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**FEASIBILITY OF BLAST FURNACE SLAG FOR STABILIZING SULFATE-BEARING
SOIL**

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**FEASIBILITY OF BLAST FURNACE SLAG FOR STABILIZING SULFATE-BEARING
SOIL**

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Abstract

Calcium-based stabilizers are frequently used by The Oklahoma Department of Transportation (ODOT) to enhance the strength and reduce the swelling potential of fine-grained soils. However, these stabilizers can lead to adverse reactions in high sulfate-bearing soils which are very common in Oklahoma. This study aimed to explore the efficacy of Ground Granulated Blast Furnace Slag (GGBFS) as an additive for high sulfate-bearing soils, by comparing the performance of GGBFS with other stabilizers like lime and Portland cement. In this research, the primary evaluation tests were the unconfined compression test (UCT), to evaluate the strength gained from the addition of the stabilizer, and the response to wetting test to study swelling behavior. Two test soils were manufactured that contained approximately 20,000 ppm of sulfate in the form of ground gypsum. In addition to the gypsum, Test Soil 1 was made with equal amounts of fine sand and kaolinite and Test Soil 2 with equal amounts of fine sand and montmorillonite.

The results indicate that adding between 6% and 12% GGBFS by dry weight of soil significantly increased the unconfined compressive strength (UCS), and the optimum amount of GGBFS was 8% by dry weight of soil for both test soils. With the addition of the 8% GGBFS, the UCS of Test Soil 1 and Test Soil 2 increased on average by 40 psi and 50 psi, respectively. These values are close to the 50 psi increase desired for chemical stabilizers according to ODOT requirements in OHD L-50. Additionally, when GGBFS was combined with a small amount of either lime (0.5% or 1%) or PC (1% or 3%), a significant increase in the UCS was observed compared to untreated samples or the ones only treated with one additive. The introduction of 1% lime and 7% GGBFS increased the UCS around 200 psi for Test Soil 1 and 94 psi for Test Soil 2. The combination of 3% PC and 7% exhibited the highest UCS increase, reaching 300 psi for Test Soil 1 and 140 psi for Test Soil 2.

The incorporation of GGBFS was observed to decrease the swelling behavior in both test soils during a response-to-wetting test lasting approximately 15 days. The addition of 8% GGBFS decreased the vertical swell from 3.3% to 1.9% for Test Soil 1 and from 5.2% to 0.3% for Test Soil 2. Most notably, both soils exhibited no apparent swelling after the first day of the test, which is in contrast to all other tests containing lime, PC or GGBFS mixed with lime or PC. When lime or PC was used alone or in combination with GGBFS, swelling continued throughout the testing period. In some cases for Test Soil 1, the final amount of swelling exceeded that of the test soil alone, which is a clear indication of adverse reactions occurring due to addition of lime or PC. That the GGBFS completely halted the swelling behavior while all the mixes containing lime or PC continued to swell at the end of the nearly 15-day tests is an important finding. It suggests that adverse reactions may not be avoidable even with small amounts of PC or lime mixed with GGBFS.

The addition of GGBFS to the test soils had a minimal impact on the Liquid Limit, Plastic Limit, and Plasticity Index of the test soils. However, for both test soils the Shrinkage Limit was significantly reduced with the addition of 8% GGBFS. For Test Soil 1 and Test Soil 2, respectively, the SL reduced from about 9.5% and 18% for the untreated soil to about 1.5% and 6% for the treated soil.

Chapter 1: Introduction

The use of GGBFS as a soil additive has demonstrated its potential to mitigate the swelling behavior of expansive soils (Wild et al. 1996 & Yadu & Tripathi 2013). Given that GGBFS is primarily composed of silicates, there is a potential to utilize it as a chemical additive for expansive soils with high sulfate content; thereby avoiding adverse reactions with calcium-based stabilizers like lime that can lead to the formation of expansive minerals such as ettringite. The use of GGBFS to stabilize expansive soils containing a high sulfate content was the focus of the experimental research described in this thesis.

Civil engineering faces a significant challenge with expansive clay soils due to their high volumetric changes caused by fluctuations in moisture content. Such changes can damage structures and foundations, jeopardizing the safety of individuals and leading to costly repairs (e.g. Marcus 2017). There are multiple ways to deal with these types of soils, including removal and replacement or moisture control or chemical soil stabilization, which is one of the most common methods, mainly employing calcium-based stabilizers like lime. However, when the expansive clay has a high sulfate content, it can lead to more significant problems when using these additives because their reaction to sulfate and water creates highly expansive crystals known as Ettringite. In Oklahoma, calcium-based additives are not recommended when the sulfate content exceeds 8000 ppm (Oklahoma Department of Transportation 2021). Consequently, it becomes imperative to conduct further investigations and explore novel additives suitable for addressing these specific soil conditions.

Ground Granulated Blast Furnace Slag (GGBFS) is a residue obtained from melting iron in a blast furnace. After being separated from iron, it is ground into a powder composed mainly of calcium-alumina-silicates. Disposing of GGBFS residues is costly and has environmental

implications, so researchers have investigated ways to repurpose them in construction. After much investigation, researchers found that GGBFS can be used for soil stabilization, with some results showing improvement in unconfined strength and reduced swelling in fine-grained soils (Yadu & Tripathi 2013). This research aimed to analyze the performance of different concentrations of GGBFS in fine-grained clay soils with a high swelling behavior and containing significant sulfate. This study primarily focused on evaluating volume change behavior and unconfined compressive strength of the soils before and after adding GGBFS. Other physical and index properties were also determined for untreated and treated test soils. Furthermore, the efficacy of GGBFS was compared with mixes containing well-known stabilizers like Lime and Portland Cement; and combinations of GGBFS with these stabilizers were utilized to analyze possible synergistic effects on strength and swelling behavior of the test soils.

Chapter 2: Literature Review

2.1 Soil Composition

Soils are defined as a loose agglomeration of different mineral and organic materials over the bedrock (Holtz et al. 2011). Soils are formed when rocks are broken down into smaller pieces through physical or chemical processes, forming different soils with different properties. According to Holtz et al. (2011), soils are a particulate material with voids, and those voids can be filled with water and air, causing some chemical and physical interactions between the fluid and the particles themselves, which makes their behavior difficult to study. Soil characteristics depend on the geological environment that formed them, making the characteristics from one soil to another highly variable. They also have a “memory,” that is, their behavior depends on the stresses and other processes they experienced in the past, which also changes their properties.

Soils are usually classified into coarse-grained soils like gravels or sands and fine-grained soils like clays and silts. Coarse-grained soils are not significantly affected by the presence of water, which is why they can be classified only according to their grain size and grain size distribution. On the other hand, fine-grained soils are greatly affected by the presence of water, so they are primarily classified on the basis of their plasticity behavior.

The two most commonly used soil classification systems are the American Association of State Highway and Transportation Officials (ASSHTO) Soil Classification System and the Unified Soil Classification System. These systems consider that the percentage of essential components in the soil can influence their properties. For example, gravel with some percentage of clay will not behave the same way as gravel without clay (Holtz et al. 2011).

2.1.1 Clay Minerals

Clay minerals result from rock alteration under low temperatures and pressures, changing

their original mineralogy and texture. Water plays a crucial role in this process, so most clay minerals are described as hydrous aluminum silicates, belonging to a mineral class called phyllosilicates (Hillier 1995). Typically, clay minerals have nominal particle diameters of less than 2 μm and consist of cation planes arranged in sheet-like structures with repeating atomic patterns. The stacking arrangement of these sheets, whether tetrahedrally or octahedrally coordinated with oxygen atoms, defines the different clay minerals. 1:1 minerals are composed of one tetrahedral sheet and one octahedral sheet in repetitive layers, while 2:1 minerals have two tetrahedral sheets with an octahedral sheet sandwiched in between. For this study, two distinct clay minerals are employed: Kaolinite, which belongs to the 1:1 mineral group, and Montmorillonite, also known as Bentonite, a well-known member of the 2:1 mineral group. Soils with high clay mineral content without and with sand are called clay, silty or sandy clay, clay loam, and silty or sandy clay loam (Holtz 1969).

The behavior of clay soils in the presence of water is significantly influenced by clay mineralogy and structure. Krohn and Slosson (1980) calculated that the damage caused by expansive soils was about \$7 billion annually in the US. According to Veith (2000), two mechanisms are involved in swelling in a clay-water interaction: interlayer swelling and water imbibition of minerals with expandable structures.

A clay mineral has three fundamental components: a tetrahedral or silica sheet, an octahedral or alumina sheet, and a water layer. The water molecules are held to the clay crystal through hydrogen bonding, and the negatively charged clay crystal surfaces attract cations in the water. In the presence of water, interlayer swelling occurs when the interlayer cations attract water molecules, separating clay layers and causing swelling (Veith 2000, Holtz 1969). Different clays have different tendencies to attract exchangeable cations. For example, Holtz (1969) explains that

calcium and magnesium are the primary exchangeable cations in most soils, except for soils of marine origin. On the other hand, aluminum and hydrogen are commonly found in acidic soils.

The other phenomenon involves the interaction between water and the surface of clay minerals. Water, a dipolar molecule with positive and negative charge centers, is electrostatically attracted to the clay crystal surface. This attraction is facilitated by hydrogen bonding, where the hydrogen atoms in water interact with the oxygen atoms on the clay surface. According to Veith (2000), this attraction is diminished with distance and has a thickness of approximately 5 to 10 molecules. Close to the surface of the clay particle, cations in the adsorbed water are held in position by electrostatic forces. Meanwhile, other cations diffuse away from the surface, seeking to balance out the cation concentrations, yet still influenced by the electrical attraction to the negatively charged clay crystal surface. These two components form together a surface known as the diffuse double layer or diffuse electrical double layer (DDL) (Figure 1). Although the water adsorbed is approximately the same, the size of the clay particle is different. Montmorillonite size particles are smaller than Kaolinite particles, which is why they tend to absorb more water and possess much greater activity and volume changes (Holtz 1969).

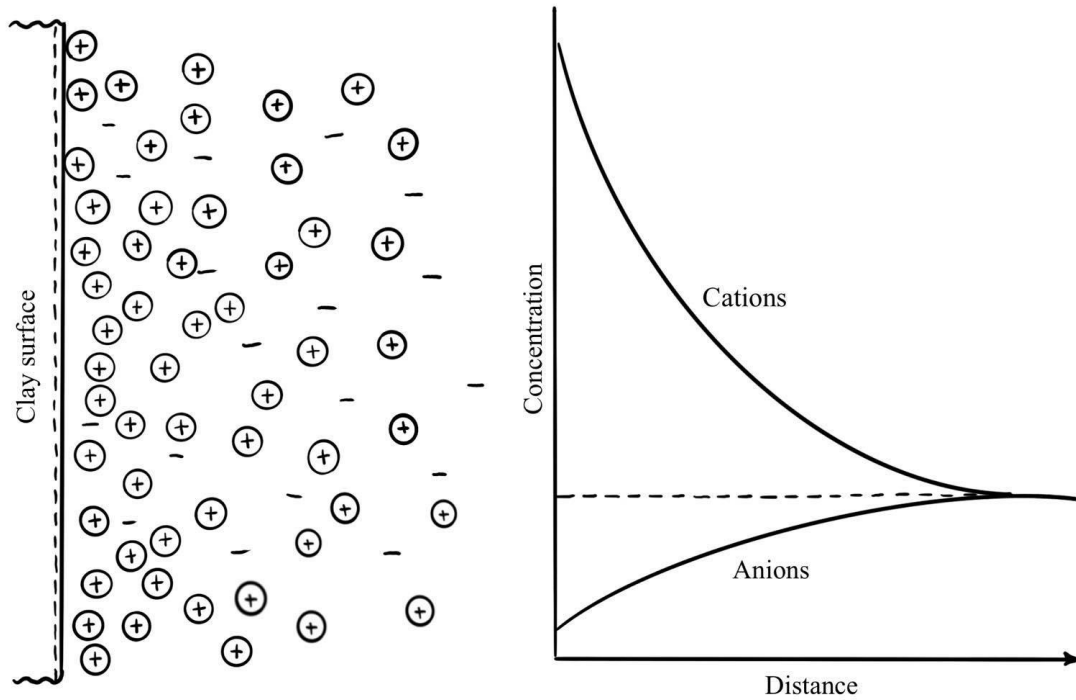


Figure 1. Diffuse double layer in a clay-water system (after Holtz, Kovacs, & Sheahan 2011).

2.1.2 Sand Minerals

Sand consists of tiny rock grains and granular materials that are finer than gravel (particles less than 4.75 mm) but coarser than silt and clay (particles larger than 0.075 mm) (WSDOT Geotechnical Design Manual 2013). It is mainly made of silicate materials and silicate rock granular particles. The prevailing mineral in most sands is quartz, although additional minerals like tourmaline, zircon, and feldspar can also be present. When soil contains more than 85% sand-sized particles by mass it is called sandy soil. Sandy soils are highly permeable, cohesionless, and possess low shear strength under low confining stress (eg. Al-Saray, Shafiqu, & Ibrahim 2021).

2.1.3 Sulfate-bearing Soils

Sulfate-bearing soils are found all across the United States. In western Oklahoma, sulfate is commonly found in soils and shale as gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) (Adams, Dukes, Tabet, Cerato, & Miller 2008). Most of these soils are expansive, which is why they need to be treated with

chemicals to reduce their volumetric changes in a process called soil stabilization. However, since the last century, it has been widely known that these sulfate-bearing soils can expand even more when treated with traditional calcium-based stabilizers, such as lime. When these stabilizers are added to the soil, the chemical reactions between the soluble sulfate with calcium from the additive and alumina from the clay produce an expansive mineral called ettringite (e.g. Al-Dakheeli et al. 2021). Al-Dakheeli et al. (2021) reported many sulfate-induced heave cases in Nevada, Texas, Kansas, and Utah. In 2004, sulfate-induced heave affected several miles of Oklahoma Highway 412, costing millions in repairs (Cerato et al. 2011).

2.2 Soil Stabilization

According to Holtz et al. (2011), clay soils are composed primarily of clay minerals, and their behavior is heavily influenced by the presence of water. Some of these clay soils can significantly change their volume depending on the change in water content. This problem in engineering is usually mitigated with soil stabilization, where some additives are added to the soil that controls the expansive behavior. Calcium-based stabilizers, such as lime or cement, are the most common treatment for this type of soil because they can improve the soil properties while controlling the volume change. However, soils with high content of sulfates can lead to more significant swelling problems when lime reacts with the sulfate and water in the soil, forming an expansive mineral known as ettringite (e.g. Puppala, Intharasombat, & Vempati 2005). According to the Oklahoma Department of Transportation, there are currently no recommendations for additives for clayey soils when the sulfate content is more significant than 8000 parts per million (Oklahoma Department of Transportation 2021).

2.2.1 Lime

Lime (CaO) is derived from limestone, a sedimentary rock composed of calcite and

aragonite, which are crystal forms of calcium carbonate (CaCO_3). Over thousands to millions of years, sedimentary deposits react with water containing dissolved calcium and are subjected to compression under other sediments, eventually forming limestone. Limestone may also contain magnesium carbonate (dolomite) along with minor amounts of clay, iron carbonate, feldspar, pyrite, quartz, and fossils of marine organisms like corals and clams (e.g. University of Kansas 2010 & Encyclopedia Britannica 2023). To produce lime, high-quality limestone deposits are subjected to extreme heat for several hours, above 825°C , changing the rock's calcium carbonate (CaCO_3) into calcium oxide (CaO). This inorganic material is commonly known as “quicklime.” Additionally, by quenching quicklime with water, we obtain calcium hydroxide ($\text{Ca}(\text{OH})_2$), also called “hydrated lime” (e.g. Madhu 2018).

Lime is widely used in environmental, metallurgical, industrial, and construction applications. In civil engineering, for example, hydrated lime can be used as an additive for road surfacing, increasing the resistance of the asphalt to water stripping. It is also mixed with cement to create concrete blocks, mortar, and “limecrete,” which increases the properties of the mix and gives a higher resistance to chemical attacks, such as sulfur and sulfate (e.g. Tsvilis et al. 2000 & Chang et al. 2005). It is also used in soil stabilization, modifying almost all fine-grained soils. The chemical reaction between the lime and the soil affects the short and long-term soil behavior. According to Eades and Grim (1960), lime addition triggers three primary chemical reactions in the initial hours: cation exchange, flocculation-agglomeration, and carbonation.

The calcium cations produced by adding lime attract the clay minerals, reducing the repulsion forces and the thickness of the DDL. Consequently, this alteration results in the clumping of clay particles, leading to a change in soil texture, a phenomenon termed flocculation-agglomeration (e.g. Jawad, I., Taha, Majeed, & Khan 2014). On the other hand, lime can also

react with atmospheric carbon dioxide, which forms an insoluble carbonate (National Research Council (U.S.) 1987). This chemical process, called carbonation, is generally undesirable due to its potential to compromise the mechanical properties of the treated soil (e.g. Bagonza, Peete, Freer-Hewish, & Newill 1987).

According to Jawad et al. (2014), solubilization of the silica and alumina within the soil occurs due to the pH increase, causing pozzolanic reactions that form Calcium Silicate Hydrates (C-S-H) and Calcium Aluminate Hydrates (C-A-H). These cementitious compounds are time and temperature-dependent, requiring years for full development. The benefits of adding lime to the soil are usually a plasticity reduction, less water absorption, reduced volumetric changes in the presence of water, and increased strength (National Lime Association 2013).

2.2.2 Portland Cement

Portland cement is obtained by a precise combination of raw materials, primarily limestone, along with clay or shale, and a series of chemical reactions. The mixture is usually pulverized and heated in a rotary kiln at a high temperature, often exceeding 1450°C (2642°F), transforming the materials into gray nodules called clinker. The clinker contains compounds like tricalcium silicate ($\text{SiO}_2 \cdot 3\text{CaO}$), dicalcium silicate ($\text{SiO}_2 \cdot 2\text{CaO}$), tricalcium aluminate ($\text{Al}_2\text{O}_3 \cdot 3\text{CaO}$), and tetra-calcium ferro-aluminate ($4\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{Fe}_2\text{O}_3$). After grinding, the clinker is blended with a measured quantity of calcium sulfate, typically gypsum, resulting in the creation of Portland cement (Spencer 2018).

Portland cement (PC) is widely used in expansive soil stabilization (e.g. Yi et al. 2014, Mehedi et al. 2018). This process is similar to adding lime in that it increases pH and forms cementitious compounds C-S-H, C-A-H, and C-A-S-H leading to increases in the soil strength. The difference from lime is that PC is intrinsically cementitious whereas lime promotes pozzolanic

reactions when mixed with soil and water, which leads to cement formation over time.

2.2.3 Ground Granulated Blast Furnace Slag

Blast furnace slag is a waste material obtained during the process of melting iron in a blast furnace. It is called Ground Granulated Blast Furnace Slag (GGBFS) when it is turned into powder. It consists of mostly silicates or aluminum-silicates, and it has latent hydraulic properties, which is why it is used with Portland cement to enhance its properties (e.g. Ouf 2001). GGBFS is used with Portland cement to increase the cement's durability and create high chemical resistance to sulfates and chloride penetration due to the components from the GGBFS. This mix is based on the activation of the hydraulic properties of GGBFS with the alkalis released during the hydration process of Portland cement (e.g. Wild et al. 1996).

GGBFS is widely known for its use with Portland Cement in recent years, but its use in soil stabilization is still a matter of study. In soils with high sulfate content, soil stabilization using a common additive like lime can lead to serious swelling problems, where lime reacts with the sulfated clay and water to form crystals like ettringite and thaumasite (e.g. Wild et al. 1996). According to Wild et al. (1996), adding GGBFS to soil composed of lime, kaolin, and gypsum reduced the swelling behavior without any notable change in the compression strength of the soil. Wild et al. (1996) also noted that, by adding GGBFS, there is a reduction in both the plastic and liquid limit. It is reported that replacing lime with GGBFS can improve the strength of the soil by 60% to 80% (Ouf 2001). Ouf (2001) points out, "The main advantages of using both lime and GGBFS relative to using lime only are a slower early rate of strength development giving more time to finish the construction and an increase in long-term strength which improves the performance."

