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Using CSA Cement for Novel Waterway Repair Materials
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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 necessary maintenance activities which can often lead to 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 economic effect. Thus, it is advantageous to reduce the repair time for maritime structures. BCSA (belitic calcium sulfoaluminate) cement is a promising repair material 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 repair mortar mixture design using BCSA cement. Properties such as compressive strength and workability were tested to select 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 the rapid repair of levees and earthen dams, but also for rapid soil stabilization. The results obtained proved that BCSA cement is a promising material for rapid underwater repairs and repairs of soil-based waterway structures.

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PROJECT DESCRIPTION

The health and performance of maritime transportation infrastructure is critical to the nation's economic and social prosperity. Much of this infrastructure has well exceeded its 50-year design life and is often in need of repair. Because waterway transportation structures are difficult to detour, the time taken by repairs is of critical importance. The fastest repair techniques should be developed in order to minimize the time out of service. The objective of this research was to investigate the properties and behavior of Belitic Calcium Sulfoaluminate (BCSA) cement mixtures for waterway repair applications. BCSA cement is a rapid setting, low-shrinkage cement which can be applied to rapid maritime infrastructure repairs. BCSA cement maintains many of the beneficial qualities of portland cement (PC) but it can reach structural strengths in only a few hours and its low shrinkage makes it an ideal repair material.

Despite the benefits of BCSA cement, it has been studied relatively little in the United States (US). The potential advantages and drawbacks of BCSA cement must be studied to determine the most suitable applications. For underwater repair applications, where construction time is critical, BCSA cement may be the best option, but mixtures must be developed that can produce the necessary properties. The goal of this work was to develop new mixtures utilizing BCSA cement that can be applied to waterway repairs. A mortar mixture capable of setting up rapidly underwater was developed, and a soil-cement mixture was developed that can rapidly stabilize slopes and waterway structures. More work is needed to fully characterize these materials in comparison to standard PC designs, however the results showed that BCSA is a promising rapid repair material in these applications and it often has better performance than PC, especially at early ages.

Motivation of the Study

The condition of the nation's infrastructure is tied directly to the economy, business productivity, employment, gross domestic product, and global competitiveness. In the 2017 Infrastructure Report Card, the American Society of Civil Engineers (ASCE) gave the infrastructure in the US an overall rating of "D+"[1]. While safety is a concern, the greatest concern at this time is the effect that the deteriorating infrastructure will have on the US economy. Recent studies indicate that infrastructure deficiencies could lead to losses of over $3.9 trillion to the US GDP, $7 trillion in business sales, and 2.5 million American jobs by 2025 [2]. ASCE estimates more than $3.3 trillion in investment is needed for rehabilitation and construction to bring the systems to an acceptable status; however, only a small portion of that money ($1.9 trillion) is expected to be allocated by the federal government. Although, funding has been sufficient to avoid large safety disasters, this funding gap means that the required maintenance and number of repairs will continue to grow.

Out of the 16 sectors considered in the ASCE report card, 10 were specially chosen as critical to the economic prosperity of the US. A majority of these 10 are directly related to maritime and multimodal transportation. Much of the maritime and multimodal transportation infrastructure in the US has well exceeded its 25- or 50-year design life and is unfortunately in desperate need of repair (Table 1). While the funding gap estimates from 2016-2025 for these sectors is astounding, this does not include the economic impact from the downtime associated with repairs, or the impact associated with extreme weather events like hurricanes which drives the need for investment even higher. Historically, the US has had the competitive advantage over other countries because of the relatively low costs of transportation. However, additional time out of service for these sectors results in longer shipping and travel delays, higher costs of goods and services, and an overall decline in business productivity and income. As the number of critical repairs grows, the need for reduced down time for each repair greatly increases.

Table 1: Transportation Related Infrastructure According to ASCE [1]

Sector	***Grade***	***Funding Gap***
Roads	D	$ 1.1T
Airports	D	$ 42B
Inland Waterways	D	$ 7.5B
Ports	C+	$ 7.5B
Bridges	C+	$ 15B
Rail	B	$ 29.4B
Levees and Dams	D	$ 109.4B

Because of its relatively low cost and ubiquity, concrete has been used to construct much of the infrastructure in the US. Traditional concrete is made with PC, but PC may not be the ideal material for some applications, particularly repairs. PC's drawbacks include the time required to achieve structural strength and shrinkage during curing which leads to cracking. These two disadvantages are particularly important for repair materials. If repair times are to be reduced, there is a need for a rapid setting cementitious material capable of meeting strength requirements quickly with little shrinkage relative to the damaged material. This project addresses these needs through the development of BCSA cement-based repair materials. Additionally, this project applied BCSA cement to soil-cement. Soil-cement is used in some maritime structures and may be used to repair maritime structures after disasters. A rapid-setting soil-cement can be deployed more quickly to bring soil-cement structures back into service with limited down-time.

Background and Literature

Background on BCSA Cement

CSA (calcium sulfoaluminate) cement was first introduced in the 1960s, but its use was not widespread until the 1970s when its popularity increased, especially in China [3], [4]. CSA was developed at the University of California, Los Angeles by Alexander Klein [5], therefore CSA is sometimes referred to as "Klein's compound" (it is also known by some chemists as ye'elemite). The initial application of CSA cement was for shrinkage compensating or self-stressing concrete due to its expansion during hydration. Shrinkage of PC was known to be a disadvantage, so CSA was developed initially as an addition to PC to counteract this phenomenon [6]. While CSA is sometimes referred to in literature as being its own cement, technically it is only one component or compound within a cement. 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 [7], [8]. Many CSA cements are intended to be used as additives to PC.

Belitic CSA or BCSA cement (or CSA-B cement) is a special variety of CSA cement which contains a large amount of belite and a smaller proportion of CSA [9]. Belite is a cement compound that is present in PC and is known to react relatively slowly with water [10]. In BCSA cement, belite reduces the early age expansion from the CSA and results in a cement with a roughly neutral volume change during hydration. All CSA based cements primarily gain strength through the formation of ettringite early during the hydration process [11]. BCSA cement also forms calcium-silicate-hydrate (CSH) at later ages. CSH is the main reaction product of PC [10]. 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 PC. This cement can reach a compressive strength greater than 4000 psi within two hours [12], while PC may take as long as 28 days to obtain the same strength. This 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. An approximate representation of the strength gain of BCSA cement concrete and PC concrete is given in Figure 1.

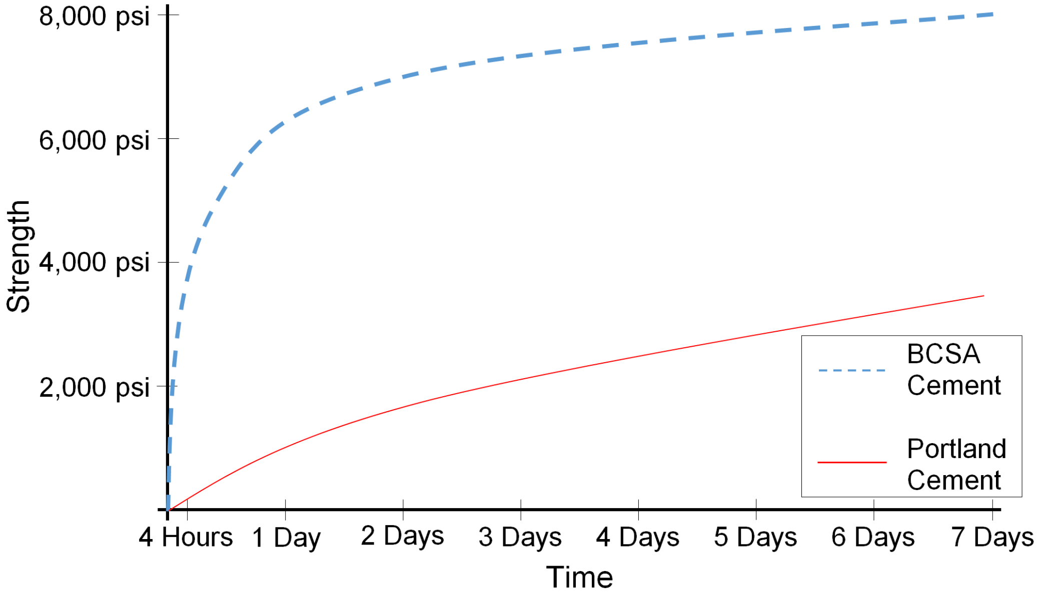

Figure 1: Approximate strength gain comparison of BCSA cement and PC

There has been recent interest in BCSA cement because it is thought of as a more sustainable alternative to PC. It takes less energy to produce BCSA cement, reducing CO_2 emissions by 20% to 40% [7], [13]. In addition to that, 50% of the CO_2 generated during the manufacture 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 [14]. BCSA calcination occurs at 2282 °F (1250 ºC) while PC needs a temperature of 2642°F (1450 ºC) [11]. BCSA cement also has low alkalinity which causes this material to be less susceptible to chemical reactions, such as alkali-silica reaction [3]. 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 US 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 [3]. While this cost disparity is significant, the benefits obtained from BCSA cement may counteract its high cost in certain applications. Additionally, due to the increasing cost of energy and new environmental regulations it is predicted that PC will be twice as expensive in 2030 as it is today [13].

