

**FREEZE-THAW RESISTANCE OF HIGH SULFATE-SALINE
SOIL STABILIZED WITH LIME, GROUND GRANULATED
BLAST FURNACE SLAG (GGBFS) AND BASIC OXYGEN
FURNACE SLAG (BOFS)**

**Submitted in fulfilment of the requirements for the degree of
Master of Science in Civil & Environmental Engineering**



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DECLARATION

I affirm that this manuscript titled "Freeze-Thaw Resistance of High-Sulfate Saline Soil Stabilized with Lime, Ground Granulated Blast Furnace Slag, and Basic Oxygen Slag" is the product of my own original work, with proper acknowledgments given for quotations and citations. Furthermore, little information of this manuscript was obtained from my conference paper titled "Stabilization of High-Sulfate Saline Soil Stabilized with Lime, Ground Granulated Blast Furnace Slag, and Basic Oxygen Slag," which I authored during my graduate studies. I also attest that this manuscript has not been previously submitted or concurrently submitted, either in full or in part, for any other degree or diploma at Nazarbayev University or any other domestic or international institution, to the best of my knowledge and perspectives.



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Abstract

Engineers face growing challenges in dealing with problematic soils, particularly those containing sulfates, for infrastructure and construction development. In cold regions, the problem is compounded by freeze-thaw cycling, which can cause durability issues. Calcium-based materials, such as ordinary Portland cement and lime, have been successful in enhancing soil properties. However, their use is often constrained by cost, excessive energy consumption, and their contribution to global carbon dioxide emissions. Furthermore, treatment of sulfate-bearing soils with calcium-based materials can lead to ettringite formation, resulting in volumetric instability and other durability issues. Thus, this study investigated the performance of various mixtures of stabilizers, including lime, ground granulated blast furnace slag (GGBFS), and basic oxygen furnace slag (BOFS), and their behavior under freeze-thaw cycles. A range of engineering, durability, and mineralogical tests were carried out in accordance with standard guidelines. The results showed that both binary and ternary mixtures exhibited similar behaviors regarding optimum moisture content (OMC) and maximum dry density (MDD). As OMC increased, there was a subsequent decrease in MDD, except for ternary mixture I, where MDD slightly increased. Ternary blend II (4% of 70% GGBFS and 30% BOFS) demonstrated the highest UCS before mellowing, and surprisingly, ternary mixture III of the same proportion had the highest UCS after mellowing. All stabilizer blends were effective in reducing the swelling behaviors of untreated soil, with 4% lime being the most effective. However, there was disparity in the DC test, with only 6% and 8% exhibiting better resistance to moisture susceptibility. From a durability standpoint, only 4% of the 70% GGBFS: 30% BOFS mixture before and after mellowing could withstand F-T cycles beyond 40 cycles (20 days) without collapsing, resisting F-T, mass loss, and swelling without collapsing. X-ray microscope analysis summarized that no significant ettringite mineral was detected in all soil samples except for low thaumasite minerals, which were observed in the “control” mellowed soil. Contrarily, the scanning electron micrograph showed the development of needle-like ettringite in almost all the ternary mixtures I and II while demonstrating massive openings and pores in the binary mixture. Therefore, ternary mixtures II and III (4% of 70% GGBFS and 30% BOFS) showed the overall best performance, which exemplifies that stabilizing sulfate-bearing soil with a higher content of slag offers the most promising performance.

Dedication

Overall, to GOD be the glory, for the great things HE has done!

Acknowledgment

As I take the time to reminisce and reflect on my journey, with the adversities experienced while pursuing education since my childhood showing no signs of slowing down and me now completing a master's degree outside the shores of my country, I am obliged to peacefully pen this piece with an immense sense of accomplishment, gratitude, and a glimmer of hope about what the future holds. This represents a significant moment in my life, one that, without a flicker of doubt, I could not have achieved without the grace of an unbiased God, the unwavering support of my loved ones, and the patience of my esteemed professors. Overall, God is marvelous, all-doing, and loving.

Standing at the facade of those civil engineering labs enclosed with gigantic and sophisticated machines and equipment staring back at me at a prestigious university like Nazarbayev University, I can say that I have discovered and exercised the power of resilience, the beauty of persistence, and tiny bits of grit in subduing these machines as the price of getting the coveted international education exposure. I am confident that this accomplishment will open new doors and present new opportunities for me to excel. The struggle with inclusive education was significantly more intense, but I refused to let these hindrances define me. Instead, I chose to persevere, to work tirelessly to overcome every obstacle, and to emerge victorious. Who would have thought that I would get to complete this thesis independently at some point? But for the inestimable trust bestowed upon me by Professor Kim and Professor Shon to undertake a giant stride in those laboratories to explore various waste materials with a view to making findings on sustainable ways to resolve global pressing and emerging civil infrastructure problems, I am blessed beyond measure.

Today, I stand here with my head held high, knowing that I have accomplished something that many thought was impossible. I am again grateful to Professor Shon for mentoring me with love, exercising a great deal of patience, overlooking my flaws, and believing in me even when I was almost defeated by impostor syndrome. To Professor Kim for providing me with the resources I needed to complete this research without giving up on me. I also appreciate my papa, my mama and my loved ones, for being my rock and my source of strength when I needed it the most.

