12-2020

Using BCSA Cement to Repair Waterway Transportation Structures

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Using BCSA Cement to Repair Waterway Transportation Structures

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science in Civil Engineering

by

Anazaria Johanis Ortega Gonzalez
University of Arkansas
Bachelor of Science in Civil Engineering, 2018

December 2020
University of Arkansas

This thesis is approved for recommendation to the Graduate Council

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Abstract

Many maritime structures (e.g., locks, dams, ports) in the US are either reaching or are past their design lives, and there are limited funds for the necessary maintenance activities which can lead to repairs that requires closures. These structures are not easy to detour and often require dewatering before repairs can be made, closures can cause delays and business-related losses which can have a large effect on the nation's economy. Thus, it is advantageous to reduce the repair time for maritime structures. BCSA (belitic calcium sulfoaluminate) cement is a promising material to perform this type of repair due to its properties. BCSA cement is a fast-setting hydraulic cement capable of reaching compressive strengths greater than 4000 psi (27.6 MPa) in less than 2 hours. BCSA also has low shrinkage and good long-term strengths. This research consisted of developing an optimal rapid-setting underwater mortar mixture design using BCSA cement. Properties such as compressive strength and workability were tested to choose the best mix design. Additionally, soil cements made with BCSA cement were compared to portland cement-based soil cements. These soil cements have applications for rapid repair of levees and earthen dams, but also for rapid soil stabilization. The results obtained prove that BCSA cement is feasible to rapidly perform underwater repairs and repairs of soil-based waterway structures.

Keywords: BCSA, underwater, repair, rapid-strength development, soil-cement.

Acknowledgment

Foremost, I would like to thank my advisor, Dr. Cameron Murray, for all his support and guidance during this chapter of my academic career. He continuously helped with my research not only by providing significant insight but also by being physically present during my lab testing and providing an extra hand when needed. Dr. Murray kept me motivated, especially when the lab work did not go as expected. He allowed me to work in his research team without prior having known me and for that, I would be always grateful. I could not have asked for a better mentor.

I also want to thank my committee members Dr. Barry and Dr. Hale for all the comments, thesis writing advice, and help in the lab.

I also want to thank my family: my mom Mireya Gonzalez, my dad Juan Ortega, and my brother Juan Ortega jr. They were unconditional present during this challenging journey. They supported me and have always encouraged me to do my best. They never stop believing in me even when I had doubts. I want to thank my friends Maria Donoso, Juan Martinez, Karla Diaz, and Lee Swagerty, who also motivated me and commented on my writing as it developed. I also want to thank Mariel Mayori, who helped me conduct some lab testing. I want to recognize the contribution of Caleb LeBow, who started this research project. Finally, I want to thank MarTREC for funding this research project and making this possible.

Dedication

I want to dedicate this thesis to my grandmother Terquida Quijada who always encouraged me to study abroad and learn English. She was the main reason I always wanted to study in the United States.

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Introduction and Document Organization

The purpose of this study was to examine the feasibility of using belitic calcium sulfoaluminate (BCSA) cement to repair waterway transportation structures. These structures are often constructed with concrete or soil (often stabilized with cement). Thus, the research was divided into two parts; developing a mortar mix design to repair concrete structures, and testing soil-cement mixtures to perform repairs in earthen structures.

To develop the mortar mix design certain parameters were considered, workability, self-consolidation ability, and compressive strength. These parameters were altered by testing different variables in the mix designs such as *w/c* (water to cement ratio), *s/c* (sand to cement ratio), chemical admixture dosage and casting conditions.

For the soil-cement mixtures, the main property tested was the compressive strength at varying ages. The variables that affected the compressive strength at different ages in this study were cement type (BCSA vs PC (portland cement)), and moisture content.

Part 1 of this thesis describes the development of a BCSA cement mortar for underwater applications. Part 2 describes the development of BCSA cement and soil mixtures and compares their compressive strengths to soil-cement made with portland cement.

Part 1: Development of a BCSA Cement Mortar for Underwater Applications

1.0 Introduction

Part 1 of this thesis provides background information of the materials used and the existing guidelines to make BCSA cement mortar mixtures for underwater applications. The procedures used to analyze the performance of this repair material is summarized and results and the conclusions were provided to give guidance for future mixtures in these applications. The main goal of this study was to produce a self-consolidating mortar that could be placed underwater and that could reach 4000 psi (27.6 MPa) compressive strength in around 3 hours.

1.1 Literature Review

CSA (calcium sulfoaluminate) cement was first introduced in 1960s, but its use was not widespread until the 1970s when its popularity increased in China especially [1, 2]. One initial application was for self-stressing concrete pipe due to its expansion during the hydration process causing a chemical prestress. Belitic CSA or BCSA cement is a special variety of CSA cement containing a large amount of belite, reducing the early age expansion and resulting in a roughly neutral volume change during hydration. BCSA cement also has low porosity and permeability which increases its resistance to deterioration [1, 3]. All CSA based cements primarily gain strength through the formation of ettringite during the hydration process which also influences the porosity and permeability of this material [4]. The term CSA cement encompasses a variety of products of which BCSA is just one. Based on the composition of different varieties of CSA cements different benefits such as rapid strength development, high rate of expansion, fast hardening, or shrinkage resistance can be obtained [5, 6]. BCSA cement is a fast-setting cement with rapid strength development which can be used as a standalone cement, i.e., not as an additive to portland cement (PC). This cement can reach a compressive strength greater than

4000 psi within two hours, while PC may take as long as 28 days to reach the same strength. The rapid strength gain at the early age of the concrete is mainly attributed to the formation of ettringite while the development of later age strength is caused by the slower hydration of belite [4].

BCSA cement is a more sustainable alternative to PC. It takes less energy to produce BCSA cement, reducing CO_2 emissions by 20% to 40% [5, 7]. In addition to that, 50% of CO_2 generated during the manufacturing of PC is due to the calcination of limestone to obtain lime, but BCSA cement uses 40% less limestone and can be calcined at a lower temperature than PC [5, 7, 8]. BCSA calcination occurs at 2282 °F (1250 ºC) while PC needs a temperature of 2642 °F (1450 ºC) [4, 8]. BCSA cement also has low alkalinity which causes this material to be less susceptible to chemical reactions, such as alkali-silica reaction [1]. BCSA cement has ample established benefits, but more research must be done to better understand its mechanical properties and to explore further uses of its unique abilities. This material has been underutilized in the USA due to a lack of research, technical barriers to its use, lower production volumes, and higher cost. Due to the lower demand for this cement and the high price of the raw material needed to produce it, BCSA cement costs around four times more than PC cement [1]. While this cost disparity is significant, the benefits obtained from BCSA cement may counteract its high cost in certain applications [1] [9]. Additionally, due to the increasing cost of energy and new environmental regulations it has been predicted that PC will be twice as expensive in 2030 as it is today [7].

Previous research has suggested potential applications for BCSA cement that take advantage of its unique properties. It can be used to prevent seepage or improve concrete products such as pre-stressed concrete members [4, 10]. BCSA cement also allows for construction in lower temperatures than PC because it is a fast-setting cement with high heat of hydration. The research presented in this paper proposes another potential application for BCSA cement: rapid-setting underwater repair grouts.

Maritime structures have an imperative role in the economy of a nation, so they must operate efficiently. Marine structures are often designed to have a 25-year service life, but some structures still in operation are over 100 years old [3]. Proper maintenance and rehabilitation measures are necessary to keep these maritime structures operating at their maximum capacity. However, structures in the USA have been poorly graded by the American Society of Civil Engineers (ASCE) [11]. These structures are not easy to detour, therefore major repairs cause delays and create business related losses affecting the national economy. Thus, it is necessary to reduce the repair time for these structures. BCSA seems ideal to perform these types of repairs due to its fast setting time and early high strength development.

There are different types of waterway transportation structures such as locks dams, breakwaters, embankments, slope protection structures, and outlet tunnels. Many of these structures are made of concrete, which is susceptible to cracking. These structures can crack due to chemical reactions, design errors, excessive loading, or weathering. For example, during cold weather, the water in concrete can freeze. If this happens, the volume of water increases building up internal hydraulic pressure and leading to cracking, spalling, or scaling of concrete which cause serious damage to the structure [3]. Concrete cracking can lead to additional problems such as rebar corrosion because the cracks expose the rebar to water. Steel corrosion also affects the serviceability of the structure because the tensile capacity of the steel is reduced and the bond between the concrete and steel is weakened. BCSA cement has a higher resistance to weathering problems, which can limit the necessity for future repairs in the structure if this material is used.

The purpose of this study is to determine whether BCSA cement can be used to perform underwater repairs due to its rapid setting and high early-age strength. As a starting point for underwater concrete using BCSA cement, a series of mortars were developed for underwater use.

1.2 Research Significance

BCSA cement has the potential to significantly reduce the repair time needed to restore waterway transportation structures. Ensuring that waterway transportation structures are well-functioning has multiple economic and social benefits. This study proposes mixture designs for BCSA cement mortars which can set underwater. This study will aid in understanding how to proportion BCSA cement mixtures for underwater applications

1.3 Experimental Procedures

1.3.1 Materials

BCSA cement was used to make the rapid setting mortars in this work. This cement is classified as very rapid hardening (VRH) conforming to ASTM C1600 [12]. The initial and final set times are 15 and 20 minutes respectively as provided by the producer per ASTM C191 [13]. It typically exceeds a compressive strength of 4000 psi (27.6 MPa) in less than 2 hours. The typical chemical composition of the BCSA cement is given in *Table 1*.

Table 1. Chemical composition of BCSA cement [14].

Chemical Compounds	Name	BCSA cement % mass
C_2S	Belite	45
C_4AF	Ferrite	2
$C_4A_3\hat{S}$	Ye'elimite	3

Table 1. Chemical composition of BCSA cement cont. [14].

Chemical Compounds	Name	BCSA cement % mass
$C\hat{S}$	Calcium sulfate	15
	Other	8

Natural river sand with a specific gravity of 2.6 and fineness modulus of 2.5 was used. The sand gradation curve has been also provided (see *Figure 1*). The sand used to make the mortar mixture was passed through a No. 4 (4.75 mm) sieve to get rid of fine gravel or any other larger particles present in the sand. The sand was also oven dried to ensure consistent moisture content between batches.