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 [15], [16]. BCSA cement also allows for construction in lower temperatures than PC because it is a fast-setting cement with a high heat of hydration. It has been used extensively for pavement repairs in the US [9].

Background on Maritime Structures and Repair

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 [17]. Proper maintenance and rehabilitation measures are necessary to keep these maritime structures operating at their maximum capacity. 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, high early-age strength development, and low shrinkage.

There are different types of waterway transportation structures which are often made of concrete such as locks, dams, breakwaters, embankments, slope protection structures, and outlet tunnels. These structures can crack due to chemical reactions, design errors, excessive loading, or weathering. For example, during cold weather, the concrete can be subjected to freezing-and-thawing cycles [3]. Concrete cracking can lead to additional problems such as rebar corrosion because the cracks expose the rebar to water and chemicals. A common repair method for cracking in concrete is to fill them with grout or mortar. This process (usually done with PC) consists of cleaning the cracked concrete and injecting or pumping grout into the crack [18]. If such a repair is performed underwater, the repair material must be able to flow freely and consolidate when pumped or injected, but it must also remain stable underwater and not wash out. Guidance for making mixtures with these properties exists for PC [19], [20], but not for newer materials like BCSA cement.

Background on Soil-Cement and Repair

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 [21]. 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 [21]–[23]. The curing methods used for soil-cement are mostly dependent on the desired application. 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.

In terms of maritime and waterway infrastructure, soil-cement has many applications. For erosion control applications, riprap (i.e., boulders, cobbles, and gravels placed along an embankment) are often used to protect shorelines against high-impact waves and weathering. However, the type of rocks 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 which required slope protection. 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 lining [22]. Soil-cement has also been used for the construction of dams. Two such examples of this are: The Sly Creek Dam and the Barney M. Davis Reservoir embankment [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 [25]. 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 levee system suggested that more that 25% of levees have failed in the past 155 years due to various conditions including flood events [25]. A study conducted by the US 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 [26]. 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 [22].

The cement content recommended for slope protection is given by AASHTO (American Association of State Highway and Transportation Officials) (Table 2). 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 3). Before conducting the compressive strength test, the soil-cement specimen must be cured at 100% humidity and placed underwater for 4 hours [22].

Table 2: Normal range of cement content for soil-cement slope protection based on AASHTO classification [22]

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 3: Minimum compressive strength requirements at 7 days for different water resources applications [22]

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

Note: 1000 psi = 6.89 MPa

Current guidelines for proportioning soil-cement are based on PC. BCSA cement is known to behave differently in terms of workability, compressive strength, setting times, etc. 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, but the mixture designs are likely to be different and its performance must be evaluated. This study compared the properties of PC and BCSA soil-cement to make recommendations on proportioning soil- cements using BCSA cement.

METHODOLOGICAL APPROACH

Materials and Methods for Repair Mortar Study

Materials Used in Repair Mortar

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 [27]. The initial and final set times are 15 and 20 minutes respectively as provided by the producer per ASTM C191 [28]. 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 4: Typical chemical composition of BCSA cement [12]

Chemical Compound	Name	BCSA cement % mass
C2S	Belite	45
C4AF	Ferrite	2
C4A3Ŝ	Ye'elimite	3
CŜ	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 2). 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.

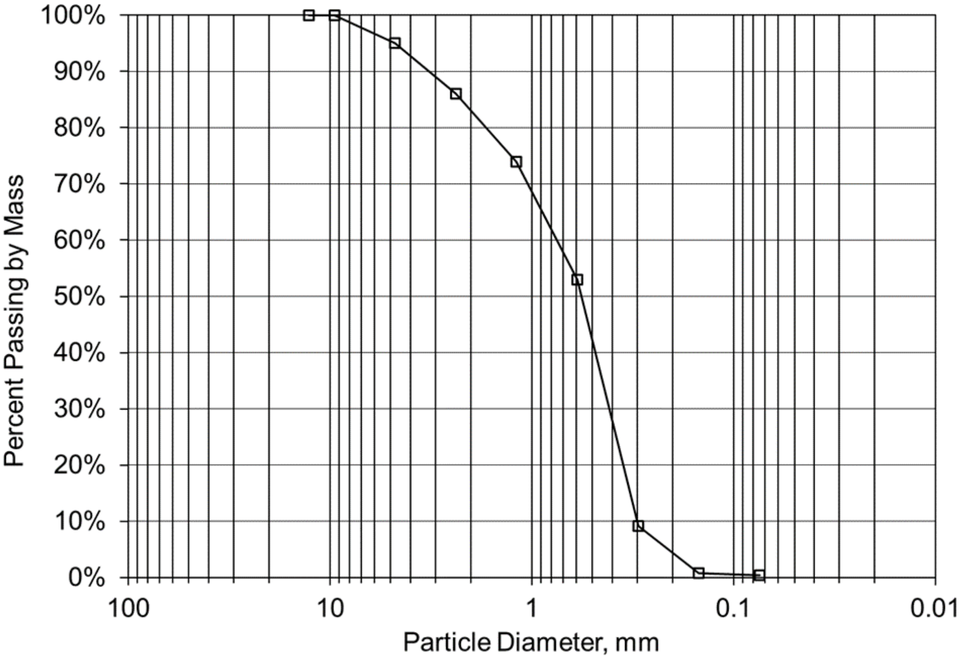

Figure 2: Gradation of sand used in mortar mixtures (Note: 1 in. = 25.4 mm)

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 [3], [29], [30]. 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 [29]. 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 [29]. 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 [3], [30]. 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 [7]. 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 [20], [31].

Mixture Proportions Used for Repair Mortar

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 5. The total volume of the mortar mixtures was 0.20 ft^3 (5663 cm^3).

Table 5: Mix Design 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
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

Repair Mortar Specimen Preparation and Testing Procedures

Once all the materials were weighed, the liquid ingredients were mixed (water, citric acid, HRWR, and VMA). Following ASTM C305 [32], 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 then was changed to medium speed 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 [33]. 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 [34]. 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 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 3). 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. 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 3: Fresh mortar specimen casting set-up.

Materials and Methods used in Soil-Cement Study

Materials Used in Soil-Cement

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 control the moisture content for all the specimens.

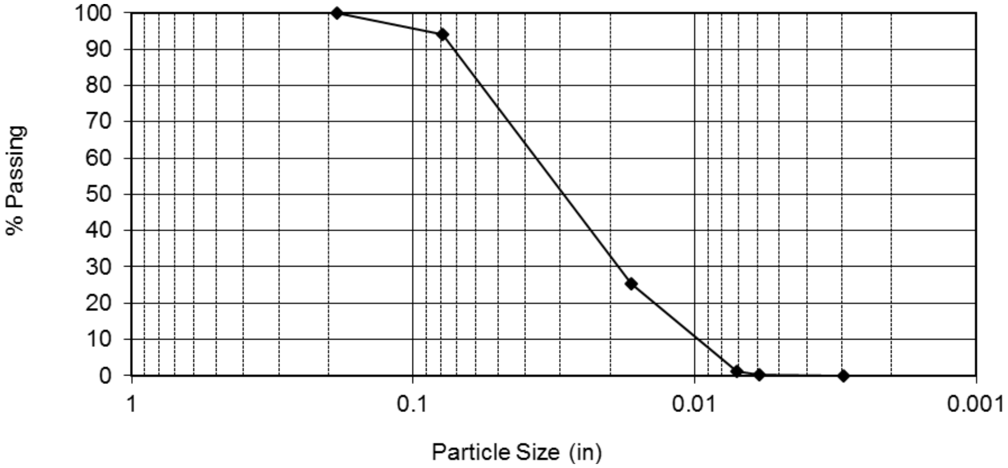

Figure 4: Gradation curve of the play sand used in soil-cement study. Note: 1 in =25.4 mm

The soil 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 2) [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.

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 as a factor that should be examined in 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 4. 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.