Some other studies found that GGBFS stabilizers produced high unconfined compressive

strength (UCS), high Optimum Dry Density (ODD), and less Optimum Water Content (OWC) in soft soils, finding that the optimum amount of GGBFS for the soil in the study was 9%. (Yadu & Tripathi 2013).

Chapter 3: Hypotheses and Objectives

3.1 Hypotheses

1. By incorporating various concentrations of GGBFS into the two prepared soils, namely one consisting of kaolinite, sand, and gypsum and the other comprising montmorillonite, sand, and gypsum, the anticipated outcomes included a decrease in swelling behavior, a reduction in the Plasticity Index (PI), and a potential improvement in unconfined compressive strength.
2. Adding GGBFS with small amounts of lime or Portland cement into the manufactured soils previously mentioned was projected to reduce the swelling behavior and improve unconfined compressive strength effectively.

3.2 Goals and Objectives

The goals of this research were:

1. To investigate the improvement of unconfined compressive strength (UCS) through the incorporation of GGBFS with or without small amounts of lime or Portland cement in two different test soils with high sulfate contents.
2. Assess the efficacy of GGBFS with or without small amounts of lime or Portland cement in mitigating the swelling behavior of two different test soils with high sulfate contents.

The objectives of this research were:

1. To evaluate the compaction characteristics of test soils with and without GGBFS.

2. Study the enhancement in unconfined compressive strength (UCS) by incorporating different concentrations of GGBFS into two manufactured test soils. The first soil composition included kaolinite, sand, and gypsum, while the second soil composition comprised montmorillonite, sand, and gypsum. Both test soils contained approximately 20,000 ppm of sulfate in the form of gypsum.
3. Measure and compare the changes in Atterberg limits between test soils treated with GGBFS and untreated soils.
4. Assess and compare the variation in pH levels between test soils treated with GGBFS and untreated soils.
5. Evaluate and quantify the swelling behavior of both GGBFS-treated and untreated test soils.
6. Analyze the chemical and mineralogical properties of the test soils with and without GGBFS.
7. Compare the performance of GGBFS-treated soils with those treated using hydrated lime or Portland cement.
8. Investigate the performance of GGBFS-treated soils containing small amounts of lime or Portland cement.

Chapter 4: Materials and Methods

4.1 Materials

Two different clay minerals: kaolinite and montmorillonite, were selected for this study. For Test Soil 1, a dry mixture consisting of 50% kaolinite, 50% fine sand, and approximately 4% gypsum was prepared. This gypsum content equates to about 20,000 ppm of sulfate. The kaolinite was obtained from the Old Hickory Clay Company, and it is referred to as Old Hickory No. 1 Glaze. The chemical components of Kaolinite are shown in Table 1 (Sheffield Pottery 2023), which comprises approximately 71% kaolinite, 22% quartz, 4% feldspar, and trace amounts of other minerals.

Table 1. Chemical constituents of Kaolinite (Material Property Data 2023).

Chemical Constituent	Percent by Weight
CaO	0.10%
K ₂ O	0.30%
MgO	0.30%
Na ₂ O	0.10%
TiO ₂	2.40%
Al ₂ O ₃	29.40%
SiO ₂	56.30%
Fe ₂ O ₃	0.90%
Loss on Ignition	9.90%
Total	99.70%
Kaolinite Al ₂ Si ₂ OH ₅ (OH) ₄	70.8%

Test Soil 2 shared similarities with Test Soil 1, except for substituting kaolinite with montmorillonite. Montmorillonite, also known as Bentonite, was obtained from Bulk Apothecary, and its chemical components are 95-100% Bentonite, less than 2% percent silica, and trace amounts of other minerals (Bulk Apothecary 2019).

4.2 Test Methods

There are presently no specified recommendations for additives in clayey soils with sulfate

content exceeding 8000 parts per million (Oklahoma Department of Transportation 2021). In this study, the test soils contained high sulfate levels, approximately 20,000 ppm, aiming to assess the effectiveness of GGBFS treatment. Soil properties with and without treatment were investigated using laboratory testing, complemented by compositional analysis using devices such as an electron microscope and XRF analyzer. Laboratory testing consisted of compaction testing, unconfined compression tests (UCTs), Atterberg limit tests, response to wetting test, pH test, bar linear shrinkage, scanning electron microscopy, and whole-rock X-ray fluorescence. The test matrix for this investigation is shown in Table 2.

Table 2. Testing Matrix. *Each grid value corresponds to the total conducted tests.

Test Method, Purpose, and ASTM Standard	Compaction Testing and calibration with Harvard Miniature Apparatus	Unconfined compression test (UCT)	Response to wetting test	Grain Size Distribution	Atterberg Limits	pH Test	Bar Linear Shrinkage	Scanning Electron Microscopy (SEM)	Whole-Rock X-Ray Fluorescence
	Optimum moisture content (OMC) and maximum dry density (MDD)	Unconfined compressive strength (UCS)	Volumetric change upon wetting	Soil classification	Liquid Limit (LL), plastic limit (PL), and plasticity index (PI)	pH	Linear shrinkage (LS)	Surface morphology and composition of materials	Elemental composition of materials
	ASTM D698 and ASTM D4609	ASTM D2166	ASTM D4546	ASTM D6913 & D7928	ASTM D4318	ASTM D4972	BS 1377		
Test Soil 1 (TS1)	12*	4	1	1	1	1	1	1	1
Test Soil 2 (TS2)	12	4	1	1	1	1	1	1	1
TS1 + GGBFS		12	1		3	1	1	3	1
TS2 + GGBFS		12	1		3	1	1	3	1
TS1 + GGBFS & Lime		12	2		2	2	1		
TS2 + GGBFS & Lime		12	2		2	2	1		
TS1 + GGBFS & PC		9	2		1	1	1		
TS2 + GGBFS & PC		9	2		1	1	1		
TS1 + Lime		3	1			1	1		
TS2 + Lime		3	1			1	1		
TS1 + PC		3	1			1	1		
TS2 + PC		3	1			1	1		

GGBFS-treated soils were prepared at different concentrations: 6%, 8%, and 12%. Upon determining the optimal GGBFS concentration, soil specimens subjected to GGBFS and lime treatment utilized 90% of the optimal GGBFS concentration along with two lime concentrations: 0.5% and 1%. In the case of specimens treated with GGBFS and PC, 90% of the established optimal GGBFS concentration was combined with two PC concentrations: 1% and 3%. The

optimal concentration was applied following the OHD L-50 (ODOT 2022) standard for soil stabilization. A fixed concentration of 3% was employed for specimens treated exclusively with PC.

4.2.1 Compaction Testing

Following ASTM Standard D698, standard compaction tests were conducted. This test aims to determine the maximum dry density and optimum moisture content of soil material for a standard compaction effort. Test soils were mixed to achieve the desired water content and compacted in a 4-inch diameter mold using three layers, each subjected to 25 blows from a standard 5.5 lb. rammer. After compaction, the specimens were weighed, and the bulk density and moisture content were determined. A compaction curve was obtained by plotting dry density against moisture content, where the maximum dry density and optimum moisture content were determined. Additionally, the Harvard miniature apparatus (Figure 2), which consists of a miniature mold of about 1.3 inches in diameter and a height of 2.9 inches, and a small drop hammer with a weight of 0.55 lb., was calibrated against the outcomes of Proctor compaction tests. After determining the optimal number of hammer drops necessary to achieve comparable densities to Proctor tests at the optimum moisture content, specimens were prepared for unconfined compression tests (UCT). This calibration process has been described in other research papers and reports (Hussey et al. 2010, Miller & Cerato 2011).

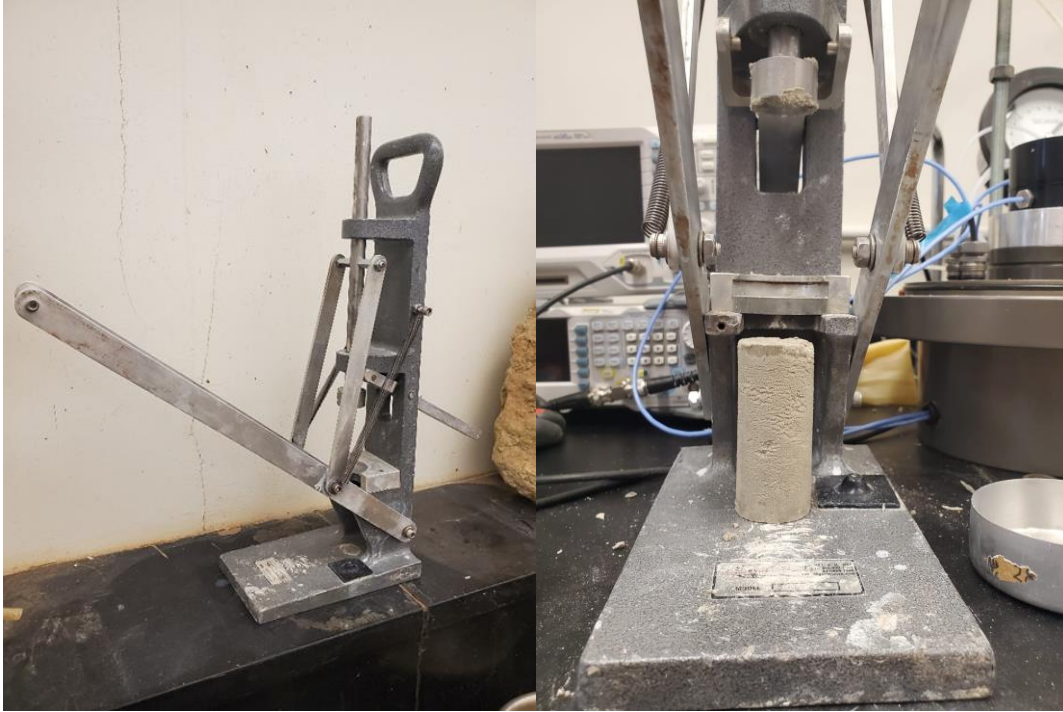


Figure 2. Harvard miniature apparatus.

4.2.2 Unconfined Compression Test (UCT)

The UCT is used to determine the unconfined compression strength of a cohesive soil specimen. The compaction of specimens occurred in a Harvard miniature mold with three lifts and a small drop hammer. The specimens were wrapped in cellophane and placed in a moisture room for 7 days after compaction. Specimens were prepared using three different concentrations of GGBFS: 6%, 8%, and 12%. For each mix, 3 nominally identical specimens were prepared. After curing, UCT specimens were tested in a soil compression testing machine following the protocol stipulated in ASTM D2166. A strain rate of 1% per minute was applied during the shearing process. Throughout shearing, the axial load on the specimen was recorded using an electronic load cell with a resolution of 1 lbf., the axial deformation was captured using a dial gauge with a resolution of 0.001 inches. The shearing process continued until failure was evident, indicated by a continuous drop in axial load (Figure 3). The unconfined compressive strength (UCS) is

calculated by dividing the maximum axial load at failure by the cross-sectional area of the specimen.

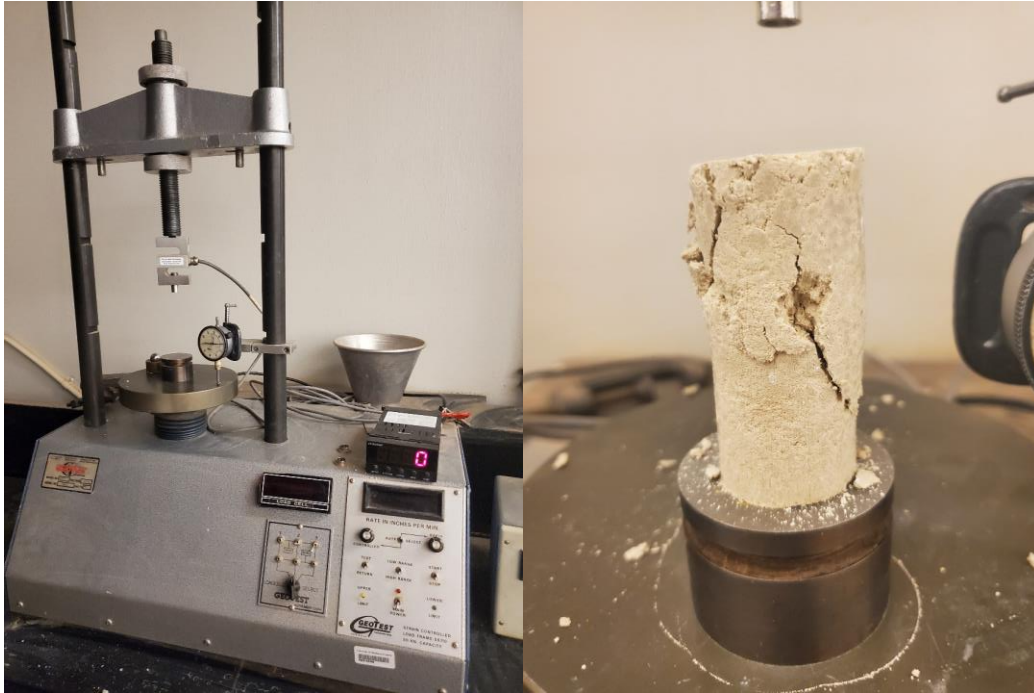


Figure 3. Compression testing machine (left) and test specimen after failure (right).

Once the optimal concentration of GGBFS was determined, 3 additional specimens were created using the same procedure with a curing time of 5 days. Subsequently, they were soaked in water for 2 days and tested to enable a comparison of strength differences between unsoaked and soaked specimens to assess durability. Hydrated lime was also employed to compare the outcomes of GGBFS with a traditional stabilizer for the curing periods, with and without soaking. Furthermore, additional specimens were tested with combinations of GGBFS and hydrated lime and GGBFS and Portland cement, with curing periods with and without soaking.

4.2.3 Response to Wetting Test

The response to wetting test, also known as the swelling potential test, is a laboratory test conducted on cohesive soils to assess their potential for volume change upon wetting. It was

conducted following ASTM Standard D4546. Soils treated with GGBFS were prepared using optimal concentrations. For specimens treated with both GGBFS and lime or PC, 90% of the optimal GGBFS concentration was combined with two different concentrations: 0.5% and 1% for Lime and 1% and 3% for PC.

Test specimens were prepared by dry mixing the Test Soil and additives, adding water, usually 1% above the optimum moisture content, and compacting the soil to the desired density and moisture content in oedometer rings in two layers. These specimens were then placed in the oedometer loading frame (Figure 4), and a seating load was applied to the weight hanger, with the dial gauge used to measure vertical deformations zeroed accordingly. The dial gauge used had a resolution of 0.0001 inches.



Figure 4. Oedometer ring and loading frame.

Once the dial gauge was zeroed, a load was applied to the weight hanger to create a vertical stress of 250 psf on the specimen. This stress level corresponds to the total overburden pressure typically experienced at a depth of 1.5 to 2 feet below the top of a pavement. After allowing the specimen to reach equilibrium under the applied load, water was added to the top of the oedometer

ring to saturate the soil specimen. During this process, dial readings were recorded at intervals over extended periods, usually lasting around 10,000 hours or more.

4.2.4 Grain Size Distribution

The grain size distribution method is a laboratory test used to determine the proportion of different-sized particles in a soil specimen. The process involves two components: Sieve analysis and hydrometer test.

Sieve analysis was realized according to ASTM D6913 by passing the material through a series of sieves with varying mesh sizes stacked in order of decreasing mesh size, with the largest sieve at the top. Then, the sieves were hand shaken to separate the soil particles based on size. After shaking, the soil retained on each sieve was removed and weighed. The percentage of soil passing through each sieve is calculated by subtracting the percentage retained on that sieve from 100%. The results are used to create a grain size distribution curve, known as the sieve analysis curve. This method was useful in determining the percentage of sand in the Test Soils.

For particles with a grain diameter of less than 2 mm, the size of a number 10 sieve, hydrometer analysis was conducted per ASTM D7928. The soil specimen was dispersed in water to create a suspension. A hydrometer, a device that measures the density of the suspension, was submerged, and density readings were recorded at specific intervals. These data were used to calculate the percentage of soil particles passing through different particle sizes, constructing the hydrometer analysis curve. Finally, the outcomes from the sieve analysis and hydrometer test are combined to form a comprehensive grain size distribution curve, providing a more detailed representation of the soil's grain size distribution. The respective tabulated values for Test Soil 1 and 2 can be found in Table 3. In both cases, the soils completely passed through the No. 40 (0.425 mm) sieve, with roughly 50% passing through the No. 200 (0.075 mm) sieve. This outcome was

expected since both soils contained 50% fine sand. The grains size distribution curve for Test Soil 1 shows that the portion passing through the No. 200 sieve is composed of clay-sized particles with about 36% finer than 0.002 mm. For Test Soil 2, the portion passing the No. 200 sieve is composed of approximately 42% particles finer than 0.002 mm.

Table 3. Grain size distribution values for Test Soil 1 and 2.

Sieves	Test Soil 1		Test Soil 2	
	D(mm)	% passing	D(mm)	% passing
4	4.750	100.00	4.750	100.00
10	2.000	100.00	2.000	100.00
40	0.425	100.00	0.425	100.0
200	0.075	54.52	0.075	50.5
	0.060	54.52	0.030	24.2
	0.043	52.70	0.021	23.2
	0.030	52.70	0.013	23.2
	0.022	50.88	0.009	22.2
	0.015	50.88	0.007	22.2
	0.011	49.06	0.003	22.2
	0.008	47.25	0.001	22.2
	0.006	45.43		
	0.004	43.61		
	0.003	41.80		
	0.001	36.34		

4.2.5 Atterberg Limits

The Atterberg limits were determined in accordance with ASTM D4318 guidelines, involving two main tests: the liquid limit (LL) and the plastic limit (PL). For the liquid limit test, the moisture content at which a soil transitions from a plastic to a liquid state was measured using a Casagrande cup. A specific amount of water was added to the soil and mixed until it showed consistency. Then, the specimen was placed in the cup, and a groove was formed through the specimen using a grooving tool. The cup was then raised and dropped multiple times, recording

the number of blows needed for the soil to close the groove. The moisture content corresponding to 25 blows was determined as the liquid limit.

The plastic limit test determines the moisture content at which soil changes from a plastic state to a semi-solid state. A small amount of soil was mixed with water until it reached a plastic consistency. The moist soil was then hand-rolled into a thread with a diameter of about 3.2 mm (1/8 inches), and the moisture content at which the thread crumbled upon rolling was measured as the plastic limit. Plasticity index (PI) can be calculated using LL and PL.

The Atterberg limit tests were performed on test soils under various conditions: with and without GGBFS, with lime, and with combinations of GGBFS and lime or Portland cement. Tests were performed both with and without curing. For tests without curing, liquid limit and plastic limit testing were conducted immediately upon mixing. In contrast, for tests with curing, the specimens were covered and allowed to sit for seven days before conducting the tests. Atterberg limits for Test Soil 1 and 2 are found in Table 4.

Table 4. Atterberg Limits for Test Soil 1 and Test Soil 2.

Type	LL	PL	PI
Test Soil 1	27	13	14
Test Soil 2	82	26	56

4.2.6 pH Testing

pH testing is a laboratory analysis used to determine the acidity or alkalinity of a substance, such as soil, water, or a chemical solution. The pH scale ranges from 0 to 14, with a pH of 7 considered neutral. A pH below 7 indicates acidity, while a pH above 7 indicates alkalinity. In this study, the pH levels of the soil, GGBFS, Lime, and soil mixed with additives were assessed following ASTM D4972 guidelines. For the soil, a soil-water suspension was prepared by mixing

it with water. The pH was determined using Method A, employing a potentiometer with a pH-sensitive electrode.

4.2.7 Bar Linear Shrinkage

The bar linear shrinkage test is a laboratory procedure employed to determine the linear shrinkage of a soil specimen during the drying process. The purpose of this test is to quantify the extent of linear shrinkage experienced by the soil specimen as it loses moisture. This test was realized according to The British Standard, BS 1377.

The test was done by preparing around 150 grams of soil, passing a #40 sieve. The soil specimen was mixed with deionized water to achieve approximately the Liquid Limit consistency. Then, a portion of the soil was placed in a semi-circular linear bar mold with dimensions approximately 6 inches in length and 1 inch in diameter. The mold dimensions were measured to ensure uniformity. The soil was compacted into three layers and tapped against a flat surface between each layer to eliminate any trapped air bubbles. Subsequently, the soil specimen in the mold was exposed to an environment with controlled temperature and humidity, allowing the soil to undergo natural drying. As the moisture content in the soil reduced during the drying process, the soil volume decreased correspondingly. This volume change caused the soil specimen to shrink. To ascertain the shrinkage limit value, intermediate mass and length readings were recorded during the air-drying process until the volume change ceased, while the water content continued to decrease. Subsequently, the mold was oven-dried for 24 hours at a controlled temperature of $110 \pm 5^{\circ}\text{C}$ (Figure 5). After drying, the final mass and length measurements were retaken.