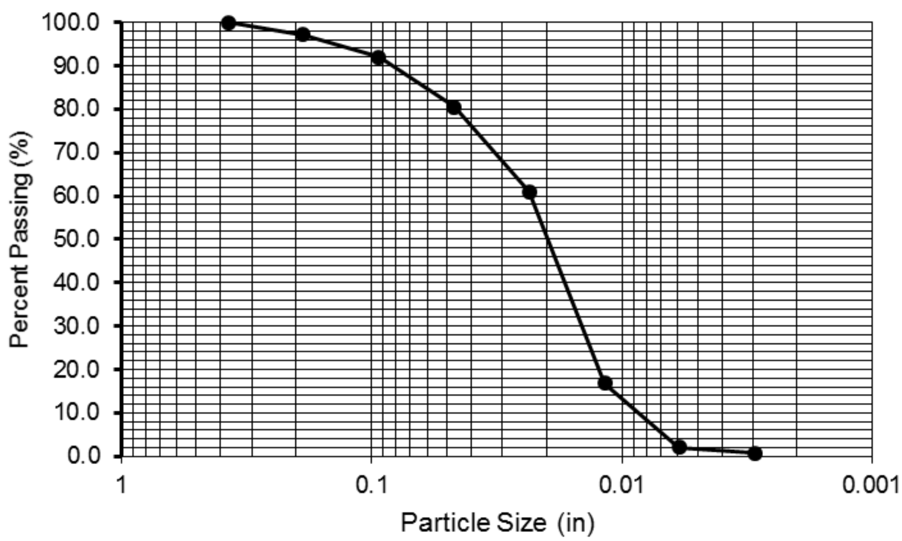

Figure 1. Sand Gradation Curve. Note: 1 in = 25.4 mm

The BCSA cement hydration process leads to the rapid formation of ettringite crystals. These crystals are the reason BCSA cement gains high strength in a very short time. The rapid hydration process also leads to fast setting times which may interfere with the proper placement of fresh mortar. Food grade citric acid has been proven to slow the setting time indefinitely if the right dosage and moisture content are available [1, 15, 16]. Thus, citric acid was used in the research project as a retarder. The citric acid admixture was made by mixing 5 lb (2.27 kg) of powdered citric acid with 1 gallon (3.78 L) of water. Research have previously shown a linear relationship between the citric acid dosage and initial setting time [15]. The dosage used also affects the difference between the initial and final setting time. As the dosage is increased the difference between the initial and final setting time increases. Citric acid also affects other properties such as the viscosity of the mix as well as the internal reaction temperature [15]. The mortar flow, a measurement of viscosity, can increase if higher citric acid dosages are employed. On the contrary, the relationship between the retarder dosage and the temperature is inversely proportional caused by the deceleration of the reaction which decreases the internal heat produced during hydration. The citric acid dosage also has a minor impact on the compressive strength, and this can be related to the change in temperature. High temperatures during curing causes higher early-age strength while low temperatures cause higher late strength which is also related to the rate of hydration and the formation of the reaction products [1, 16]. Another factor that affects the rate of the reaction is the water temperature, for example hot water can work as a catalyzer during hydration. Since BCSA cement uses more water than PC to hydrate, enough water should be available to avoid self-desiccation for the reaction to occur [5]. A polycarboxylate based high range water reducer (HRWR) was used to develop adequate workability and mortar flow. A viscosity modifying admixture (VMA) was also used. The use of a VMA results in an anti-washout mortar that can be used for underwater applications. The VMA improves mortar cohesion, reduces segregation, and allows self-consolidation. VMAs are beneficial for environmental reasons in this application because they can reduce water pollution caused by materials separation (washed-out products) when mortar or concrete is placed underwater [17, 18, 19].

1.3.2 Mixture Proportions:

Five different water to cement ratios (*w/c*) were used to determine the effect on compressive strength. Currently, there is little published work showing the relationship between *w/c* and strength for BCSA cement mixtures. Two different casting conditions were compared: dry and wet (underwater). Next, the sand to cement ratio (*s/c*) was changed at the same five water to cement ratios to demonstrate the influence of the *s/c* on the compressive strength and flow. Admixture dosages of 20 fl. oz/cwt (1304 mL/100 kg cement) each of HRWR and VMA was used, and the citric acid dosage was 7 fl. oz/cwt. (456 mL/100 kg cement). This dosage of citric acid was expected to provide approximately 35 minutes of working time. All the ingredients were proportioned based on the *w/c* and the *s/c*. These values have been summarized in *Table 2.* The total volume of the mortar mixtures was 0.20 ft^3 (5663 cm^3).

Table 2. Mix designs summary.

w/c	*s/c*	Cement (lb)	Sand (lb)	HRWR (lb)	Citric Acid (lb)	VM (lb)	Water (lb)
0.44	1.00	10.26	10.26	0.1246	0.0436	0.1246	4.35
	1.25	9.42	11.78	0.1145	0.0401	0.1145	4.07
	1.50	8.82	13.24	0.1071	0.0375	0.1071	3.74
0.42	1.00	10.44	10.44	0.1268	0.0444	0.1268	4.21
	1.25	9.57	11.97	0.1163	0.0407	0.1163	3.95
	1.50	8.96	13.43	0.1088	0.0381	0.1088	3.61
0.40	1.00	10.63	10.63	0.1291	0.0452	0.1291	4.08
	1.25	9.73	12.16	0.1182	0.0414	0.1182	3.82
	1.50	9.09	13.64	0.1104	0.0386	0.1104	3.49

Table 2. Mix designs summary cont.

w/c	*s/c*	Cement (lb)	Sand (lb)	HRWR (lb)	Citric Acid (lb)	VM (lb)	Water (lb)
0.36	1.00	11.03	11.03	0.1340	0.0469	0.1340	3.79
	1.25	10.07	12.57	0.1223	0.0428	0.1223	3.55
	1.50	9.38	14.07	0.1139	0.0399	0.1139	3.22
0.34	1.00	11.24	11.24	0.1364	0.0478	0.1364	3.64
	1.25	10.24	12.79	0.1244	0.0435	0.1244	3.40
	1.50	9.53	14.3	0.1158	0.0405	0.1158	3.08

Note. 1 kg =2.2 lb; 1kg= 1000 g

1.3.3 Specimen Preparation and Testing

Once all the materials were weighed, the liquid ingredients were mixed (water, citric acid, HRWR, and VMA). According to ASTM C305-14 [20], an electric powered paddle mixer was used. The cement was added next and these ingredients were mixed at a low speed for 30 seconds. The sand was then added gradually over 30 seconds without stopping the mixer. The mixer was stopped, and the speed was changed to medium for 30 seconds. After this, the mixer was stopped again to scrape any dry material off the sides and the bottom of the mixer. Then, the mixer ran for one minute at medium speed until a homogenous mixture was obtained. The mortar was left sitting in the mixer for 3 minutes while a mortar flow test was run according to ASTM C1437-15 [21]. The flow was later calculated as the percent increase of the original mortar diameter. After the flow test was done, 24 mortar cubes [2 in. (50.8 mm)] were made per ASTM C109/C109 M16-a [22]. This ASTM requires compaction of the material in two layers using a plastic rod, but for this research application self-consolidated mortar was needed, so the ASTM C109/C109 M16-a was modified. The self-consolidation of the mix was achieved by using a plastic funnel and letting the mortar flow freely into the mold during casting. Twelve mortar cubes were poured under dry conditions, and the other twelve were poured into molds that were entirely submerged underwater (see *Figure 2*). Once all the specimens were cast, the excess material from the top was removed using a plastic rod to create a smooth surface. After that, they were moved and stored in an environmental chamber at 70°F (21.1 °C) and 50% relative humidity. The underwater samples remained submerged inside the environmental chamber. It typically took 2 to 2.5 hours for the mortar cubes to set. Setting time was not measured, the demolding time was selected qualitatively by observing the surface condition of the cubes and pressing on them gently with a gloved finger. They were then taken out of their molds and placed in a water tank in the environmental chamber for curing. A lime bath was not used since lime water can degrade the strength of BCSA cement mixtures. The compressive strength of the specimens was measured at 3 hours, 1 day, 7 days and 28 days. Three cubes were tested and averaged to obtain the compressive strength at each age.

Figure 2. Fresh mortar specimen casting set-up.

1.4 Results and Discussion.

1.4.1 Physical Appearance

The physical appearance of the specimens was influenced by the *w/c* and the *s/c* ratio. Samples with a higher *w/c* showed smooth surfaces in comparison to those with a lower *w/c* whenever the *s/c* was constant. There was also physical difference between samples cast underwater and those cast in a dry surface. The cubes cast underwater showed more voids that those cast in a dry condition. The size of the voids increased as the *w/c* was decreased (see *Figure 3*). When samples using different *s/c* ratios were compared at the same *w/c*, there was a difference in the surface appearance of the samples which can be explained in terms of the flow. Higher flow usually leads to smoother surfaces. Thus, samples with higher sand content had a lower flow which caused the specimens to have rough surfaces.

Figure 3. Mortar cubes using different w/c and 1.25 s/c. (A) dry sample using a 0.42 w/c; (B) wet sample using a 0.42 w/c; (C) dry sample using a 0.36 w/c; (D) wet sample using a 0.36 w/c.

1.4.2 Mortar Flow

The flow was measured using five different w/c and three different s/c. These two parameters affect the cement content of the mix design. The VMA and HRWR dosages was influenced by the cement content. Lower sand to cement ratios required higher cement content and having higher cement content resulted in higher VMA dosages. VMA has been shown to reduce the flow. A slightly difference in the mortar flow for the samples using *w/c* (0.42, 0.40, 0.36, and 0.34) was observed (*see Figure 4*). This can be attribute to the viscosity modifier dosage counteracting the effect of the lower s/c. On the other hand, the addition of HRWR increases the mortar flow.

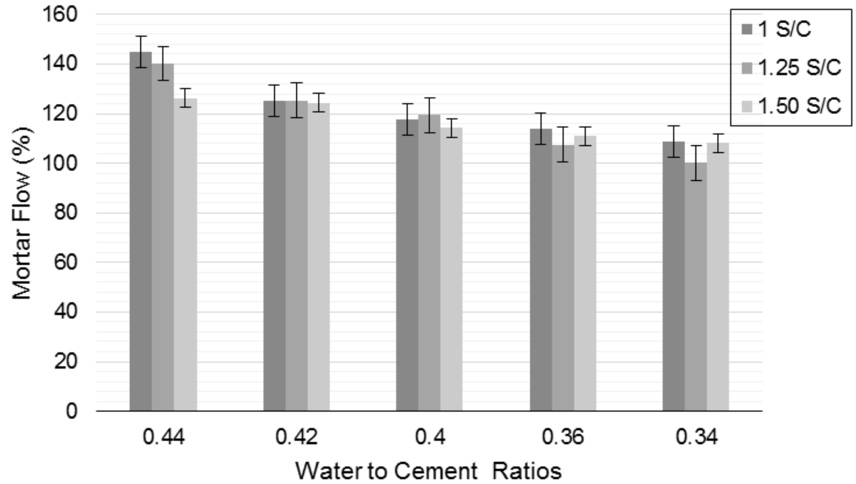

Figure 4. Mortar flow percent using different s/c and w/c.

High flow was necessary to facilitate self-consolidation of the samples, however higher flows may promote washout in underwater applications. VMA was used in all mixtures to prevent washout. VMA has been shown to affect flow, so addition or subtraction of VMA from the mixture is another variable to be considered when attempting to maximize mortar flow. There was a roughly linear relationship between the VMA dosages and the mortar flow. As the VMA dosage increased the mortar flow decreased. However, higher *s/c* required lower VMA dosages to reach similar mortar flows as those with lower *s/c* (see *Figure 5*).

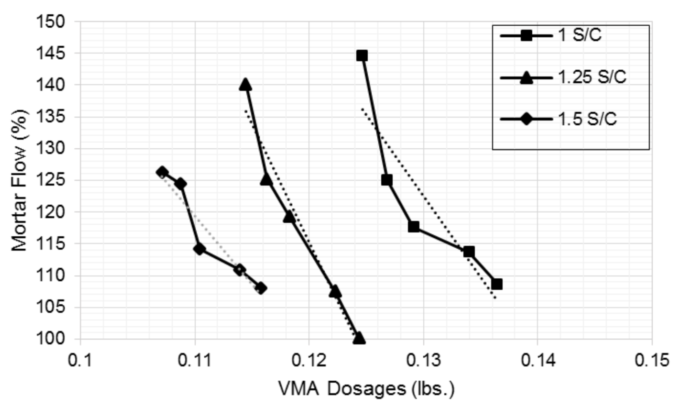

Figure 5. Relationship between the mortar flow and the VMA dosages. Note: 1kg =2.2 lb;1kg= 1000 g

1.4.3 Compressive strength

The compressive strength was affected by different factors: *w/c*, *s/c*, mortar flow and the casting conditions. The research mainly focused on the early age compressive strength rather than the 28-day compressive strength because it is anticipated that BCSA would only be used if high early strengths were desired (*Table 3*).

