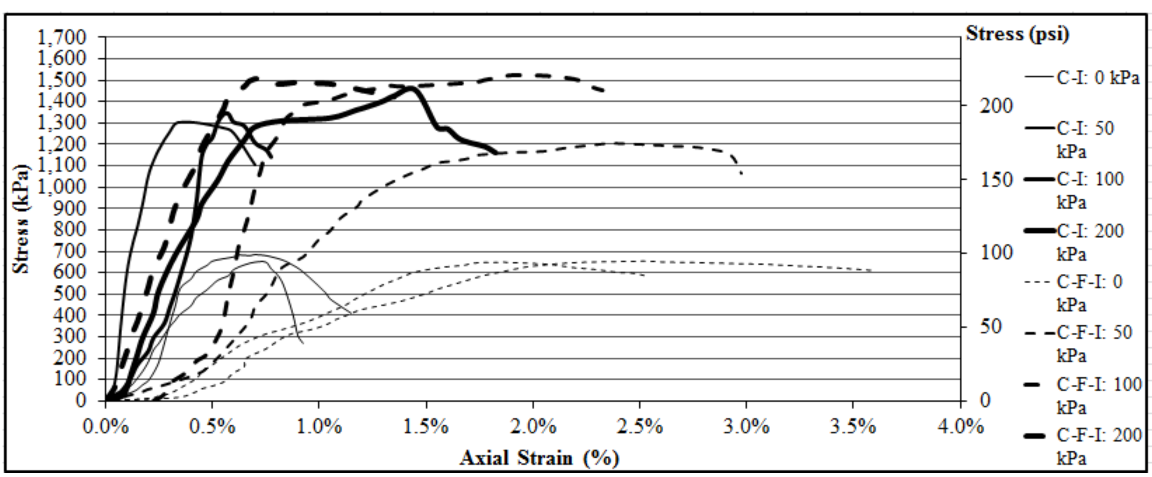

Figure 3.20. Stress-Strain Plots of Specimens Under Curing Stress (56 Day)

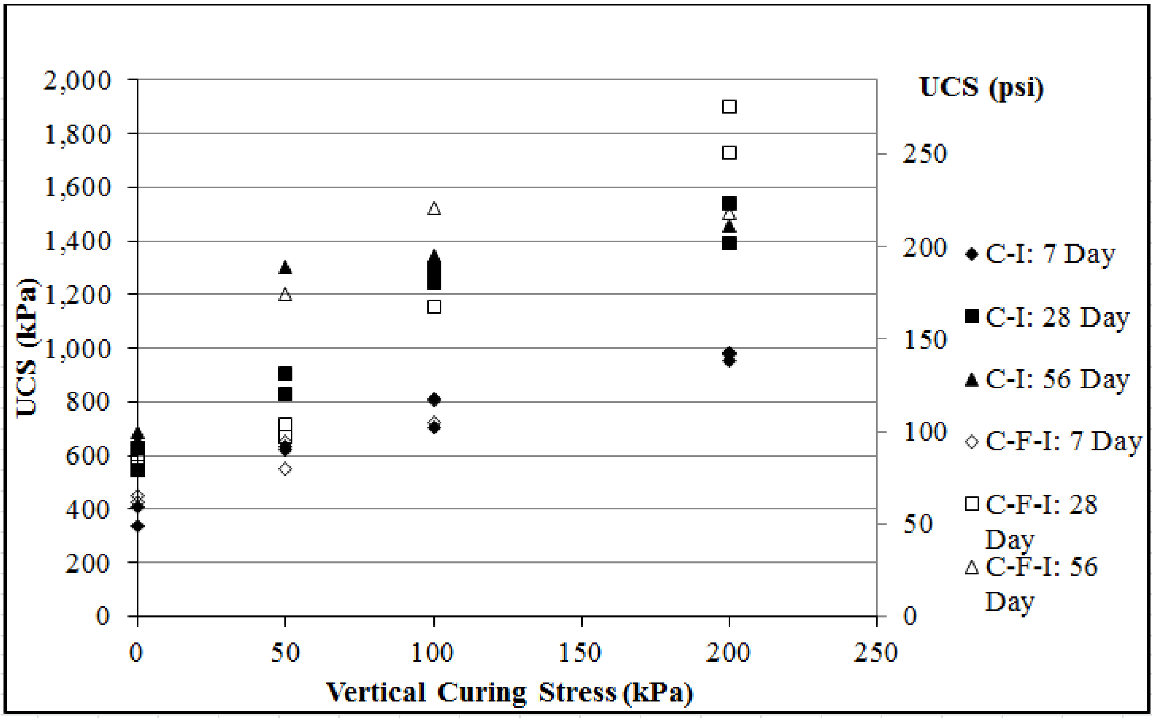

Figure 3.21. UCS Increase with respect to Curing Stress

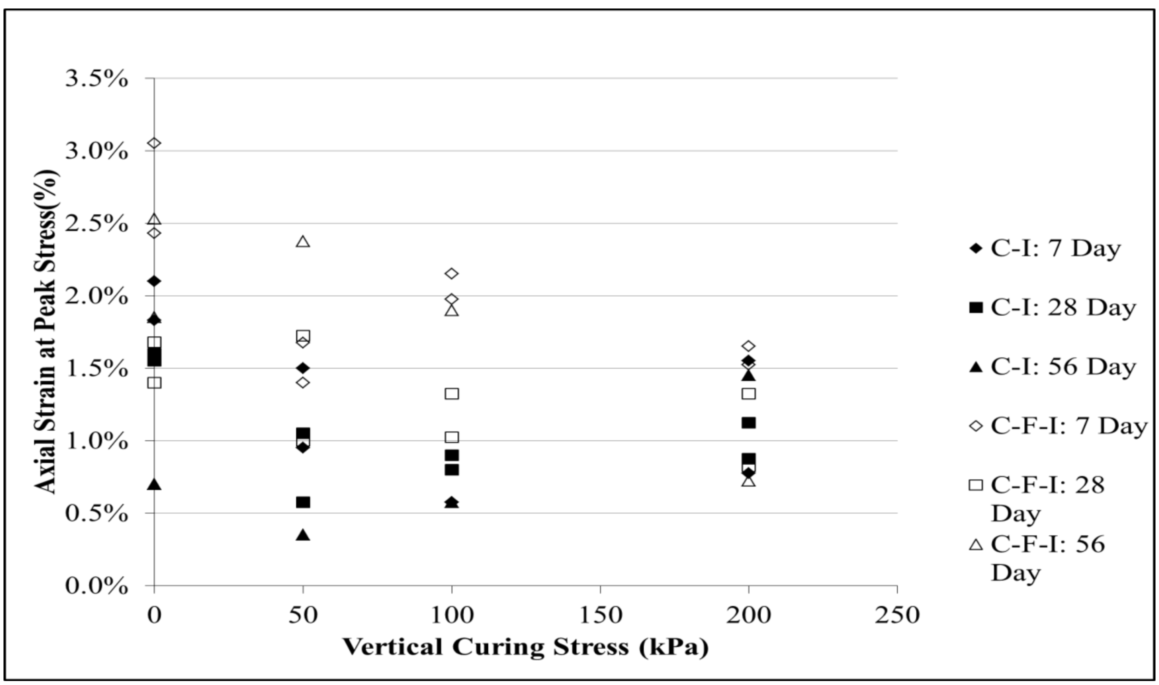

Figure 3.22. Tracking Strain Values at Failure versus Curing Stress

For cement-improved specimens cured 28 days, 50 kPa curing stress resulted in a 47% increase in UCS, 100 kPa curing stress resulted in a 116% increase in UCS, and a