Figure 5. Oven-dried specimens for the bar linear shrinkage.

The length of the soil specimen was carefully measured three times using a digital caliper, and the average length was used to calculate the linear shrinkage. For the shrinkage limit, the changes in length observed during the air-drying period were plotted against the corresponding water content. The shrinkage limit was determined as the first water content at which no further variation in the length of the soil specimen was observed, signifying the point at which the shrinkage process ceased.

4.2.8 Scanning Electron Microscopy

Scanning Electron Microscopy (SEM) is a powerful imaging technique to study materials surface morphology and composition at high magnification. This method was done using the Samuel Roberts Noble Microscopy Laboratory at the University of Oklahoma. SEM operates by scanning a focused electron beam across the specimen surface, generating various signals upon interaction with the atoms in the material. Detectors capture the SEM images, measuring the intensity of emitted signals. This process involves scanning the electron beam in a raster pattern across the specimen's surface, resulting pixel-by-pixel data, creating a high-resolution image of

the specimen. An example of SEM taken for Test Soil 1 is shown in Figure 6. Test Soil specimens mixed with different concentrations of GGBFS were subjected to SEM to observe and compare the presence of reaction products with specimens lacking GGBFS. Photographs were taken at different magnifications to analyze the specimens in detail.

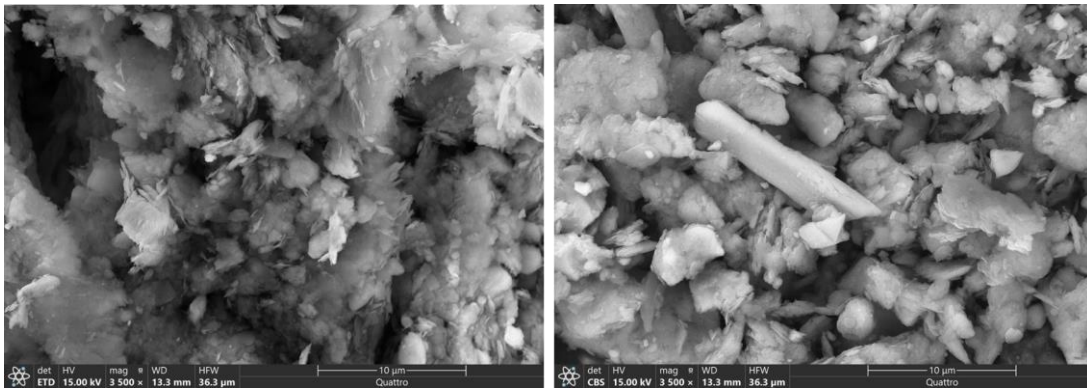


Figure 6. Test Soil 1 untreated (left) and treated (right) with 8% GGBFS.

4.2.9 Whole-Rock X-Ray Fluorescence

ALS Global conducted whole-rock X-ray fluorescence (XRF) analysis to determine the elemental composition of the raw materials and soil mixes. XRF analysis is based on the principle that when a specimen is exposed to high-energy X-rays, the atoms in the specimen become excited, resulting in the emission of characteristic X-rays with energies corresponding to specific elements present in the specimen. The XRF instrument is equipped with a spectrometer that analyzes the energies of these emitted X-rays, generating a spectrum that graphically represents the elements in the specimen and their respective concentrations.

The main focus of the analysis was to assess the concentrations of calcium and sulfur in the specimens. To prepare the specimens for accurate and reliable XRF analysis, each weighing around 10 grams, they underwent pulverization to ensure they passed through a number 80 sieve. In the whole-rock analysis, the specimens were melted to create fused disks, which were used for the XRF testing to determine the elemental composition.

Chapter 5: Test Results and Discussion

5.1 Compaction Testing

Both Test Soil 1 and 2 underwent compaction using the Harvard miniature apparatus, and their respective compositions and compaction procedures were as follows. Test Soil 1 was composed of 50% kaolinite, 50% sand, and approximately 20,000 ppm of sulfate in the form of gypsum. The soil was compacted using the Harvard miniature apparatus into three equal layers at 12 blows per layer. Compaction curves were developed for untreated and treated soil with different concentrations of GGBFS: 0%, 6%, 8%, and 12%. Multiple specimens were tested at each compaction point until consistent results were achieved. The maximum dry densities (MDDs) were 118, 121, 119.5, and 119 pcf, respectively, while their corresponding optimum water contents (OMCs) were 12.2, 11.3, 12.5, and 12.1%. These curves are presented in Figure 7, where each point represents a single specimen tested. Treated soils had a slightly higher MDD compared to untreated soil. However, the OMC was similar for all, except for GGBFS at 6%, which also gave the highest MDD. This lack of pattern may be attributed to the methodology employed. Given that the test soil and the additives were mixed and immediately tested for compaction, it is possible that the interactions between the soil and GGBFS may have influenced the results.

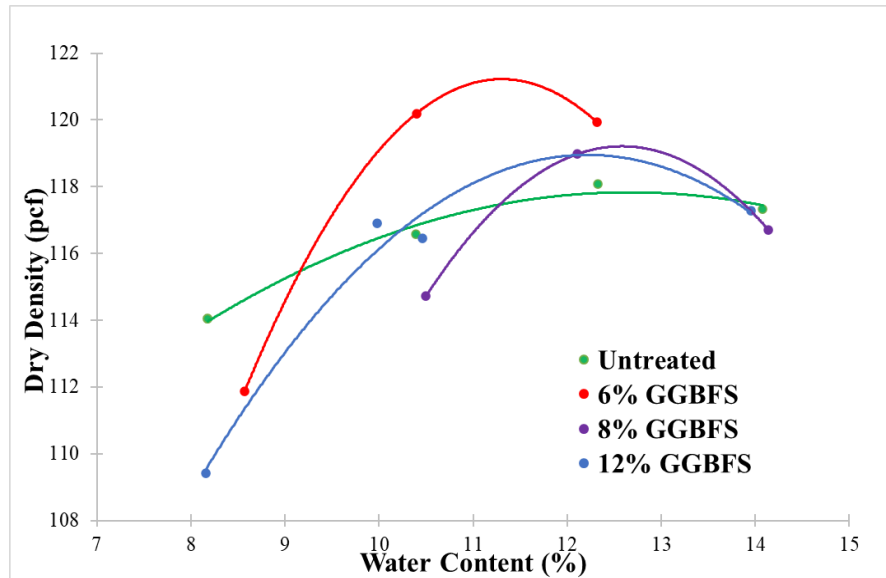


Figure 7. Compaction curves for Test Soil 1.

Test Soil 2 was tested in a manner similar to Test Soil 1. The main difference was that Test Soil 2 contained bentonite instead of kaolinite. Compaction involved the Harvard miniature apparatus with three equal layers compacted at 15 blows per layer. Like Test Soil 1, compaction curves were developed for untreated and treated soil with different concentrations of GGBFS based on dry mass: 0%, 6%, 8%, and 12%. Multiple specimens at each compaction point were also made to ensure consistent results. The MDDs for this case were 103.2, 101.7, 100.5, and 102.4 pcf, respectively, while their corresponding OMCs were 22.2, 22.5, 21.7, and 21.5%. These curves are presented in Figure 8, where each point represents one specimen tested. Similar to the findings of Test Soil 1, Test Soil 2 exhibited no significant MDD changes or consistent patterns in OMC. Again, the experimental methodology may have contributed to this lack of pattern, potentially due to variable rate of reactions occurring between the soil and GGBFS from the outset of the tests. The outcomes of these compaction tests aided in determining the range of moisture contents selected to produce unconfined compression test specimens.

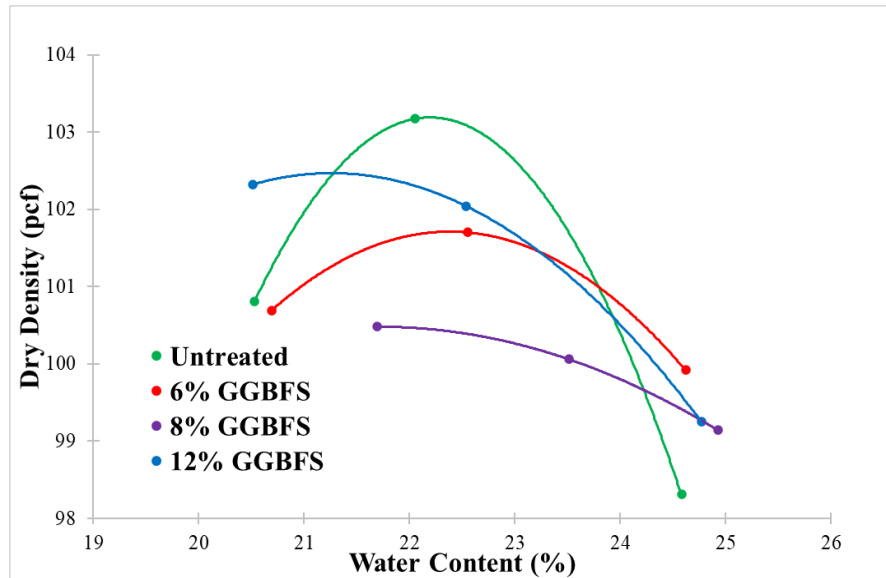


Figure 8. Compaction curves for Test Soil 2.

5.2 Unconfined Compression Test (UCT)

5.2.1 Test Soils Untreated and Treated with GGBFS

To assess the performance of GGBFS as a stabilizer, a series of UCTs were conducted. The optimal amount of GGBFS depended on the compaction characteristics of each Test Soil, which is why three concentrations of GGBFS were chosen (6, 8, and 12%). Based on the results of compaction testing, three specimens were prepared using the same compaction effort with different moisture contents around the OMC for each Test Soil. After preparing the untreated and treated soil specimens, they were wrapped in cellophane with two different curing periods, one for seven days and the other for five days, which was then soaked in water for two more days. After curing, specimens were tested in a compression testing machine until failure.

Results for Test Soil 1 and 2 after seven-day curing periods are shown in Figures 9 and 10, respectively, where each point represents the outcome of one specimen. Results for each test can be found in Appendix A. For Test Soil 1, the optimal water content for strength gain was between 10% and 11% for treated specimens. In this range of water content, there was an increase in the

average unconfined compressive strength (UCS), above the untreated soil UCS, of approximately 35, 40, and 42 psi for 6%, 8%, and 12% GGBFS, respectively. The peak strength between specimens treated with 8% and 12% GGBFS was minimal, which is why no higher concentrations of GGBFS were tested. This also indicates that the optimum concentration of GGBFS for Test Soil 1 was about 8% by dry soil weight. While the data displays a consistent trend, scattered points with similar characteristics could be attributed to slight variations in moisture content during the mixing process. The samples were sequentially prepared, and moisture loss might have occurred between the creation of individual specimens, as well as slightly different densities due to human error.

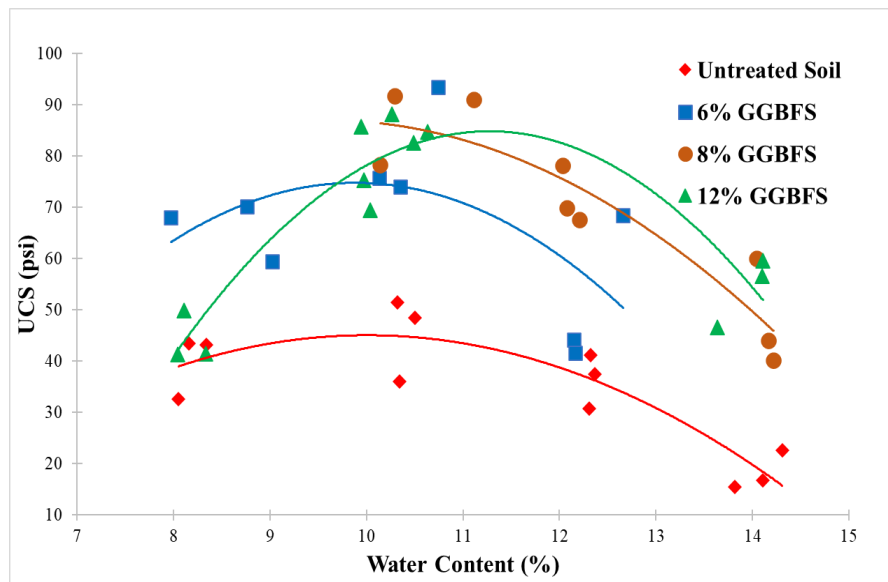


Figure 9. Unconfined compression strength vs. water content for Test Soil 1.

For Test Soil 2, the optimal water content for treated specimens was between 21% and 22%. By looking at the values of UCS in this range, the UCS on average increased above the untreated UCS by 47, 50, and 52 psi for treated specimens with GGBFS concentrations of 6%, 8%, and 12%, respectively. Similar to Test Soil 1, there was not a significant increase of strength in specimens with GGBFS concentrations from 8% to 12%, which is why the optimal GGBFS

concentration was noted to be around 8% by dry soil weight. The optimal water content for strength gain was selected to be 11% for Test Soil 1, with the optimal GGBFS concentration being 8%. For Test Soil 2, the optimal water content was selected at 23% for an optimal GGBFS concentration of 8%. Similar to Test Soil 1, scattered points might be attributed to moisture loss during the specimen preparation. The observed downward trend in untreated Test Soil 2 is not fully understood, but it may be attributed to the significant influence of water content on the diffuse-double layer and behavior of high PI soils.

According to ODOT method OHD L-50 for chemically treated soils, the desired UCS increase must be at least 50 psi but no more than 150 psi. This was accomplished for all chemically treated specimens for Test Soil 2 but not for Test Soil 1, although Test Soil 1 treated specimens were close to meeting this goal. Additionally, an increase in unconfined compression strength of 42 psi is not trivial, considering for example that the range of unconfined strength for clayey soils ranges from about 4 psi for soft up to about 60 psi for hard clays.

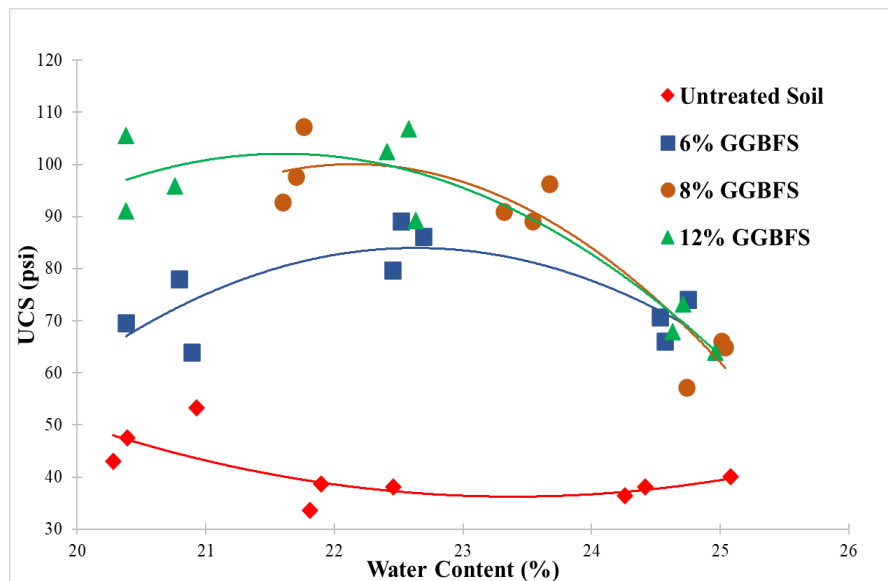


Figure 10. Unconfined compression strength vs. water content for Test Soil 2.

For the second curing period, which consisted of 5 curing days followed by a soaking

period in water for two more days, the optimal GGBFS concentration was used to prepare the specimens. While all Test Soil 1 specimens disintegrated in water, some Test Soil 2 specimens remained intact for testing. However, their UCS decreased considerably compared to the unsoaked specimens, as shown in Figure 11.

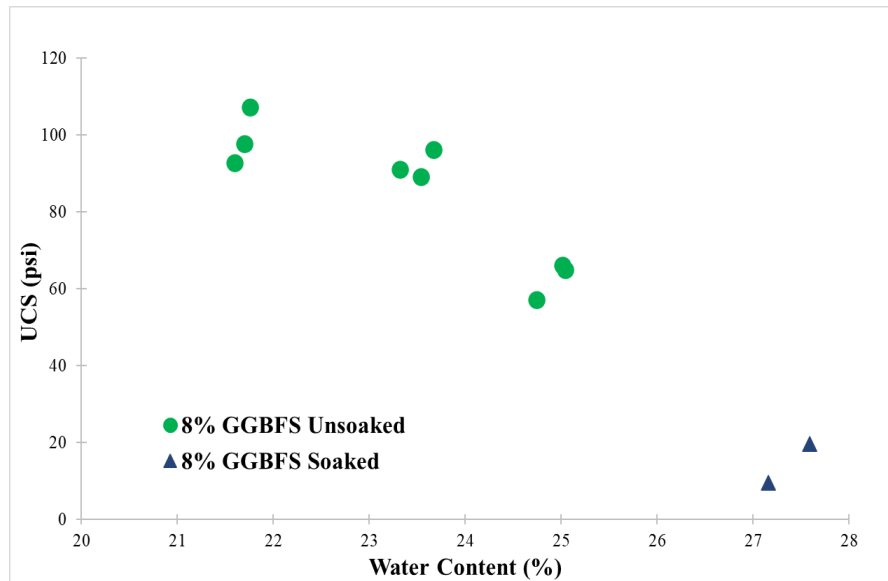


Figure 11. Comparison of UCS of soaked and unsoaked specimens treated with 8% GGBFS for Test Soil 2.

5.2.2 Test Soils Treated with Lime

Test Soils were prepared with hydrated lime based on guidance found in OHD L-50 for chemically treated soils. Upon analyzing the grain size distribution and plasticity of both Test Soil 1 and Test Soil 2, it was found that the AASHTO classification system classified Test Soil 1 as A-2-6 and Test Soil 2 as A-2-7. However, test soils were synthesized within the lab using relatively pure clay minerals, and the percentage of the sand fraction used was fine sand. Consequently, lime dosages were selected based on the lime dosing rates of soils A-6 and A-7-6. For Test Soil 1, the recommended concentration was 4%, whereas for Test Soil 2, it was 6%. For these tests, the water content implemented for the specimens was slightly higher than the optimum of GGBFS-treated

specimens to aid lime activation. Results for each test can be found in Appendix B.

As shown in Figure 12, for Test Soil 1 with lime, the unsoaked specimen UCS increased on average by 25 psi. This is similar to the increase observed in specimens treated with 6% GGBFS, but less than observed for 8% GGBFS, which was 40 psi. On the other hand, soaked specimens disintegrated in water before being tested.

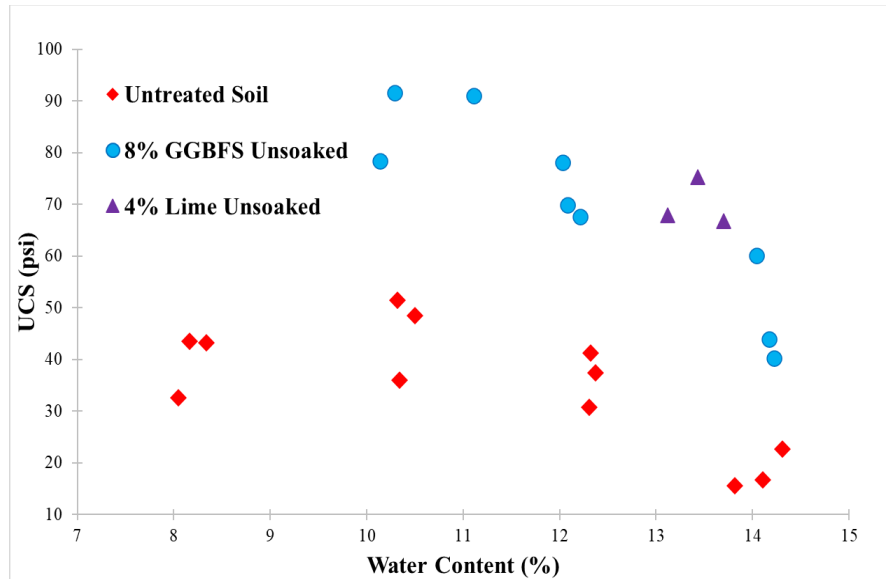


Figure 12. Comparison of UCS for soaked and unsoaked specimens for Test Soil 1 treated with 8% GGBFS or 4% lime.