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List of Acronyms, Elements and Abbreviations

AASHTO	American Association of State Highways and Transportation Officials
ASTM	American Standard Test Method
BOF (s)	Basic Oxygen Furnace Slag
C-A-H	Calcium-Aluminate-Hydrate
CaO	Calcium Oxide
CBMs	Calcium Based Materials
CBR	California Bearing Ratio
C-S-H	Calcium-Silicate-Hydrate
DC	Dielectric Constant
EDS	Energy Dispersive Spectroscopy
F-T	Freezing and Thawing AND/OR Freeze-Thaw
GGBFS	Ground Granulated Blast Furnace Slag
H ₂ O	Water
KOH	Potassium Hydroxide
LL	Liquid Limit
MDD	Maximum Dry Density
Mg(OH) ₂	Magnesium Hydroxide
MR	Resilient Modulus
NaOH	Sodium Hydroxide
OH	Hydroxide
OMC	Optimum Moisture Content
OPC	Ordinary Portland Cement
PI	Plasticity Index
PL	Plastic Limit
RDME	Relative Dynamic Modulus of Elasticity
SEM	Scanning Electronic Microscopy
UCS	Unconfined Compressive Strength
UPV	Ultrasonic Pulse Velocity
USCS	Unified Soil Classification System
XRD	X-Ray Diffraction
XRF	X-Ray Florescence

Chapter One - Introduction

1.1 Preamble

Every roadway or highway construction relies on quality soil for structural durability, and these constructions have been documented in the literature when sulfate saline soils were used oblivious of their unusual performance, in particular their lower bearing capacity and other critical areas [1, 2]. Saline soils are special soils with a high soluble salt content that exceeds a certain threshold [3, 4]. Soil salinization is common in arid and semiarid locations. Still, the soil processes are also expanding in humid climate zones, particularly in coastal areas where groundwater is contaminated by seawater that come through rivers and estuaries, creating soil salinization in huge areas [5]. Issanova et al. [5] continued that these soils are distributed unevenly and common in Kazakhstan's southern and central regions. Saline soils cover 111.6 million hectares in Kazakhstan, accounting for 41% of the country's soils [6]. These salty soils are split into “coarse-grained saline and fine-grained saline soils” [3].

1.2 Statement of Problem

As urbanization and population growth continue to increase, there is a surging demand for land to be used for housing, transportation, and other civil infrastructures. However, engineers are increasingly faced with the challenge of dealing with problematic soils such as sulfate-containing soils for construction, which can result in a variety of geotechnical conditions, such as bearing failure, excessive settlement, instability, erosion, and water infiltration. associated with construction.

This phenomenon is exemplified in several Asian regions, including Kazakhstan, where there is severe climate arises. For instance, Kazakhstan experiences scorching summers and bone-chilling winters, particularly in the northern regions. The long winter seasons also subject the region to severe freeze-thaw cycles, posing additional challenges. Moreover, the saline soil in Kazakhstan, enriched with sodium sulfate, exhibits properties akin to expansive clay, exhibiting swelling or contraction in response to moisture fluctuations through crystallization or dissolution. This soil presents a considerable hurdle for road and railroad engineers in cold climates due to its relatively high solubility and corrosivity [4, 7, 8]. Having sulfate-saline soil also exhibits undesirable characteristics that result in problems like “roadbed swelling and frost boiling” [7].

Furthermore, the sodium sulfate in saline soil is alarmingly high, leading to its expansion or shrinkage through "crystallization or dissolution with moisture change" [4, 9]. As a result of these characteristics, some pavements constructed on the saline surface have experienced different types of damage in the form of failures such as cracks, ravels, ruts, and landslides on newly constructed roads [2]. Hence, they are referred to as inferior construction materials with poor mechanical and geotechnical properties [10]. The behavior of these materials under freezing and thawing cycles is a very complex phenomenon [11].

In regions characterized by low temperatures or cold climates, the formation of ice lenses among particles during freezing and the abundant water content has a substantial effect on the mechanical properties of these soils [12]. Consequently, both the strength and bearing capacity of the foundation soil can be substantially diminished [13-15]. Therefore, it is essential for engineers to take into account the detrimental consequences of these phenomena when designing and building infrastructure in such areas. To address this pressing issue, some studies have suggested treating or stabilizing these sulfate soils with waste or sustainable materials to serve as a reliable base or subbase road materials, and pavement for average roads under freeze-thaw cycling [4]. However, there is still a dearth of literature on the freeze-thaw resistance of sulfate soils stabilized with waste materials. Thus, this merited additional research to evaluate the effectiveness of these stabilization techniques and their potential to alleviate the deleterious effects of high sulfate-saline soils induced by F-T cycles.

1.3 Rationale of the Study

Various stabilization materials to treat saline soils have been the subject of numerous research. However, the choice of Portland cement is the commonest method of stabilizing poor soils until there have been several calls for alternatives due to the harmful environmental effects associated with the use of cement. With respect to sulfate saline soil stabilization, lime has been previously investigated as a stabilizer [7], whereas other studies have delved further into the use of binders like fly ash for the purpose of solidifying these materials [16]. However, Kazakhstan is a country blessed with a plethora of natural resources, particularly by-products or final steel waste materials. Extensive research has investigated the application of steel slags in road infrastructure materials, and it has been established that these slag materials offer substantial benefits in terms of their environmental sustainability, mechanical strength, and economic viability [17-20].

In view of the dearth of references relating to the behaviors of sulfate-saline soil stabilized with lime-slag additives subjected to F-T cycles, this paper investigates the engineering and durability behaviors of saline soils treated with binders such as GGBFS, BOFS, and Lime.

1.4 Research Hypotheses

The hypotheses that would be tested for this are given below.

- Saline soils stabilized with lime, GGBFS, and BOFS experience improved strength.
- Saline soils stabilized with lime, GGBFS, and BOFS experience improved durability.
- The stabilization of saline soil with lime, GGBFS, and BOFS can resist freezing-thawing cycles.
- Mellowed soils can improve mechanical and durability properties of saline soil while providing resistance to freeze-thaw cycles.

1.5 Research Objectives

The purpose of the research is to explore the feasibility of chemical additives such as lime, GGBFS, and BOFs to stabilize saline soil and examine the long-term mechanical and durability performances of these stabilized materials. In accomplishing this purpose, the following specific objectives are essential:

1. Evaluate the strength performance of the sulfate saline soil stabilized with lime, GGBFS, and BOFS.
2. Evaluate the durability performance of the sulfate saline soil stabilized with lime, GGBFS, and BOFS.
3. Investigate the freezing-thawing resistance of high sulfate salinized soil stabilized with lime, GGBFS, and BOFS.
4. Investigate the feasibility of employing pre-compaction techniques “mellowing” as an alternative soil stabilization approach.
5. Justify the feasibility of stabilized sulfate saline soil as pavement construction material.