Table 3. Average compressive strengths in psi measure at 3 hours.

s/c	1		1.25		1.50	
w/c	Dry	Wet	Dry	Wet	Dry	Wet
0.44	5350	3990	4810	3660	4440	2750
0.42	5640	2480	5470	4290	5350	3580
0.40	7030	3020	6470	3670	5930	2130
0.36	3360	1510	6900	4160	3930	1500
0.34	4310	2230	6290	2040	4140	1530

Note: 1000 psi = 6.89 MPa

A compressive strength target of 4000 psi (27.6 MPa) at 3 hours after casting was selected since this was considered a likely goal for rapid structural repairs. Almost all the dry specimens using a 1.0 *s/c* achieved compressive strengths higher than 4000 psi (27.6 MPa) within 3 hours, but none of the wet specimens did. The highest compressive strength achieved by the wet specimens was 3990 (27.5 MPa) psi using a 0.44 *w/c*. This sample had the highest mortar flow which facilitated self-consolidation of the sample and decreased the number and size of voids which may have resulted in a higher compressive strength. The dry compressive strength at the 0.44 *w/c* was 5350 psi (36.9 MPa). If the compressive strength for the dry and wet specimens are compared, there was a 25% difference between these two values. The highest overall compressive strength for the dry samples was 7030 psi (48.5 MPa) at a 0.40 w/c (see *Figure 6*, *Figure 7*).

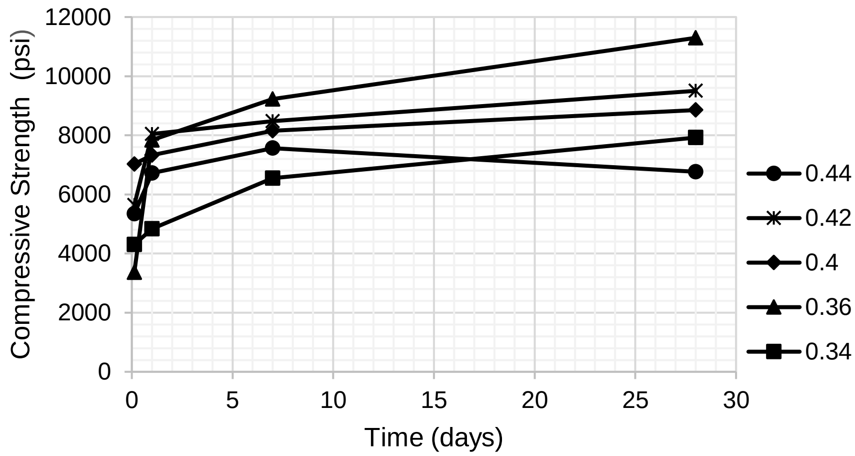

Figure 6. Compressive strength of dry specimens using 1.0 s/c. Note: 1000 psi = 6.89 MPa

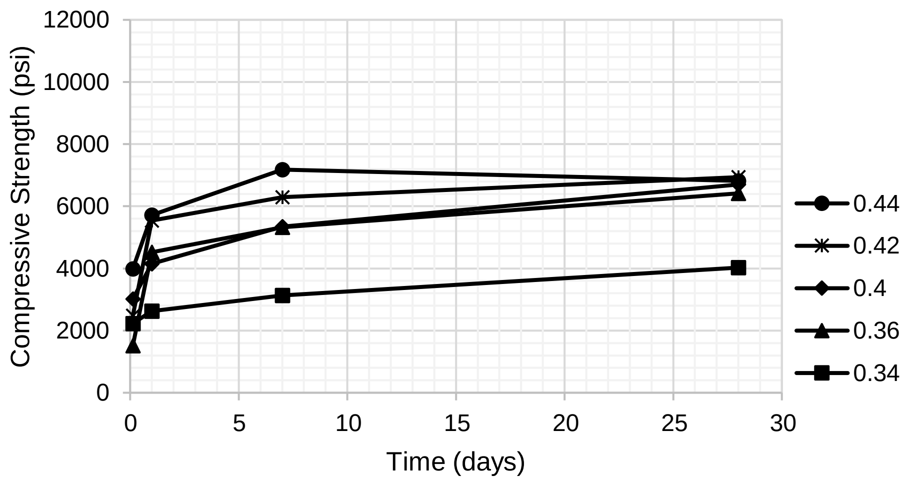

Figure 7. Compressive strength of wet specimens using 1.00 s/c. Note: 1000 psi = 6.89 MPa

The compressive strengths for all dry samples were higher than 4000 psi (27.6 MPa) within 3 hours for specimens using 1.25 s/c (*Figure 8*). The highest dry compressive strength was 6900 psi (47.6 MPa) using 0.36 w/c. The highest compressive strength for the wet specimen was 4290 psi (29.58 MPa) using a 0.42 w/c (*Figure 9*). The dry compressive strength using a 0.42 w/c was 5470 psi (37.7 MPa). If the dry and wet compressive strength using a 0.42 w/c are compared, a 23% difference was observed.

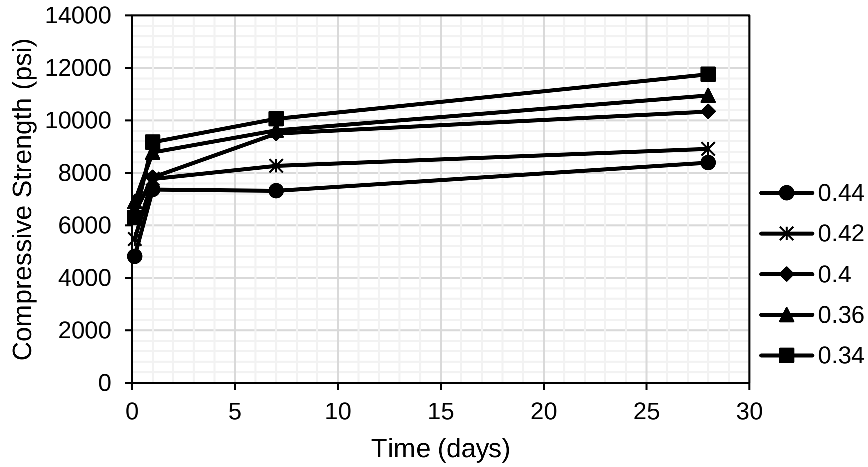

Figure 8. Compressive strength of dry specimens using 1.25 s/c. Note: 1000 psi = 6.89 MPa

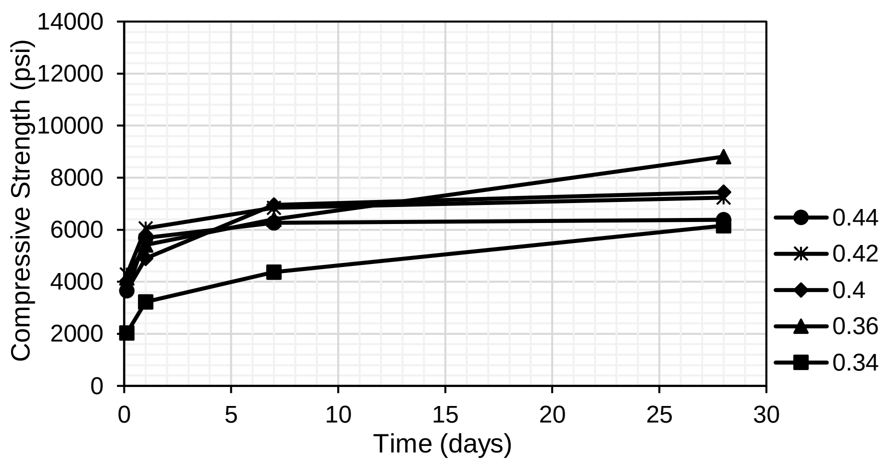

Figure 9. Compressive strength of wet specimens using 1.25 s/c. Note: 1000 psi = 6.89 MPa

Samples using a 1.50 *s/c* also achieved strengths greater than 4000 psi (27.6 MPa) at 3 hours of age when samples were cast in a dry condition, but none of the wet specimens reached a compressive strength greater than 4000 psi (27.6 MPa).The highest compressive strength was 5930 psi (40.9 MPa) using a dry cast condition and 0.40 *w/c (see Figure 10).* Specimens with lower *w/c* (0.34, 0.36) did not achieve the highest dry compressive strengths due to poor flow. The highest compressive strength for the wet specimens using was 3580 psi (24.7 MPa) using a 0.42 *w/c (see Figure 11).* If the dry and wet specimens are compared using a 0.42 *w/c* and 1.50 *s/c*, there is 33% difference since the compressive strength for the dry sample is 5350 psi (36.9 MPa). All the values summarized were obtained at 3 hours. For this type of application based on the compressive strength, mortar flow and physical appearance, the recommended mix design for underwater use was a 0.42 *w/c* and 1.25 *s/c*.

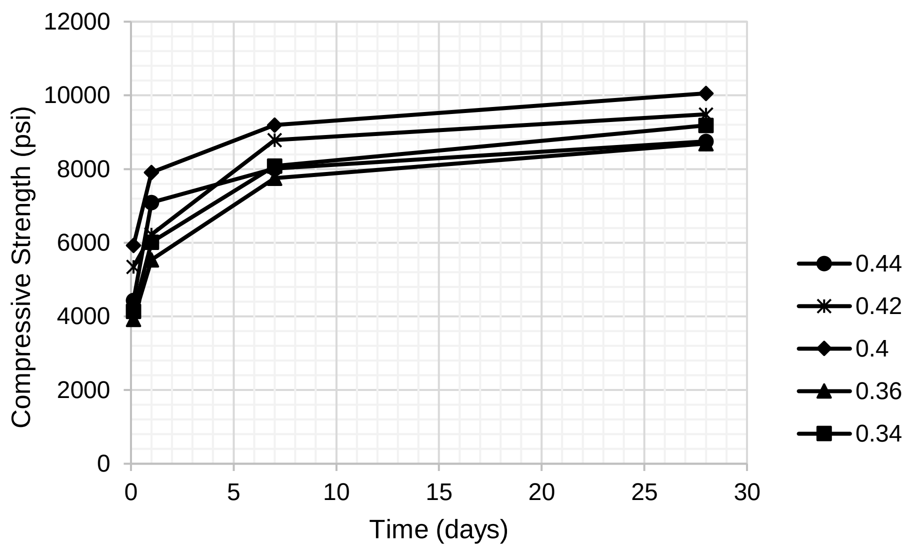

Figure 10. Compressive strength of dry specimens using 1.5 s/c. Note: 1000 psi = 6.89 MPa