Results for Test Soil 2 are shown in Figure 13. Unsoaked specimens had an average increase in UCS of about 27 psi compared to the untreated soil. The increase in strength was lower than the average increase of all GGBFS-treated specimens. Unlike soaked specimens for Test Soil 1, soaked specimens for Test Soil 2 could be tested, but their UCS decreased considerably, with an average UCS value of 29 psi.

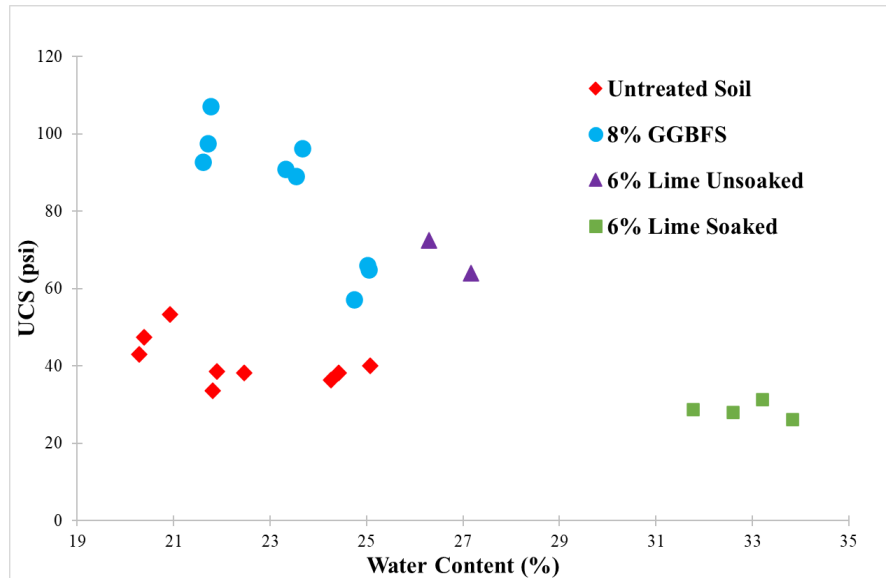


Figure 13. Comparison of UCS for soaked and unsoaked specimens for Test Soil 2 treated with GGBFS or 6% lime.

5.2.3 Test Soils Treated with GGBFS and Lime, GGBFS and Portland Cement, and GGBFS and Sodium Carbonate

Some studies have shown that GGBFS by itself possesses a very low rate of hydration (Song et. al 2000 & Yi, Liska, Jin, & Al-Tabbaa 2016). To improve this, GGBFS can be activated by adding certain chemicals. According to Ouf (2001): “The most commonly used activators are calcium hydroxide, calcium sulphate, ordinary Portland cement, sodium hydroxide, sodium carbonate, and sodium sulphate”. To investigate the strength enhancement of GGBFS, specimens were made with 0.5% lime and 7% GGBFS, 1% lime and 7% GGBFS, 1% PC and GGBFS, 3% PC and GGBFS, and 3% sodium carbonate (SC) and GGBFS. Similar to the specimens treated only with lime, the water content implemented was about 1% higher than the optimum of GGBFS-treated specimens to aid lime activation; 12% and 24% for Test Soil 1 and 2, respectively. Results for each test can be found in Appendix C.

For Test Soil 1, the average UCS test results for all treated and untreated specimens are

shown in Figure 14, where the missing bars in the soaked specimens column indicate that they could not be tested after the soaking process. Unsoaked specimens treated with a combination of lime (0.5% and 1%) and GGBFS exhibited a substantial increase in average UCS values, exceeding 200 psi compared to the untreated specimens. Moreover, the soaked specimens displayed notably improved performance compared to specimens treated solely with GGBFS or lime. These specimens withstood the soaking process and exhibited higher UCS values than untreated soil specimens. Interestingly, it was noted that specimens treated with 0.5% lime and 7% GGBFS demonstrated a higher UCS than those treated with 1% lime and 7% GGBFS. While the reason for this behavior is unclear, some researchers (e.g. Wild et. al. 1999) have suggested that a lower lime dosage is adequate to activate GGBFS, with higher amounts potentially delaying the cementitious reactions. However, the appropriate amount of lime to activate the GGBFS has not been established yet and requires further study (Wild et al. 1999 and Ouf 2001). Chemical treatment with 1% PC and 7% GGBFS differed notably from 3% PC and 7% GGBFS. While the first treatment for unsoaked exhibited a similar UCS increase to specimens treated with 8% GGBFS, the latter showed a significant increase in the UCS, with an average of more than 300 psi compared to untreated specimens. We can conclude that 1% PC was insufficient to activate the GGBFS. However, none of the specimens could be tested after the soaking process. Concerning the specimens treated with SC (1% and 3%) and 7% GGBFS, only unsoaked specimens were tested, and both mixes gave a similar UCS average to those treated only with 8% GGBFS, so it seems that SC at this dosage did not activate the GGBFS.

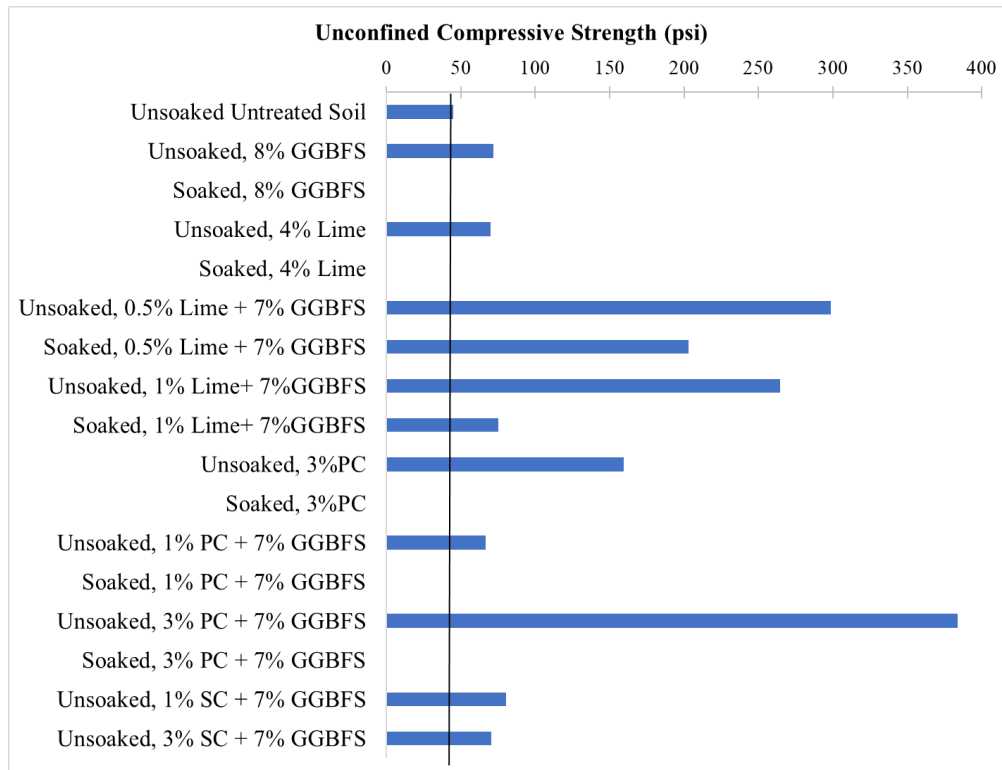


Figure 14. Unconfined compression strength for treated and untreated Test Soil 1 specimens.

Figure 15 shows average UCS test results of all treated and untreated specimens for Test Soil 2. Unsoaked specimens treated with a mixture of lime and GGBFS significantly increased the UCS compared to untreated specimens. The average UCS increased by 65 psi for specimens treated with 0.5% lime and 7% GGBFS and by 94 psi for specimens treated with 1% lime and 7% GGBFS. Even the soaked specimens displayed enhanced average UCS values in comparison to the unsoaked, untreated specimens. For soaked specimens treated with 0.5% lime and 7% GGBFS, the average UCS increased by 15 psi, while those treated with 1% lime and 7% GGBFS showed an average UCS increase of 79 psi. In contrast to Test Soil 1, it appears that a 1% lime dosage was sufficient to activate the GGBFS effectively in Test Soil 2. Treated unsoaked specimens with 1% PC and 7% GGBFS showed a slightly higher strength than those treated with 8% GGBFS, showing an average increase of about 78 psi compared to untreated specimens. Compared to untreated soil

and among all the treatments used, unsoaked specimens treated with 3% PC and 7% GGBFS displayed the most significant average UCS increase of 140 psi. However, soaked specimens with a mix of PC and GGBFS disintegrated before the testing process. Regarding specimens treated with SC, only unsoaked specimens were tested with a mix of 3% SC and 7% GGBFS. Their UCS increase was the lowest of all treated specimens, with an average UCS increase of about 16 psi compared to untreated specimens.

For both test soils, an addition of lime or PC into GGBFS greatly enhanced the UCS for unsoaked specimens, whereas the addition of lime with GGBFS also increased the UCS for soaked specimens. On the other hand, the addition of SC into a mix with GGBFS showed a lower UCS compared to any other treated specimens with GGBFS. It was concluded that SC with the dosage used in this study did not activate GGBFS; in fact, it seemed to reduce the effectiveness of GGBFS. This could be due, in part, to the method of mixing SC with GGBFS, where SC was introduced in granular form without prior dissolution in water before mixing. This approach might have significantly delayed the activation of GGBFS. Bernal et al. (2015) observed that the addition of sodium carbonate, after complete dissolution in water, to GGBFS mortars resulted in increased UCS after 7 days, with a continuous gradual strength increase observed with longer curing periods up to 56 days.

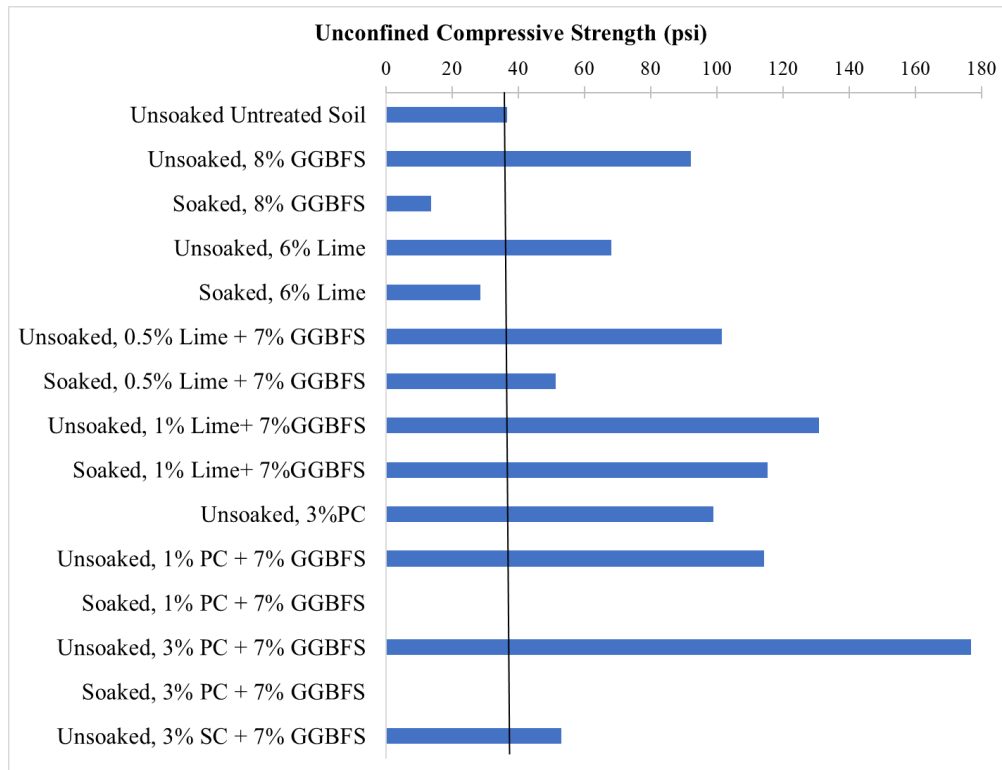


Figure 15. Unconfined compression strength for treated and untreated Test Soil 2 specimens.

5.3 Response to Wetting Test

Determination of volumetric changes under the presence of water was key to determine whether GGBFS by itself or in conjunction with small amount of other additives, such as lime or PC, could be used for soil stabilization in sulfate-bearing soils. Swelling behavior was tested after inundation of the specimen under one-dimensional loading conditions using a vertical pressure of 250 psf. This vertical pressure is similar to that at a depth of 2-feet below the top of pavement. Test results can be found in Figure 16 and 17 for Test soil 1 and 2, respectively, with tabulated values for each test attached in Appendix D.

Untreated Test Soil 1 exhibited a gradual swelling behavior over the course of 1 day, followed by a slight reduction in the rate of swelling, reaching a vertical swell of around 3% after 6 days. In contrast, the treated specimen with GGBFS displayed a similar behavior during the initial 60 minutes. However, the GGBFS-treated soil stopped swelling, stabilizing at a vertical

swell of 1.9%. This remained constant until the conclusion of the 6-day test. The specimen treated with lime exhibited a gradual increase in swelling during the initial 200 minutes, albeit at a slower rate compared to the untreated soil. However, after this initial period, the swelling rate dramatically escalated, ultimately reaching a vertical swell of approximately 6% by the end of the 7-day test, which is about double that of the untreated soil. This behavior was expected in sulfate-bearing soils, where the sudden increase in swelling is likely due to ettringite formation. In the case of 0.5% lime and 7% GGBFS, and 1% lime and 7% GGBFS, the vertical swell was also higher than the untreated Test Soil 1, which suggests that the presence of lime facilitated the development of ettringite-type minerals. In the case of specimens treated with 1% PC and 7% GGBFS, as well as 3% PC and 7% GGBFS, minimal swelling was observed for nearly a day but then it started to increase until the end of the test after 8 days, with a vertical swell of 0.6% and 1.7%, respectively. A similar behavior was observed in the one treated with only PC, with a vertical swell of about 1.3%. This could indicate that the addition of PC could be used to activate GGBFS without causing adverse swelling behavior. However, further investigation with longer tracking periods is needed to validate this observation. Since SC did not suffice as an activator for GGBFS based on UCS, no further testing was conducted.

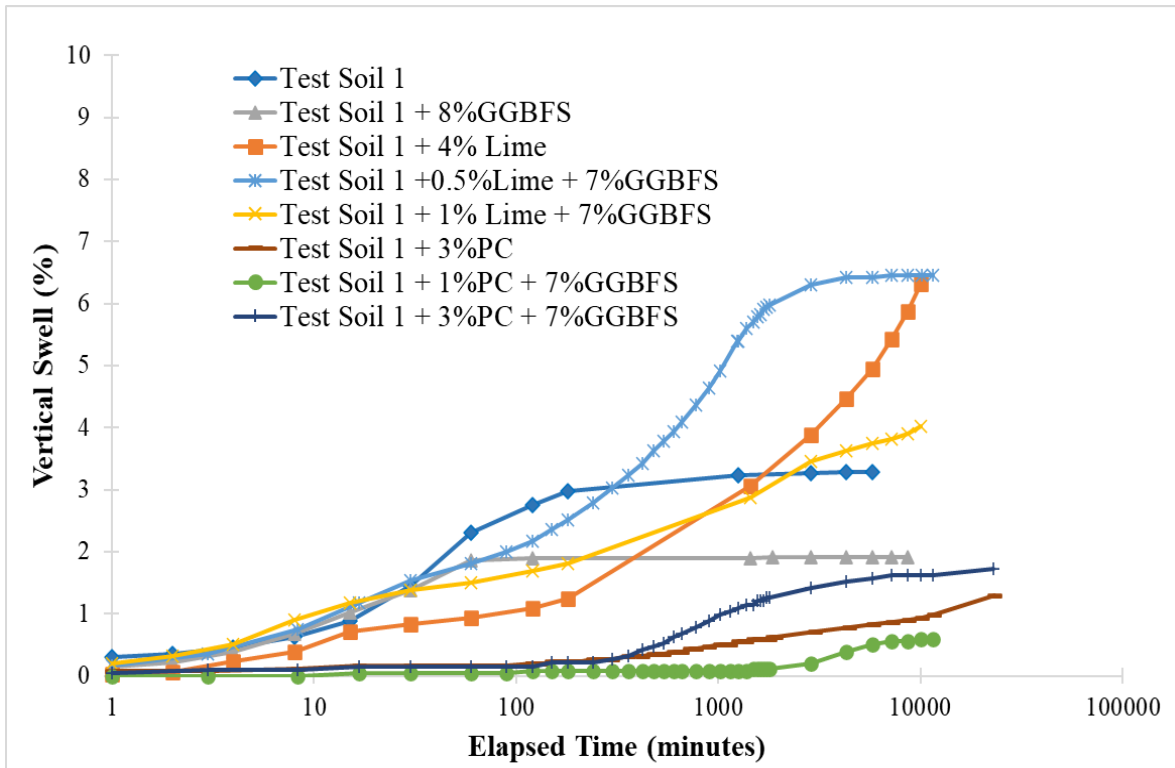


Figure 16. Vertical swell versus elapsed time from response to wetting tests on Test Soil 1 with and without chemical treatment.

In the case of Test Soil 2, untreated soil showed a notable swelling behavior attributed to the high reactivity of bentonite clay present in the soil. When treated with 8% GGBFS, the soil showed minimal swelling, reaching a vertical swell of approximately 0.4% after 7 days. Similarly, specimens treated with 0.5% lime and 7% GGBFS, as well as those treated with 1% lime and 7% GGBFS, displayed no significant swelling for nearly 6 days. However, a slight increase in swelling was observed after 7 days, reaching vertical swells of 1.4% and 0.2%, respectively. When the soil was treated with lime or PC, swelling started to become apparent after 3 days, reaching a vertical swell of around 2% and 1.8%, respectively. For specimens treated with 1% PC and 7% GGBFS, no apparent swelling was observed during the first 5 days, but it gradually increased to nearly 1% after 7 days. When 3% PC and 7% GGBFS were added, the swelling behavior remained insignificant for the initial 3 days but then began to increase, ultimately reaching a vertical swell

of 3.0%. It appears that the distinct mineral compositions of Test Soil 1 and Test Soil 2 influence the rate at which ettringite minerals can form. According to Mitchell and Dermatas (1992), the swelling behavior depends on the quantity and rate of release of alumina, with kaolinite exhibiting a higher release rate compared to montmorillonite.