1.6 Thesis Structure

The present thesis is composed of five chapters, each of which provides a comprehensive examination of the utilization of sulfate-bearing soils in pavement construction, specifically focusing on stabilization methods and their application. **Chapter one** provides a comprehensive

summary of the contextual background on sulfate-bearing soils, presenting the current trends in these soils, outlining the justification for the research, and outlining the research's aims and contributions to the field. **Chapter two** undertakes an exhaustive review of the literature, collating, scrutinizing, and amalgamating all relevant data on soil stabilization, encompassing the mechanisms, sulfate-bearing soils, sulfate levels, stabilizing agents and techniques, and empirical evidence on the F-T cycle resistance of waste slag and other sustainable binders. **Chapter three** outlines the materials, mix design, test methods, and curing conditions utilized in the study, furnishing an intricate characterization of the sulfate-bearing saline soil, lime, and slag-based materials, alongside the extensive experimental program formulated for inquiry. **Chapter four** presents the findings of the experimental tests and examines the influences of selecting different binary and varying ternary mixtures on the sulfate-bearing saline soil, assessing their geotechnical properties and durability parameters. Finally, **Chapter five** synthesizes the discoveries and provides suggestions for future research in the domain.

Chapter Two – Literature Review

2.1 Introduction

The task conducted a desk study to collect rich data from a quality database and critically reviewed relevant articles on the research topic. Various materials from several sources would be studied to gain in-depth knowledge of the topic, including the previous experimentation programs, mix design, curing strategy as well as analysis techniques. This literature serves as a building block to obtaining information on the common approach used to investigate the stabilization of saline soil with slags and lime. Ultimately, the desk study focuses on the experimental and analytical strategies used to analyze the characteristics and behaviors of parameters and mixture proportions encompassing ground granulated blast furnace slag, basic oxygen slag, and lime.

2.2 Sulfate Bearing Soil

Sulfate-bearing soil, sulfate-induced soil, sulfate-contained soil, and sulfate-rich soil are all used interchangeably in the paper as they typically mean the same thing. In the literature, several sources of sulfate soils are recorded [21] and are widespread in Asia, particularly across China and Kazakhstan. Saline soil, like expansive clay, is characterized by a high content of sodium sulfate (Na_2SO_4). The volumetric behavior of this soil is susceptible to alterations in moisture levels, as it can undergo changes through the processes of crystallizing or dissolving the Na_2SO_4 [4]. These soils also exhibit sulfate in the forms of gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$), potassium sulfate (K_2SO_4), and magnesium sulfate (MgSO_4) [21, 22]. Sulfate reactivity is profoundly regulated by the soil's moisture-absorbing capacity and solubility conditions. Sulfate saline soil has a high concentration of soluble sulfates such as Na_2SO_4 and NaHSO_4 , which can be harmful to engineering projects. Na_2SO_4 is one of these substances that presents specific difficulties because its solubility changes significantly with temperature. Na_2SO_4 tends to crystallize and transform into the hydrated substance $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$ when the temperature drops. Due to the considerable increase in salt volume caused by this process, structures built on this soil may fail due to deformation [8]. Without further ado, these soils containing sulfates can present significant challenges in the construction of pavements, including cracking, collapse, and settlement of pavement layers. It is logical to anticipate that the behavior of individual saline soils to stabilization will differ due to variations in characteristics among different regions [23].

2.3 Sulfate Level

The degree of content of sulfate present in soils is termed as sulfate level. It is critical for improving high sulfate soils as they result in sulfate heave which has destructive effects on the pavement [24]. Berger et al. [25] itemize the severity and threshold of sulfate levels in the soil as presented in Table 2.1.

Risk Level	Sulphate Concentration	
	Parts per Million	Percentage of Dry Weight
Low risk	>3000 ppm	>3%
Moderate risk	3000–5000 ppm	3–5%
Moderate to high risk	5000–8000 ppm	5–8%
High to unacceptable risk	>8000 ppm	>8%
Unacceptable risk	>10,000 ppm	>10%

Table 2.1 Severity of Sulfate Levels in Soil (Berger et al. [25])

2.4 Soil Stabilization and its Mechanisms

2.4.1 General

Soil stabilization is generally used for enhancing the characteristics of the existing soil from a geotechnical perspective. Soil stabilization has become one of the useful solutions to treat weak soils to accomplish the required engineering properties such as strength, permeability, compressibility, and plasticity [26]. These are some of the specifications required for structures to be placed safely without undergoing large settlements. In that respect, stabilization is essential for improved durability of civil infrastructures to resist undesirable effects of F-T or wet-dry cycles, and even erosion [26].

2.4.2 Chemical Stabilization using traditional binders

Calcium-based materials, including cement and lime, have been greatly deployed as common stabilizing agents for soil containing sulfates [22, 27, 28]. These materials result in heave stimulated by sulfate through the development of ettringite and thaumasite minerals when reacted with accompanying free alumina and the concerned soluble sulfate soils, which then cause the soil to expand [21, 29, 30]. Thaumasite, as a known silicate mineral, often appears as acicular radiating groups of colorless to white prismatic hexagonal crystals [31]. Its structural formula is represented by $\text{Ca}_3\text{Si}(\text{OH})_6(\text{CO}_3)(\text{SO}_4)12\text{H}_2\text{O}$. Ehwaitat et al. [32] reported in their review that thaumasite has a greater tendency to cause swell than ettringite minerals.

While the subsequent sections present comprehensive synopses of cement and lime stabilizers derived from prior scholarly literature, particular emphasis is placed on lime stabilizer.

Cement Stabilizer

Cement is one of the oldest binding or admixing agents that have been commonly used for improving and stabilizing soils. Ordinary Portland Cement (OPC) is the most common one in this case, albeit there are various other types of cement. In general, Portland cement stabilizes soils more effectively and favorably than lime at the same stabilizing agent dosage [26]. However, as addressed previously, cement use is associated with many drawbacks and thus, limited the focus on lime as the preferred chemical additive.