200 kPa curing stress increased the UCS of cement-improved specimens cured 28 days by approximately 150%. For cement-fiber-improved specimens cured 28 days, 50 kPa curing stress resulted in a 22% increase in UCS, 100 kPa curing stress resulted in 115% increase in UCS, and a 200 kPa curing stress increased the UCS of cement-fiber-improved specimens cured 28 days by approximately 219%.

For cement-improved specimens cured 56 days, 50 kPa curing stress resulted in a 95% increase in UCS, 100 kPa curing stress resulted in a 101% increase in UCS, and a 200 kPa curing stress increased the UCS of cement-improved specimens cured 56 days by 118%. For cement-fiber-improved specimens cured 56 days, 50 kPa curing stress resulted in a 85% increase in UCS, 100 kPa curing stress resulted in 134% increase in UCS, and a 200 kPa curing stress increased the UCS of cement-fiber-improved specimens cured 56 days by approximately 131%.

In general, the UCS increased more with respect to curing stress in the specimens that were improved only with cement, although the percent increase in the cement-fiber-improved specimens were not much lower. From this analysis, it should be safe to conclude that higher curing stresses lead to higher UCS. An observation that can be made from Figures 3.18-3.21 is that the UCS of both cement-improved and cement-fiber improved specimens increased not only with curing stress, but also with curing time. Since conventional practice is to use the UCS at 28-day curing time with no consideration of curing stress, it can be seen that this method is conservative. By using the UCS at 28-day curing time without curing stress as a reference, the UCS at 120-day curing time could increase 30~40% for both cement- and cement-fiber-improved specimens.

Table 3.6. Peak UCS and Strain Values for Specimens Subject to Curing Stress

	Curing Time	Curing Stress (kPa)	Peak Strength (kPa)	Peak Strength (psi)	Strain at Peak Strength (%)
Cement-Improved	7 Day	50	623.3	90.4	1.50%
		50	636.5	92.3	0.95%
		100	814.2	118.1	0.58%
		100	702.3	101.9	0.58%
		200	985.4	142.9	1.55%
		200	956.9	138.8	0.78%
	28 Day	50	904.2	131.1	1.05%
		50	827.4	120.0	0.58%
		100	1244.4	180.5	0.80%
		100	1297.0	188.1	0.90%
		200	1393.6	202.1	0.88%
		200	1540.7	223.5	1.13%
	56 Day	50	1303.6	189.1	0.35%
		100	1343.1	194.8	0.58%
		200	1455.0	211.0	1.45%
Cement-Fiber-Improved	7 Day	50	651.8	94.5	1.40%
		50	548.7	79.6	1.68%
		100	805.4	116.8	1.98%
		100	722.0	104.7	2.15%
		200	976.6	141.6	1.53%
		200	985.4	142.9	1.65%
	28 Day	50	715.5	103.8	1.00%
		50	667.2	96.8	1.73%
		100	1156.6	167.7	1.03%
		100	1292.7	187.5	1.33%
		200	1900.6	275.7	1.33%
		200	1729.4	250.8	0.83%
	56 Day	50	1204.9	174.8	2.38%
		100	1523.1	220.9	1.90%
		200	1507.7	218.7	0.73%

Table 3.7. Properties Obtained from Stress-Strain Curves

	Curing Time	Curing Stress (kPa)	Initial Tangent Modulus (kPa)	Chord Modulus (kPa)	Toughness (kPa)
Cement-Improved	7 Day	50	11700	72300	6.4
		50	8800	111900	5.6
		100	39500	346100	4.9
		100	21900	198600	3.6
		200	21900	88300	9.9
		200	20500	144300	7.5
	28 Day	50	8800	131700	9.4
		50	43900	207800	4.5
		100	43900	163900	8.0
		100	17600	287500	13.6
		200	8800	281700	10.0
		200	8800	190200	13.5
	56 Day	50	70300	452700	6.8
		100	70300	238800	6.4
		200	26300	206300	15.1
Cement-Fiber-Improved	7 Day	50	6600	97400	9.7
		50	23400	44500	7.6
		100	11000	110600	13.8
		100	8800	91000	11.7
		200	8800	120000	12.7
		200	57000	119700	11.5
	28 Day	50	8800	106400	6.3
		50	13200	66700	11.0
		100	26300	222800	13.5
		100	26300	209400	13.2
		200	5300	337400	24.5
		200	26300	354100	19.4
	56 Day	50	4400	113700	21.4
		100	43900	376200	20.8
		200	131700	239400	14.7

A disadvantage of having a high UCS in this study is that specimens with high UCS tended to fail at a very low vertical strain. For example, one of the cement-improved specimens cured for 28 days with 100 kPa curing stress actually failed at 0.8% vertical strain, while the vertical strain reached about 1.6% for both specimens without curing stress when failure occurred. This behavior can also be observed in the cement-fiber-improved specimens as well. The overall trend is the higher curing stress, the lower vertical strain when peak strength is reached. This is caused by the mixture becoming brittle when curing stress is applied during specimen preparation.

The intoduction of fiber (0.3% by weight) had little effect on the UCS when compared to cement-improved specimens with the same curing conditions. The inclusion of fiber improved the post-peak strength degradation compared to cement-improved specimens. The cement-improved specimens showed brittle behavior by exhibiting a sudden drop in stress over a short strain range after peak strength was reached. With fiber included, specimens could withstand the application of loads close to peak strength over a larger strain range.

It can be seen from Figure 3.21 that the UCS of the specimens increases almost linearly with curing stress for both improved soil mixtures and curing times of 7, 28, and 56 days. This conclusion may not hold true if higher curing stresses are present during the curing process; it may be helpful to study the effects of higher curing stresses in the future. From a standpoint of practice, the typical depth for cement soil mixing technology is around 20 m below ground surface and occasionally 30 to 50 m. It may be worthwhile to study the effects of higher vertical curing stress, like 400 kPa in the future. Curing stress tended to increase the density of the mixtures during this series of testing, and as the curing stress increased, the density increased.