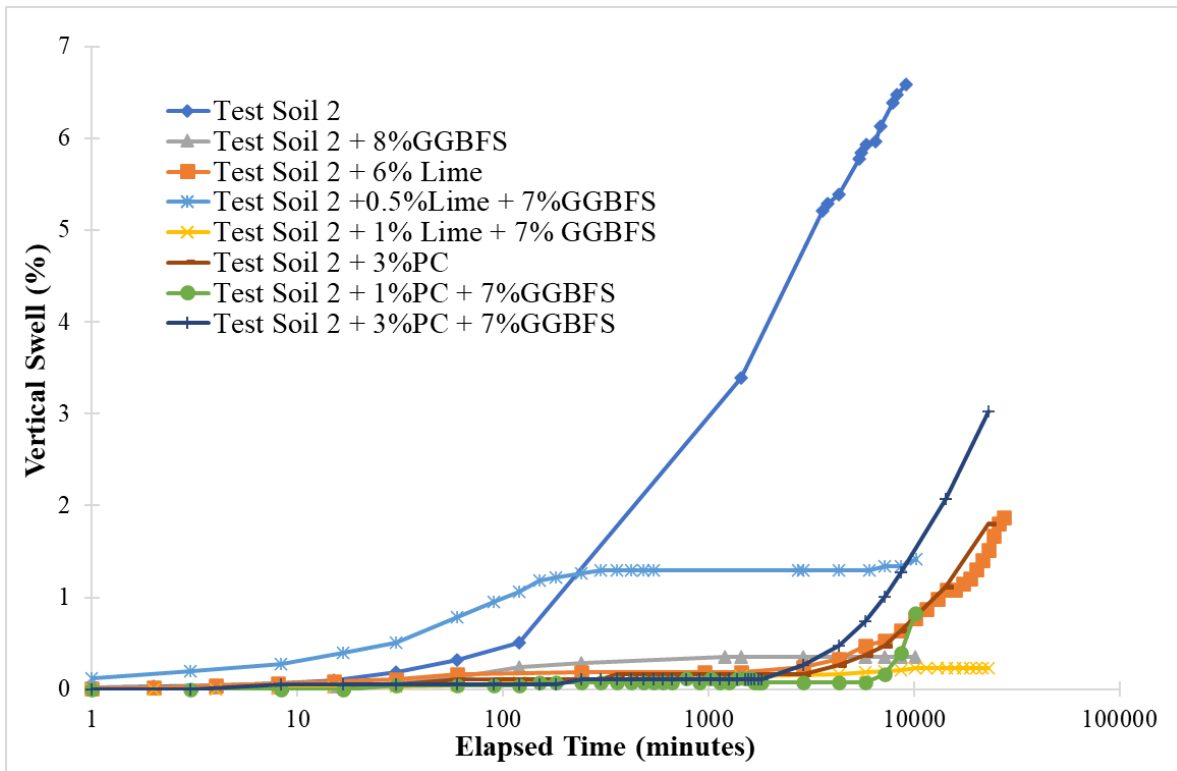


Figure 17. Vertical swell versus elapsed time from response to wetting tests on Test Soil 2 with and without chemical treatment.

The results from both Test Soil 1 and Test Soil 2 suggest that GGBFS has the potential to effectively mitigate the swelling of sulfate-bearing soils without inducing adverse reactions. When GGBFS was introduced to both soils, a noticeable reduction in swelling was observed compared to untreated soils. However, when lime or PC were added to activate the GGBFS, mixed results were obtained. In the case of Test Soil 1, specimens treated with lime and GGBFS exhibit a higher vertical swell than those untreated. However, for Test Soil 2, the swelling behavior was reduced for several days, although there was observed a slightly upward trend around the end of the test.

This could indicate that ettringite formation was still happening, but at a very slow rate. When PC and GGBFS were used, the swelling behavior was suppressed for an extended period in both Test Soils. However, there was a slight resurgence in swelling observed in both cases. This suggests that certain reactions may take place over longer durations than those tested here. Therefore, conducting further swelling tests with extended testing periods is advisable to gain a more comprehensive understanding of this behavior.

5.4 Atterberg Limits

Liquid limit (LL) and plastic limit (PL) tests were both conducted on Test Soil 1 and Test Soil 2. These tests embraced untreated specimens as well as specimens treated with GGBFS, lime, GGBFS and lime, and GGBFS and PC. For most of these tests, the procedure involved mixing the test soil with the respective additives, followed by the addition of water without any curing period. However, to assess potential changes and slow reaction that might occur in treated specimens when given time to cure, a subset of treated specimens was tested after being allowed to cure for 7 days. Results for Test Soil 1 and Test Soil 2 are shown in Tables 5 and 6, respectively. In the case of Test Soil 1, without any curing time, addition of different concentrations of GGBFS (6%, 8%, and 12%) resulted in a marginal increase in the LL and Plasticity Index (PI). A similar trend was observed in specimens treated with lime and GGBFS, although in specimens treated with PC and GGBFS, a slight reduction of both LL and PI was observed. For specimens allowed to cure, those treated with GGBFS and 1% lime along with 7% GGBFS displayed behavior similar to that without curing time. The only exception was the specimens treated with 0.5% lime and 7% GGBFS, which exhibited an increase in LL and a decrease in PI. Conversely, specimens treated with PC and GGBFS showed an increase in both LL and PI compared to those without curing time.

Table 5. Atterberg Limits results for Test Soil 1.

Stabilizer	No curing time			7-Day curing time		
	LL	PL	PI	LL	PL	PI
Untreated	27	13	14	-	-	-
GGBFS 6%	28	12	16	-	-	-
GGBFS 8%	31	13	18	33	16	17
GGBFS 12%	30	14	16	-	-	-
Lime 4%	37	23	14	-	-	-
Lime 0.5% + GGBFS 7%	35	17	18	29	21	8
Lime 1% + GGBFS 7%	38	20	18	36	22	14
Lime PC 1% + GGBFS 7%	26	14	12	35	19	16

Results for Test Soil 2 without any curing time indicated a decrease in the PI for all treated specimens, except for the ones treated with PC and GGBFS, which exhibited an increase in LL and a decrease in PL. Specimens treated solely with GGBFS showed a marginal decrease in PI. Notably, specimens treated with lime and a combination of lime and GGBFS had the most pronounced influence in reducing the PI of the soil, with lime likely playing a significant role in this effect. In specimens subjected to curing time, those treated with GGBFS showed a slight decrease in PL and PI, while those treated with lime and GGBFS displayed a notable decrease in both LL and PI. Similarly, for specimens treated with PC and GGBFS, there was also a reduction in LL and PI.

Table 6. Atterberg Limits results for Test Soil 2.

Stabilizer	No curing time			7-Day curing time		
	LL	PL	PI	LL	PL	PI
Untreated	82	26	56	-	-	-
GGBFS 8%	75	22	53	82	24	58
GGBFS 12%	76	22	54	-	-	-
Lime 6%	57	35	22	-	-	-
Lime 0.5% + GGBFS 7%	67	24	43	51	33	18
Lime 1% + GGBFS 7%	53	34	19	52	39	13
Lime PC 1% + GGBFS 7%	87	21	66	75	26	49

It can be concluded that GGBFS had a minor influence on the plasticity of both test soils. Notably PI reduction was only observed when either lime or PC was added to the mix. For Test Soil 2, a substantial decrease in PI was observed in specimens treated with 1% lime and 7% GGBFS. In the case of Test Soil 1, the decrease of PI was observed in specimens treated with 0.5% lime and 7% GGBFS after 7 days of curing. The limited impact of GGBFS on the plasticity of the test soils might be due to its relatively low activation process and the importance of pH to facilitates the formation of hydration products between GGBFS and the soil (e.g. Arkurk et al. 2019), which will be discussed in the next section.

5.5 pH Testing

pH test results are presented in Figures 18 and 19 for Test Soil 1 and Test Soil 2, respectively. Tabulated values are found in Appendix F. Regarding the additives, GGBFS, lime, PC, and SC have pH values of 10.14, 12.63, 11, and 11.74, respectively. The untreated Test Soil 1 has a pH value of 7.36, which is considered nearly neutral. Untreated Test Soil 2 had a pH of 8.65, which is slightly basic. All treated specimens exhibited an increase in pH, with the most significant increases observed in specimens treated with lime or lime and GGBFS, reaching pH values close to 12. This elevation in pH is of particular importance due to its potential to enhance the solubility of silica and alumina within the soil when the pH surpasses 12.4, thereby facilitating pozzolanic reactions. This may account for the substantial improvement in UCS when lime was added alongside GGBFS. However, it's worth noting that reactions involving alumina, calcium, and sulfate are more likely to occur, leading to the production of ettringite, which might explain the vertical swell observed in lime-GGBFS specimens. In the quest for non-calcium-based additives capable of increasing pH without triggering adverse reactions, sodium carbonate (SC) was considered. It has been shown that using sodium carbonate as an activator can be a slow

process, and the addition of secondary additives may accelerate the hydration process (Akturk et. al. 2019). Moreover, Arkurk et. al. (2019) found that achieving a minimum pH of 11.5 is essential for initiating an effective alkali-activation reaction, allowing OH ions to break the Si-O and Al-O bonds in GGBFS, facilitating the formation of hydration products. However, SC alone did not produce a significant increase in pH, and there was minimal impact on UCS with this addition. As previously mentioned, the lack of dissolution of granular SC in water before mixing it with GGBFS could have reduced the effectiveness of using SC as an activator. Even so, it can be inferred that higher SC/GGBFS ratios, coupled with longer curing periods, might activate GGBFS more effectively. Hence, further research using different additives is recommended to explore alternative options to lime for increasing pH.

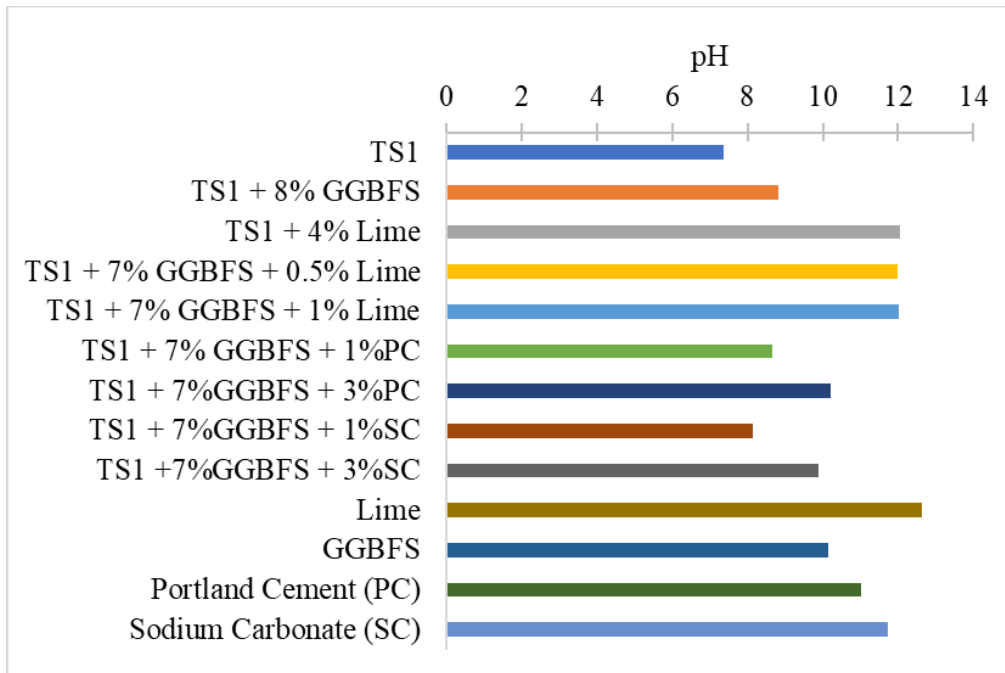


Figure 18. pH of Test Soil 1 with and without any treatments and chemical additives used.

In the case of Test Soil 2, results were similar to the ones found in Test Soil 1. Specimens treated with lime or lime and GGBFS exhibited the most significant pH increase, around 12, and their UCS also showed substantial improvement compared to specimens treated with only GGBFS

or lime. However, the upward trend in swelling behavior observed at the end of swelling tests for lime-GGBFS specimens suggests that this increase in the pH may also be contributing to the ettringite formation in the soil at a very slow rate. This could be attributed to the slower release of alumina from montmorillonite compared to kaolinite.

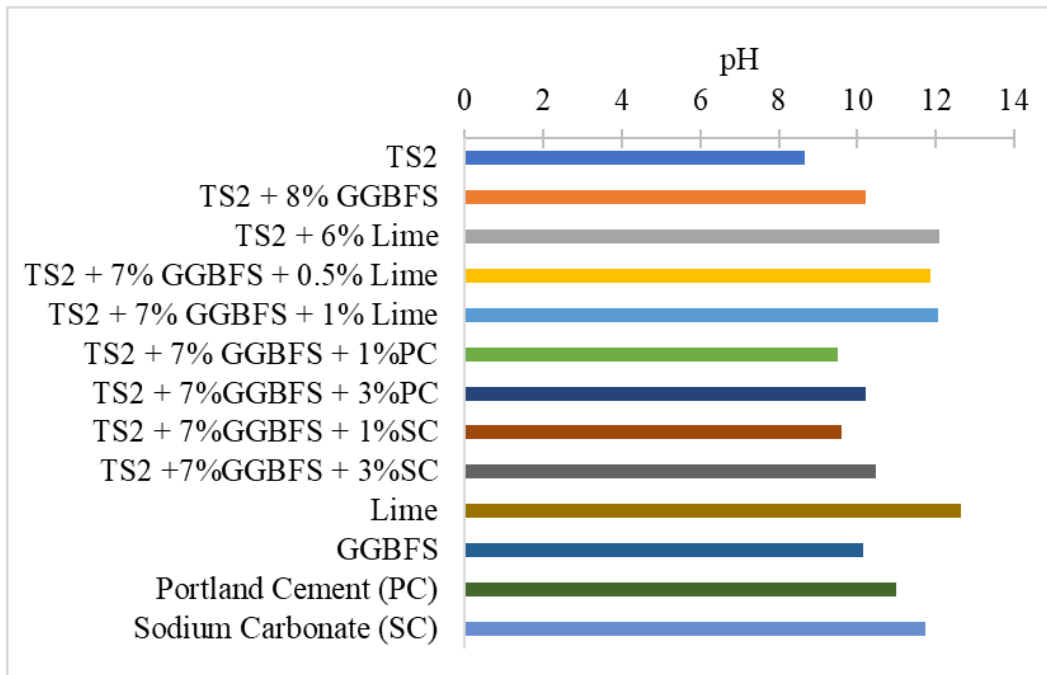


Figure 19. pH of Test Soil 2 with and without any treatments and chemical additives used.

Figures 20 and 21 illustrate the variations in pH, LL, PL, and PI for Test Soil 1 and Test Soil 2, respectively. Positive values signify an increase in the parameter compared to untreated soil, while negative values indicate the opposite trend. By looking at Figure 26, we can see a rough correlation in LL, PL, and PI when the pH increases. Specimens treated with lime or lime and GGBFS, which exhibited a significant rise in pH, also experienced substantial increases in LL and PL compared to those treated solely with GGBFS or GGBFS and PC. All treated specimens displayed an increase in PI, except for those treated with GGBFS and PC, which exhibited a slight decrease.

An opposite pattern was observed on Test Soil 2, where treated specimens with pH values

close to 12 showed a notable decrease in LL. Regarding PL, the results were somewhat less consistent. Lime-GGBFs treated specimens showed a notable increase in PL, except for the one treated with 0.5% lime and 7% GGBFS. Since the PI depends on both the LL and PL, results did not seem to follow a clear trend.

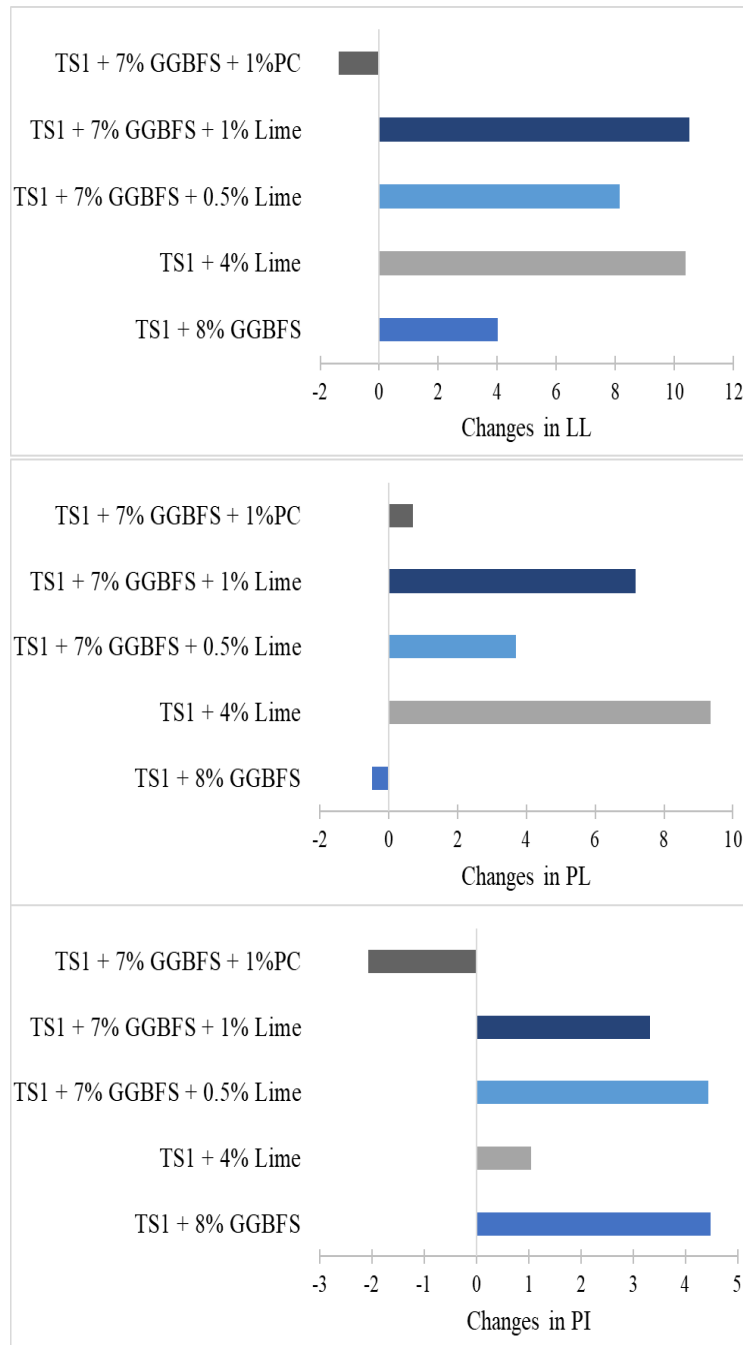


Figure 20. Changes in pH and Atterberg Limits (with no curing) for Test Soil 1 using different

additives.

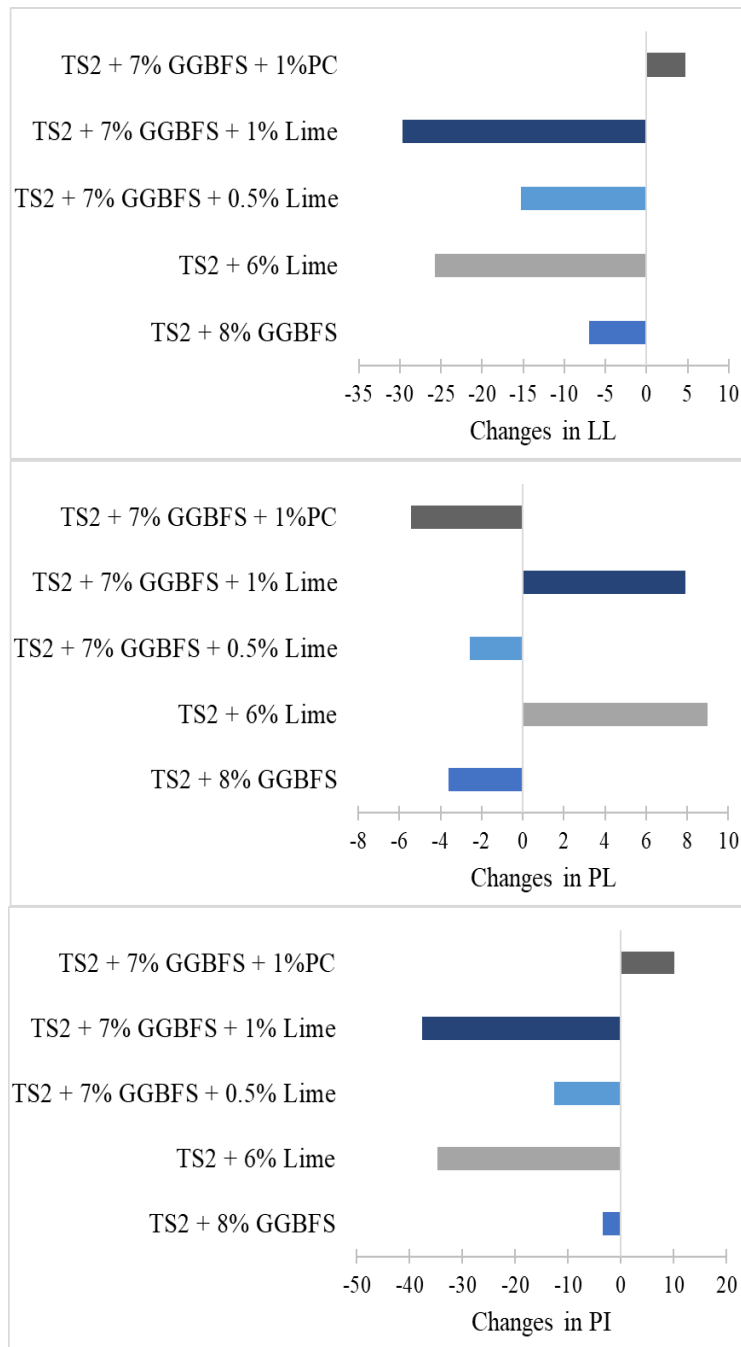


Figure 21. Changes in pH and Atterberg Limits (with no curing) for Test Soil 2 using different additives.