Lime Stabilizer

The most popular forms of lime for soil stabilization are quicklime and hydrated lime, mainly because they can produce enough calcium ions to meet the needs of the soil [31, 33]. The production of lime culminates from burning limestone and is utilized in different forms when stabilizing different soils [26]. When lime is employed to stabilize soil, the soil's engineering properties record some improvements, which include enhanced strength, toughness, enhanced workability and resilience, volumetric stability, and resistance to deleterious moisture effects and perpetual deformation [31, 34]. Studies by Puppala et al. [35] highlight that lime stabilization is crucial in lowering soil swelling when sulfate levels are about 1000 ppm. However, it is noteworthy that when sulfate-bearing soils are treated with lime and exposed to moisture, the formation of ettringite minerals may occur, resulting in the accelerated soil swelling potential [29]. Ettringite, illustrated in Figure 2.1, is a weak sulfate material and when hydrated, significant heaving occurs. Consequently, this sulfate heaving can cause severe deterioration of various civil infrastructures, such as highways, and runways among other civil infrastructures erected on these calcium-based stabilized sulfate-bearing soils [29, 36].

Moreover, from a freezing-thawing cycle standpoint. When there is an increased curing period of lime-stabilized soil, it results in less volume change and a higher resilience modulus [11, 37]. The stabilizing technique, according to countless studies, involves adding lime to a system of clay-based soil that contains water, which triggers “hydration, cation exchange, and pozzolanic reactions” [38]. The lime quickly reacts with the soil's moisture to make hydrated lime ($\text{Ca}(\text{OH})_2$), which during the hydration process generates a significant quantity of heat. On these premises, the

lime employed with other binders to stabilize sulfate-contained soils needs to be handled with great caution.

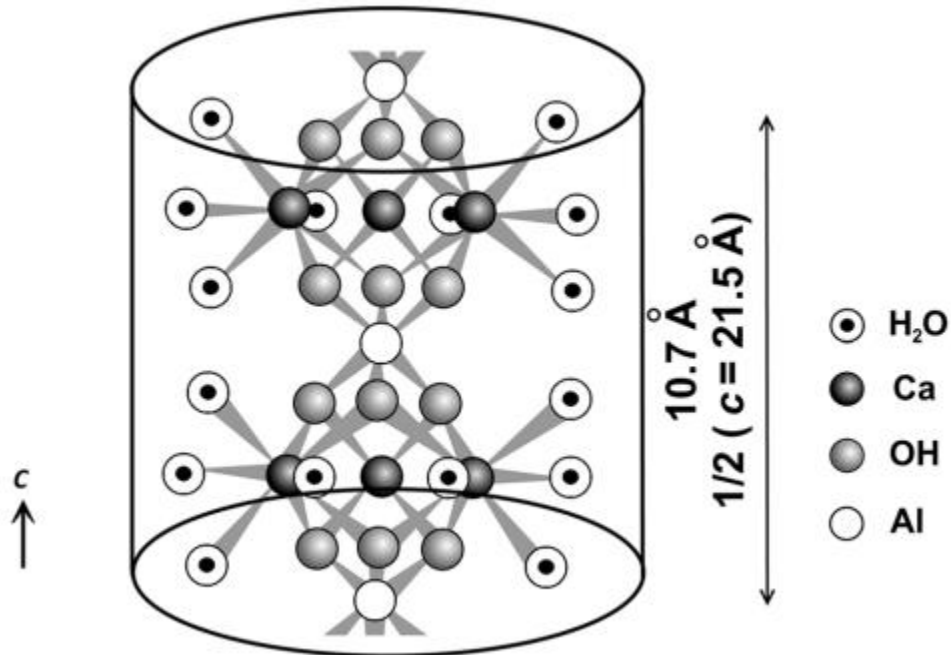


Figure 2.1 Schematic of the ettringite's mineral structure (Puppala et al. [24]).

2.4.3 Chemical Stabilization using non-traditional Binders

Sequel to numerous calls for sustainability as well as mitigation of sulfate heave concerns associated with the use of CBMs for treating sulfate-rich soils, non-traditional binders or supplementary cementitious materials has been subjected to wide exploration to replace these CBMs partially or wholly for treating sulfate-bearing soils. The rationale for incorporating and considering these materials as stabilizing agents is their pozzolanic ability and other measures of controlling landfill and other environmental challenges associated with the accumulation and hazardous exposure of these wastes. Thus, it is important to highlight that these by-product wastes are less expensive than traditional binders [39]. Various other supplementary cementitious materials also exist in the literature, however, for this study, slag wastes, such as ground granulated blast furnace slag and basic oxygen furnace slags will be extensively discussed.

Ground Granulated Blast Furnace Slag (GGBFS)

Ground granulated blast furnace slag (GGBFS) is a residue from the steel industry acquired through the rapid quenching of molten slag and thus, usually landfilled. The rapid cooling process yields GGBFS with heightened cementitious properties, albeit at the expense of reduced molten slag crystallization [40]. When GGBFS is used independently, exhibits limited strength-enriching properties due to its dormant hydraulic binding characteristics [26, 41]. Hence, an alkali is required to accelerate and complete the activation process and provide binding properties for soils. Many candidates explored in literature are CBMs, cement kiln dust, NaOH, KOH, and Mg(OH)₂.

As previously reported in the literature, GGBFS has been frequently activated with lime in soil stabilization applications, using either “quicklime or hydrated lime” [22, 42]. The resultant binder created by the activation of GGBFS with lime has been investigated for various applications, including the stabilization of sulfate soil. Additionally, lime has the benefit of hastening the hydration of GGBFS into calcium silicate hydrate (CSH) gel, significantly improving the strength and swelling characteristics of soils. Previous literature has documented the positive influence of the addition of activated GGBFS in soil stabilization on the engineering properties of soil, such as higher dynamic modulus, strength, and durability [33, 43, 44]. Other intriguing performance advantages brought about by the application of GGBFS include increased permeability, reduced ettringite formation for reducing swelling, and durability enhancement [34]. As a result, CBMs can be partially or entirely replaced with GGBFS.