The properties outlined in Table 3.7, chord modulus and toughness, are plotted against curing stress in Figures 3.23 and 3.24, respectively. The chord moduli for all specimens cured for 56 days under curing stress appear to increase up to a curing stress of 100 kPa, and then become stable. The moduli for cement-improved and cement-fiber-improved specimens cured for 7 and 28 days under curing stress appear to increase in a linear fashion up through the 200 kPa curing stress, with cement-fiber-improved specimens cured 28 days under curing stress increasing the fastest with respect to curing stress. Toughness progression is much harder to describe, but a general increase in toughness is seen for all specimens, except the cement-fiber-improved specimens cured for 56 days under curing stress. Once again, the toughness for the cement-fiber-improved specimens cured for 28 days under curing stress increased the most with respect to curing stress.

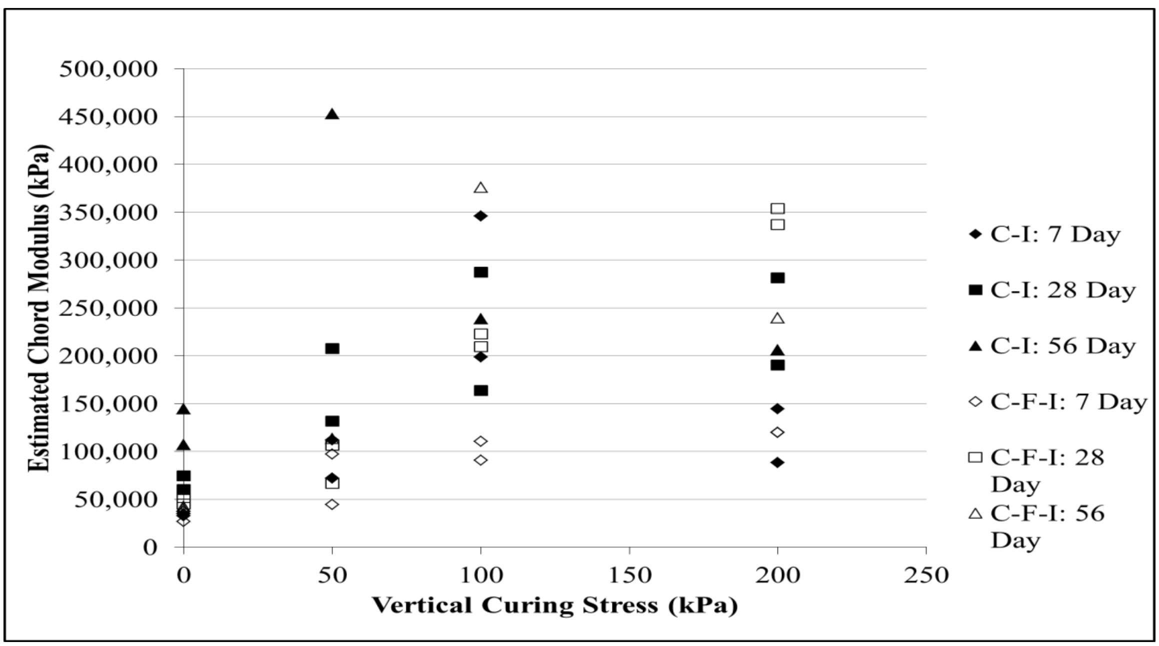

Figure 3.23. Tracking Chord Moduli versus Curing Stress

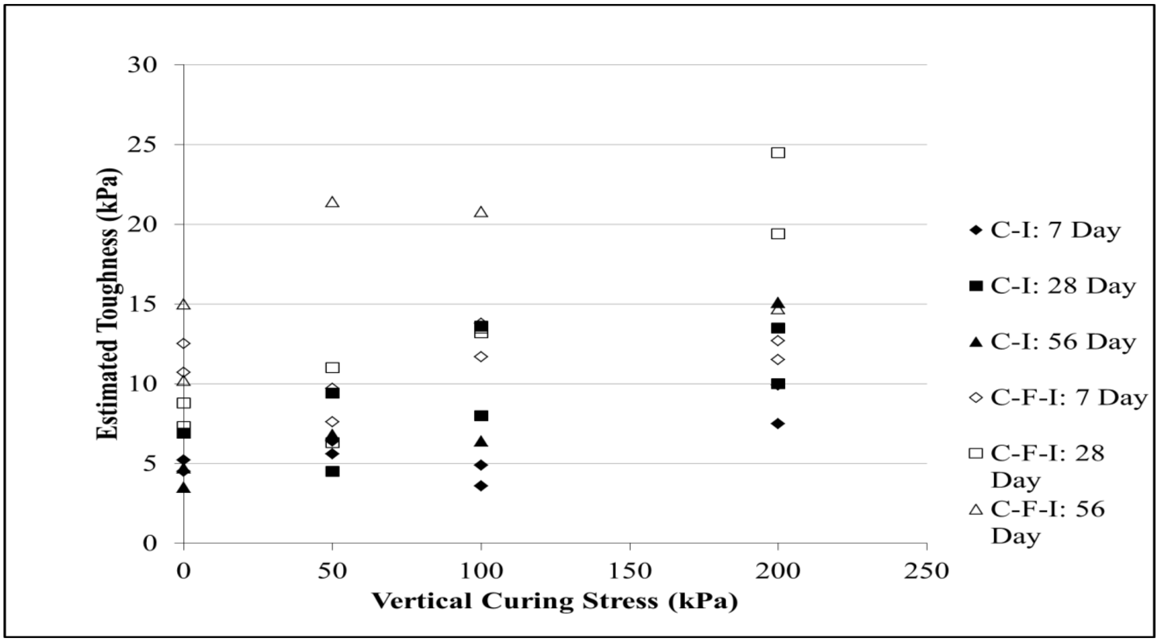

Figure 3.24. Tracking Toughness versus Curing Stress

CHAPTER 4

MODELING STRENGTH GAIN

4.1 MODEL INFORMATION

Predicting the UCS of cement-soil mixtures can be very useful in today's construction practices and designs. By assuming strength gain over time, designers can design post-installation uses with greater accuracy. Also, strength increase with cement-treated soils can include improved properties such as lower consolidation rates and lower overall settlement which may result from construction activities or design loads.

Strength progression with respect to curing time has been a highly researched topic within the field of soil treatment. Hashim (2008), Horpibulsuk et al (2011), Horpibulsuk (2003), O'Rourke and McGinn (2004), Christensen (1969), Wooten and Foreman (2005), Lorenzo and Bergado (2006), Shihata and Baghdadi (2001), and Altun et al (2009) have all presented results that relate strength gain in treated soils to the curing time. In order to compare the rate of strength increase and model a prediction formula, data were extracted from these sources from numerical tables and given plots. In the case that only plots were given, values were estimated by formatting a graph with the exact layout of the original graph and overlaying those two graphs to make sure the data points were identical in positioning. These sources and relevant samples are shown in Table 4.1. These sources were chosen because they are relatable to this research; samples are cement-treated clays. These clays are then divided by soil classification, low plasticity clay or high plasticity clay. By taking different types of clay into account, conclusions may be drawn about the strength progression rates that result from different mixture ingredients.