Soil-Cement Specimen Preparation

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 [35] 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 standard Proctor test method, the number of blows was recalculated and adjusted based on the volume of the mold (Equation 1).

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

Where *E* is the compaction effort and *V* is the volume of the mold of the mold. The value for the standard test compaction effort, *E*, is 12,400 lb.* ft/ ft^3 (600 kN-m/m^3). 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 determined following the procedures in ASTM D2216-19 [36]. The compaction curve obtained is given in *Figure 13*. The optimum moisture content of the soil mixture was 9.2% and the maximum dry unit weight was 132.03 lb/ft^3.

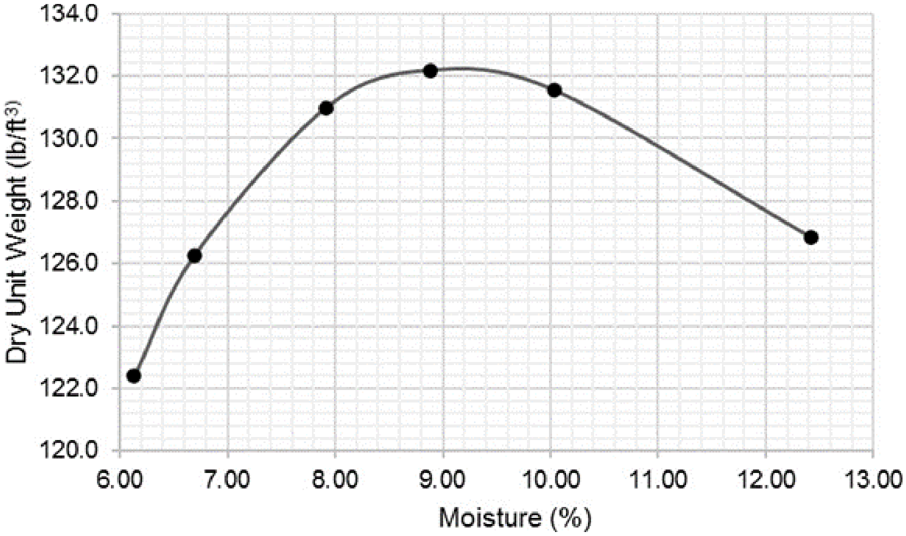

Figure 5: Compaction curve of soil mixture used in study. Note: 1 kN/m^3 = 6.3659 lb/ft^3

Two water contents were chosen for the soil-cement strength testing. One moisture content was dry of optimum (7.5%) and the other was wet of optimum (10%). Soil compacted dry of optimum typically has a higher strength than soil compacted wet of optimum, but it was questioned whether the higher moisture content soil-cement mixture would contain more available water and lead to increased cement hydration and thus, higher strength. 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 [35]. 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 [37]. 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 6).

Figure 6: Curing of the soil-cement specimens

The soil-cement specimens were tested in unconfined compression to failure for setting times of 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 (> 7 days) 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 6). 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 6: 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

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 7).

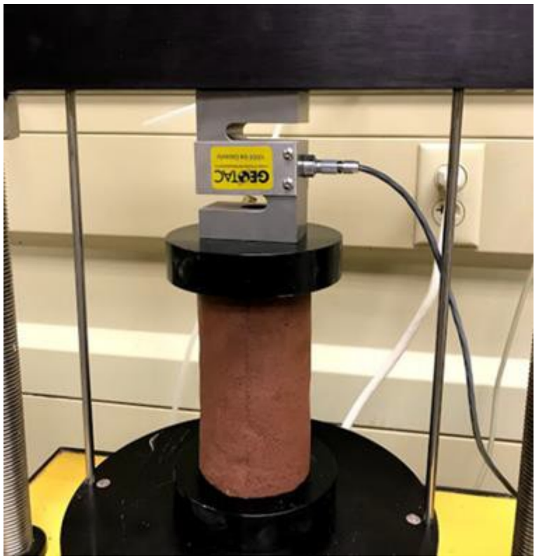

Figure 7: Set-up for a uniaxial unconfined compressive strength test.

The system recorded the load-deformation relationship of the specimen while it 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 was 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.

RESULTS/FINDINGS

Results of Repair Mortar Testing

Physical Appearance of Mortar Specimens

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 dry. 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 8: Physical appearance comparison of repair mortars at s/c of 1.25: (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

Mortar Flow Results

The flow was measured for mixtures with five different *w/c* and three different *s/c* before casting the mortar into molds in the dry-cast and wet-cast condition. Since all mixtures contained citric acid, VMA, and HRWR at the same dosage rate, their effect on mortar flow was assumed to be similar for every *w/c* and *s/c* tested. The *w/c* had minimal effect on flow – the water content was the primary impact. At a given *s/c*, an increase in water content increased the mortar flow. As shown in Figure 3, a lower *s/c* provided higher flow for a given water content. An improved flow was expected to yield comparatively better strengths, since these mixtures were able to self-consolidate more completely.

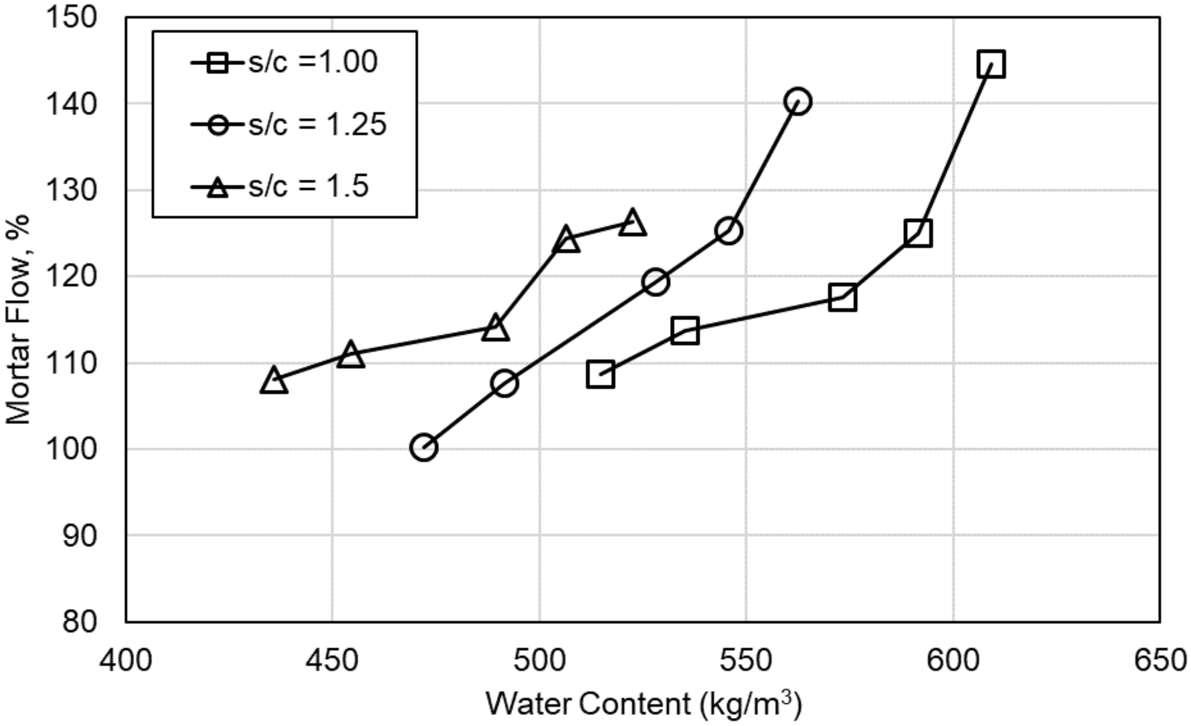

Figure 9: Flow of mortar mixtures compared to water content and s/c

Compressive Strength Results at 3-Hours of Age

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 6).

Table 7: Average compressive strengths in psi measured at 3 hours

s/c	1		1.25		1.50	
w/c	Dry-cast	Wet-cast	Dry-cast	Wet-cast	Dry-cast	Wet-cast
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 likely 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 (Figure 6).