Basic Oxygen Furnace Slag (BOFS)

Similar to the GGBFS, basic oxygen furnace slag (BOFS) is also a residue from the steel industry produced from iron production. These materials are usually widespread globally and it presents environmental challenges when improperly disposed of. Generally, one ton of pig iron yields approximately 300 kg of Blast Furnace Slag, and 1000 kg of raw steel yields around 130 kg of BOF slag [45]. Based on statistics from European Slag Association, the application of BOF and other secondary steel slags as road infrastructure materials in Europe has experienced an increased significant surge, soaring from “6.6 million tons in 2000 to 10.6 million tons in 2012” [19]. Additionally, global steel production increased to 1599.5 million tons in 2015, a remarkable surge of over 200 percent in 48 years, and further rose to 1666.2 million tons of crude steel produced a year later [20, 46].

Researchers are recently considering the use of these slags as materials in road constructions because they were found to be environmentally, and economically viable [17-20, 47]. Also, BOFS have considerable engineering properties such as higher specific gravity, high mechanical strength, high bulk density, high water absorption, and lower L.A. abrasion [45, 46]. In addition, these authors continued that BOFs have high angularity and particle shape and an excellent interlocking mechanism.

However, there are debates concerning the impracticality of using this slag as a standalone owing to its poor hydraulic activity as well as its expansive behavior triggered by the moisture-induced hydration of CaO and MgO and the oxidized metallic component [48]. Conversely, the authors reported that when mixed with other binders like GGBFS and other calcium-based compounds, the results were satisfactory. Like GGBFS, lime is usually added to the BOF slag to mitigate slag's deleterious components, including phosphorus, gaseous carbon monoxide, and silicon before use as stabilizing materials [17, 19].

Previous studies have also reported the feasibility of using lime to activate BOFS and its resulting impacts. Abdi [49] for instance, compared the engineering properties of BOF slag and lime and found that lime had better stabilizing effects even though they both enhanced the strength and durability of kaolinite soil. However, the combination of BOF slag and lime considerably enhanced strength growth and ability to withstand F-T cycling.

2.4.4 Mechanisms of Stabilization

According to Talluri et al. [21], the treatment of saline or expansive soils with lime initiates a cascade of reactions resulting in alterations in plasticity and strength. These reactions may encompass "cation exchange, flocculation/agglomeration, pozzolanic reactions, or carbonation" reactions [31]. The first two reactions are known as "modification reactions" because they improve workability, plasticity, and shear strength. Based on the soil clay mineralogy, water conditions, and level of effect, lime is needed to trigger cation exchange reactions. When stabilizers such as lime are mixed with soil, cation exchange consequently occurs, causing flocculation and agglomeration of soil particles as shown in Figure 2.2 [26]. This causes the soil to exhibit a rougher particle size distribution, increased permeability & hydraulic conductivity, and reduced plasticity. The lime-soil mixture is immediately subjected to this process, which lasts for only a short period. The remaining two reactions, on the other hand, are categorized as stabilizing reactions, which

result in a long-term increase in strength because of the creation of a substance called pozzolan [21].

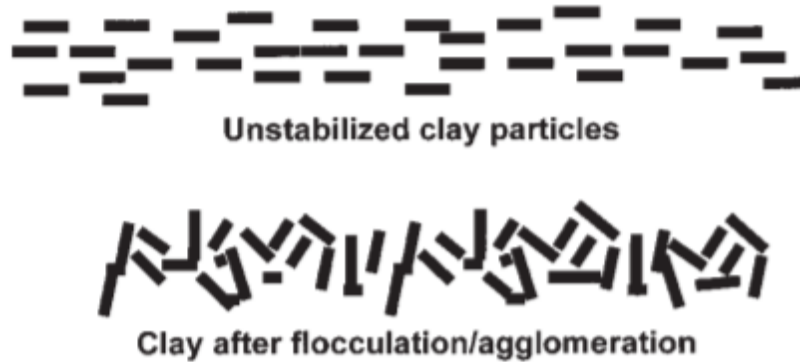
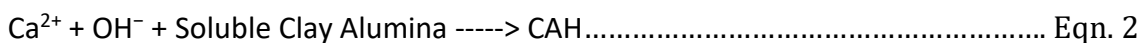


Figure 2.2 Soil Stabilization Mechanisms [26]

The authors continued that when sulfate-rich soils or expansive clays are subjected to lime treatment, their pH elevate to 12.4, causing clay alumina and silica to discharge and combine with calcium and H₂O to form pozzolanic compounds. Some cement-like compounds are produced when lime is added to a clay-water structure through pozzolanic processes involving lime, water, soil silica, and alumina [50]. Following the reaction of free Ca²⁺ from the lime with the silica and alumina that resulted from the breakdown of the clay particles, the results are formulations of calcium-silicate-hydrate (C-S-H) and calcium-aluminate-hydrate (C-A-H) [51, 52]. These reactions are summarized in equations 1 and 2, respectively. Similar to how cement gels are generated when cement is moistened, these cementitious gels bind soil particles and improve the material's strength and stiffness. While the pozzolanic reaction may linger for months or even years, the compressive strength, resilient modulus, shear strength, and stiffness of lime-treated soils continue to increase during the curing process [26, 52-54].



2.5 Other Methods of Sulfate Soil Stabilization

2.5.1 *Pre-compaction Mellowing*

Mellowing is another stabilization strategy that enables the development of undesirable minerals prior to compaction [21]. It enables the solubilization of the sulfate concentration in the soil thus that tolerable or no sulfate is present later for preventing ettringite or thaumasite [24]. The procedure entails adding the optimum amount of lime to the soil before compaction, enabling the lime to react with the soil and develop ettringite minerals. Several standards call for a suitable mellowing period to be between one and seven days [26]. However, when the sulfate level of the soil is high, it could be challenging to mellow them due to the inability of sulfate to completely dissolve during the process [24]. Various studies have attempted to delay compaction by conducting a mellowing process to understand their behaviors.