Specimens were prepared in the same manner as this study in the study by Christensen (1969). Mixing effort was not mentioned, but mixed specimens were stored in polyethylene bags at room temperature. Specimens for the study by Lorenzo and Bergado (2006) were prepared by mixing in room temperature and curing in PVC molds in 25 degree Celsius room temperature and 97% relative humidity. Specimens used in the study by Horpibulsuk et al (2011) were obtained from field soil samples at a depth of 3 meters. This soil was then mixed with cement at an unstated power and cured in vinyl bags in a humidity room at a temperature of 20 degrees Celsius.

By knowing the mixing methods of each study and using studies which use similar mixing procedures, it easier to compare rates of strength gain for UCS tests because the rate of mixing, time of mixing, and torque used during mixing will affect the degree of uniformity of samples; as these parameters increase, so should the quality of material mixing. Also, curing environment is very important as chemical reactions will be affected by the curing area’s humidity and temperature.

Table 4.1. Soil and Improvement Method Information for Studied Soils

Soil	Source	Source Identifier	Soil Type	Treatment Type	Dosage Rate	Days Cured
1	Starcher (2013)	Cement-Improved	50% Kaolin, 50% Fine Nevada Sand	Portland Cement	10% by weight	7, 14, 28, 56, 90, 120, 182, 433
2	Starcher (2013)	Cement-Fiber-Improved	50% Kaolin, 50% Fine Nevada Sand	Portland Cement and Nylon Fibers	10% cement content by weight, 0.3% fiber content by weight	7, 14, 28, 56, 90, 120, 182, 433
3	Starcher (2013)	Cement-Improved, 50 kPa Curing Stress	50% Kaolin, 50% Fine Nevada Sand	Portland Cement	10% by weight	7, 28, 56
4	Starcher (2013)	Cement-Improved, 100 kPa Curing Stress	50% Kaolin, 50% Fine Nevada Sand	Portland Cement	10% by weight	7, 28, 56
5	Starcher (2013)	Cement-Improved, 200 kPa Curing Stress	50% Kaolin, 50% Fine Nevada Sand	Portland Cement	10% by weight	7, 28, 56
6	Starcher (2013)	Cement-Fiber-Improved, 50 kPa Curing Stress	50% Kaolin, 50% Fine Nevada Sand	Portland Cement and Nylon Fibers	10% cement content by weight, 0.3% fiber content by weight	7, 28, 56
7	Starcher (2013)	Cement-Fiber-Improved, 100 kPa Curing Stress	50% Kaolin, 50% Fine Nevada Sand	Portland Cement and Nylon Fibers	10% cement content by weight, 0.3% fiber content by weight	7, 28, 56
8	Starcher (2013)	Cement-Fiber-Improved, 200 kPa Curing Stress	50% Kaolin, 50% Fine Nevada Sand	Portland Cement and Nylon Fibers	10% cement content by weight, 0.3% fiber content by weight	7, 28, 56
9	Horpibulsuk et al (2011)		Bangkok Clay	Fly Ash and Portland Cement	10-30% by weight	7, 14, 28, 56, 90, 120

Table 4.1. Continued

Soil	Source	Source Identifier	Soil Type	Treatment Type	Dosage Rate	Days Cured
10	Horpibulsuk et al (2003)		Bangkok Clay	Fly Ash and Portland Cement	10-30% by weight	7, 14, 28, 56, 90, 120
11	O'Rourke and McGinn (2004)		Clay	Portland Cement Type I/II	Approx. 18-20%	7, 14, 28, 56, 365, 50 day wet grab samples
12	Christensen (1969)	1	Montmorillonite and Kaolinite	Portland Cement	5% by weight	7, 28, 90
13	Christensen (1969)	1	Montmorillonite	Portland Cement	3% by weight	7, 28, 90
14	Christensen (1969)	2	Montmorillonite	Portland Cement	5% by weight	7, 28
15	Christensen (1969)	2	Montmorillonite	Portland Cement	3% by weight	7, 28
16	Christensen (1969)	4	Montmorillonite	Portland Cement	5% by weight	7, 28
17	Christensen (1969)	4	Montmorillonite	Portland Cement	3% by weight	7, 28
18	Christensen (1969)	11	Montmorillonite	Portland Cement	5% by weight	7, 28, 90
19	Christensen (1969)	11	Montmorillonite	Portland Cement	3% by weight	7, 28, 90
20	Lorenzo and Bergado (2006)	RMC = 80%	Bangkok Clay	Portland Cement	10% by weight	7, 14, 28
21	Lorenzo and Bergado (2006)	RMC = 100%	Bangkok Clay	Portland Cement	10% by weight	7, 14, 28
22	Lorenzo and Bergado (2006)	RMC = 130%	Bangkok Clay	Portland Cement	10% by weight	7, 14, 28
23	Lorenzo and Bergado (2006)	RMC = 160%	Bangkok Clay	Portland Cement	10% by weight	7, 14, 28

4.2 Modeling Results

The plots of normalized data are separated into separate graphs; Figure 4.1 contains normalized values for the cement-improved and cement-fiber improved specimens from this study, Figure 4.2 contains normalized values for the cement-improved and cement-fiber-improved specimens subjected to curing stress, Figure 4.3

contains normalized values for studies on improved low plasticity clay, and Figure 4.4 includes the values for studies on improved high plasticity clay.

In order to compare the rates of strength gain, the given sets of data were modeled by a linear fit, logarithmic fit, and a power function fit. These three line fits were used because the variability in fit was small when compared to other fit types. When fitting the original data, it was found that it is harder to compare the rate of strength progression because of differing types of soil and binder dosage rate were selected. These non-normalized strengths lead to large differences in strength values, caused by the different chemical make-up of the treated soils.

In order to simplify the data, strength values were normalized by dividing by 28-day strength and then re-plotted with the three fit types. In cases where data had more than one 28-day strength reported, the multiple points were averaged and then normalized by that average. This leads to some data that does not cross at a value of 1 at 28 days for the UCS divided by the 28-day UCS, as seen in data used from this study. The data supplied by this study for cement-improved and cement-fiber improved data show an increase in UCS up to 433 day curing time. In Figure 4.1, only the power function fit and logarithmic fit are displayed because the R^2 values for those fits were much closer to one than the linear fit. From this figure, trendlines indicate that cement-fiber-improved specimens increase in UCS more over the same amount of curing days with respect to 28-day strength.