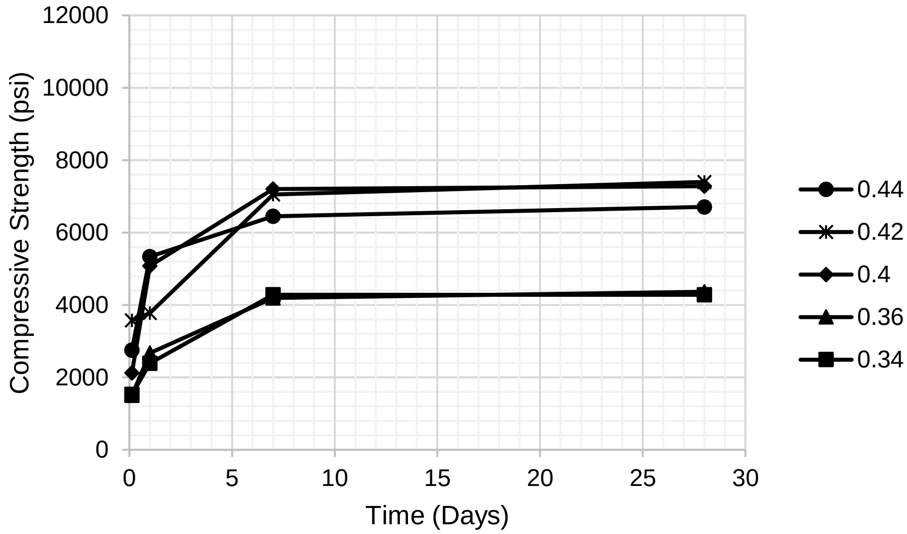

Figure 11. Compressive strength of wet specimens using 1.5 s/c. Note: 1000 psi = 6.89 MPa

1.5 Conclusions

The goal of this study was to proportion a mortar mixture using BCSA cement suitable for underwater use. The mixture was intended to achieve a compressive strength of 4000 psi (27.6 MPa) within 3 hours when placed underwater while being self-consolidating. Mortar flow was measured as well as compressive strength for “dry” and “wet” specimens (wet being cast underwater). Conclusions from the work are as follows:

1. Mortar flow affected the physical appearance of the specimen. Lower mortar flow created a rough surface in the mortar specimens and resulted in more voids and lower strength. This could primarily be controlled by using a lower *s/c*. High mortar flow improved the specimen self-consolidation which also affect the compressive strength.
2. The casting conditions also affected the physical appearance of the samples.
3. Casting samples underwater reduced the maximum compressive strength by 23% to 33% when tested at 3 hours. Compressive strengths were consistently lower for samples cast

underwater, but it was possible to reach 4000 psi (27.6 MPa) in 3 hours for many of the mixtures tested.

4. High VMA and HRWR dosages were needed when using low *s/c* to improve workability and consistency.
5. More research should be conducted to further understand the relationship between *s/c* and compressive strength for this type of application.

Part 2: Development of a BCSA Soil-Cement Mixture

2.0 Introduction

This part of the study consisted of making a soil-cement mixture using two types of binder (PC and BCSA). Uniaxial unconfined compressive strength tests were conducted to determine the feasibility of this material for soil stabilization and investigate the strength gain potential. Existing studies on soil-cement have mostly used PC, but BCSA is a promising alternative to replace PC, especially for applications where rapid strength gain is desired. Soil-cement made with BCSA can be either used to repair existing structures or allow fast construction of new ones. In general, adding cement to soil increases the load-bearing capacity of the soil. Soil-cement is a durable, economical material with low permeability.

This study describes the different applications of soil-cement, and highlights the guidelines used to cast soil-cement specimens for lab testing. Soil-cements have been used in water resources applications, pavement applications and deep soil mixing. This study provides information on the early strength gain of BCSA soil-cement that can be applied to all these different applications.

The results presented in this part of the thesis include observations on the physical appearance of the soil-cement specimens, stress-strain mechanism, failure strain and maximum compressive strength.

2.1 Literature Review

Soil cement can be defined as a mixture of soil, cementitious materials, water, and other pozzolanic admixtures. These materials are compacted and cured to meet specific engineering requirements. Soil-cement is considered an economical material since it can be prepared in-situ with existing soils. The cement content, soil type, moisture content, and compaction effort are the main factors that affect the soil-cement properties and characteristics [23]. Standardized tests are conducted to determine the moisture content needed for compaction of the sample as well as to ensure adequate cement hydration.

The ideal soils for making soil-cement are granular soils since they can be improved using lower cement contents. Sandy materials with low fines contents can be also used to make soil-cement, but this material will require more cement than granular soils. Clayey and silty soil can also be improved by adding cement, but the cement content needed would depend upon the pulverization of the soil [23, 24, 25].

The curing method used for soil-cement will mainly depend on the desirable application of the material [23, 24, 25]

2.1.1 Different applications of Soil-cement.

Soil-cement has been used for different applications including erosion reduction, pavement subgrades, and deep mixing for foundations. Soil-cement is a strong, cost effective, and durable material. The ubiquitous nature of cementitious materials reduces the extra cost tied to long-distance hauling of stronger soils to a site and soils can easily be improved in-place with cement.

2.1.2 Erosion Related Applications

For erosion related applications, another control alternative includes the use of riprap (i.e., boulders, cobbles, and gravels placed along an embankment) which protects shorelines against high-impact waves and weathering. However, the type of rock used for riprap can be unavailable at locations where slope protection work is needed resulting in higher costs. After War World II, many water resources projects were carried out around the US; however, the economic feasibility of using riprap as the main slope protection method was debatable. This motivated the U.S. Bureau of Reclamation to start researching new sustainable alternatives such as soil-cement. In 1951 the U. S Bureau of Reclamation started testing soil-cement samples using sandy soils, and they concluded that this material was erosion resistant. The initial application of soil-cement was slope protection, but it later expanded into streambank stabilization, channel application, and pond linings [24].

Soil-cement for streambank protection is used to prevent lateral or overtopping erosion in places where there is a high risk of flooding. A natural disaster such as flooding can result in significant property losses. Each year more structures in the US are damaged by flood events. The number of extreme precipitation events has increased by 9% from 1958 to 2012 [26]. The definition of extreme varies based on location, season, and precipitation historical record. Earthen levees have been directly affected by the increase of extreme precipitations events and flooding. In fact, a research study conducted on the California levees system suggested that more that 25% of levees have failed in the past 155 years due to various conditions including flood events [26]. Certain factors causing levee failures include slope stability problems, overtopping erosion, internal erosion, and seepage. A study conducted by the Army Corps of Engineers recommended the used of the stair-step method in conjunction with the plating method for levee rehabilitation. The combination of both methods was suggested not only to reduce the cost, but also to prevent a new failure caused by underseepage or overtopping erosion [27]. Protective armoring of the levee surface either through vegetation or another material has been shown to drastically reduce the failures due to overtopping erosion. Soil-cement mixtures could be used for this type of armoring or as a rapid patch material after a damaging event.

Soil-cement can be also used for channel coating. This application first started in 1943 when the hydraulics laboratory at Oklahoma State University tested an open flume using a soil-cement mixture as lining. The soil-cement mix consisted of 60% sand, 40% clay, and 8% cement. This flume was tested for 6 days using a constant water rate of 150 ft^3/s (4.25 m^3/s) with a velocity of 28 ft/s (8.6 m/s). The use of soil-cement resulted in minimized water losses and erosion protection for the flume. Soil-cement has lower permeability reducing the change in water depth or water losses due to seepage. This property also allows soil-cement to be used for pond lining applications [24].

The cement content recommended for slope protection is given by AASHTO (American Association of State Highway and Transportation Officials) (*Table 4*). Higher cement contents than those used in pavement applications are recommended because the soil-cement used in erosion related applications is exposed to more extreme environmental conditions. The U.S Bureau of Reclamation recommends the use of soils with a maximum plasticity index (PI) of 8%. Additionally, minimum compressive strength requirements should be met based on the desired application (Table 5). Before conducting the compressive strength test, the soil-cement specimen must be cured at 100% humidity and placed underwater for 4 hours [24].

Table 4. Normal range of cement content for soil-cement slope protection based on AASHTO classification [24].

AASHTO soil group	% by volume of soil	% by weight of dry soil
A-1-a	7-9	5-7
A-1-b	9-11	7-10
A-2-4	9-12	7-11
A-2-5	9-12	7-11
A-2-6	9-12	7-11
A-2-7	9-12	7-11
A-3	10-14	9-13

Table 5. Minimum compressive strength requirements at 7 days for different water resources applications [24].

Application	Compressive strength at 7 days (psi)
Liners	500
Soil embankment protection	600
Grade control	1000
Spillways	2000

Note: 1000 psi = 6.89 MPa

Another superseded application of soil-cement includes the construction of dams using this material. Two examples of this are: The Sly Creek Dam and the Barney M. Davis Reservoir embankment [28].

2.1.3 Pavement Applications

For pavement applications, soil-cement can be generated using different types of soil (sand, clay, silt, etc), crushed stone, and recycled materials including old roadways. This last method is known as full-depth reclamation [23]. This process consists of compacting the pulverized recycled roadway, cement, and water to build a strong long-lasting base for the new roadway. Soil-cement can be classified as cement-treated base or cement-modified soil. Cement treated based improves the pavement subgrade by mixing coarse aggregates or granular soils with cement and water. This material should be hardened to be able to resist material loss due freezing and thawing cycles and different weather conditions. On the other hand, cement-modified soil does not have to harden. It is the result of mixing soil materials with small quantities of cement and water to increase its load-bearing capacity and reduce its plasticity [25]. The physical properties of soil-cement can be modified by changing the type of soil used, cement content, and curing conditions. Soil-cement specimens for cement-treated base applications are cured underwater. The 28-day compressive strength of the saturated specimens is usually specified between 300 (2.06 MPa) and 800 psi (5.5 MPa) [23]. Some core samples have been taken from roads after being in service for many years. These cores have shown a compressive strength increase. Thus, the cement in the mixture continues to hydrate for many years after placement. Granular soils are preferred over clay when selecting a soil for the soil-cement mixture. Clay will require higher cement content to obtain the degree of improvement desired. AASHTO provides a table with normal rage of cement content (as a percentage) required based on the soil classification (*Table 6*). For cement modified soils, the soil classification given by AASHTO is limited to A-1, A-2-4, A-2-5, and A-3 [25]. Curing is not required for cement-modified soils but using a water sprayer to add some moisture over the soil surface is recommended. This contributes to the hydration of the cement.

Table 6. Normal range of cement content for soil-cement pavement application based on AASHTO classification [23].

AASHTO Soil Group	Cement percentage by weight of soil
A-1-a	3-5
A-1-b	5-8
A-2-4	5-9
A-2-5	5-9
A-2-6	5-9
A-2-7	5-9
A-3	7-11
A-4	7-12
A-5	8-13
A-6	9-15
A-7	10-16

2.1.4 Deep Soil Mixing

Deep soil mixing is a method used to improve the mechanical and physical characteristics of an in-place soil to meet the project site specifications. By adding a binder (i.e., cement) to the native soil, the compressive strength is increased, and the permeability reduced. However, to use this method for soil improvement, specialized equipment is needed. Deep soil mixing can be carried out using a cement slurry and adding this to the soil which is also known as wet mixing or by adding the dry cement to the soil directly (known as dry mixing). Factors used to determine the type of deep mixing needed include the soil type and moisture content. Soft soils with higher moisture contents allow for the use of dry deep soil mixing [29].