5.6 Bar Linear Shrinkage

Results from the bar linear shrinkage provide two parameters: the linear shrinkage (LS) and shrinkage limit (SL). LS represents the maximum percentage decrease in soil length when it is subjected to oven drying, while SL indicates the water content percentage at which the soil no longer undergoes shrinkage during the drying process.

Results for Test soil 1 are shown in Figure 22 whereas for Test Soil 2 they are shown in Figure 23, encompassing untreated and treated specimens with GGBFS, lime and GGBFS, and PC and GGBFS. Tabulated values are found in Appendix G. In the case of Test Soil 1, it's notable that the LS increased in lime-GGBFS treated specimens, suggesting more significant volume changes during the drying process. This increase in LS may be linked to the observed vertical swell in lime-GGBFS treated specimens, which can be influenced by the elevated pH resulting from lime addition. Conversely, specimens treated with GGBFS alone showed a slight decrease in LS, while those treated with PC and GGBFS exhibited no significant change in LS. Moreover, all treated specimens experienced a substantial reduction in SL. This reduction in SL is advantageous because it implies that the treated soils can undergo shrinkage without cracking at lower water content levels. However, for lime-GGBFS treated specimens, their LS might suggest that more pronounced volumetric changes could occur if the water level varies. In contrast, Test Soil 1 treated solely with GGBFS or PC and GGBFS would exhibit similar volumetric changes than untreated under similar conditions.

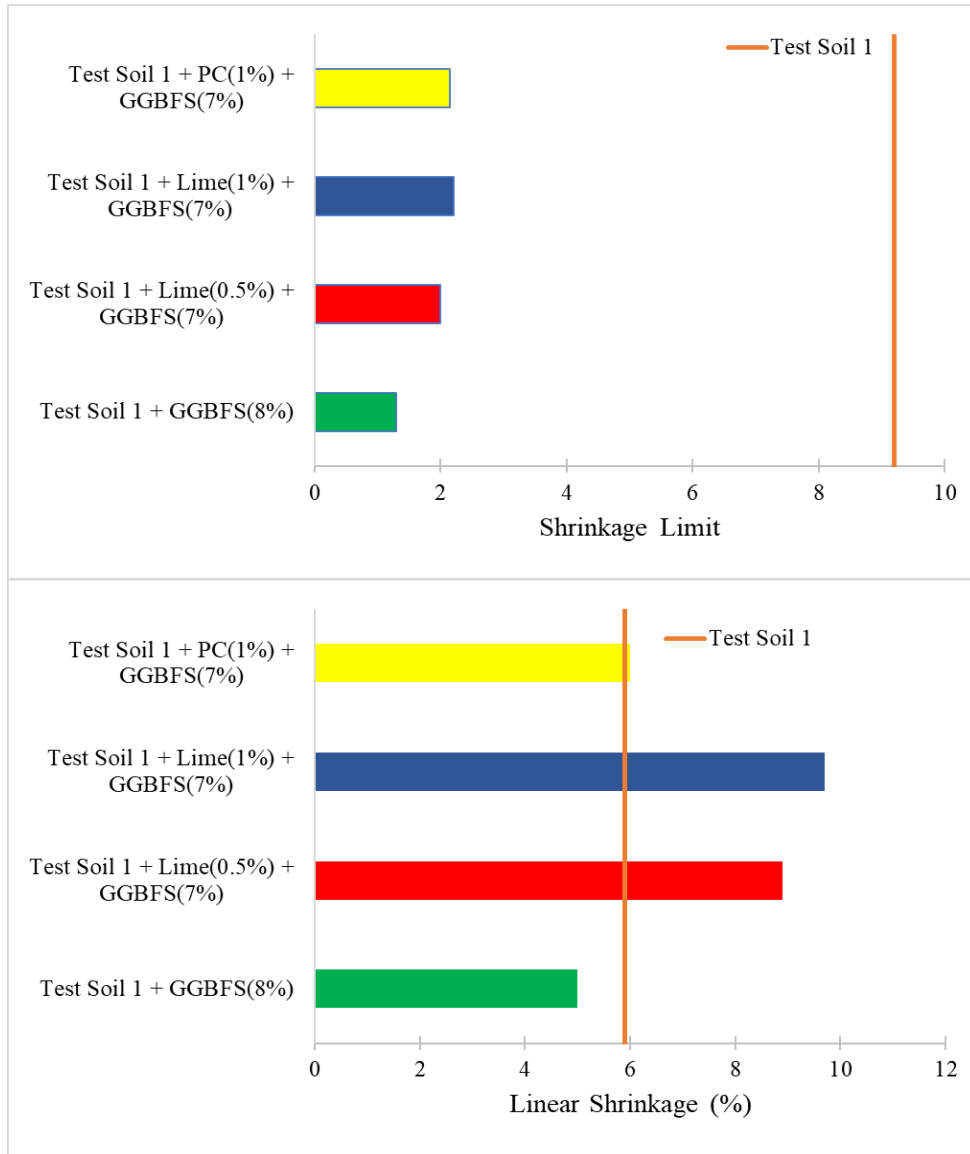


Figure 22. Linear Shrinkage and Shrinkage Limit for Test Soil 1 with and without using chemical additives.

For Test Soil 2, specimens treated with lime and GGBFS exhibited a reduction in both LS and SL. This indicates a decrease in the activity of the soil as a result of the chemical treatment. It can be inferred that Test Soil 2, containing highly active minerals like montmorillonite, was particularly influenced by the pH increase resulting from treatment. In contrast, specimens treated with GGBFS or GGBFS and PC showed a marginal change in LS. However, similar to other

treated specimens, the SL decreased.

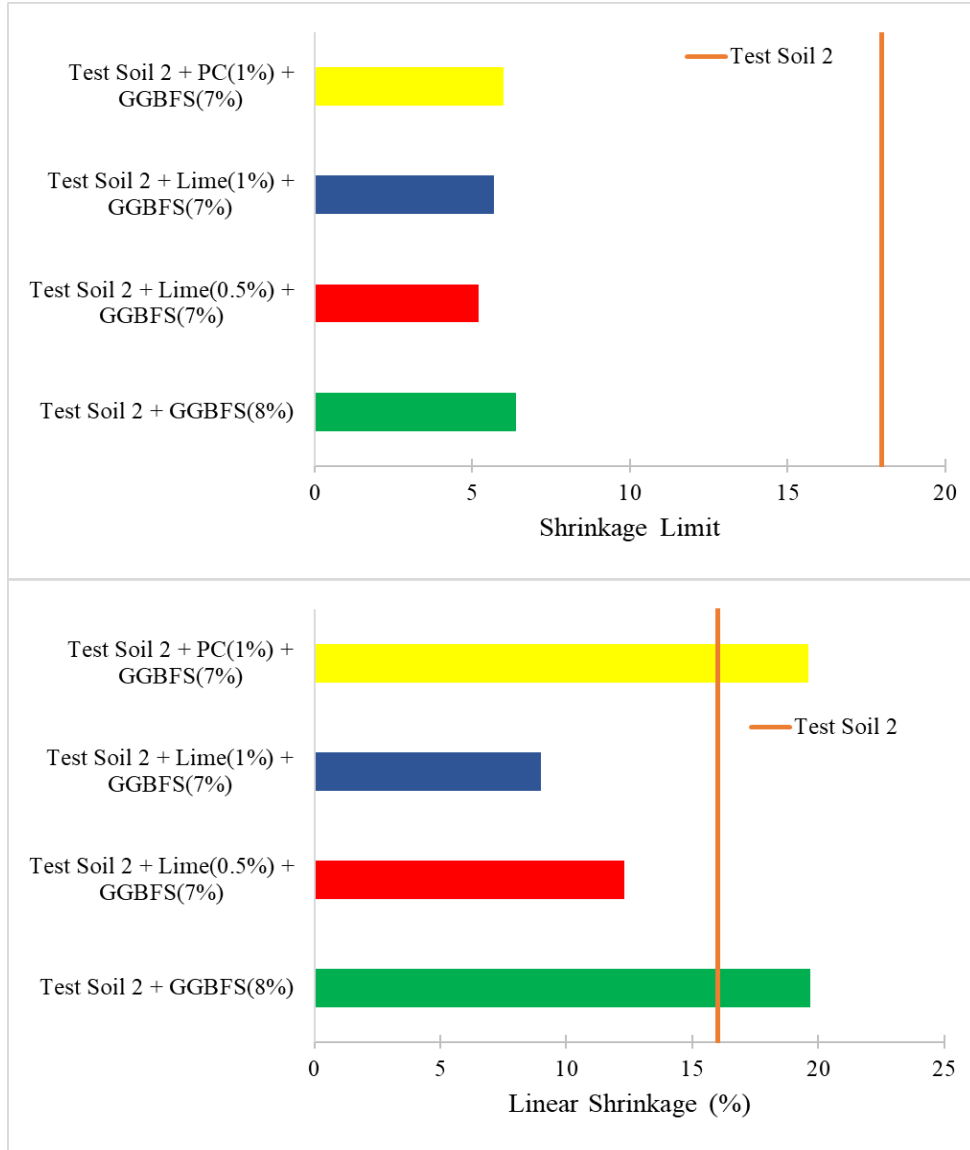


Figure 23. Linear Shrinkage and Shrinkage Limit for Test Soil 2 with and without using chemical additives.

Figures 24 and 25 illustrate the variations in pH, SL, and LS for Test Soil 1 and Test Soil 2, respectively. It appears that there was a reduction in SL as pH increased for Test Soil 1. In the case of Test Soil 2, the decrease in SL is even more pronounced. Concerning LS, specimens that exhibited the highest increase in pH, specifically those treated with lime and GGBFS, showed an

increase in LS for Test Soil 1. However, for Test Soil 2, specimens treated with 1% lime and 7% GGBFS, as well as 1% PC and 7% GGBFS, demonstrated the most significant decrease in LS. Interestingly, the specimen treated with 0.5% lime and 7% GGBFS exhibited a slight increase in LS for Test Soil 2.

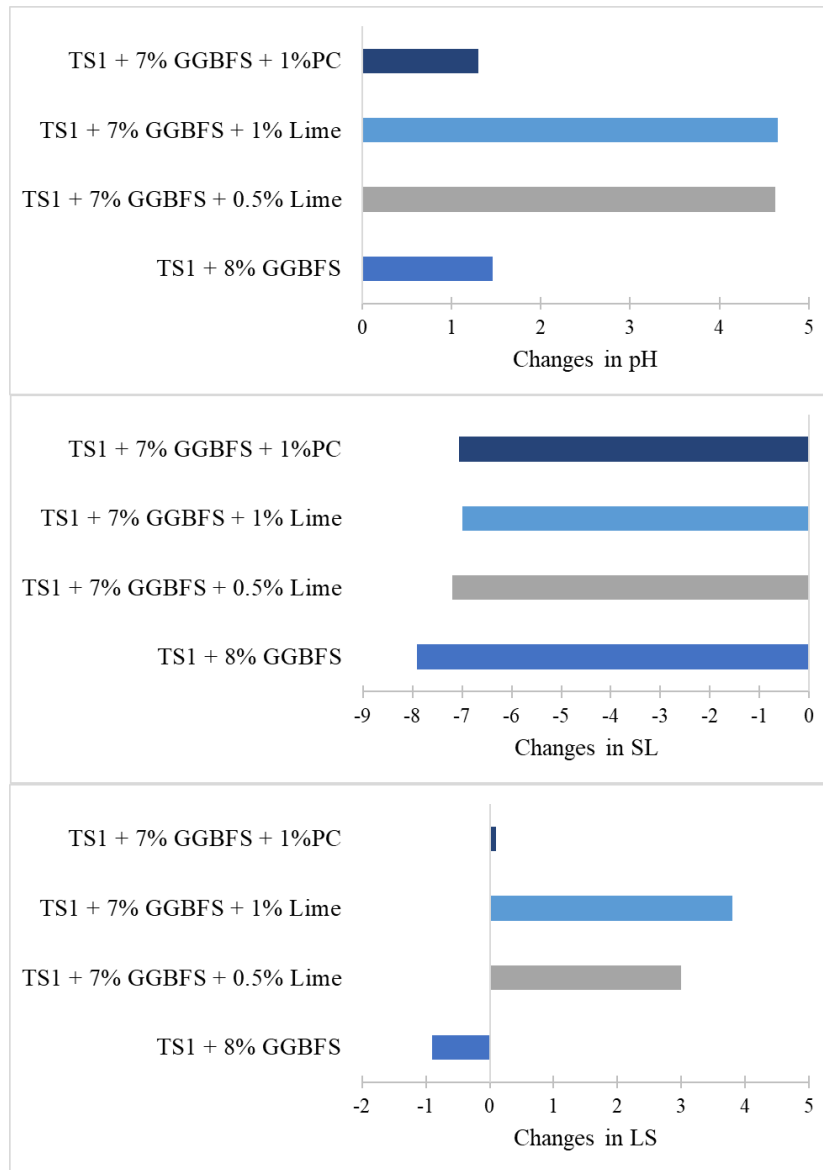


Figure 24. Changes in pH, SL, and LS for Test Soil 1 with and without using chemical additives.

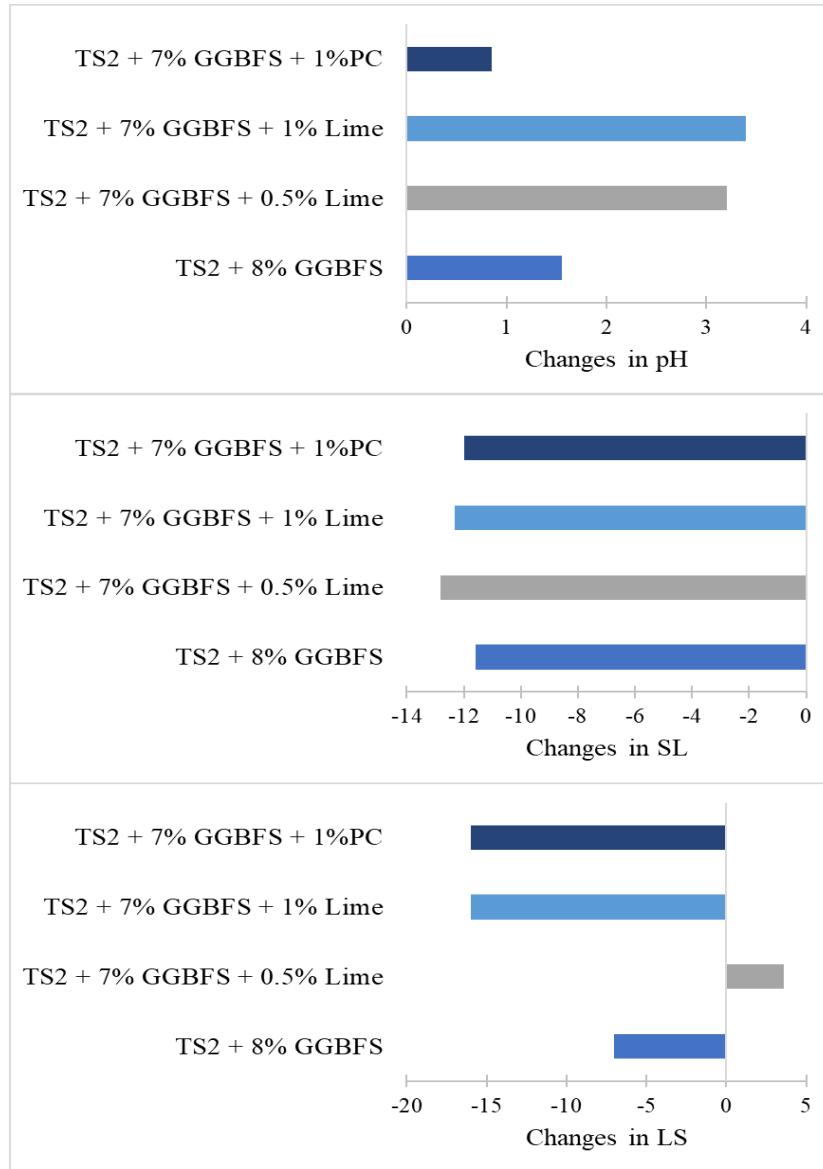


Figure 25. Changes in pH, SL, and LS for Test Soil 2 with and without using chemical additives.

5.7 Scanning Electron Microscopy

Scanning electron microscopy was employed to analyze Test Soil 1 and Test Soil 2 specimens treated with various concentrations of GGBFS (6%, 8%, and 12%). The primary objective was to investigate potential alterations in the microstructure of both test soils that could indicate the development of reactions in treated specimens. At a magnification range of 350 mm, it becomes apparent that there are more crystal-shaped elements present in the GGBFS-treated

soils, which could be indicative of the presence of cementitious reaction products. A comparison between untreated and GGBFS-treated Test Soil 1 specimens, specifically those treated with 8% GGBFS (as shown in Figure 26), reveals the presence of some elements with a stick-like morphology rather than the plate-like shape observed in untreated soil.

Regarding Test Soil 2 (Figure 27), variations in microstructure were primarily evident in specimens treated with 8% GGBFS. In the untreated soil, the finer particles adhering to the sand particles exhibited a smoother, plate-like shape. In contrast, in the soil treated with GGBFS, there was an apparent presence of more crystalline-shaped particles, suggesting potential reactions with the stabilizer.

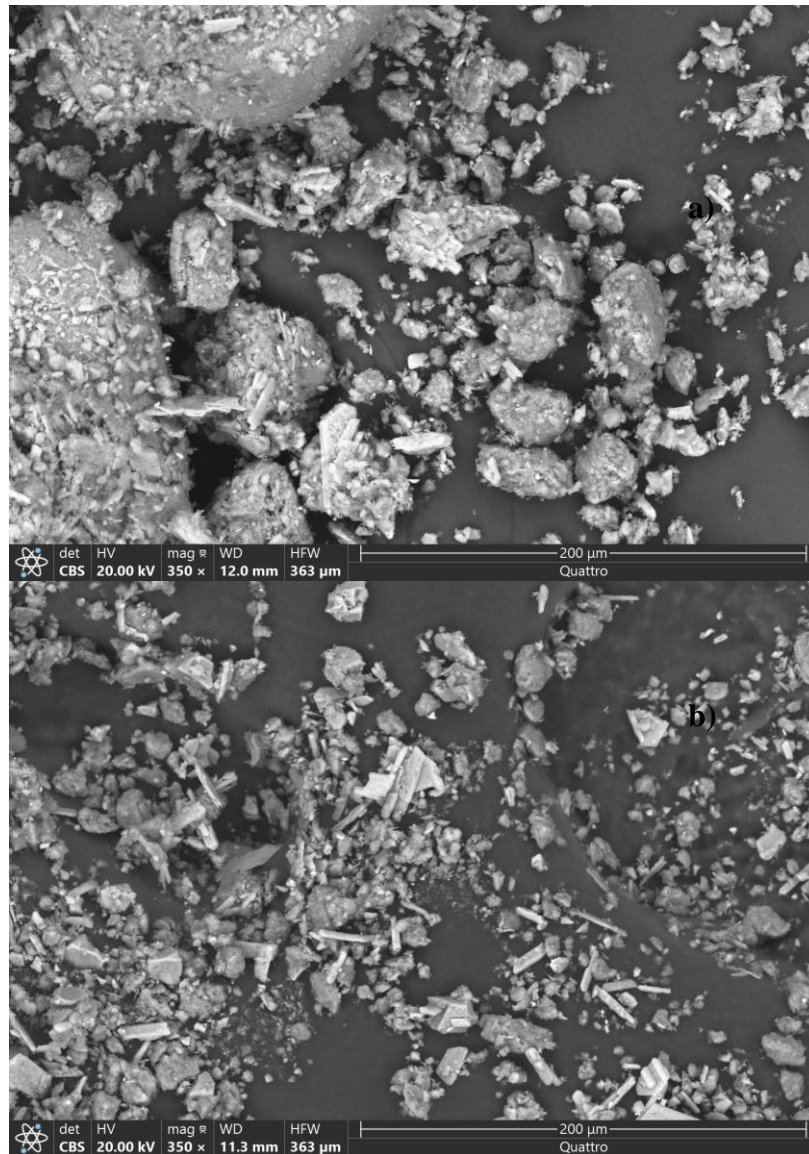


Figure 26. SEM photographs a) CBS mode, untreated Test Soil 1, and b) CBS mode, Test Soil 1 treated with 8% GGBFS.