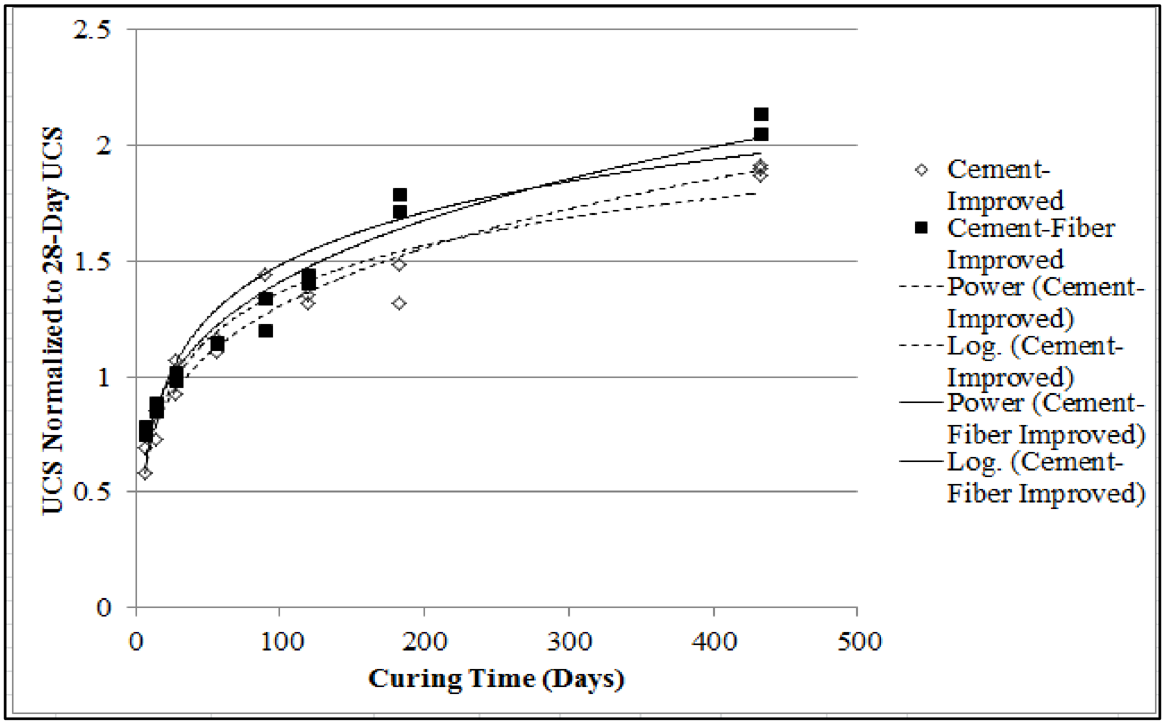

Figure 4.1. Strength Progression of Treated Soils

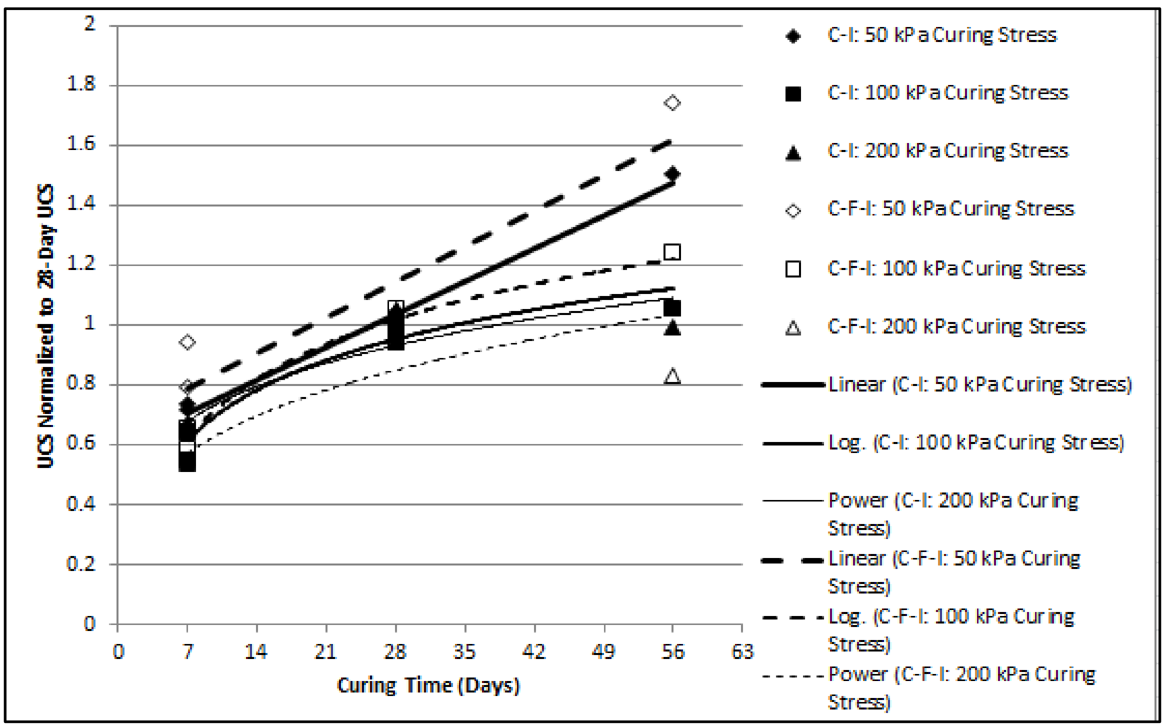

Figure 4.2. Strength Progression for Specimens Subject to Curing Stress
(CI: Cement-Improved, C-F-I: Cement-Fiber-Improved)