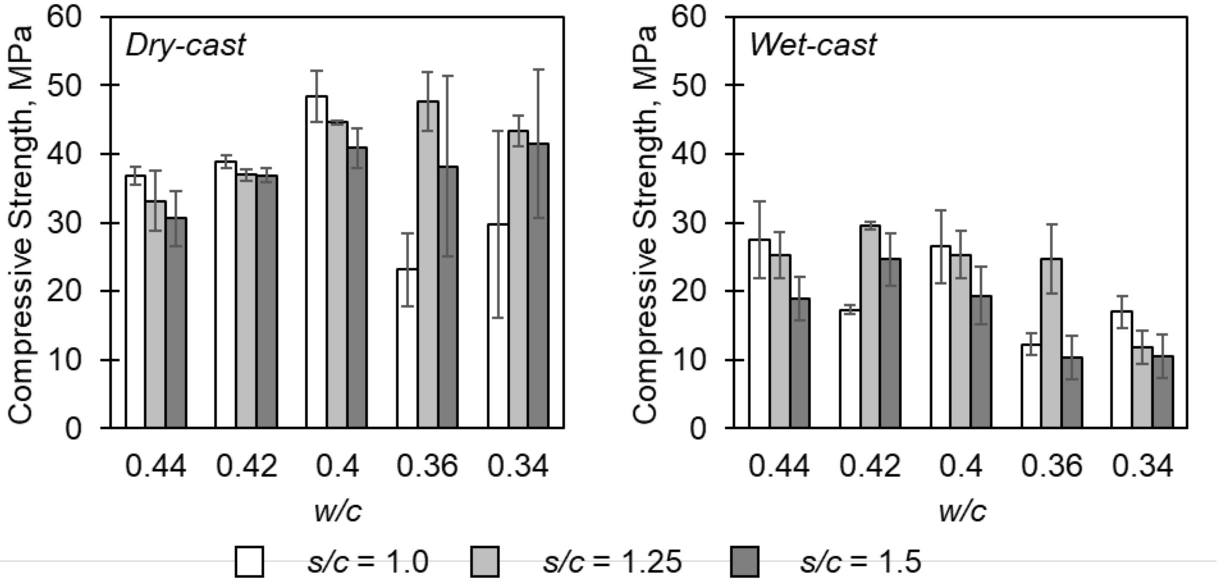

Figure 10: Comparison of 3-hour compressive strengths of mortar cubes

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 6). The highest dry compressive strength was 6900 psi (47.6 MPa) using 0.36 *w/c* and 1.25 *s/c*. The highest compressive strength for the wet specimen was 4290 psi (29.58 MPa) using a 0.42 *w/c*. 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.

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 6). 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 6). 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*.

Compressive Strength Results at Later Ages

While the main focus of the study was to achieve a compressive strength of at least 4000 psi (27.6 MPa) at 3 hours of age when placing the mortar underwater, later age strengths are almost always important as well. BCSA is often mistaken for calcium aluminate cement which loses strength over time due to a phenomenon known as "conversion." [10] BCSA cement does not lose strength to conversion. Referring to Figure 7, most wet-cast specimens continued to gain strength up to 28 days of age. On average, 90.0% of the cube's 28-day strength was achieved by 7 days. Past work has shown BCSA cement concrete can continue to gain strength years after placement [15].

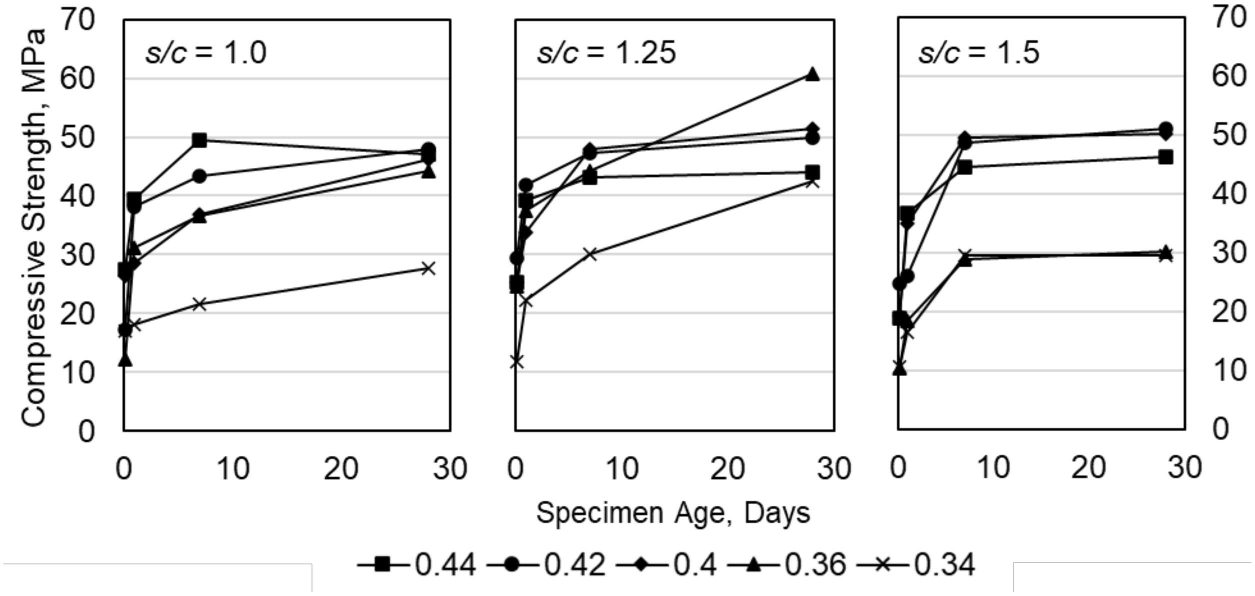

Figure 11: Compressive strength gain of wet-cast samples in first 28 days

Comparing to the compressive strength of dry-cast specimens (Figure 8), the behavior was mostly the same as the wet-cast cubes. The dry-cast specimens achieved 88.8% of their 28-day compressive strength by 7 days of age on average. Overall, compressive strengths of dry-cast cubes were higher than the wet-cast companion cubes. At 3 hours, wet-cast strengths were 53% of the corresponding dry-cast cube strengths, on average. This relationship was 64% for 1-day, 69% for 7-day, and 68% for 28-day strengths. Lower strengths were observed for the *s/c* of 1.5, likely attributable to the generally low mortar flow for these specimens. There was an inconsistent effect of *w/c* on compressive strength gain. At a *w/c* of 0.34 for example, the lowest strengths were observed at a *s/c* of 1.0 while the highest strengths were observed at a *s/c* of 1.25. These specimens had similar mortar flow values, so inconsistencies in the consolidation of the samples is likely to blame.

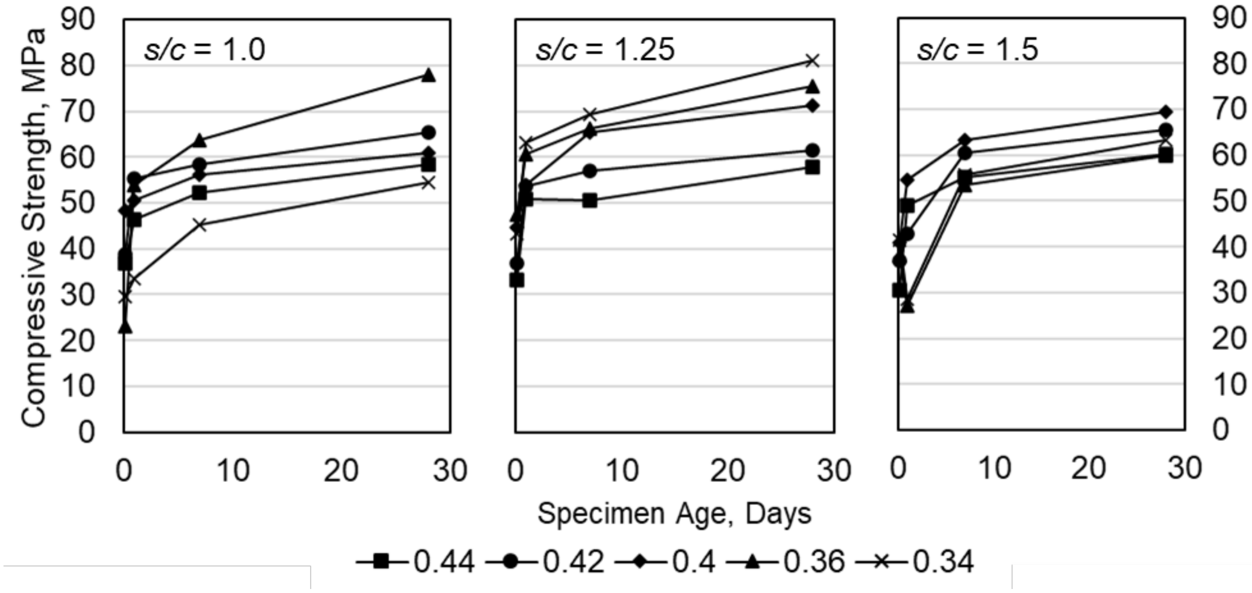

Figure 12: Compressive strength gain of dry-cast samples

Results of Soil-Cement Study

Visual Descriptions of Specimens

The main observed difference at early age was that specimens using PC appeared to be at higher moister than the specimens using BCSA even though the water contents were the same (Figure 13). This difference can likely be attributed to the higher water demand BCSA cement has in comparison to PC and the difference in setting time [7]. Some color change was observed after one day and seven days, especially in areas where the cement content was perhaps more concentrated (Figure 14).