For instance, according to Talluri et al. [55], their experimental study investigates the feasibility of lime stabilization with pre-compaction mellowing with the aim to stabilize six different high-sulfate soils such as Dallas (12,000 ppm), US-82 (12,000), Riverside (20,000 ppm), FM-1417 (24,000), Austin (36,000 ppm) and Childress (44,000 ppm). The following mellowing periods, "0, 3, and 7 days" were carefully studied. The study could not successfully stabilize soil containing sulfate levels of above 30,000 ppm with the pre-compaction mellowing as these soils (Austin and Childress) led to higher volumetric swell strains upon treatment with lime. Four other soils with lesser sulfate levels resulted in lesser volumetric swell strains. Shon et al. [56] characterized mellowed soils with a view to mitigating volumetric expansion in high sulfate-bearing soil. In their study, they employed stabilizers such as hydrated lime and Class F fly ash to control the sulfate present in the sulfate through different interval mellowing processes prior to three-dimensional swelling and unconfined compressive strength. After the process of mellowing, a combination of lime and fly ash causes the soil mixture to expand less and retain more of its unconfined compressive strength. Berger et al. [25] also conducted a study to stabilize soils using a similar pre-compaction mellowing approach albeit with lower sulfate levels as compared to the previous studies. In all instances, the test soils' pH was found to be greater than 10, which suggests that both pozzolanic and sulfate reactions have taken place. The success of mellowing approach in preserving soil stability was ascribed to the episodes of expansion and diminished sulfates while mellowing, leaving no extra consumption following compaction. Thus, it exemplifies the essence of another stabilization techniques reported in previous scholarly literature [21].

2.6 Empirical Evidence

As previously recounted earlier, sulfate-contained has the natural tendency to swell or shrink especially when stabilized with calcium-based materials. Thus, various researchers have made some considerable progress in treating sulfate-rich soils with blends of supplementary cementitious materials. For instance, Celik and Nalbantoglu [29] attempted the treatment of sulfate-rich soils using GGBFS and lime to understand their efficacies on plasticity and swell potential. As a prerequisite, sulfate soil with a concentration of 2,000 ppm, 5,000 ppm, and 10,000 ppm was treated with lime. The outcome of the treatment of all concentration of sulfate-contained soils except 2000 ppm was disastrous as there were excessive swelling and plasticity in those soils. Thus, adding 6% GGBFS to the soil stabilized with lime significantly enhanced the plasticity and swell potential of the soils as there was a substantial reduction in the swelling potential from 8% to 1%. Conversely, due to the treatment of this sulfate soil with a lime binder, the plasticity index of such soil also reduced from 31% to 25%. The presence of some needle-like ettringite mineral formation, caused by the reaction between the calcium from the lime stabilizer and the reactive alumina and sulfate present in the soil, was discovered through a scanning electron microscope (SEM) test, which provided evidence of the abnormal swell increase from 10,000 ppm soil treated with lime.

Li et al. [22] highlighted the presence of other forms of sulfate, including sodium sulfate (Na_2SO_4) and magnesium sulfate (MgSO_4), in the soils and therefore, treated these soils with different proportions of reactive magnesia-activated GGBFS. The swelling of Ca-sulfate soil improved by increasing the ratio of GGBFS-MgO (i.e., 9:1 and 8:2) whereas the swelling of Mg-sulfate soil reduced with a decrease in the ratio of GGBFS-MgO (6:4). XRD and SEM micrographs confirmed that the swelling potential of Ca-sulfate treated soil with 6:4 ratio of GGBFS-MgO as there was the presence of ettringite, unlike other mixtures. Conversely, no ettringite was detected in the Mg-sulfate-treated soil with any ratio of GGBFS: MgO but in cement-treated soil. Stabilizing Ca-sulfate soil with GGBFS: MgO led to a higher UCS than in Mg-sulfate soil, which substantiated that the strong performance of soils significantly depends on the type of sulfate soil. This disparity in swelling and strength behavior was also observed in a study by Ebailila et al. [30] when they attempted to stabilize sulfate soil with blends of lime-GGBFS and lime-silica fume. The lime-GGBFS treated sulfate soil was more effective than lime-silica fume in terms of strength performance but reversely in terms of swelling performance. Despite several attempts to stabilize

sulfate soils, their behaviors when subjected to freeze-thaw actions have not received sufficient attention. Many studies either investigated the behaviors of untreated sulfate-bearing soil under freeze-thaw action [57, 58] or the mechanical behaviors of treated sulfate soils [11, 59, 60].

However, Zhou et al. [4] studied the behaviors of cement-treated saline soil subjected to 60 F-T cycles. The stabilized soil specimens cured at 7 and 28 days were placed in a freezing chamber configured at $25 \pm 2^\circ\text{C}$ for 12 hours and moved to a moist room at a constant temperature of $20 \pm 2^\circ\text{C}$ and an RH greater than 95 percent again to thaw for 11 hours. Based on the scope of failure patterns, salt crystallization, and salt and water migration for this study, the researcher reported and concluded that the presence of external water during the F-T test presented destructive effects on the stabilized saline soils thus led to the loss of strength with increasing freezing and thawing cycles. The stabilized soil specimens under F-T cycles get eroded and consequently turned powdery due to the slow accumulation of salt especially when the moisture content was reached. Thus, the study recommended an increment of stabilizing contents while curing for a longer time to provide better resistance to F-T cycles.

2.7 Summary

This chapter painstakingly reviewed the challenges associated with soils with poor engineering properties especially saline and other sulfate-contained soils. Also, it presented the review of sulfate-bearing soils and their concentration as well as their stabilization with calcium-based materials. Ultimately, over the past decades, these traditional stabilization materials like cement and lime have been widely used due to the significant mechanical properties associated with these sulfate soils even though there was a need to investigate the durability metrics. Moreover, various literature exists on the use of non-traditional stabilizers to contain the negative environment through partial or full replacement of calcium-based materials, the feasibility of stabilizing these soils in extreme weather otherwise known as freezing and thawing action needed urgent and thorough attention. Undoubtedly, there is potential for correct blends of waste materials with activators to foster the freezing-thawing resistance of sulfate-contained soils. Thus, this view is a motivation for future research to develop adequate blends of supplementary cementitious or alternative materials for sufficiently stabilizing these problematic soils.

Chapter Three – Experimental Program

3.1 Introduction

This section intends to determine the physical, chemical, and mineralogical properties of the raw materials to conduct various laboratory experiments. Figure 3.1 summarizes the experimental programs that guided the determination of the physical, chemical, and mineralogical properties of novel soil stabilizers.