Current guidelines for the aforementioned soil-cement applications are based on the use of PC type I/II as a binder material. Using a different binder material will require changes to the current guidelines to meet design specifications such as compressive strength. Another cementitious alternative for soil-cement is BCSA cement (belitic calcium sulfoaluminate cement). This material has properties that could be beneficial for soil-cement applications. BCSA cement can achieve a high compressive strength at early age [4000 psi (27.6 MPa) in less than 2 hours] [4]. This material is also fast setting which can shorten the overall duration of a project and allow fast structural repairs after natural hazards. Additionally, the production of BCSA cement releases less CO_2 into the atmosphere, making this material an environmentally friendly alternative [2, 8]. Lower shrinkage also makes BCSA a good alternative to PC in many applications. Theoretically, BCSA could be utilized in all the same applications as PC soil-cement but would result in faster construction times which would be ideal for repairs or time-critical work.

The purpose of the study was to compare the ultimate compressive strengths of soil-cement using two different binders: BCSA, and PC. Specifically, the early strength gain was examined in order to explore the potential benefits of BCSA soil-cement mixtures. Cement-modified specimens were made at two different moisture content, and their compressive strengths were tested after different curing times. Dry soil-cement mixing was used to determine the impact of the soil moisture content in the strength development of the sample.

2.2 Research Significance

Current guidelines for proportioning soil-cement are based on PC. BCSA cement is an alternative to PC with faster setting times, faster strength gain, and low shrinkage. For these reasons it may be an ideal solution for repairing soil-cement structures (especially waterway structures) or for use in time-critical projects requiring soil stabilization. This study compared the properties of PC and BCSA soil-cement to make recommendations on proportioning soil-cements using BCSA cement.

2.3 Experimental Procedures

2.3.1 Materials

The soil for the soil-cement specimens was comprised of two types of commercially available soils: a lean clay typically used for pottery known as red art clay and basic sand known as play sand available at most improvement stores. The gradation curve of the sand is given in *Figure 12*. The sand was oven-dried before any material testing was conducted to ensure equal moisture content for all the specimens.

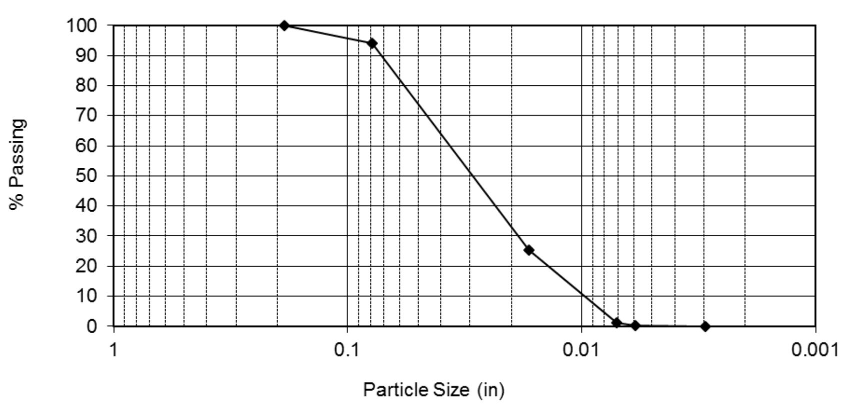

Figure 12. Gradation curve of the play sand. Note: 1 in =25.4 mm

The mixture consisted of 30% clay and 70% sand which gave a liquid limit (LL) of 22, plastic limit (PL) of 12 and plasticity index (PI) of 10. The soil classified as an A-2-4 according to the AASHTO classification system and as a clayey sand (SC) according to the Unified soil classification system (USCS). In this study, 6% cement by weight of soil was used which is within the AASHTO recommended range of 5-9% when A-2-4 soil is used for cement modified soil applications (*Table 6*) [23]. Increasing the cement content can improve the mechanical properties of the soil-cement mixture if enough water is available to allow complete hydration of cement; otherwise, a lack of water can be detrimental for the mechanical properties. This must be balanced against the cost of cement, which is increased for BCSA cement compared to PC [1]. The same quantity of cement was used for the soil-cements in this study whether it contained PC or BCSA cement. The effects of increased cement content were outside of the scope of this study, but it is recommended for future studies where soil erodibility is considered in addition to compressive strength. The typical compositions of the cements used in this study are given in *Table 7*. The soil-cement mixtures were tested at water contents of 7.5 % and 10 % to examine the effects of added moisture on strength and cement hydration.

Table 7. Chemical composition of cement by % mass [14].

Chemical Compound	Name	PC	BCSA cement
C_3S	Alite	59	-
C_2S	Belite	17	45
C_3A	Aluminate	7	-
C_4AF	Ferrite	9	2
$C_4A_3\hat{S}$	Ye'elimite	-	30
$C\hat{S}$	Calcium Sulfate	2	15
Other		6	8

2.3.2 Procedures

2.3.2.1 Sample preparation and compaction:

Preliminary research was carried out to determine the maximum dry density and optimum moisture content of the soil. 2.5 lb (1155 g) of sand was mixed with 1.09 lb (495 g) of clay while varying the moisture content (MC) to determine the optimum water content. The water weight for the soil mixture was calculated by multiplying the total weight of the soil by the MC. An electric mixer was used to mix the clay, sand, and water. The dry ingredients were added first and mixed at a low speed for 1 minute. Once all the sand and clay were combined, the water was added and mixed at a medium speed for another minute. The soil samples were then bagged, sealed, labeled, and placed in a seal container where they remained for 24 hours. After 24-hours, the specimens were compacted. ASTM D698 [30] guidance was followed to compact the sample, but this test was modified by using a smaller proctor mold of 37.2 in^3 (610 cm^3) instead of the standard mold. To ensure that the energy delivered to the sample followed the standard laboratory compaction effort prescribed by the test method, the number of blows was recalculated and adjusted based on the volume of the mold (Equation 1).

$$E = \frac{(Hammer\ Weight) \times (Drop\ Height) \times (\#Blows) \times (\#Layers)}{V} \quad (1)$$

Where, E stands for compaction effort and V volume. The value for the standard test compaction effort, E, is 12400 lb.* ft/ ft ^{3}(600 kN-m/m3).

The soil mixture was placed in three equal layers by volume, and 16 blows per layer were delivered to compact the soil specimen. The moisture content of the soil specimen was determine following the procedures in ASTM D2216-19 [31]. The compaction curve obtained is given in *Figure 13*. The optimum moisture content of the soil mixture was 8.8%.

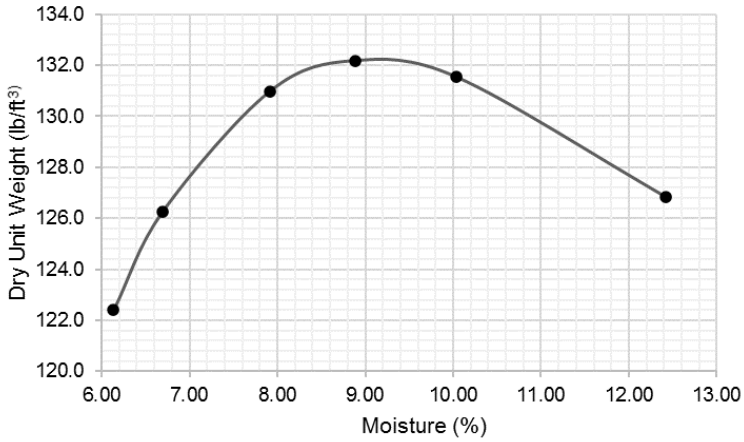

Figure 13. Compaction curve of the soil mixture. Note: 1 kN/ m^3 = 6.3659 lb/ ft^3

Two water contents were chosen to perform soil-cement testing. One moisture content was dry of optimum (7.5%) and the other one was wet of optimum (10%). These two water contents were used for each cement type. The moisture content for the soil-cement specimen was calculated using the weight of the soil plus the weight of the cement as the total dry weight of the specimen. This resulted in 3.64 lb (1650 g) of soil for each soil-cement specimen and 6% of cement by dry weight of the soil resulted in 0.218 lb (99 g) of cement.

Once the optimum moisture content of the soil mixture was determined and two target moisture contents selected, the soil cement samples were made. The soil portion of the mixtures were prepared a day before the specimens were compacted following the same procedures used to determine the optimum water content. The moist soil and the cement (either PC or BCSA) were mixed at a medium speed for 50 seconds and then compacted in accordance with ASTM D698 [30]. All samples were demolded after 30 minutes, and then they were stored in an insulated foam cooler with exception of the 30-minute compressive strength samples. The unconfined compression test of these samples was performed immediately. The uniaxial unconfined compression of all specimens was conducted in accordance with ASTM D1633-17 method B

[32]. To cure the samples and promote cement hydration, a plastic container with water was also placed inside the cooler to increase ambient moisture in the cooler (see *Figure 14*).

Figure 14. Curing of the soil-cement specimens

The soil-cement specimens were tested in unconfined compression to failure at 30 minutes, 1 hour, 3 hours, 1 day, and 7 days. BCSA cement is anticipated to be used only when very early strength is desired, so later age strengths were not examined. Three soil-cement samples were used to compute the average maximum axial compressive strength for each condition tested resulting in a total of 60 soil-cement specimens. Additionally, two control groups without cement were tested for both moisture contents (7.5% and 10%) (six additional samples). The table below summarizes the designations and corresponding mix details (*Table 8*). These groups are: 0% CC at 7.5% MC, 0% CC at 10%, 6% BCSA at 7.5% MC, 6% BCSA at 10% MC, 6% PC at 7.5% MC and 6% PC at 10% MC, where CC stands for cement content and MC moisture content.

Table 8. Mix design classification for the soil-cement mixtures

MC	7.5%	7.5%	7.5%	10%	10%	10%
Cement Content (%)	0	6	6	0	6	6
Cement Type	-	BCSA	PC	-	BCSA	PC

2.3.2.2 Uniaxial Unconfined Compressive Strength

Uniaxial unconfined compression (UC) strength testing was performed on all samples to determine the ultimate strength of the material and the strain corresponding to the peak stress. The UC test was conducted using a universal load frame which was connected to an automated testing system (see *Figure 15*).

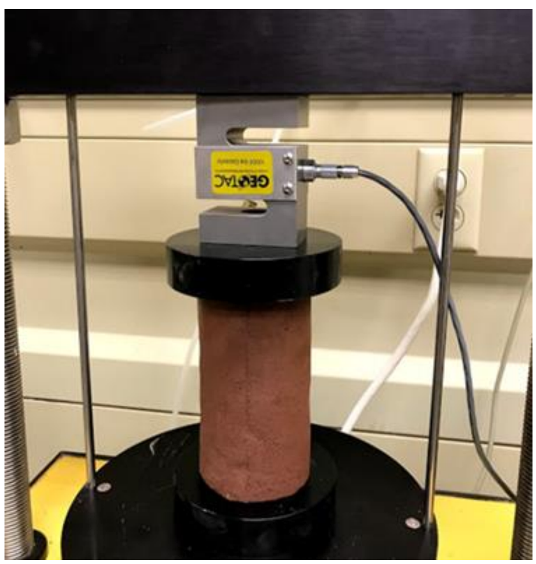

Figure 15. Set-up for a uniaxial unconfined compressive strength test.

The system recorded the load-deformation relationship of the specimen while sheared at a constant strain rate of 1.0%/ min. The maximum unconfined compressive strength was defined as the peak stress observed for a given specimen. At the peak stress, the corresponding strain value is considered the failure strain. After the failure strain occurred, the stress tended to decrease as more strain was applied and exhibited a strain-softening behavior.