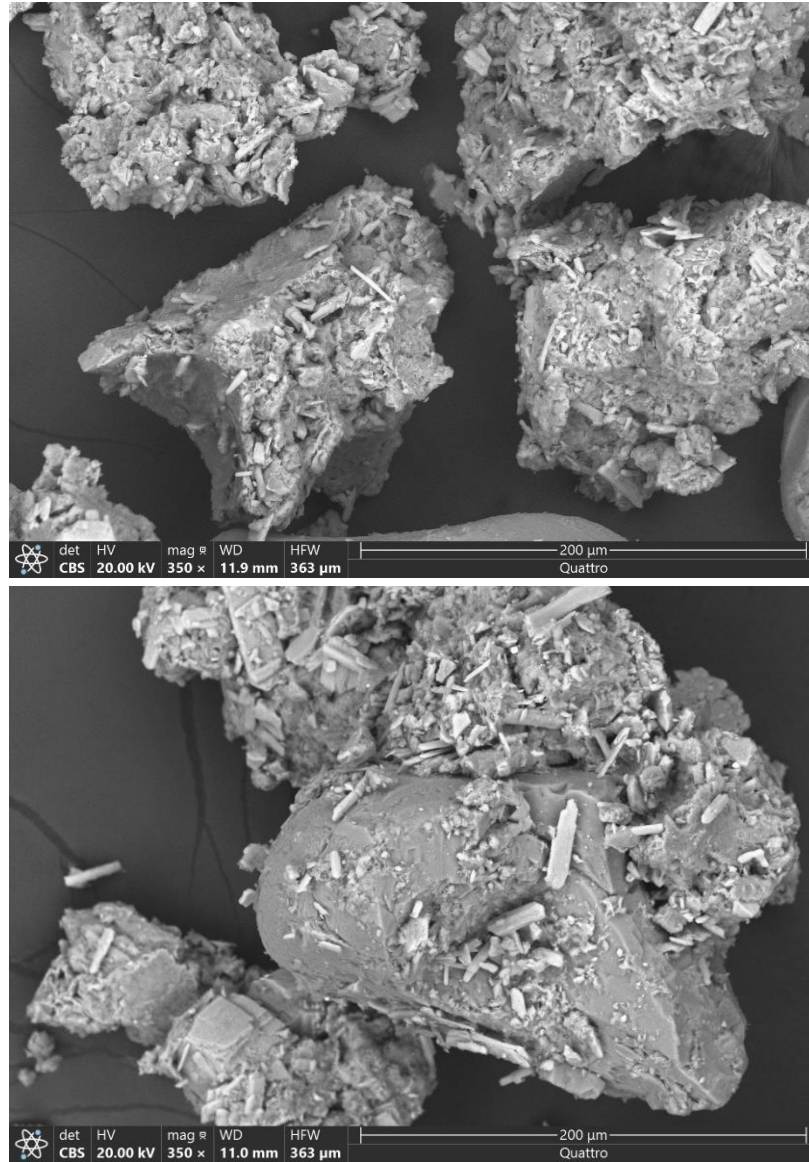


Figure 27. SEM photographs a) CBS mode, untreated Test Soil 2, and b) CBS mode, Test Soil 2 treated with 8% GGBFS.

5.8 Whole-Rock X-Ray Fluorescence Testing

The purpose of whole rock XRF analysis was to examine the composition of the GGBFS for testing and to assess the amount of sulfur in the different materials used to create both test soils. The chemical constituents of GGBFS are shown in Table 7. These components are similar to the ones found in the literature, composed primarily of silica, alumina, calcium, and magnesium (e.g.

Ouf 2001).

Table 7. Chemical constituents of GGBFS.

Chemical Constituent	Percent by Weight
SiO ₂	40
Al ₂ O ₃	8.1
CaO	38.5
MgO	10.4
K ₂ O	0.5
TiO ₂	0.4
Other minerals	11.11

Table 8 provides data on the elemental sulfur content of GGBFS and the components utilized in the test soils. Test Soil 1 and Test Soil 2 exhibit sulfur contents that correspond to approximately 14,080 and 20,072 ppm of sulfate, respectively. As both test soils were prepared using the same process, the lower sulfate content observed in Test Soil 1 might be attributed to the use of a poorly mixed sample during the whole rock XRF analysis. Moreover, both soils remain significantly high when considering chemical treatment alternatives.

Table 8. Elemental sulfur content and calculated equivalent sulfate content for test materials (Miller & Prada 2022).

Material	XRF Sulfur %	Calculated SO₄ %	Calculated SO₄ ppm
Gypsum	22.1	66.21	662076
GGBFS	1.05	3.15	31456
Kaolinite	0	0	0
Bentonite	0.43	1.29	12882
Sand	0	0	0
Test Soil 1	0.47	1.41	14080
Test Soil 2	0.67	2.01	20072
Test Soil 1 + 8% GGBFS	0.72	2.16	21570
Test Soil 2 + 8% GGBFS	1.02	3.06	30557

Chapter 6: Conclusions and Recommendations

6.1 Conclusions

The purpose was to investigate the potential of using GGBFS as a stabilizer for high sulfate bearing soils. Two test soils with 20,000 ppm of sulfate were evaluated. Test Soil 1 was composed of 50% kaolinite, 50% fine sand, and 20,000 ppm of sulfate in the form of gypsum. Test Soil 2 was similar to Test Soil 1 but using montmorillonite instead of kaolinite. Laboratory tests included compaction tests, unconfined compression tests, swelling test, liquid and plastic limit tests, bar linear shrinkage tests, pH tests, scanning electron microscopy and whole rock XRF testing. Selected tests were conducted in both test soils with two different activators (lime and PC) to assess the performance of GGBFS in comparison with common additives. Since GGBFS is a latent hydraulic material, multiple activators (lime, PC, and SC) were used to selected tests to evaluate their effectiveness without unacceptable swelling behavior. The results of these tests suggest the following:

1) Unconfined compression strength (UCS) increased with the addition of GGBFS in both test soils at a similar moisture content. Notably, the addition of 8% GGBFS appeared to be the most favorable concentration in terms of achieving a balance between strength improvement and the proportion of stabilizer added. Following a curing period of 7 days, Test Soil 1 exhibited a UCS increase of approximately 40 psi when compared to untreated soil, while Test Soil 2 displayed a UCS increase of around 50 psi. In the case of Test Soil 1, the UCS increase did not meet the minimum threshold of 50 psi, as specified for chemical stabilizers by the Oklahoma Department of Transportation (2021). Similarly, Test Soil 2 only marginally surpassed this threshold. However, it is noted that an increase of 40 to 50 psi in strength is not trivial. GGBFS specimens subjected to a soaking period of two days disintegrated before testing.

2) The addition of 7% GGBFS, in conjunction with two activators, lime and PC, resulted in a significant increase in UCS compared to untreated soil and soil treated solely with GGBFS. In the case of Test Soil 1 treated with 1% lime and 7% GGBFS, the UCS increased by approximately 200 psi in comparison to untreated soil. Test Soil 2 subjected to the same treatment yielded an UCS increase of 94 psi. When Test Soil 1 was treated with 1% PC and 7% GGBFS, the UCS was comparable to specimens treated with GGBFS alone. Conversely, Test Soil 1 treated with 3% PC and 7% GGBFS exhibited a substantial UCS increase of about 300 psi, while Test Soil 2 with the same treatment showed an UCS increase of 140 psi. It was noted that larger amounts of PC were required to effectively activate GGBFS when compared to lime. Regarding the third activator, sodium carbonate (SC), the percentages utilized in this study (1% and 3%) proved insufficient to effectively activate GGBFS.

3) The addition of 8% GGBFS was observed to significantly decrease the swelling behavior in both test soils. In Test Soil 1, the addition of GGBFS resulted in a vertical swelling strain of 1.9% compared to 3.3% without treatment. In the case of Test Soil 2, the swelling percentage decreased from 5.2% to 0.3% with the addition of GGBFS.

4) When lime was used as an activator, Test Soil 1 exhibited a percent swell higher than untreated soil. For Test Soil 2, the swelling behavior initially decreased, and there were no noticeable changes for several days, although a slight increase was observed towards the end of the test. As mentioned earlier, these varying behaviors between Test Soil 1 and Test Soil 2 could be attributed to the differential release of alumina, with Test Soil 1, composed of 50% kaolinite, having a higher release compared to Test Soil 2, which is composed 50% montmorillonite.

5) When PC was used as a GGBFS activator, Test Soil 1 showed no apparent swelling for 12 hours, and started to slowly increase until the test was ended, reaching a percent swell of 0.59

and 1.73% for specimens treated with 1% PC and 7% GGBFs and 3% PC and 7% GGBFS, respectively. In the case of Test Soil 2, no apparent swelling was observed for more than a day; after that the one treated with 3% PC and 7% GGBFS began swelling until the end of the test, reaching a percent swell of 3.0%. Regarding the treatment with 1% PC and 7% GGBFS, their swelling behavior was slower, reaching a vertical swell of 0.8%. Although the vertical swell for both test soils was lower than without treatment, longer periods of testing are recommended for a better understanding of this behavior.

6) The addition of GGBFS had a minor influence on the plasticity of both test soils. The addition of lime and GGBFS produced a notable PI reduction for Test Soil 2 with and without curing, whereas for Test Soil 1, PI reduction was only observed after 7-day curing.

7) It was observed that changes in pH in the soils mixed with different additives are greatly correlated with the plasticity and shrinkage behavior of both soils. Moreover, the increment of pH facilitates the pozzolanic reactions but also facilitates reactions involving alumina, calcium, and sulfate, leading to the production of ettringite minerals.

6.2 Recommendations and Future Investigations

1) This investigation highlights that GGBFS can enhance the strength and reduce the swelling of sulfate-bearing soils; nevertheless, it requires an activator to fully unlock its latent properties. Previous studies have indicated that the pH of the initial solution affects the rate of reaction (e.g. Akturk et. al. 2019 & Song et. al. 2000).

2) There is potential to employ non-calcium-based chemicals to raise the pH and activate GGBFS without the risk of generating ettringite minerals. For instance, MgO has demonstrated great efficacy as a GGBFS activator (e.g., Yi, Liska, Jin, & Al-Tabbaa 2016). Although sodium carbonate did not activate GGBFS in this study, it is possible that higher concentrations able to

raise the pH as well as longer curing periods may yield positive results.

3) The use of natural sulfate-bearing soils is needed to assess the performance of GGBFS in the field.

4) Although the use of GGBGFS showed a decrease of swelling behavior on both test soils, some reactions might occur at a slower rate than the testing periods employed in this research, which is why longer testing periods are recommended, especially if a calcium-based additive, such as lime or PC, were to be used as a GGBFS activator.

5) The distinct responses between Test Soil 1 and Test Soil 2 with the addition of GGBFS could be explored in future investigations to gain deeper understanding of the chemical reaction involved.

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Appendix

Appendix A. Unconfined compression tests for Test Soils treated with GGBFS.

Test Soil 1.

Specimen No.	Soil Type	w (%)	γ_d (pcf)	UCS (psi)
SG7-1	50% K+50% S+20,000ppm	8.05	113.53	32.59
SG7-2	50% K+50% S+20,000ppm	8.16	114.83	43.48
SG7-3	50% K+50% S+20,000ppm	8.34	113.77	43.16
SG9-1	50% K+50% S+20,000ppm	10.32	117.7	51.49
SG9-2	50% K+50% S+20,000ppm	10.5	115.75	48.48
SG9-3	50% K+50% S+20,000ppm	10.34	116.33	36.01
SK11-1	50% K+50% S+20,000ppm	12.32	118.26	41.24
SK11-2	50% K+50% S+20,000ppm	12.31	119.69	30.76
SK11-3	50% K+50% S+20,000ppm	12.37	117.92	37.41
SK13-1	50% K+50% S+20,000ppm	14.31	116.79	22.66
SK13-2	50% K+50% S+20,000ppm	14.11	116.01	16.69
SK13-3	50% K+50% S+20,000ppm	13.82	119.24	15.51
SG6-91	50% K+50% S+20,000ppmSulf+6% GGBFS	9.02	103.98	59.48
SG6-92	50% K+50% S+20,000ppmSulf+6% GGBFS	8.76	108.72	70.14
SG6-93	50% K+50% S+20,000ppmSulf+6% GGBFS	7.97	115.1	67.98
SG6-111	50% K+50% S+20,000ppmSulf+6% GGBFS	10.35	120.22	74.04
SG6-112	50% K+50% S+20,000ppmSulf+6% GGBFS	10.13	122.78	75.78
SG6-113	50% K+50% S+20,000ppmSulf+6% GGBFS	10.74	120.06	93.43
SG6-131	50% K+50% S+20,000ppmSulf+6% GGBFS	12.66	119.6	68.42
SG6-132	50% K+50% S+20,000ppmSulf+6% GGBFS	12.15	119.74	44.19
SG6-133	50% K+50% S+20,000ppmSulf+6% GGBFS	12.16	120.44	41.57
G9-1	50% K+50% S+20,000ppmSulf+8% GGBFS	10.14	115.24	78.36
G9-2	50% K+50% S+20,000ppmSulf+8% GGBFS	10.29	114.15	91.69
G9-3	50% K+50% S+20,000ppmSulf+8% GGBFS	11.11	114.79	91.07
G11-1	50% K+50% S+20,000ppmSulf+8% GGBFS	12.03	120.63	78.19
G11-2	50% K+50% S+20,000ppmSulf+8% GGBFS	12.08	119.09	69.92
G11-3	50% K+50% S+20,000ppmSulf+8% GGBFS	12.21	118.87	67.65
G13-1	50% K+50% S+20,000ppmSulf+8% GGBFS	14.22	116.28	40.24
G13-2	50% K+50% S+20,000ppmSulf+8% GGBFS	14.17	116.54	43.99
G13-3	50% K+50% S+20,000ppmSulf+8% GGBFS	14.04	117.31	60.1
SG12-71	50% K+50% S+20,000ppmSulf+12% GGBFS	8.33	107.1	41.5
SG12-72	50% K+50% S+20,000ppmSulf+12% GGBFS	8.04	11.64	41.3
SG12-73	50% K+50% S+20,000ppmSulf+12% GGBFS	8.11	109.56	49.93
SG12-91	50% K+50% S+20,000ppmSulf+12% GGBFS	10.04	116.28	69.44
SG12-92	50% K+50% S+20,000ppmSulf+12% GGBFS	9.97	116.94	75.32
SG12-93	50% K+50% S+20,000ppmSulf+12% GGBFS	9.94	117.5	85.75
SG12-111	50% K+50% S+20,000ppmSulf+12% GGBFS	10.26	117.06	88.23

SG12-112	50%K+50%S+20,000ppmSulf+12%GGBFS	10.49	116.24	82.63
SG12-113	50%K+50%S+20,000ppmSulf+12%GGBFS	10.63	116.05	84.75
SG12-131	50%K+50%S+20,000ppmSulf+12%GGBFS	14.11	116.97	59.66
SG12-132	50%K+50%S+20,000ppmSulf+12%GGBFS	13.64	120.17	46.63
SG12-133	50%K+50%S+20,000ppmSulf+12%GGBFS	14.1	117.57	56.55

	Specimen No.	Soil Type	w (%)	g _d (pcf)	UCS (psi)
Soaked	KG-S1	50%K+50%S+20,000ppmSulf+8%GGBFS	NA*	NA	NA
Soaked	KG-S2	50%K+50%S+20,000ppmSulf+8%GGBFS	NA	NA	NA
Soaked	KG-S3	50%K+50%S+20,000ppmSulf+8%GGBFS	NA	NA	NA

*Specimens fell apart before testing.

Test Soil 2.

Specimen No.	Soil Type	w (%)	γ _d (pcf)	UCS (psi)
B21-1	50% B, 50%S, 20,000 ppm gypsum	20.93	100.27	53.28
B21-2	50% B, 50%S, 20,000 ppm gypsum	20.28	100.11	43.01
B21-3	50% B, 50%S, 20,000 ppm gypsum	20.39	102.06	47.49
B23-1	50% B, 50%S, 20,000 ppm gypsum	21.9	103.05	38.63
B23-2	50% B, 50%S, 20,000 ppm gypsum	21.81	103.21	33.57
B23-3	50% B, 50%S, 20,000 ppm gypsum	22.46	103.26	38.1
B25-1	50% B, 50%S, 20,000 ppm gypsum	25.08	97.57	40.07
B25-2	50% B, 50%S, 20,000 ppm gypsum	24.42	97.88	38.14
B25-3	50% B, 50%S, 20,000 ppm gypsum	24.26	99.49	36.4
BG6-211	50% B, 50%S, 20,000ppmSulf + GGBFS (6%)	20.79	101.55	77.99
BG6-212	50% B, 50%S, 20,000ppmSulf + GGBFS (6%)	20.38	100.79	69.64
BG6-213	50% B, 50%S, 20,000ppmSulf + GGBFS (6%)	20.89	99.74	64.01
BG6-231	50% B, 50%S, 20,000ppmSulf + GGBFS (6%)	22.52	102.36	89.09
BG6-232	50% B, 50%S, 20,000ppmSulf + GGBFS (6%)	22.45	101.33	79.71
BG6-233	50% B, 50%S, 20,000ppmSulf + GGBFS (6%)	22.69	101.41	86.22
BG6-251	50% B, 50%S, 20,000ppmSulf + GGBFS (6%)	24.57	99.17	66.14
BG6-252	50% B, 50%S, 20,000ppmSulf + GGBFS (6%)	24.75	101.06	74.02
BG6-253	50% B, 50%S, 20,000ppmSulf + GGBFS (6%)	24.53	99.54	70.7
BG8-211	50% B, 50%S, 20,000ppmSulf + GGBFS (8%)	21.6	101.49	92.83
BG8-212	50% B, 50%S, 20,000ppmSulf + GGBFS (8%)	21.76	99.99	107.24
BG8-213	50% B, 50%S, 20,000ppmSulf + GGBFS (8%)	21.7	99.98	97.65
BG8-231	50% B, 50%S, 20,000ppmSulf + GGBFS (8%)	23.67	99.4	96.22
BG8-232	50% B, 50%S, 20,000ppmSulf + GGBFS (8%)	23.54	99.85	89.14
BG8-233	50% B, 50%S, 20,000ppmSulf + GGBFS (8%)	23.32	100.95	90.97
BG8-251	50% B, 50%S, 20,000ppmSulf + GGBFS (8%)	25.01	100.37	66.09

BG8-252	50% B, 50%S, 20,000ppmSulf + GGBFS (8%)	24.74	98.12	57.2
BG8-253	50% B, 50%S, 20,000ppmSulf + GGBFS (8%)	25.04	98.94	64.99
BG12-211	50% B, 50%S, 20,000ppmSulf + GGBFS (12%)	20.38	102.21	105.57
BG12-212	50% B, 50%S, 20,000ppmSulf + GGBFS (12%)	20.76	102.03	95.89
BG12-213	50% B, 50%S, 20,000ppmSulf + GGBFS (12%)	20.38	102.73	91.05
BG12-231	50% B, 50%S, 20,000ppmSulf + GGBFS (12%)	22.58	102.05	106.86
BG12-232	50% B, 50%S, 20,000ppmSulf + GGBFS (12%)	22.41	101.61	102.48
BG12-233	50% B, 50%S, 20,000ppmSulf + GGBFS (12%)	22.63	102.45	89.28
BG12-251	50% B, 50%S, 20,000ppmSulf + GGBFS (12%)	24.71	99.34	73.19
BG12-252	50% B, 50%S, 20,000ppmSulf + GGBFS (12%)	24.63	100.49	67.91
BG12-253	50% B, 50%S, 20,000ppmSulf + GGBFS (12%)	24.96	97.94	63.96

	Specimen No.	Soil Type	w (%)	γ_d (pcf)	UCS (psi)
Soaked	BG-S1	50% bentonite, 50% sand, 20,000 ppm gypsum + GGBFS (8%)	27.59	95.53	19.67
Soaked	BG-S2	50% bentonite, 50% sand, 20,000 ppm gypsum + GGBFS (8%)	27.16	95.96	9.45
Soaked	BG-S3	50% bentonite, 50% sand, 20,000 ppm gypsum + GGBFS (8%)	NA*	NA	NA

* Specimens fell apart before testing.