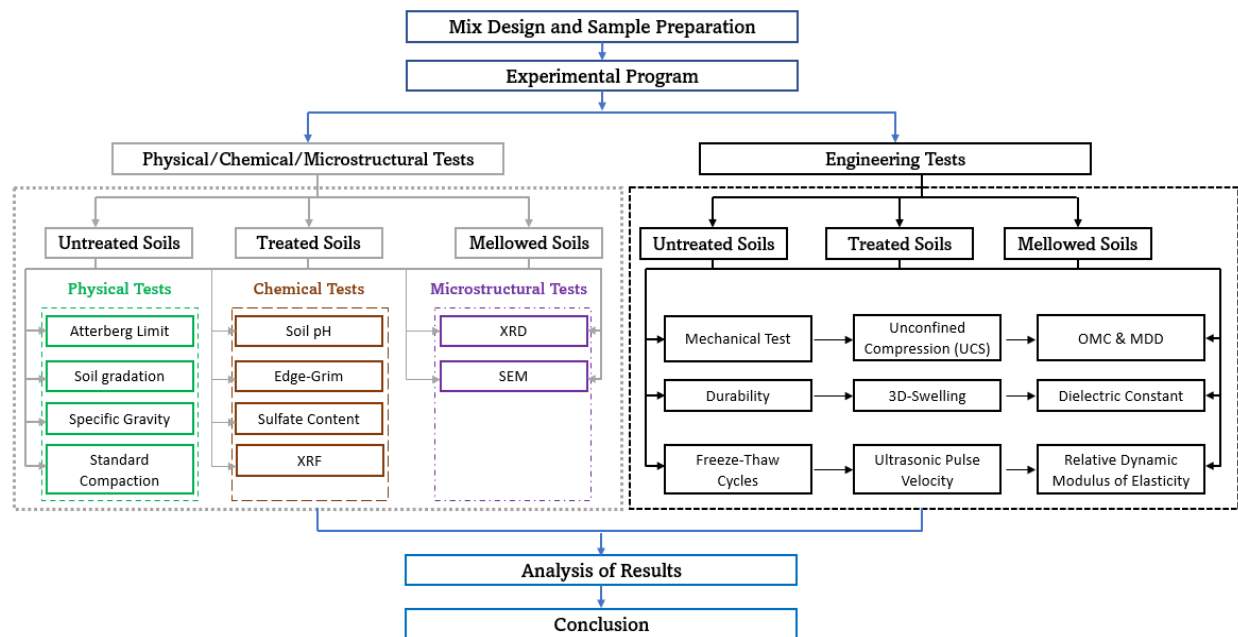


Figure 3.1 Experimental Program

3.2 Materials Properties

The materials to be used for the study are Saline soils, three binders (Lime, Ground Granulated Blast Furnace Slag, and Basic Oxygen Furnace Slag), and a solution (Water). These materials (see Figure 3.2) except water were obtained from the university laboratory and their characterization was performed to understand their properties.

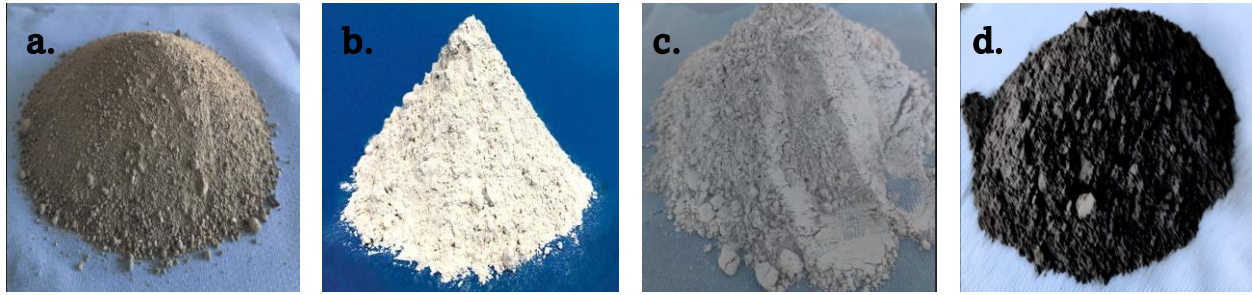


Figure 3.2 showing stabilizing materials, which include (a). Saline Soil (b) Lime (c) GGBFS (d) BOFS

3.3 Mix Design and Test Method

3.3.1 Soil Mixtures and Sample Preparation

To prepare specimens for various testing, the collected saline soils were first air-dried for 24 hours and placed inside the oven to oven dry for an extra 24 hours at 105°C. The soil sample was then sieved through a 2-mm sieve to get rid of larger particles. Following the preceding steps, the samples were mixed with a different proportion of binders (see Table 3.1). A different percentage of water was used during the proctor compaction of each of the mixtures to establish their respective optimum moisture content (OMC) and maximum dry density (MDD).

For tests such as 3D-Swelling, dielectric, Freeze-thaw, and UPV, the samples were prepared in cylindrical mold size 101.50 mm [4 in] x 116.50 mm [4.6 in] (diameter x height), where each mixture system was compacted with an optimum moisture content (OMC). In contrast, the mold size used for the unconfined compressive strength test was 50 mm x 100 mm (diameter x height) with each mixture also compacted with an OMC before being covered with cling film to prevent moisture loss.

Mixing Proportion

The mix proportion, curing conditions, as well as freeze-thaw conditions tabulated below, are obtained after a careful Eades-Grim experiment guiding the lime content before subsequent experimental testing.

Table 3.1 Mix design.

Mixture Number	Mixtures	Mixture Parameter
1	Soil	Control

2	Soil + 4% lime	Binary mixture
3	Soil + 6% lime	
4	Soil + 8% lime	
5	Soil + 4% lime + 2% [50%GGBFS:50% BOFS]	Ternary mixture I
6	Soil + 4% lime + 4% [50%GGBFS:50% BOFS]	
7	Soil + 4% lime + 2% [70%GGBFS:30% BOFS]	Ternary mixture II
8	Soil + 4% lime + 4% [70%GGBFS:30% BOFS]	
9	Soil + 4% lime + 2% [70%GGBFS:30% BOFS]	Ternary mixture III
10	Soil + 4% lime + 4% [70%GGBFS:30% BOFS]	

Note:

¹ Ground Granulated Blast Furnace Slag (GGBFS); Basic Oxygen Furnace Slag (BOFS)

² Mixtures 9 and 10: Soils mellowed with 4% lime for up to 30 days

Curing Conditions

Table 3.2 summarizes the test level, otherwise, and curing conditions employed in this study. Other factors such as conditions and number of specimens were also provided in the table.