2.4 Results and Discussion

2.4.1 Visual Description of Specimens

2.4.1.1 Soil-cement specimens at 7.5% MC

The main observed difference at early age was that specimens using PC appeared moister than the specimens using BCSA even though the water contents were the same (see *Figure 16*). This difference can likely be attributed to the higher water demand BCSA cement has in comparison to PC and the difference in setting time [5] Some color change was observed after one day and seven days especially in areas where the cement content was perhaps more concentrated (see *Figure 17).*

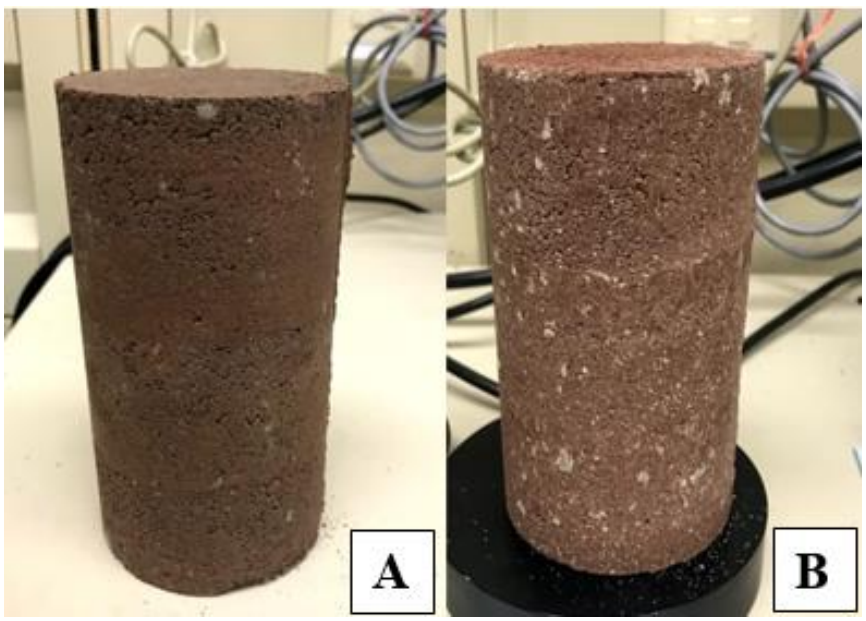

Figure 16. Comparison of soil-cement specimen using different binders tested at 1 hour. (A)PC soil-cement specimen; (B) BCSA soil-cement specimen

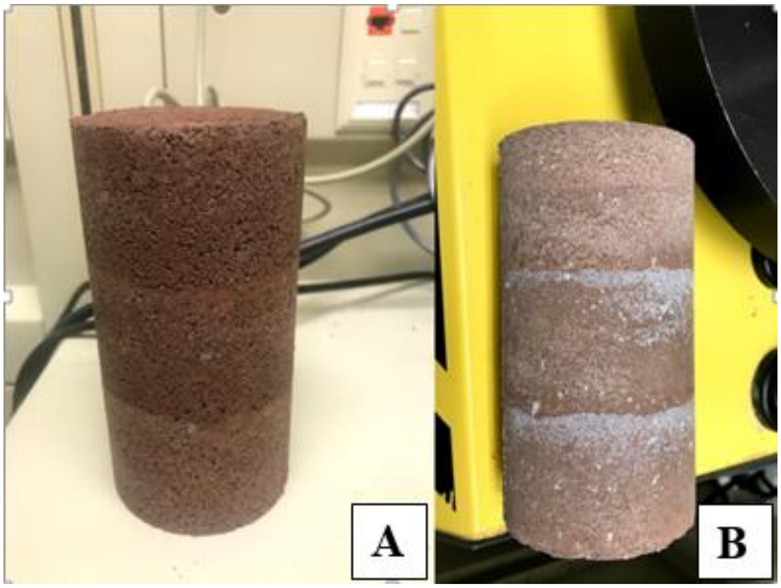

Figure 17. Comparison of soil-cement specimen using different binders tested at 7 days. (A) PC soil-cement specimen; (B) BCSA soil-cement specimen

2.4.1.2 Soil-cement specimen at 10% MC

The specimens using a higher moisture content had a brighter red color due to the high saturation of the clay. Visual differences were observed when comparing the BCSA and PC specimens (see *Figure18*). The PC blended with the soil evenly, leaving only small sections of the soil-cement with a dark grey color while the white from the BCSA cement was seen more prominently in the surfaces of the specimens. This could be due to the original color differences of the binders used since BCSA is lighter in color than PC or this could be a sign that PC was being hydrated more completely while BCSA cement was not. At one day and seven days the specimen using BCSA turned a lighter red color, but the PC specimens kept the bright red color observed when they were cast (see *Figure 19*). Referring to Figure 19, BCSA specimens appeared less moist at later ages, perhaps because more of the available moisture was recruited for cement hydration. It is possible that higher MC is required when using BCSA since it may require more water to hydrate.

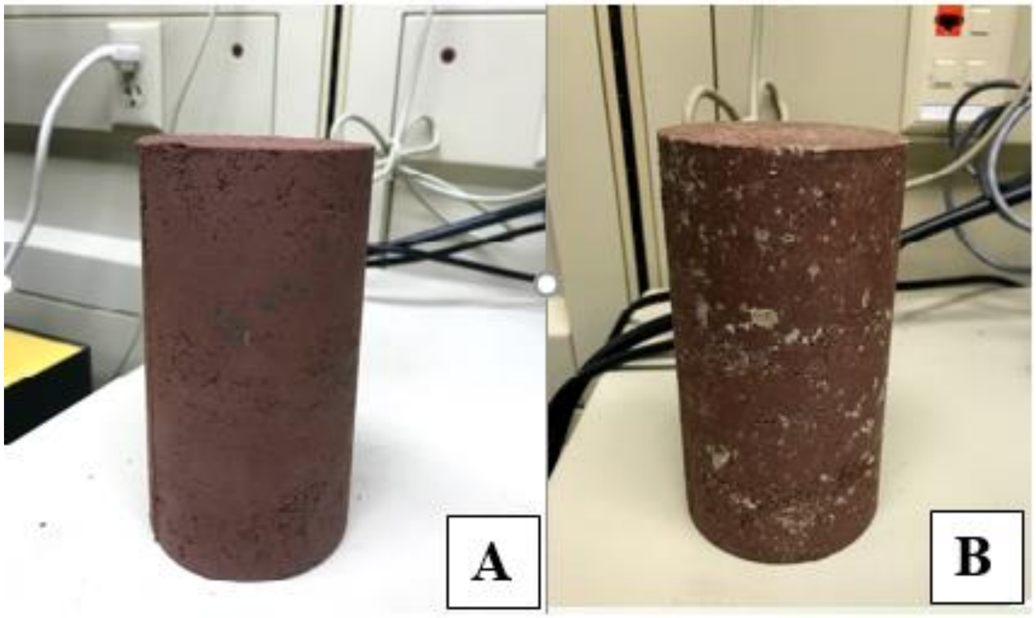

Figure 18. Visual difference of samples using both binders at 10% MC. (A) PC specimen; (B) BCSA specimen.

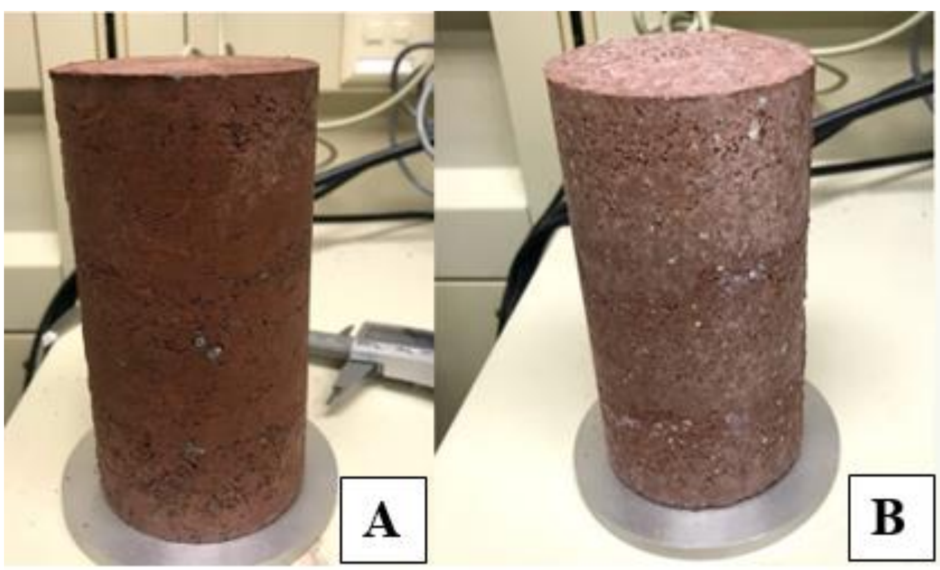

Figure 19. Visual difference between specimens using both binders at 1 day. (A) PC specimen; (B) BCSA specimen.

2.4.2 Failure Mechanism in UC

2.4.2.1 Soil-cement

Most soil-cement samples failed in shear (*Figure 20*). Generally, cracks started forming at the bottom of the specimens, then propagated to the top of the sample. The failure mode of the soil-cement specimens using a 7.5% MC were more brittle in comparison to those at 10 % MC.

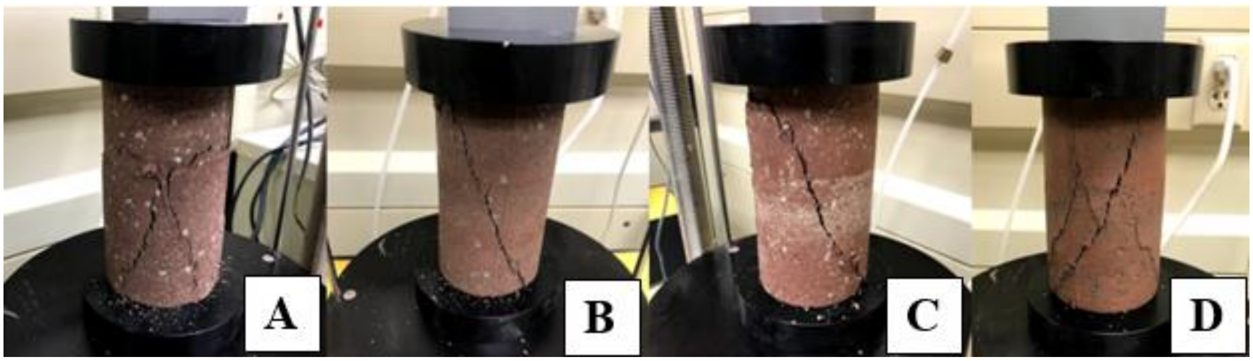

Figure 20. Failure mechanism for soil cement specimens tested at 3 hours. (A) BCSA at 7.5% MC; (B) PC at 7.5% MC ;(C) BCSA at 10% MC; (D) PC at 10% MC.

2.4.2.2 Control Group

The soil samples using 7.5% MC failed in shear, and no significant change in height was noticed after the UC was completed. For the control group using 10% MC, the samples plastically deformed before failing in shear (*Figure 21*).