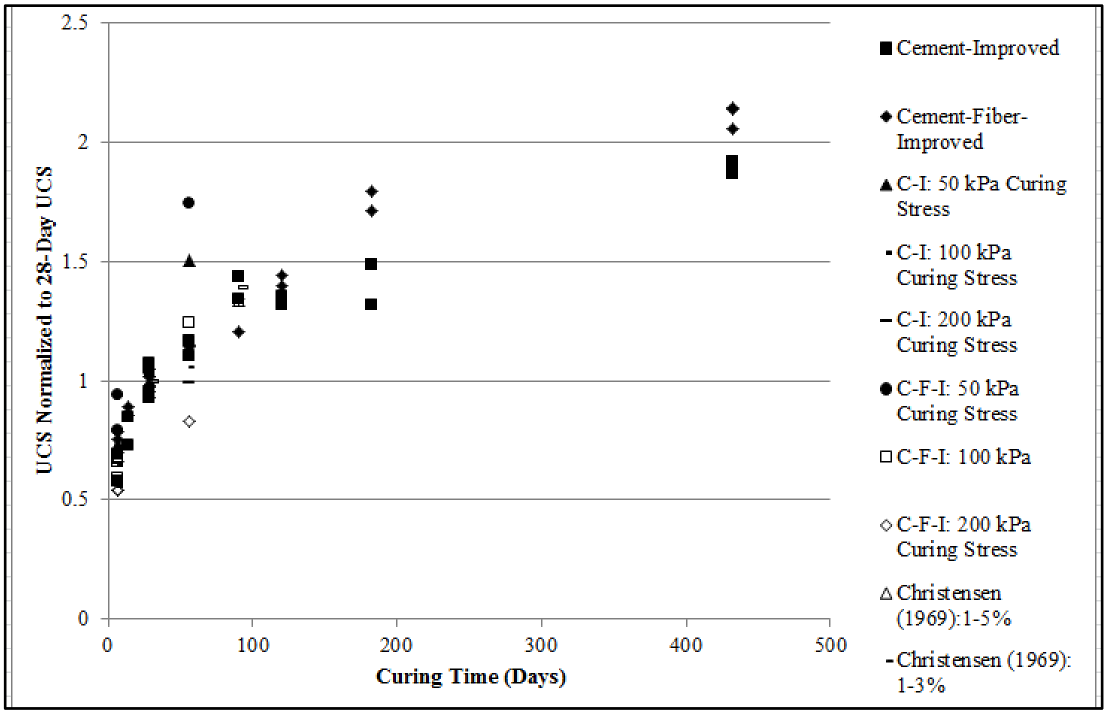

Figure 4.3. Strength Progression for Treated Low Plasticity Clays

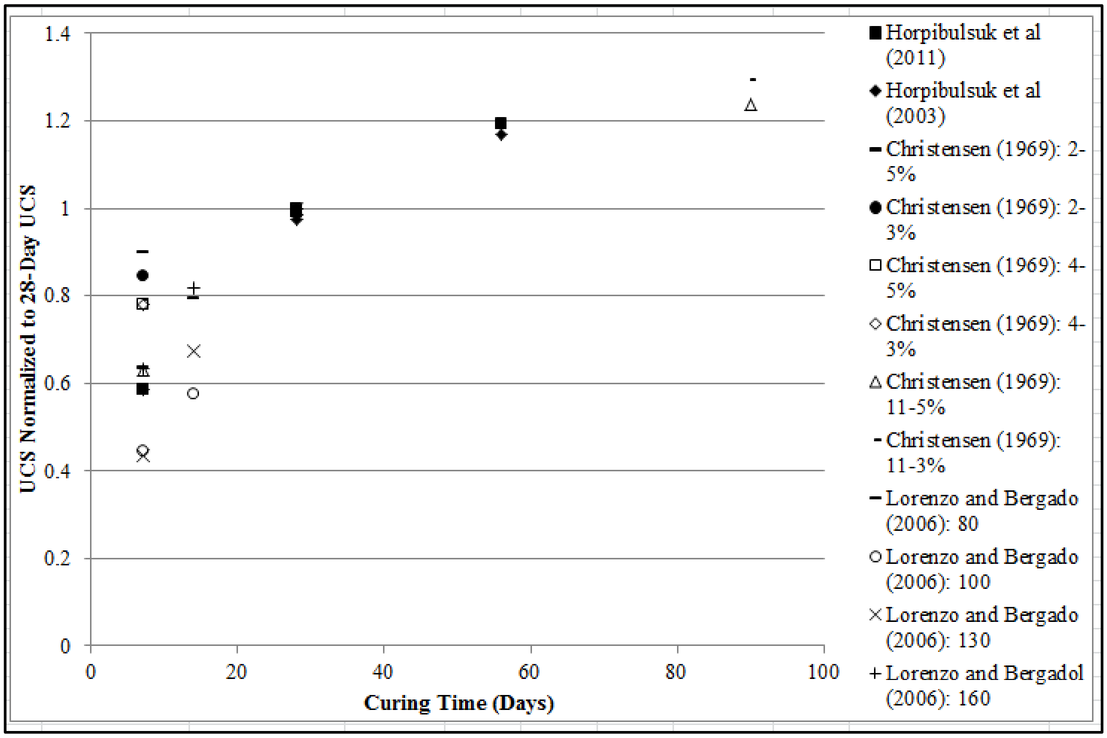

Figure 4.4. Strength Progression for Treated High Plasticity Clays

Strength progression for cement-improved samples subjected to curing stress tended to occur slower than progression for the cement-improved specimens without curing stress. This is indicated by smaller slope values on the logarithmic and linear fit equations. Strength increases for cement-fiber-improved specimens were similar for specimens that did and did not experience curing stress. From Figure 4.2, we see that strength gain was slowest in the cement-fiber-improved specimens cured under 200 kPa stress and fastest in the cement-improved specimens that were cured under a 50 kPa curing stress.

In Figure 4.3, the treated low plasticity clay specimens from this study and other sources are shown. From this plot, it can be seen that the sources report that strength gain occurs and appears to be slower after the 28-day curing time. Clay from the study by Lorenzo and Bergado (2006) show the fastest increase in strength gain, although the clay from Harpibulsuk et al (2011) and Harpibulsuk et al (2003) increase at about the same rate. These are very similar because Bangkok clay was used in each study along with a 10% cement content by weight. Horpibulsuk et al (2011) shows that for this Bangkok clay, the rate of strength increase is relatable between cement contents of 10% and 30% by weight. Clay samples from Christensen (1969) show a slower trend of strength increase mainly due to a dosage rate of 3% or 5% cement content by weight. Also, this is a bentonite mixture which has a lower initial shear strength than the other clays tested.

Best fit lines obtained from Figures 4.3 and 4.4 are included for clay soils in Table 4.2, seen at the end of this chapter. In order to see if all the data could be modeled by best fit equations, data for low plasticity clay specimens were replotted in Figure 4.5, while data for high plasticity clay specimens were replotted in Figure 4.6.

Results from Figure 4.5 indicate that low plasticity clay soils can be grouped together and modeled very well, regardless of cement dosage rate. The following strength progression equations are obtained from the best-fit lines shown:

$$UCS/UCS_{28\text{-}day} = 0.003*(\text{Curing Days}) + 0.08688$$

$$UCS/UCS_{28\text{-}day} = 0.2956*\ln(\text{Curing Days}) + 0.0535$$

$$UCS/UCS_{28\text{-}day} = 0.4111*(\text{Curing Days})^{0.2605}$$

From these results, the best fit line is the power fit with an R^2 value of 0.89. This estimation is closely followed by the fit of the data of cement-improved and cement-fiber-improved specimens presented in this paper.