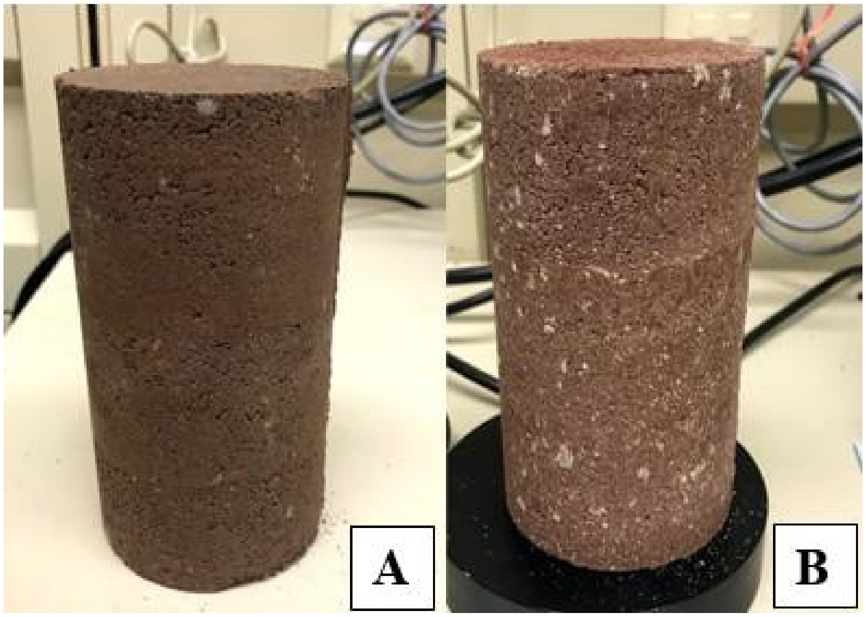

Figure 13: Comparison of soil-cement specimens at 7.5% MC 1-hour after mixing - (A) PC specimen, (B) BCSA cement specimen

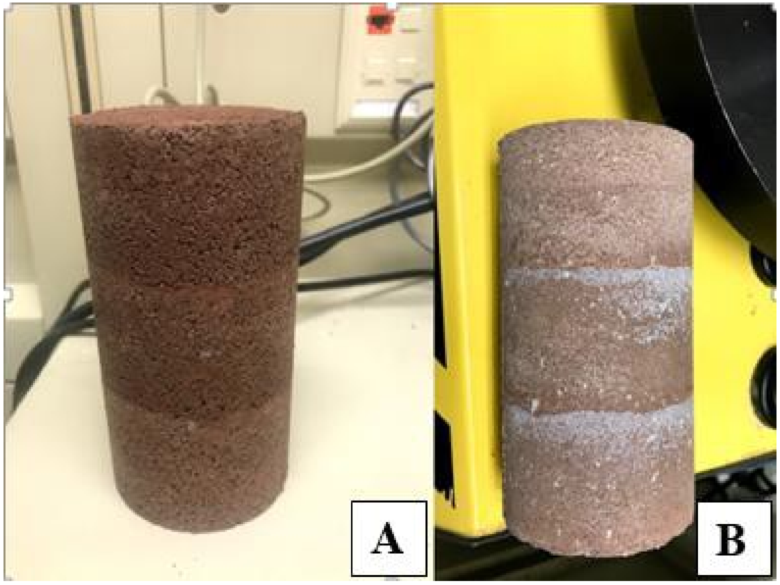

Figure 14: Comparison of soil-cement specimen at 7.5% MC 7 days after mixing - (A) PC specimen; (B) BCSA cement specimen. Note the visibility of cement in (B) where the layers were compacted.

The specimens at a higher moisture content (10%) had a brighter red color due to the high saturation of the clay. Visual differences were observed when comparing the BCSA and PC specimens at 1-hour after casting (Figure 15). 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 cement 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 (Figure 16). Referring to Figure 16, BCSA soil-cement 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 cement since it may require more water to hydrate completely.

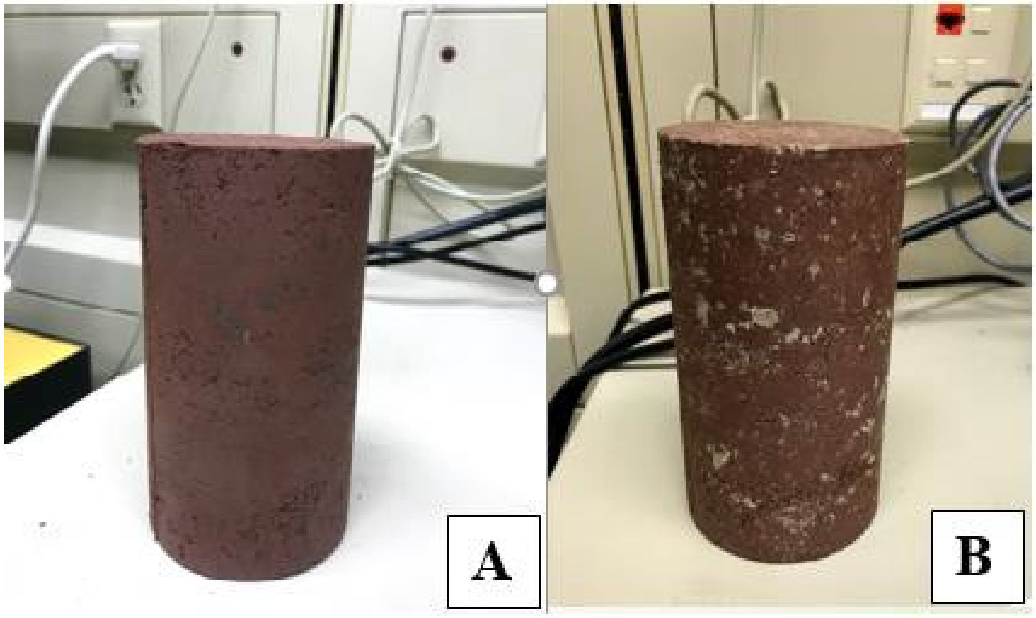

Figure 15: Visual difference of samples using both binders at 10% MC at 1-hour after mixing - (A) PC specimen; (B) BCSA specimen.

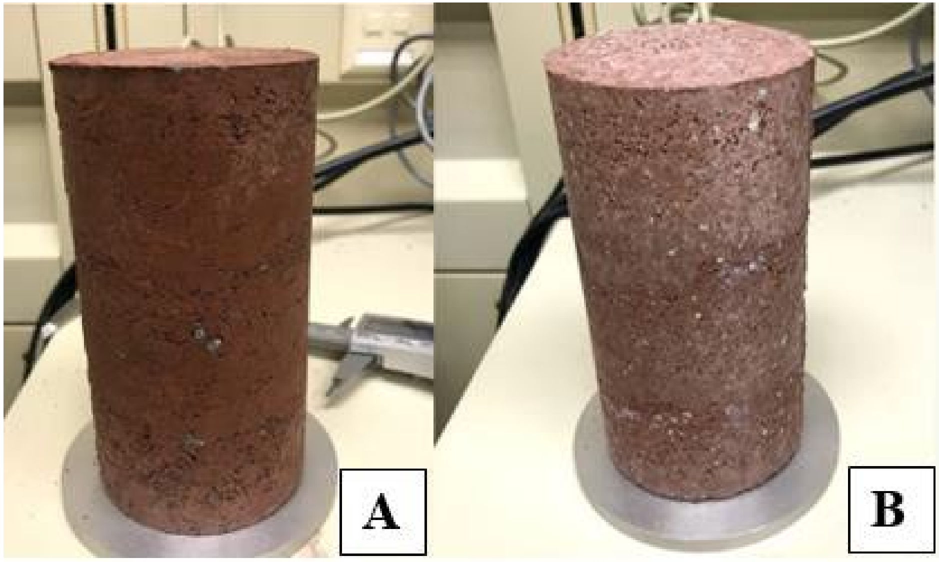

Figure 16: Visual difference between specimens using both binders at 10% MC at 1 day. (A) PC specimen; (B) BCSA cement specimen.

Types of Failures in UC Testing

Most soil-cement samples failed in shear (Figure 17). 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.