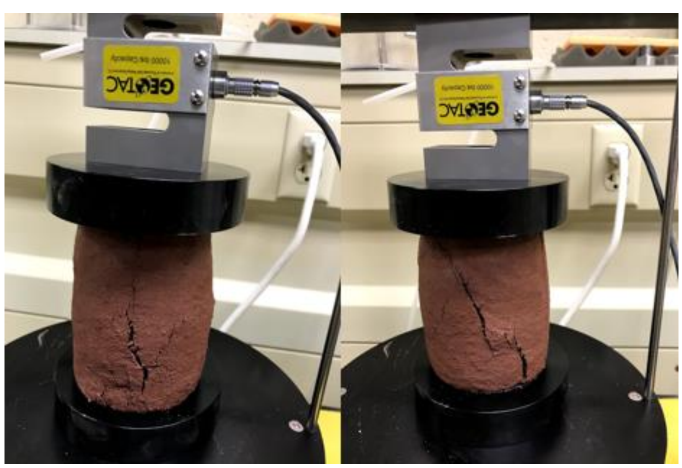

Figure 21. Failure mechanism of the control group using 10% MC

2.4.3 Strain-Stress Relationship

The strain-stress relationship was dependent on binder type, curing time and moisture content.

2.4.3.1 Soil-Cement at 7.5% MC, 1 hour

The early age failure strain of the 7.5% MC sample using BCSA was approximately 0.7%-0.8% (see *Figure 22*). The PC curve had a strain at peak of approximately 1%.The strain-stress curve of the specimens using PC appeared flatter (i.e., less strain-softening) than the BCSA curve. The higher strain-softening of the BCSA curve could be due to the BCSA beginning to form cement reaction products earlier than PC. The peak stress applied to the BCSA soil-cement samples was 131 psi (0.90 MPa) on average at one hour compared to only 50 psi (0.34 MPa) for the PC samples. This illustrates the rapid hardening of BCSA and highlights the potential to reach specified strengths very quickly using BCSA. The PC strengths at 1 hour were similar to the control group.

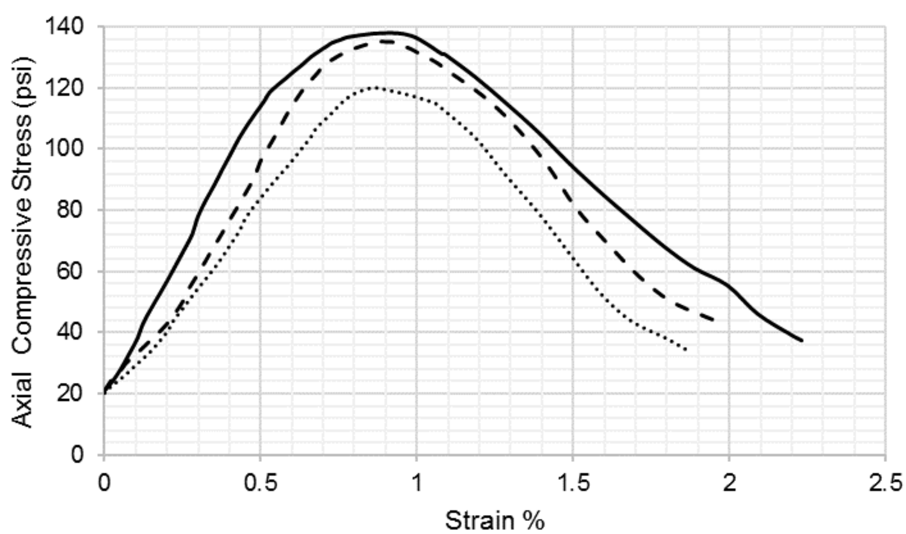

Figure 22. Strain-stress relationship measure at 1 hour using BCSA cement at 7.5% MC. Note: 1000 psi = 6.89 MPa

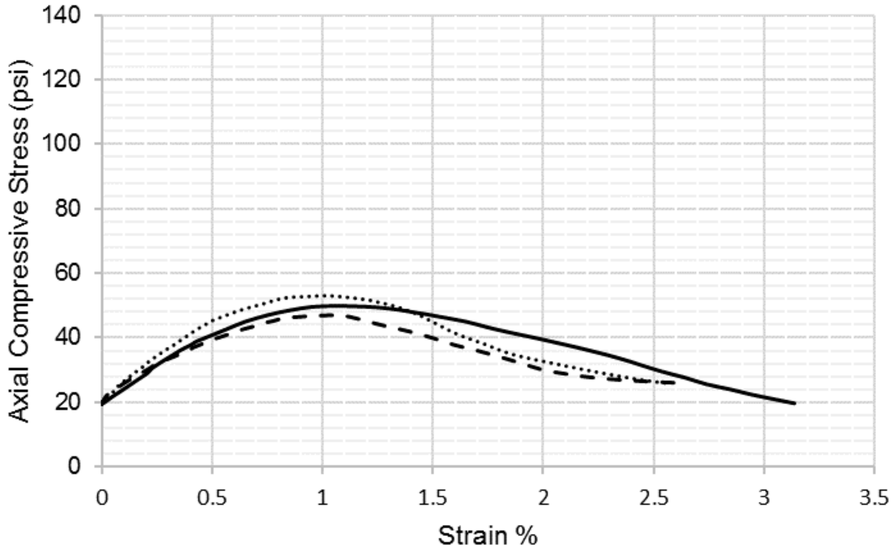

Figure 23. Strain-stress relationship measure at 1 hour using PC cement at 7.5% MC.

Note: 1000 psi = 6.89 MPa

2.4.3.2 Soil-Cement at 10 % MC, 1 hour

Similarly, the PC curve at 10% MC seemed flatter than the BCSA. The strain at peak was approximately 2% for the BCSA specimens while it was approximately 4% for the PC samples (see *Figures 24-25*).The specimens using a BCSA cement underwent low deformations before failing at early age (1 hr) in comparison to PC. These values are higher than the strain percent obtained at 7.5% MC. However, the percent difference between PC samples is higher than the BCSA if the peak values obtained at 10% MC are compared to those at 7.5%. Overall, the soil-cement specimens using a higher moisture content (10%) had a higher strain at failure in comparison to those using 7.5%.The strengths of the 10% MC specimens containing BCSA cement was 97 psi (0.67 MPa) on average compared to 33 psi (0.22 MPa) for the PC samples.

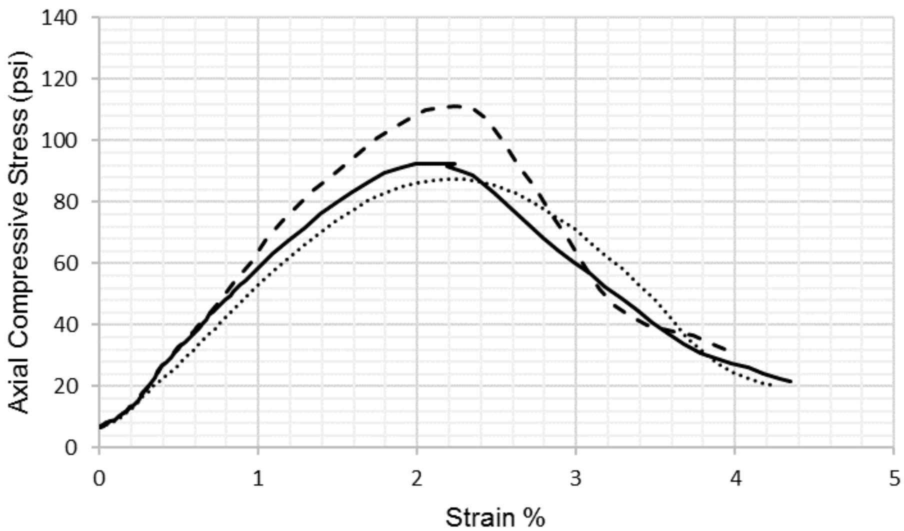

Figure 24. Strain-stress relationship measure at 1 hour using BCSA cement at 10% MC. Note: 1000 psi = 6.89 MPa

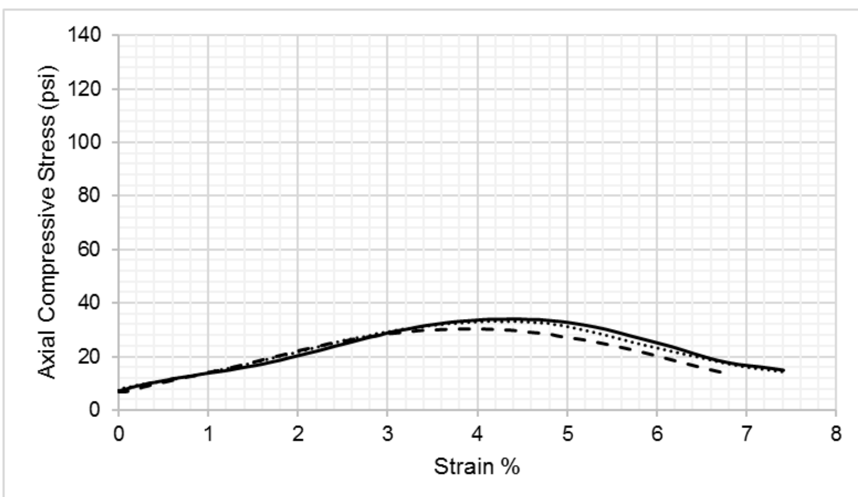

Figure 25. Strain-stress relationship measure at 1 hour using PC cement at 10% MC. Note: 1000 psi = 6.89 MPa.

2.4.3.3 Control Group, 1 hour

The stress-strain relationship for 10% MC control samples resulted in the highest strain at peak of all groups tested. This value is about 15% of the specimen height (*Figure 26*). This curve can be also described as a strain hardening curve and is typical for a softer clayey soil. The strain at peak for the control group at 7.5% is about 3% which is higher than the soil-cement specimens tested at the same time using either (PC or BCSA) (see *Figure 26*). The peak compressive strengths of the unmodified samples were 33 psi (0.22 MPa) and 20 psi (0.13 MPa) on average for 7.5% and 10%, respectively. At 1 hour, the PC improved the average compressive strength by 156% and 165%, for 7.5% MC and 10% MC, respectively, while BCSA improved the soil strength by 409% and 485%, for 7.5% MC and 10% MC, respectively.

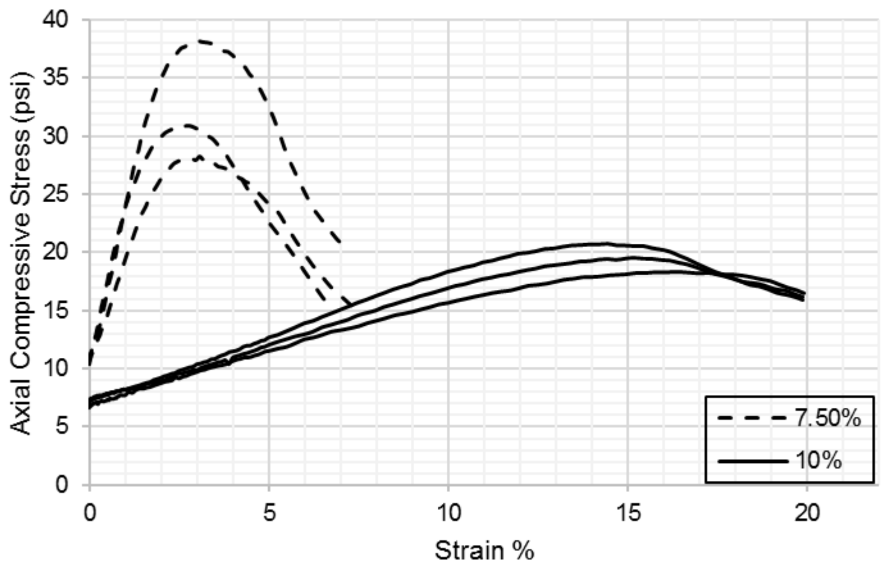

Figure 26. Strain-stress relationship measure at 1 hour at 7.5% and 10% MC. Note: 1000 psi = 6.89 MPa.