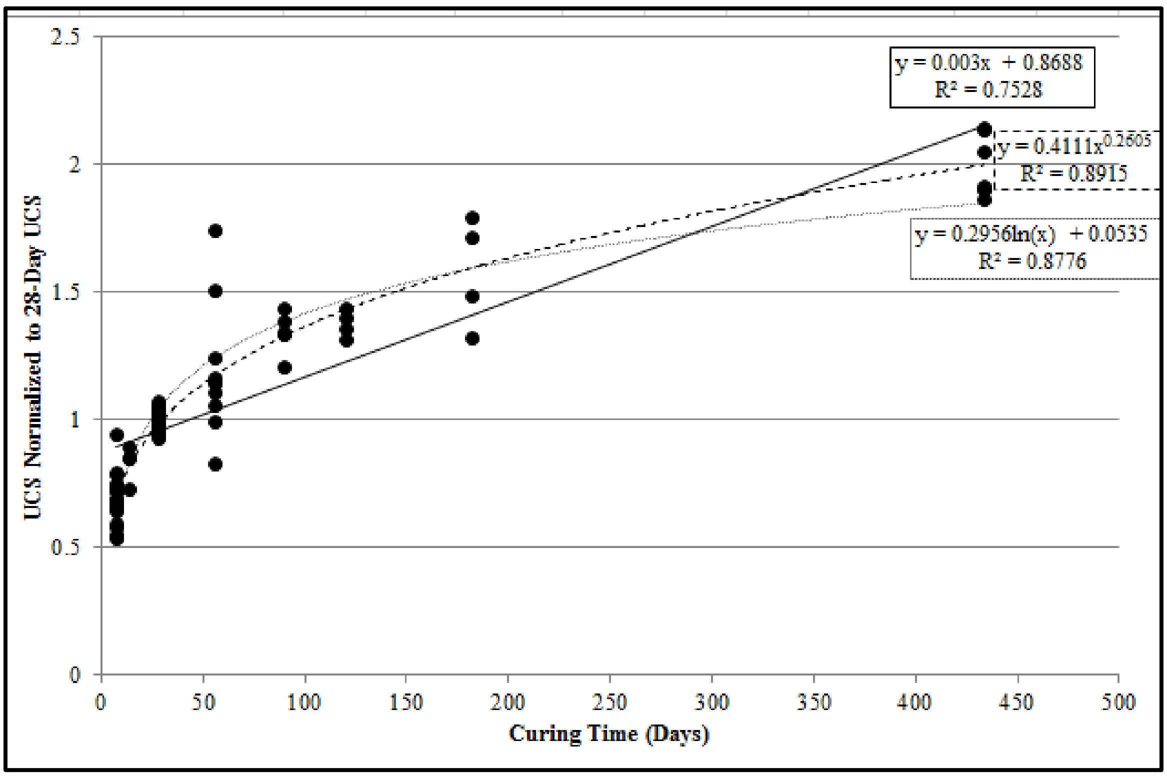

Figure 4.5. UCS Progression for Treated Low Plasticity Clay Soils

Results from Figure 4.6 show that it is difficult to group together specimens of high plasticity clay. The variability in strength gain causes the best-fit line quality to deteriorate by causing lower R^2 values. In any case, the following equations result as the model's best-fit lines:

$$UCS/UCS_{28\text{-}day} = 0.0084*(\text{Curing Days}) + 0.665$$

$$UCS/UCS_{28\text{-}day} = 0.2414*\ln(\text{Curing Days}) + 0.1813$$

$$UCS/UCS_{28\text{-}day} = 0.3711*(\text{Curing Days})^{0.2859}$$

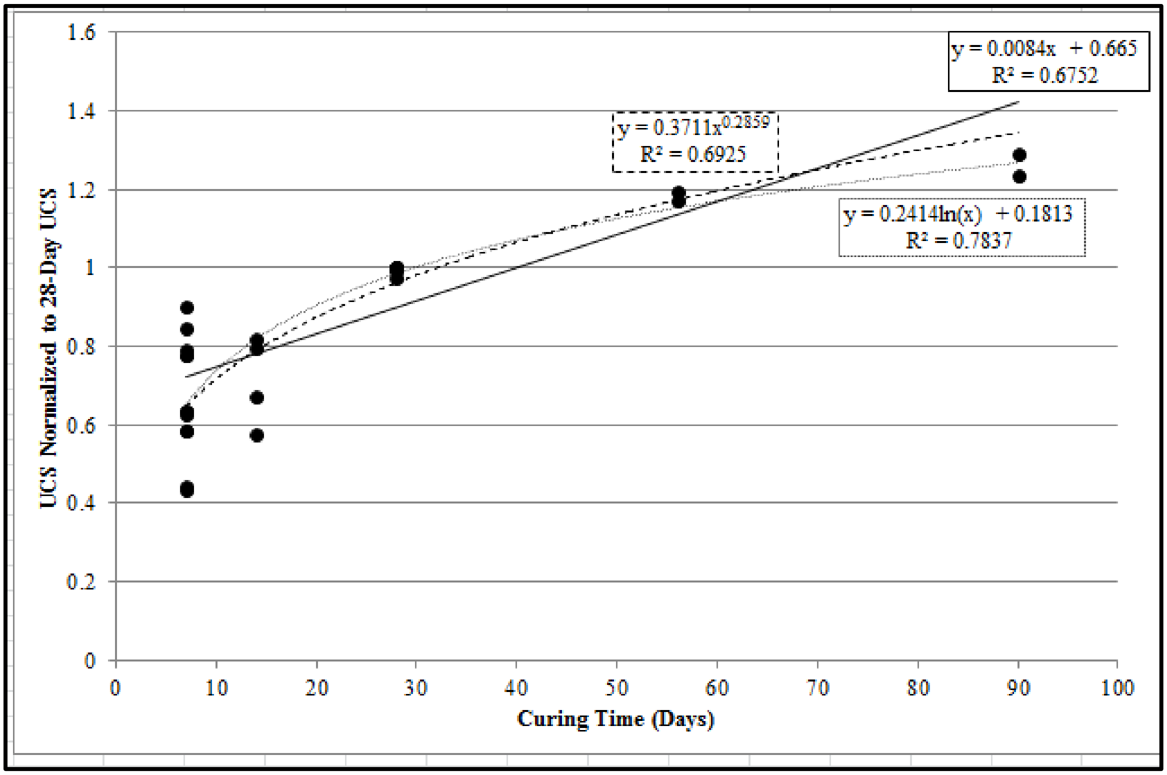

Figure 4.6. UCS Progression for Treated High Plasticity Clays

From these results, the best fit line is the logarithmic fit with an R^2 value of 0.78. As such, the strength gain model equations for cement-treated low plasticity clay and cement-treated high plasticity clays are, respectively:

$$\mathbf{UCS/UCS_{28\text{-}day} = 0.4111*(Curing\ Days)^{0.2605}}$$

$$\mathbf{UCS/UCS_{28\text{-}day} = 0.2414*\ln(Curing\ Days) + 0.1813}$$

These UCS prediction equations can only effectively project strength values for specimens that are prepared in a laboratory setting because laboratory studies were used to formulate best-fit equations and mixing processes and curing conditions are different from what would be experienced by installed CSM in in-situ applications. These equations can be correlated to field conditions with the use of input data from field samples. Field studies, such as the one provided by O'Rourke and McGinn (2004), suggest that samples obtained from the field do not always increase in strength with curing time, but can decrease slowly in strength in a linear fashion.