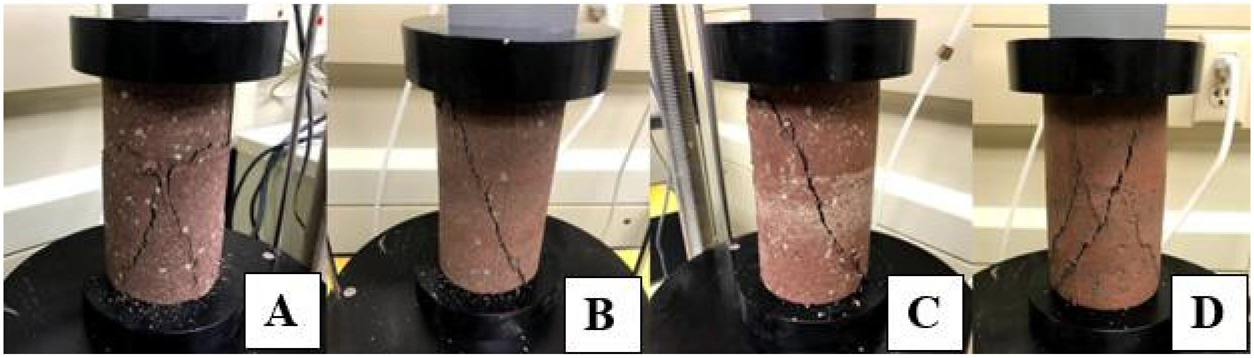

Figure 17: Failure mechanism for soil-cement specimens tested at 3 hours. (A) BCSA at 7.5% MC; (B) PC at 7.5% MC ;(C) BCSA at 10% MC; (D) PC at 10% MC.

The soil-only control 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 18).

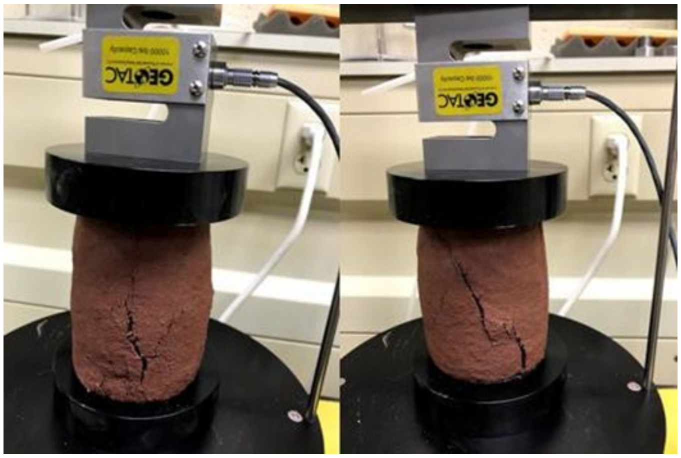

Figure 18: Failure mechanism of the control group (no cement) using 10% MC

Results of UC Testing on Soil-Cements

1-Hour Tests on 7.5% MC Samples

The early age failure strain of the 7.5% MC sample using BCSA cement was approximately 0.7%-0.8% (see Figure 19). The PC curve had a strain at peak of approximately

1% (Figure 20). 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 by 1 hour of age. The peak stress of 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 (shown in a later section).

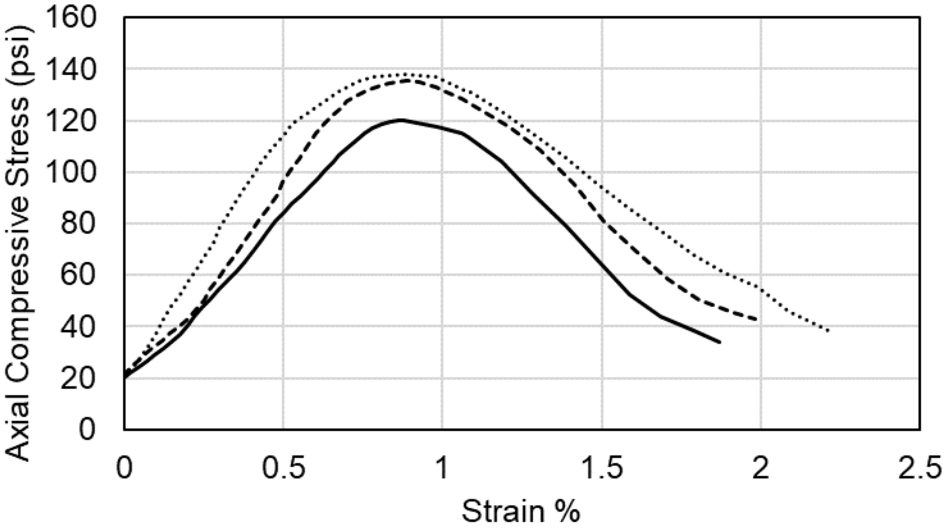

Figure 19: Stress-strain relationship for BCSA cement soil-cement at 7.5% MC at 1-hour, note: 1,000 psi = 6.89 MPa

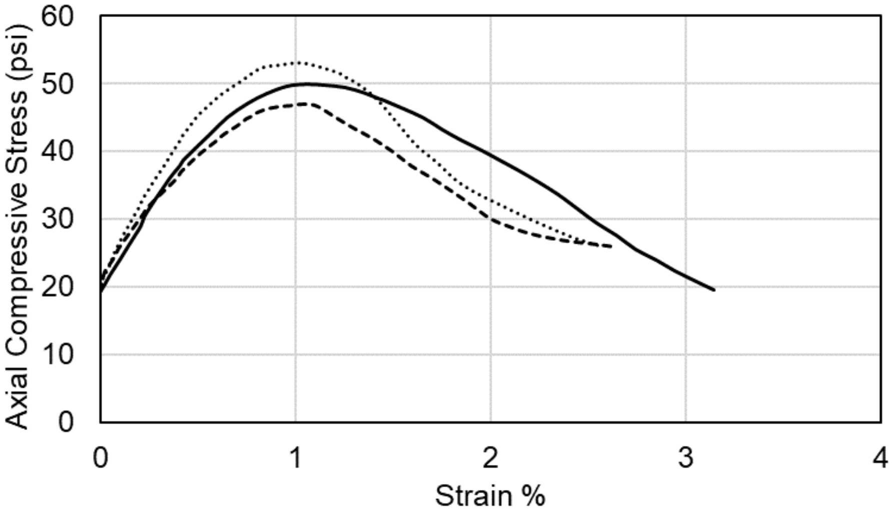

Figure 20: Stress-strain relationship for PC soil-cement at 7.5% MC at 1-hour, note: 1,000 psi = 6.89 MPa

1-hour Tests on 10% MC Samples

Similar to the 7.5% MC samples, 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 Figure 21 and Figure 22). The specimens using a BCSA cement underwent lower deformations before failing at early age (1 hr) in comparison to PC. These values are higher than the peak strain 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 compressive 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.

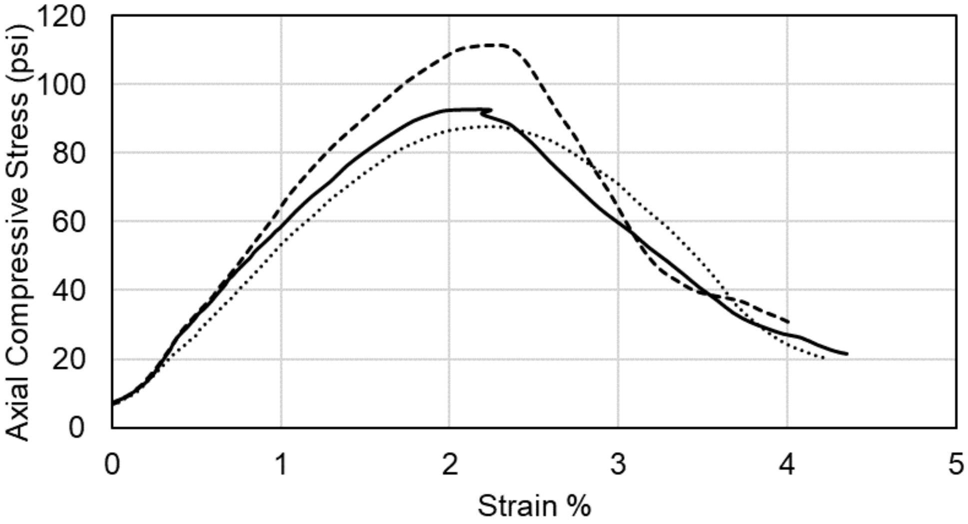

Figure 21: Stress-strain relationship for BCSA cement soil-cement at 10% MC at 1 -hour, note: 1,000 psi = 6.89 MPa