Appendix B. Unconfined compression tests for Test Soils treated with GGBFS.

Test Soil 1.

	Specimen No.	Soil Type	w (%)	γ_d (pcf)	UCS (psi)
Unsoaked	KL-U1	50% K+50%S+20,000ppmSulf+4% Lime	13.12	113.43	67.94
Unsoaked	KL-U2	50% K+50%S+20,000ppmSulf+4% Lime	13.43	109.08	75.31
Unsoaked	KL-U3	50% K+50%S+20,000ppmSulf+4% Lime	13.7	107.66	66.75
	Specimen No.	Soil Type	w (%)	γ_d (pcf)	UCS (psi)
Soaked	KL-S1	50% K+50%S+20,000ppmSulf+4% Lime	NA*	NA	NA
Soaked	KL-S2	50% K+50%S+20,000ppmSulf+4% Lime	NA	NA	NA
Soaked	KL-S3	50% K+50%S+20,000ppmSulf+4% Lime	NA	NA	NA

* Specimens fell apart before testing.

Test Soil 2.

	Specimen No.	Soil Type			
Unsoaked	BL-U1	50% bentonite, 50% sand, 20,000 ppm gypsum+Lime (6%)			
Unsoaked	BL-U2	50% bentonite, 50% sand, 20,000 ppm gypsum+Lime (6%)	27.17	89.34	64.05
Unsoaked	BL-U3	50% bentonite, 50% sand, 20,000 ppm gypsum+Lime (6%)	26.29	92.05	72.48
	Specimen No.	Soil Type			
Soaked	BL-S1	50% bentonite, 50% sand, 20,000 ppm gypsum+Lime (6%)	31.76	90.14	28.75
Soaked	BL-S2	50% bentonite, 50% sand, 20,000 ppm gypsum+Lime (6%)	32.59	85.02	28.05
Soaked	BL-S2	50% bentonite, 50% sand, 20,000 ppm gypsum+Lime (6%)	33.21	87.23	31.45
Soaked	BL-S2	50% bentonite, 50% sand, 20,000 ppm gypsum+Lime (6%)	33.83	86.28	26.26

Appendix C. Unconfined compression tests for Test Soils treated with GGBFS and lime, GGBFS and PC, and GGBFS and SC.

Test Soil 1.

	Specimen No.	Soil Type	w (%)	γ_d (pcf)	UCS (psi)
Unsoaked	KLG-U1	50% K+50% S+20,000ppmSulf+7%G GBFS+1%Lime	13.16	112.36	282.12
Unsoaked	KLG-U2	50% K+50% S+20,000ppmSulf+7%G GBFS+1%Lime	13.17	112.02	256.3
Unsoaked	KLG-U3	50% K+50% S+20,000ppmSulf+7%G GBFS+1%Lime	13.26	110.7	255.33
	Specimen No.	Soil Type	w (%)	γ_d (pcf)	UCS (psi)
Soaked	KLG-S1	50% K+50% S+20,000ppmSulf+7%G GBFS+1%Lime	20.5	103.82	77.37
Soaked	KLG-S2	50% K+50% S+20,000ppmSulf+7%G GBFS+1%Lime	18.22	107.85	83.64
Soaked	KLG-S3	50% K+50% S+20,000ppmSulf+7%G GBFS+1%Lime	18.77	106.75	66.39
	Specimen No.	Soil Type	w (%)	γ_d (pcf)	UCS (psi)

Soaked	0.5KLG -S1	50%K+50%S+20,000ppmSulf+7%G GBFS+0.5%Lime	15.46	111.88	200.99
Soaked	0.5KLG -S2	50%K+50%S+20,000ppmSulf+7%G GBFS+0.5%Lime	16.07	111.48	204.92
Soaked	0.5KLG -S3	50%K+50%S+20,000ppmSulf+7%G GBFS+0.5%Lime			
	Specimen No.	Soil Type	w (%)	γ_d (pcf)	UCS (psi)
Unsoaked	0.5KLG -U1	50%K+50%S+20,000ppmSulf+7%G GBFS+0.5%Lime	11.32	110.27	248.27
Unsoaked	0.5KLG -U2	50%K+50%S+20,000ppmSulf+7%G GBFS+0.5%Lime	11.22	111.4	308.14
Unsoaked	0.5KLG -U3	50%K+50%S+20,000ppmSulf+7%G GBFS+0.5%Lime	11.18	113.63	348.81
	Specimen No.	Soil Type	w (%)	γ_d (pcf)	UCS (psi)
Unsoaked	KPC- U0	50%K+50%S+20,000ppmSulf+7%G GBFS+1%PC	10.96	154.06	482.49
Unsoaked	KPC- U1	50%K+50%S+20,000ppmSulf+7%G GBFS+1%PC	11.92	115.37	50.73
Unsoaked	KPC- U2	50%K+50%S+20,000ppmSulf+7%G GBFS+1%PC	11.81	113.37	77.29
Unsoaked	KPC- U3	50%K+50%S+20,000ppmSulf+7%G GBFS+1%PC	11.61	113.93	76.26
	Specimen No.	Soil Type	w (%)	γ_d (pcf)	UCS (psi)
Unsoaked	KSG- U1	50%K+50%S+20,000ppmSulf+7%G GBFS+1%SC	11.2	116.82	87.73
Unsoaked	KSG- U2	50%K+50%S+20,000ppmSulf+7%G GBFS+1%SC	11.26	113.4	80.7
Unsoaked	KSG- U3	50%K+50%S+20,000ppmSulf+7%G GBFS+1%SC	11.44	113.86	73.56
	Specimen No.	Soil Type	w (%)	γ_d (pcf)	UCS (psi)
Unsoaked	KSG- U1	50%K+50%S+20,000ppmSulf+7%G GBFS+3%SC	10.95	118.21	92.47
Unsoaked	KSG- U2	50%K+50%S+20,000ppmSulf+7%G GBFS+3%SC	11.27	112.53	53.23
Unsoaked	KSG- U3	50%K+50%S+20,000ppmSulf+7%G GBFS+3%SC	11.41	114.87	71.27
	Specimen No.	Soil Type	w (%)	γ_d (pcf)	UCS (psi)
Unsoaked	KSG- U1	50%K+50%S+20,000ppmSulf+7%G GBFS+3%PC	10.82	117.24	384.62
Unsoaked	KSG- U2	50%K+50%S+20,000ppmSulf+7%G GBFS+3%PC	11.11	115.82	376.91

Unsoaked	KSG-U3	50%K+50%S+20,000ppmSulf+7%G GBFS+3%PC	11.12	116.44	389.56
	Specimen No.	Soil Type	w (%)	γ_d (pcf)	UCS (psi)
Unsoaked	TPC1	50%K+50%S+20,000ppmSulf+3%PC	11.16	119.94	201.61
Unsoaked	TPC2	50%K+50%S+20,000ppmSulf+3%PC	11.28	114.54	132.6
Unsoaked	TPC3	50%K+50%S+20,000ppmSulf+3%PC	11.19	118.4	152.31

Appendix D. Response to wetting tests for Test Soils 1 and 2 untreated and treated.

Test Soil 1		Test Soil 1 + 8% GGBFS		Test Soil 1 + 4% Lime	
time[min]	ϵ %	time [min]	ϵ %	time [min]	ϵ %
0.5	0.29	0.5	0.08	0.5	0
1	0.31	1	0.14	1	0.02
2	0.35	2	0.22	2	0.06
4	0.45	4	0.39	4	0.23
8	0.62	8	0.68	8	0.38
15	0.89	15	1.03	15	0.71
30	1.45	30	1.39	30	0.83
60	2.3	60	1.87	60	0.93
120	2.76	120	1.9	120	1.09
180	2.98	1440	1.9	180	1.24
1260	3.23	1860	1.91	1440	3.07
2880	3.26	2880	1.91	2880	3.89
4320	3.28	4320	1.91	4320	4.47
5760	3.29	5760	1.91	5760	4.95
		7200	1.91	7200	5.43
		8640	1.91	8640	5.88
				10080	6.32

Test Soil 1 + 0.5% Lime + 7% GGBFS		Test soil 1 + 1% Lime + 7% GGBFS		Test Soil 1 + 3% PC	
time [min]	ϵ %	time[min]	ϵ %	time [min]	ϵ %
0.02	0	0.5	0.12	0.08	0
0.08	0	1	0.2	0.17	0
0.17	0.04	2	0.31	0.5	0.04
0.5	0.08	4	0.51	1	0.08
1	0.16	8	0.91	3	0.08
3	0.35	15	1.18	8.33	0.12
8.33	0.75	30	1.38	16.67	0.16
16.67	1.18	60	1.5	30	0.16
30	1.54	120	1.69	60	0.16
60	1.81	180	1.81	90	0.16
90	2.01	1440	2.87	120	0.2
120	2.17	2880	3.46	120.08	0.2
150	2.36	4320	3.62	120.17	0.2
180	2.52	5760	3.74	120.5	0.2
240	2.8	7200	3.82	121	0.2
300	3.03	8640	3.9	123	0.2
360	3.23	10080	4.02	128.33	0.2
420	3.43			136.67	0.2
480	3.62			150	0.24
540	3.78			180	0.24
600	3.94			210	0.24
660	4.09			240	0.28
780	4.37			270	0.28
900	4.65			300	0.28
1020	4.92			360	0.31
1247.63	5.39			420	0.31
1260	5.39			480	0.35
1380	5.59			540	0.35
1500	5.71			600	0.39
1560	5.79			660	0.39
1620	5.83			720	0.43
1680	5.91			780	0.43
1740	5.94			900	0.47
1800	5.98			1020	0.51
2880	6.3			1140	0.51
4320	6.42			1260	0.55

5760	6.42			1380	0.55
7200	6.46			1500	0.59
8640	6.46			1620	0.59
10115.32	6.46			1680	0.59
11520	6.46			1740	0.59
				1800	0.59
				1860	0.63
				1920	0.63
				3000	0.71
				4440	0.79
				5880	0.83
				7320	0.87
				8760	0.91
				10200	0.94
				11640	0.98
				23160	1.3

Test Soil + 1% PC + 7% GGBFS		Test Soil 1 + 3% PC + 7% GGBFS		Test Soil 2	
time [min]	ϵ %	time [min]	ϵ %	time [min]	ϵ %
0.08	0	0.08	0	0.5	0.02
0.17	0	0.17	0	1	0.02
0.5	0	0.5	0.05	2	0.03
1	0	1	0.05	4	0.04
3	0	3	0.1	8	0.06
8.33	0	8.33	0.1	15	0.1
16.67	0.04	16.67	0.16	30	0.18
30	0.04	30	0.16	60	0.32
60	0.04	60	0.16	120	0.51
90	0.04	90	0.16	1440	3.39
120	0.08	120	0.16	3600	5.21
150	0.08	150	0.21	3780	5.29
180	0.08	180	0.21	4320	5.39
240	0.08	240	0.21	5400	5.78
300	0.08	300	0.26	5520	5.84
360	0.08	360	0.31	5880	5.93
420	0.08	420	0.42	6480	5.96
480	0.08	480	0.47	6900	6.13

540	0.08	540	0.52	7920	6.39
600	0.08	600	0.63	8220	6.48
660	0.08	660	0.68	9180	6.58
780	0.08	780	0.78		
900	0.08	900	0.89		
1020	0.08	1020	0.99		
1140	0.08	1140	1.05		
1260	0.08	1260	1.1		
1380	0.08	1380	1.15		
1500	0.12	1500	1.15		
1560	0.12	1560	1.2		
1620	0.12	1620	1.2		
1680	0.12	1680	1.2		
1740	0.12	1740	1.25		
1800	0.12	1800	1.25		
2880	0.2	2880	1.41		
4320	0.39	4320	1.52		
5760	0.51	5760	1.57		
7200	0.55	7200	1.62		
8640	0.55	8640	1.62		
10080	0.59	10080	1.62		
11520	0.59	11520	1.62		
		23040	1.73		

Test Soil 2 + 8% GGBFS		Test Soil 2 + 6% Lime		Test Soil 2 + 0.5% Lime + 7% GGBFS	
time [min]	ϵ %	time [min]	ϵ %	time [min]	ϵ %
0.5	-0.02	0.5	0	0.08	0.04
1	0.02	1	0.01	0.17	0.04
2	0.02	2	0.02	0.5	0.08
4	0.02	4	0.04	1	0.12
8	0.02	8	0.06	3	0.2
15	0.03	15	0.09	8.33	0.28
30	0.06	30	0.11	16.67	0.39
60	0.13	60	0.16	30	0.51
120	0.24	240	0.18	60	0.79
240	0.29	960	0.18	90	0.94
1200	0.35	1440	0.19	120	1.06

1440	0.35	2880	0.24	150	1.18
2880	0.35	4320	0.33	180	1.22
4320	0.35	5760	0.47	240	1.26
5760	0.35	7200	0.53	300	1.3
7200	0.35	8640	0.64	360	1.3
8640	0.35	10080	0.77	420	1.3
10080	0.35	11520	0.87	480	1.3
		12960	0.98	540	1.3
		14400	1.08	2730.3	1.3
		15840	1.08	2880	1.3
		17280	1.15	4320	1.3
		18720	1.2	6044.52	1.3
		20160	1.31	7200	1.34
		21600	1.4	8640	1.34
		23040	1.52	10303.02	1.42
		24480	1.67		
		25920	1.8		
		27360	1.87		

Test Soil 2 + 1% Lime + 7% GGBFS		Test Soil 2 + 3% PC		Test Soil 2 + 1% PC + 7% GGBFS	
time[min]	ε %	time [min]	ε %	time [min]	ε %
0.5	0	0.02	0	0.02	0
1	0	0.02	0	0.03	0
2	0	0.08	0	0.05	0
4	0	0.17	0	0.07	0
8	0.01	0.5	0	0.07	0
15	0.02	1	0	0.08	0
30	0.03	3	0	0.17	0
60	0.04	8.33	0	0.5	0
120	0.07	16.67	0	1	0
1440	0.14	30	0.05	3	0
4320	0.16	60	0.11	8.33	0
5760	0.18	90	0.11	16.67	0
7200	0.2	120	0.11	30	0.04
8640	0.21	150	0.11	60	0.04
10080	0.23	180	0.11	90	0.04
11520	0.23	240	0.11	120	0.04

12960	0.23	300	0.11	150	0.08
14400	0.23	360	0.16	180	0.08
15840	0.23	420	0.16	240	0.08
17280	0.23	480	0.16	300	0.08
18720	0.23	540	0.16	360	0.08
20160	0.23	600	0.16	420	0.08
21600	0.23	660	0.16	480	0.08
23040	0.23	780	0.16	540	0.08
		900	0.16	600	0.08
		1020	0.16	660	0.08
		1140	0.16	780	0.12
		1260	0.16	900	0.08
		1380	0.16	1,020.00	0.12
		1500	0.16	1,140.00	0.08
		1560	0.16	1,260.00	0.08
		1620	0.16	1,380.00	0.12
		1680	0.16	1,500.00	0.12
		1740	0.16	1,560.00	0.12
		1800	0.16	1,620.00	0.12
		2880	0.16	1,680.00	0.08
		4320	0.26	1,740.00	0.08
		5760	0.37	1,800.00	0.08
		7200	0.48	2880	0.08
		8640	0.64	4320	0.08
		14181.55	1.11	5760	0.08
		14181.55	1.11	7200	0.16
		23040	1.8	8640	0.39
				10080	0.83

Test Soil 2 + 3% PC + 7% GGBFS

Test Soil 2 + 3% PC + 7% GGBFS			
time [min]	ε %	time [min]	ε %
0.02	0	300	0.11
0.03	0	360	0.11
0.08	0	420	0.11
0.17	0	480	0.11
0.5	0	540	0.11
1	0	600	0.11
3	0	660	0.11
8.33	0.05	780	0.11
16.67	0.05	900	0.11
30	0.05	1,020.00	0.11
60	0.05	1,140.00	0.11
90	0.05	1,260.00	0.11
120	0.05	1,380.00	0.11
150	0.05	1,500.00	0.11
180	0.05	1,560.00	0.11
240	0.11	1,620.00	0.11
		1,680.00	0.11
		1,740.00	0.11
		1,800.00	0.11
		2,880.00	0.26
		4,320.00	0.48
		5,760.00	0.74
		7,200.00	1.01
		8,640.00	1.27
		14,198.38	2.07
		14,198.38	2.07
		23,040.00	3.02

Appendix E. Grain Size Distribution

Test Soil 1			Test Soil 2		
Sieves	D(mm)	% passing	Sieves	D(mm)	% passing
4	4.75	100	4	4.75	100
10	2	100	10	2	100
40	0.425	100	40	0.425	100
200	0.075	54.52	200	0.075	54.52
	0.06	54.52		0.031	45.43
	0.043	52.7		0.02	43.61
	0.03	52.7		0.011	43.61
	0.022	50.88		0.008	41.8
	0.015	50.88		0.006	41.8
	0.011	49.06		0.003	41.8
	0.008	47.25		0.001	41.8
	0.006	45.43			
	0.004	43.61			
	0.003	41.8			
	0.001	36.34			

Appendix F. pH Results

Test Soil 1		Test Soil 2	
Type	pH	Type	PH
TS1	7.36	TS2	8.65
TS1 + 8% GGBFS	8.82	TS2 + 8% GGBFS	10.2
TS1 + 4% Lime	12.05	TS2 + 6% Lime	12.11
TS1 + 7% GGBFS + 0.5% Lime	11.99	TS2 + 7% GGBFS + 0.5% Lime	11.86
TS1 + 7% GGBFS + 1% Lime	12.01	TS2 + 7% GGBFS + 1% Lime	12.05
TS1 + 7% GGBFS + 1%PC	8.66	TS2 + 7% GGBFS + 1%PC	9.5
TS1 + 7%GGBFS + 3%PC	10.21	TS2 + 7%GGBFS + 3%PC	10.21
TS1 + 7%GGBFS + 1%SC	8.13	TS2 + 7%GGBFS + 1%SC	9.59
TS1 +7%GGBFS + 3%SC	9.9	TS2 +7%GGBFS + 3%SC	10.47
Lime	12.63	Lime	12.63
GGBFS	10.14	GGBFS	10.14
Portland Cement (PC)	11	Portland Cement (PC)	11
Sodium Carbonate (SC)	11.74	Sodium Carbonate (SC)	11.74

Appendix G. Bar Linear Shrinkage Results

Type	SL	Type	LS%
Test Soil 1	9.2	Test Soil 1	5.9
Test Soil 1 + GGBFS (8%)	1.3	Test Soil 1 + GGBFS (8%)	5
Test Soil 1 + Lime (0.5%) + GGBFS (7%)	2	Test Soil 1 + Lime (0.5%) + GGBFS (7%)	8.9
Test Soil 1 + Lime (1%) + GGBFS (7%)	2.2	Test Soil 1 + Lime (1%) + GGBFS (7%)	9.7
Test Soil 1 + PC (1%) + GGBFS (7%)	2.14	Test Soil 1 + PC (1%) + GGBFS (7%)	6
Test Soil 2	18	Test Soil 2	16
Test Soil 2 + GGBFS (8%)	6.4	Test Soil 2 + GGBFS (8%)	19.7
Test Soil 2 + Lime (0.5%) + GGBFS (7%)	5.2	Test Soil 2 + Lime (0.5%) + GGBFS (7%)	12.3
Test Soil 2 + Lime (1%) + GGBFS (7%)	5.7	Test Soil 2 + Lime (1%) + GGBFS (7%)	9
Test Soil 2 + PC (1%) + GGBFS (7%)	6	Test Soil 2 + PC (1%) + GGBFS (7%)	19.6