Table 4.2. Model Fits for each Set of Soil Data

Soil	Source	Source Identifier	Logarithmic Fit	R^2	Linear Fit	R^2	Power Fit	R^2
1	Starcher (2013)	Cement-Improved	y=0.294ln(x)+0.012	.95	y=0.0025x+0.91	.86	$y=0.445x^{0.251}$	.97
2	Starcher (2013)	Cement-Fiber-Improved	y=0.330ln(x)-0.039	.92	y=0.0029x+0.95	.90	$y=0.404x^{0.254}$	.96
3	Starcher (2013)	Cement-Improved, 50 kPa Curing Stress	y=0.315ln(x)+0.074	.84	y=0.016x+0.60	.98	$y=0.387x^{0.31}$	.91
4	Starcher (2013)	Cement-Improved, 100 kPa Curing Stress	y=0.245ln(x)+0.137	.94	y=0.01x+0.6	.75	$y=0.334x^{0.309}$	.92
5	Starcher (2013)	Cement-Improved, 200 kPa Curing Stress	y=0.187ln(x)+0.318	.86	y=0.007x+0.68	.64	$y=0.434x^{0.229}$	.88
6	Starcher (2013)	Cement-Fiber-Improved, 50 kPa Curing Stress	y=0.312ln(x)+0.19	.61	y=0.017x+0.67	.85	$y=0.495x^{0.259}$	.65
7	Starcher (2013)	Cement-Fiber-Improved, 100 kPa Curing Stress	y=0.289ln(x)+0.055	.97	y=0.013x+0.57	.92	$y=0.325x^{0.335}$	.97
8	Starcher (2013)	Cement-Fiber-Improved, 200 kPa Curing Stress	y=0.204ln(x)+0.189	.66	y=0.007x+0.6	.37	$y=0.328x^{0.286}$	.72

Table 4.2. Continued

Soil	Source	Source Identifier	Logarithmic Fit	R^2	Linear Fit	R^2	Power Fit	R^2
9	Horpibulsuk et al (2011)		y=0.292ln(x)+0.018	.00	y=0.0121x+0.56	.93	$y=0.302x^{0.347}$	.99
10	Horpibulsuk et al (2003)		y=0.281ln(x)+0.038	.00	y=0.0117x+0.56	.93	$y=0.306x^{0.338}$	.99
11	O'Rourke and McGinn (2004)				y=-0.07x+1.00	.00		
12	Christensen (1969)	1	y=0.253ln(x)+0.183	.99	y=0.007x+.70	.93	$y=0.416x^{0.261}$	.99
13	Christensen (1969)	1	y=0.260ln(x)+0.189	.98	y=0.008x+0.72	.97	$y=0.434x^{0.257}$	.99
14	Christensen (1969)	2	y=0.073ln(x)+0.76	1	y=0.005x+0.87	1	$y=0.774x^{0.077}$	1
15	Christensen (1969)	2	y=0.112ln(x)+0.627	1	y=0.0074x+0.79	1	$y=0.667x^{0.122}$	1
16	Christensen (1969)	4	y=0.159ln(x)+0.470	1	y=0.01x+0.71	1	$y=0.549x^{0.180}$	1
17	Christensen (1969)	4	y=0.159ln(x)+0.471	1	y=0.01x+0.71	1	$y=0.55x^{0.179}$	1
18	Christensen (1969)	11	y=0.239ln(x)+0.177	.99	y=0.007x+0.68	.84	$y=0.385x^{0.267}$	.97
19	Christensen (1969)	11	y=0.194ln(x)+0.393	.98	y=0.006x+0.79	0.97	$y=0.54x^{0.191}$	.99
20	Lorenzo and Bergado (2006)	RMC = 80%	y=0.263ln(x)+0.115	.99	y=0.017x+0.53	.99	$y=0.335x^{0.328}$	.99
21	Lorenzo and Bergado (2006)	RMC = 100%	y=0.401ln(x)-0.385	.91	y=0.027x+0.23	.99	$y=0.136x^{0.585}$	.96
22	Lorenzo and Bergado (2006)	RMC = 130%	y=0.408ln(x)-0.373	.99	y=0.026x+0.27	.99	$y=0.136x^{0.6}$	.99
23	Lorenzo and Bergado (2006)	RMC = 160%	y=0.264ln(x)+0.119	1	y=0.017x+0.54	.96	$y=0.337x^{0.329}$	.99

CHAPTER 5

Conclusions and Considerations for Future Studies

A series of consolidation tests and UCS tests on unimproved soils, cement-improved soils, and cement-fiber-improved soils were conducted to gain a basic knowledge of the mechanical behavior of these mixtures. UCS tests were analyzed based on strength gain due to curing time and strength gain due to curing stress and curing time. According to the UCS results presented, the UCS of cement-soil mixture increases with curing time and curing stress. It is seen that strength gain can be modeled as a power function as related to curing time for these cement-treated low plasticity clay soils. Also, the strength gain of high plasticity clays treated with cement can be modeled by a logarithmic function of time. Generally, the cement-improved soil behaves as a brittle material, although the introduction of fiber can greatly increase the ductility, or strain experienced at failure, of the mixture by postponing the development of cracks. Strain values at failure are increased by 0.6 to 1.5% in parallel specimens by including fiber reinforcement. In this study, the fiber used has a high tensile strength, which explains why the cement-fiber-improved specimens could tolerate high shear stresses even after peak strength is reached. The existence of fiber in the cement-soil mixture does not significantly change the unconfined compressive strength. The stiffness of the mixture can be significantly increased when the mixture is cured under vertical curing stress, compared with the mixture without curing stress. For example, cement-improved specimens at 7-day curing time can experience a 100% increase in secant modulus by applying 50 kPa curing stress; when applying 100 kPa curing stress, the secant modulus can be up 10 times the original modulus. From consolidation test results, it can be seen that the introduction of cement or cement and fiber can reduce the compressibility index by 30-70% and the swelling index by 45-60%.

Future work should include the development of a comprehensive numerical model through collecting high quality data, including consolidation results, UCS results, and triaxial data. Also, a comprehensive constitutive model for cement-soil mixture under complex loading conditions can be developed after model parameters are calibrated. In addition, UCS tests provide valuable information, such as shear strength, elastic modulus, and strain at failure values, which describes the behavior of cement soil mixtures under monotonic loading. Also, the post peak strength behavior is demonstrated. The limitations of using UCS as design criterion are obvious due to the perceived strength gain with respect to curing time and curing stress and the need for different tests, like triaxial extension or compression tests, to model specific application failure modes. As such, triaxial tests should also be conducted to study the behavior of cement-soil mixture under more complicated loading conditions, such as cyclic loading. Other considerations for moving forward include formulating prediction models of failure behavior in applications and centrifuge testing. Then, these results should be correlated to field results in order to develop design equations for the use of installed CSM in in-situ applications.

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