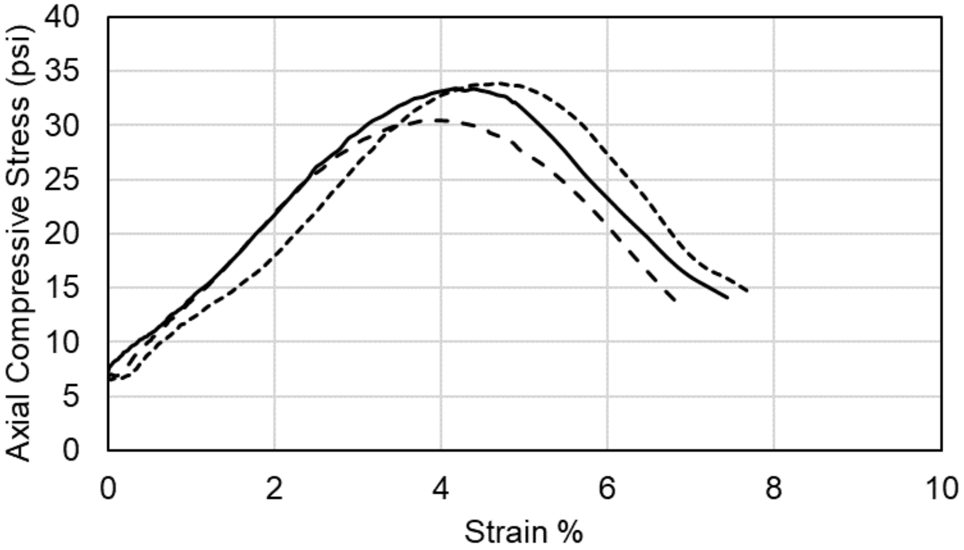

Figure 22: Stress-strain relationship for PC soil-cement at 10% MC at 1-hour, note: 1,000 psi = 6.89 MPa

1-Hour Tests on Control Soil Mixtures (No Cement)

The stress-strain relationship for 10% MC control samples resulted in the highest strain at peak of all groups tested. This value was about 15% of the specimen height (Figure 23). 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% was 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.

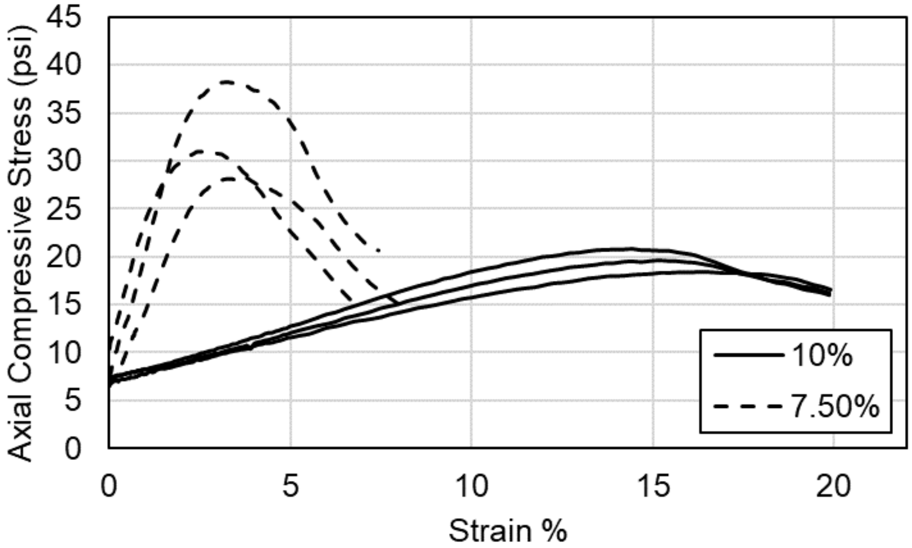

Figure 23: Stress-strain relationship for soil-only samples at 1-hour, note: 1,000 psi = 6.89 MPa

Comparison of Peak Stresses Achieved at Different Testing Ages

The comparison between the control group strengths and the soil-cement specimen strengths at 7.5% MC 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 the soil-only samples. The samples using BCSA cement 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 soil-cement compressive 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 compressive 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-day control group strength is compared to the PC and BCSA soil-cement specimens, the inclusion of cement led to an 676% and 627% increase in strength, respectively (Figure 24).

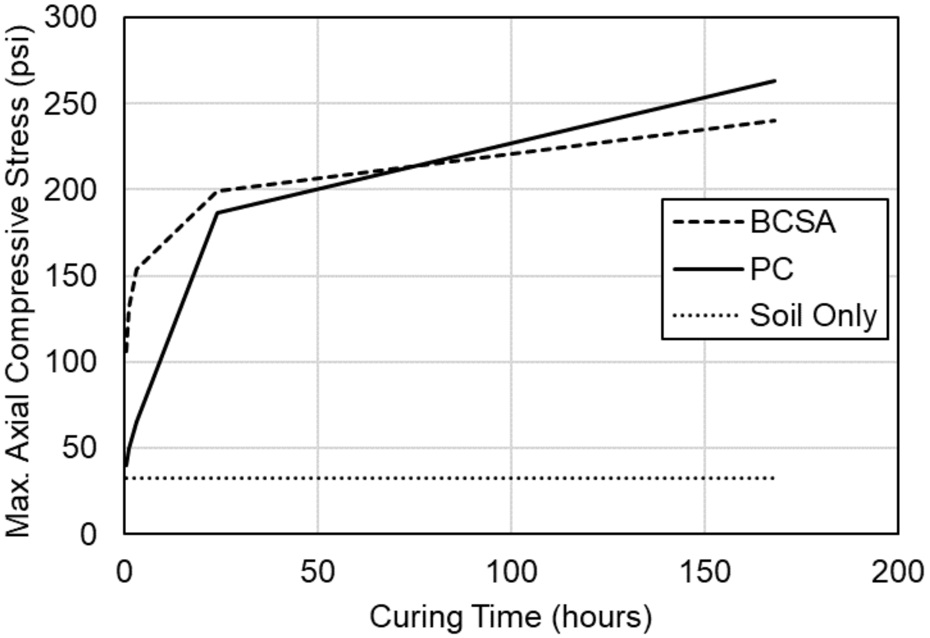

Figure 24: Comparison of maximum compressive strength achieved for 7.5% MC samples, note: 1,000 psi = 6.89 MPa

Considering the 10% MC samples, 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 soil-cement strength was 194% higher than the PC soil-cement 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 the 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 25). 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.

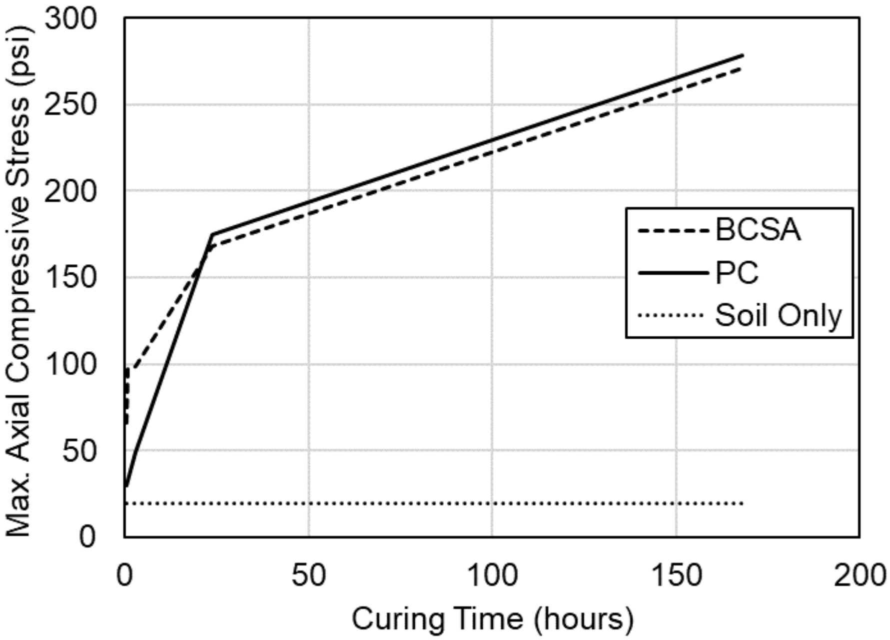

Figure 25: Comparison of maximum compressive strength achieved for 10% MC samples, note: 1,000 psi = 6.89 MPa

Scanning Electron Microscopy of BCSA Soil- Cement Samples

Towards the end of the research study, a budget revision and no-cost extension were requested to take images of BCSA soil-cement samples and measure the length of the ettringite crystals present in these samples at different ages. Samples of soil cement were ground into a powder and placed in the scanning electron microscope (SEM) at three different ages (3 hours, 1 day, and 7 days). The FEI Nova Novalab Dual-Beam SEM in the NANO building at the University of Arkansas was used for the testing. Images of the BCSA soil-cement are given in Figures 26, 27, and 28, representing 3-hour, 1-day, and 7-day old samples, respectively. Ettringite crystal lengths were often similar at any age, but the density of the crystals appeared to increase as time went on, showing the fast formation of ettringite and how it can continue to form out to 7 days after mixing. It seemed easier to find large clusters of ettringite at later ages. The increased presence of ettringite likely contributed to the strength gains observed at these different ages. It was difficult to determine if other reaction products were present, certainly ettringite was the primary reaction product that was visible in the SEM images. If the BCSA cement still had access to moisture after 7 days, other reaction products such as calcium silicate hydrate would be likely to form.