2.4.4. Failure Strain

2.4.4.1 7.5% MC

The failure strain was higher for the soil-cement samples made with PC at all ages. The strain at failure increased for the BCSA specimens until the samples were 1 day old, and then it decreased at 7 days old. The PC soil-cement specimens generally kept increasing (see *Figure 27*). The strain at peak for the control group was 3%.

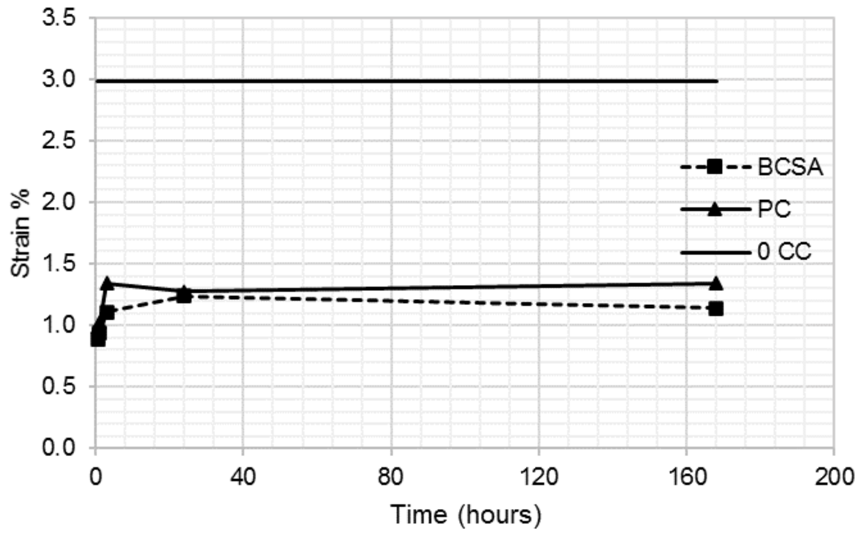

Figure 27. Strain at peak using 7.5% MC.

2.4.4.2 10 % MC

The strain had an inverse relationship with time for 10% MC samples. As the time increase the strain at failure decreased until 1 day of age. Then the strain seems to remain constant. It is likely that at one day sufficient strength is provided by the cement to fundamentally change the failure of the specimens whether using PC or BCSA. The overall change in the strain at peak of samples made with BCSA is smaller than the samples made with PC. PC samples reached higher strain percentages at early ages, most likely because cement hydration had not occurred at a sufficient level to provide any soil improvement at this age. There was 42% percent difference between samples made with BCSA and PC. However, the gap between both strains values decreased as the specimens aged (*Figure 28*). The strain at peak for the control group was 15%, as it exhibited a strain-hardening behavior.

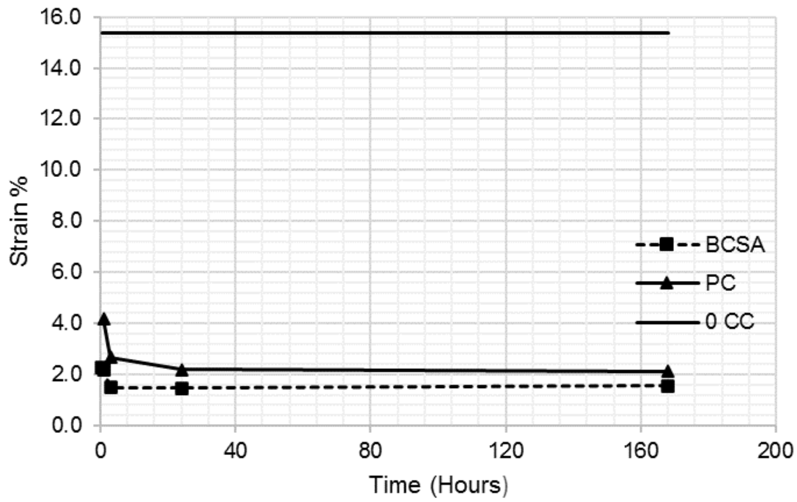

Figure 28. Strain at peak using 10% MC.

2.4.5 Maximum Axial Compressive Strength

The three maximum stress values obtained from the UC tests were averaged. These values varied by 3% to 25%. The variance was within the allowed variance given by the PCA (Portland Cement Association) guidelines for erosion control applications [24]. The increase in compressive strength can be attributed to cementation and soil suction. However, the soil-suction can affect the hydration process, and therefore cementation. The soil-suction reduces the amount of water available for the cement hydration process.

2.4.5.1 7.5 % MC

The comparison between the control groups' strengths and the soil-cement specimens' strengths shows the improvement in strength due to the addition of cement to the system. Increases in specimen strengths were observed for PC and BCSA specimens compared to soil-only. The samples using BCSA developed high early strength faster than the specimens using PC, but increases in strength were noticed for PC specimens after one-day of age. The average BCSA strength at 30 minutes was 93 psi (0.64 MPa) while the strength for the PC specimens tested at the same time was 40 psi (0.28 MPa). The BCSA strength was 56% higher than the PC at 1 day.

The 7-day strength for the PC specimens was 256 psi (1.76 MPa) on average while the average BCSA strengths were 240 psi (1.65 MPa). At seven days the PC specimen strength was 6% greater than the BCSA specimens. The control group strength was 33 psi (0.23 MPa), thus; if the 7-days strength is compared to the PC and BCSA soil-cement specimens, this leads to an 87% and 86% increase in strength, respectively (see *Figure 29*).

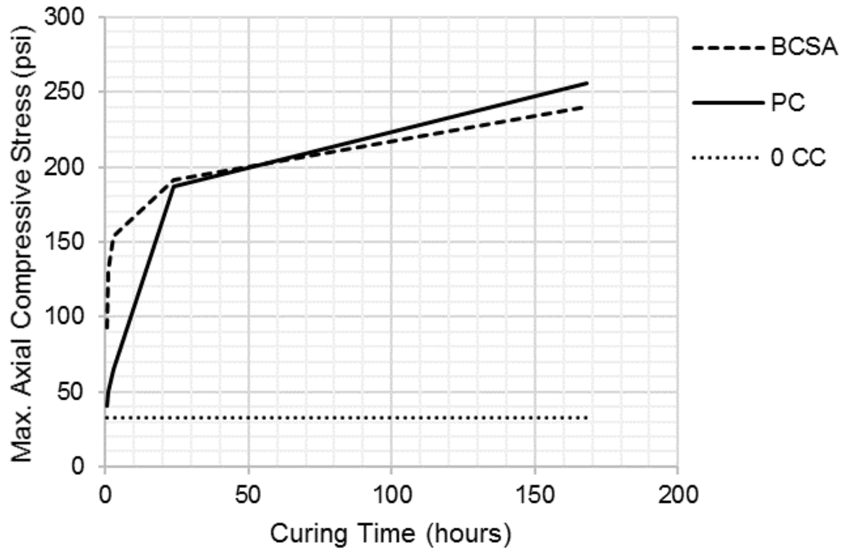

Figure 29. Maximum compressive strengths at 7.5% MC. Note: 1000 psi = 6.89 MPa

2.4.5.2 10% MC

The strength obtained from the control group was 20 psi (0.14 MPa) while the 1-hour strengths for the soil-cement specimens were 97 psi (0.67 MPa) and 33 psi (0.23 MPa) on average for BCSA and PC specimens, respectively. The early age strength was higher for the specimens made using BCSA cement. The 1-hour BCSA strength was 66% higher than the PC strength obtained at the same time. At 7 days, the strength of the PC specimens was higher than the strength of the BCSA specimens. The 7-day strengths for the PC specimens were 279 psi (1.92 MPa) compared to 270 psi (1.86 MPa) for the BCSA specimens. There was a 3% difference between 7-day strengths of the soil-cement specimens. The 7-day strength for the soil-cement samples were higher using 10% MC in comparison to the 7.5% MC (*Figure 30*). This difference in strength at 7 days is mainly attributed to the additional formation of hydration products due to a higher moisture content available at 10% MC.

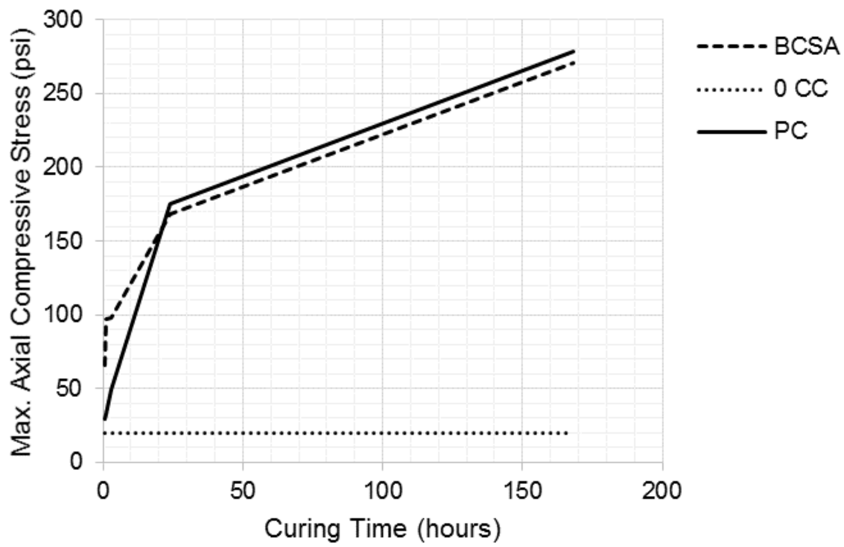

Figure 30. Maximum compressive strengths at 10 % MC. Note: 1000 psi = 6.89 MPa

2.5 Conclusions

The main purpose of this study was determining the moisture-strength-time relationship of soil-cement mixtures of sand, clay, and BCSA. The guidelines available for soil-cement design are mainly based on the use of PC; thus, this study also include soil-cement specimens made from PC for comparison. Different moisture contents (7.5% 10%) and curing times were tested. Conclusions from the testing performed include:

1. Samples using BCSA cement developed higher early strengths (up to 3 hours) than those using PC. BCSA samples improved the strength of soil at 1 hour of age by 409 % and 485% for 7.5% MC and 10% MC respectively.
2. The PC soil-cement specimens had higher 1-day and 7-day compressive strengths, but overall, 7-day strength improvement compared to soil-only samples was relatively similar for PC and BCSA.
3. The soil-cement samples should be made using water contents wet of optimum to provide enough water for the hydration of BCSA cement.
4. Low moisture content does not allow the BCSA soil-cement specimens to fully hydrate which is detrimental to the ultimate compressive strength. More research is needed to better understand how curing conditions (i.e., submerged specimens) would affect these results.
5. The soil-cement specimen maximum compressive stress had between 3% and 25% variability.
6. Both PC and BCSA samples seem to have not reached their ultimate strengths within 7 days. Higher later-age strengths are expected in both.

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