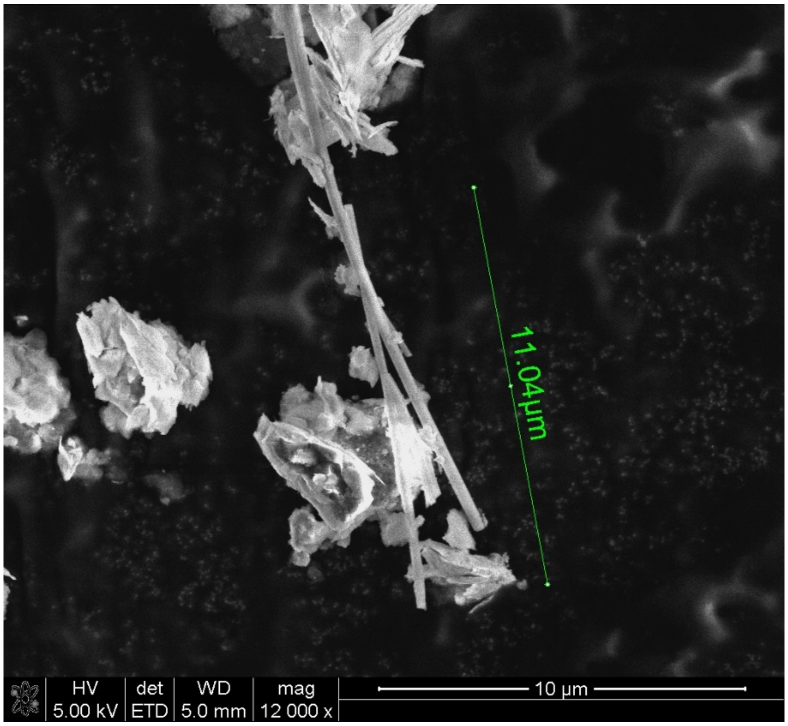

Figure 26: SEM image of ettringite crystals in BCSA soil-cement at 3-hours

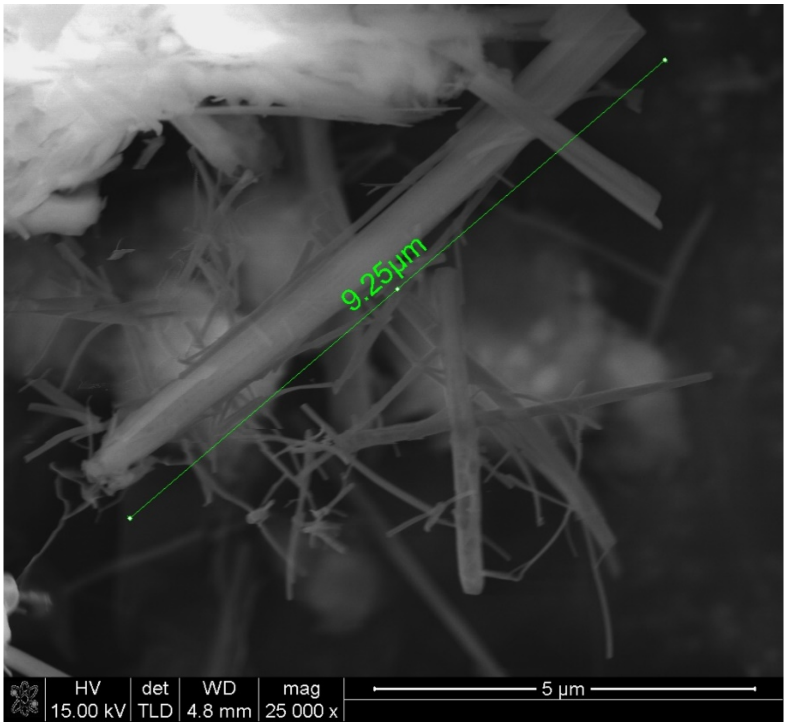

Figure 27: SEM image of ettringite crystals in BCSA soil-cement at 1-day

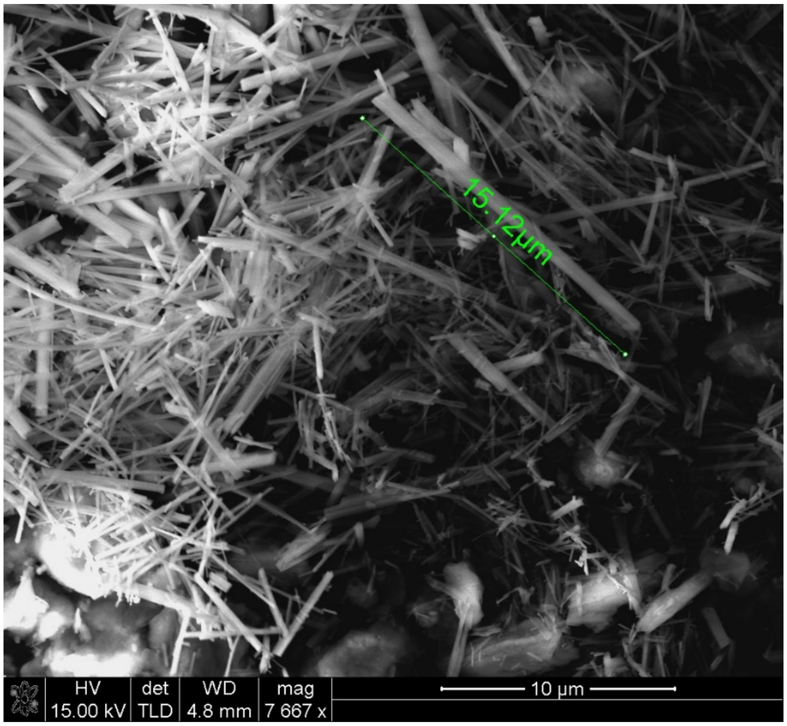

Figure 28: SEM image of ettringite crystals in BCSA soil-cement at 1-day

IMPACTS/BENEFITS OF IMPLEMENTATION

This study represents the first known use to the authors of BCSA cement in soil-cement mixtures. The comparison of these fast strength-gain materials to PC provides data for practitioners who may want to use a rapid-setting material for repair or fast construction applications. The soil-cement mixtures developed here are not only for maritime applications, but they can also be applied to deep soil mixing, roadway base construction, or building foundation systems. The cement content should be examined for these other applications to determine the relationship between the moisture content and resulting hydration and strength. Additionally, additives (e.g., a retarder) were not used in this soil-cement study, but they may provide improved hydration at lower moisture contents and longer initial set times which should also be examined in future studies. This is the basis for a proposed MarTREC project in FY 2022.

The development of a BCSA mortar which can set up underwater and gain strength very quickly was also a novel contribution. This mixture can be used in repair applications (especially for dams and locks) or for new construction and may serve as a basis for future mixtures to be used in underwater applications.

RECOMMENDATIONS AND CONCLUSIONS

Underwater Mortar Study Conclusions

The goal of this study was to proportion a mortar mixture using BCSA cement suitable for underwater use. The mixture developed is expected to be suitable as a repair material. 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-cast” and “wet-cast” specimens. 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 improved 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. These dosages were obtained by trial-and-error, but the effects of admixtures on BCSA cement behavior should be studied more in the future.
5. More research should be conducted to further understand the relationship between *s/c* and compressive strength for this type of application.

Soil-Cement Study Conclusions

The main purpose of this study was to determine 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 included soil-cement specimens made from PC for comparison. Different moisture contents (7.5% and 10%) and curing/setting 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 soil-cement 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 (10% moisture content only) 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. Lower moisture contents do 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., higher humidity or submerged) 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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