Table 3.2 Testing and Curing Conditions

Properties	Test Name	Test level	Total # of specimen	Test condition
Soil characterization	Gradation (Sieve analysis)	-	3	-
	Atterberg limit (Cone penetration)	-	3	-
	Specific gravity	-	3	-
	Sulfate content	-	3	-
	Edge-Grim Test	-	3	-
	XRD analysis	-	3	-
	MDD-MC relationship	-	3	-
Mechanical Property Durability	Unconfined compressive strength	3, 14, 28	4x3=12	In-air curing w/ plastic sheet
	3D-swelling test	Up to 28-day	2	Tube suction
	¹ Freeze-Thaw test after 3D-swelling test	60 cycles		In-air
	² Dielectric constant	60 cycles		
	³ Freeze-Thaw test	60 cycles	4	In-air Bottom-saturation

¹ Use 3D-swelling test specimens² Use F-T test specimens; After test is over, XRD analysis is required.³ Use new F-T test specimens

3.3.2 Physical Property Tests

The physical tests for the purpose of characterizing soils include soil gradation, Atterberg limit, specific gravity, standard proctor compaction, sulfate content determination, and soil pH. Conversely, to determine the mineralogical composition of a soil sample, X-Ray Diffraction was employed.

Atterberg limit Test

The Atterberg limit test was investigated to ascertain the plastic limit W_p , Liquid Limit W_L , and the Plasticity Index I_p of the sulfate saline soil in the laboratory. Although the liquid limit was performed using the cone penetration method and the cone penetrometer device is as shown in Figure 3.3. On the other hand, a plastic limit test was performed according to ASTM D4318-17 [61], which involved rolling samples on a glass plate until they crumble. The plasticity index of the soil samples was determined using Equation 3.



Figure 3.3 Setup of cone penetrometer for liquid limit determination

$$I_p = LL - PL \dots\dots\dots \text{Eqn. 3}$$

Where:

I_p is the plasticity index of the soil sample.

LL is the liquid limit of the soil sample.

PL is the plastic limit of the soil sample.

Soil Gradation Test

The soil gradation test was carried out in the laboratory to evaluate the particle sizes of soil samples. The apparatuses that were used to determine the grain size distribution are shown in Figure 3.4.



Figure 3.4 Setup of Soil Gradation (Particle Size Distribution)

Specific Gravity Test

The specific gravity of soil solids (G_s) can be obtained by determining the ratio of the mass of a given volume of soil solids to the mass of an equal volume of distilled water. This experiment was performed in the laboratory by measuring all the materials for the purpose of performing the foregoing computation. The particle density was determined using the pycnometer method as shown in Figure 3.5, in accordance with ASTM D854 [62]. Three trials of the pycnometer were adopted then the average of the findings was computed using equation 4 given below.

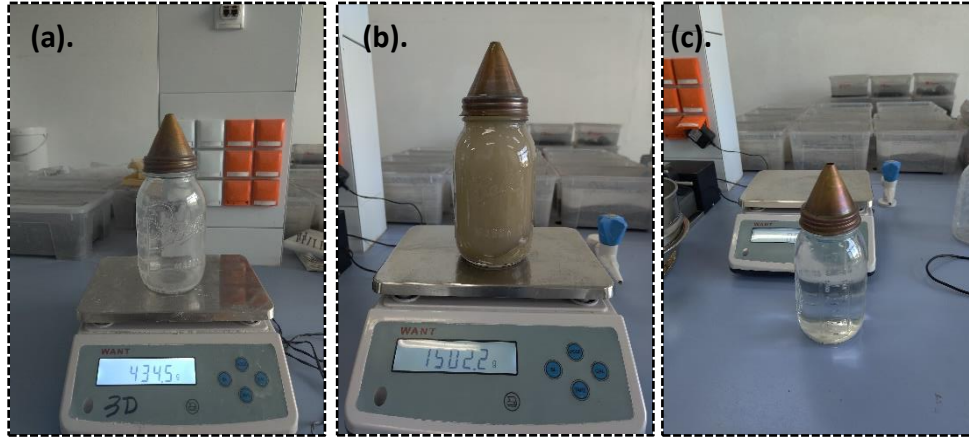


Figure 3.5 Setup for Specific Gravity using pycnometer (a). dry (b.) solution (c). water

$$\rho_s = \frac{m_4}{(m_1+m_0)-(m_3+m_2)} \times \rho_L \dots\dots\dots \text{Eqn. 4}$$

where:

ρ_s is the particle density Mg/m^3 .

ρ_L is the particle density of distilled water at the test temperature Mg/m^3 .

m_0 is the mass of dry pycnometer, in g.

m_1 is the mass of the pycnometer filled with the distilled water, in g.

m_2 is the mass of the pycnometer with the saline soil sample, in g.

m_3 is the mass of the pycnometer with the soil and distilled water, in g.

m_4 is the mass of the soil sample, in g.

Eades-Grim Test

The test involves determining the lime quantity needed to induce enduring strength modifications, usually through monitoring the pH variations of a soil suspension upon the addition of different lime percentages. Figure 3.6 shows the various soil solutions and apparatus used to conduct the experiment as per Tex-121-E [63].



Figure 3.6 Setup of Eades-Grim Test for determining the standard lime content.

Standard Proctor Compaction

Standard Proctor Compaction test is a test that helps to evaluate the moisture content and dry density of samples to primarily obtain a variety of curves (polynomial trendlines) that highlights the curves' peak points which are equivalent to optimum moisture content (OMC) and maximum dry density (MDD). This test (see Figure 3.7) was carried out in accordance with ASTM D698 [64]. Preliminarily, it was crucial to determine compaction parameters to establish the moisture contents and dry densities of different soil mixtures for accomplishing the compaction curves.

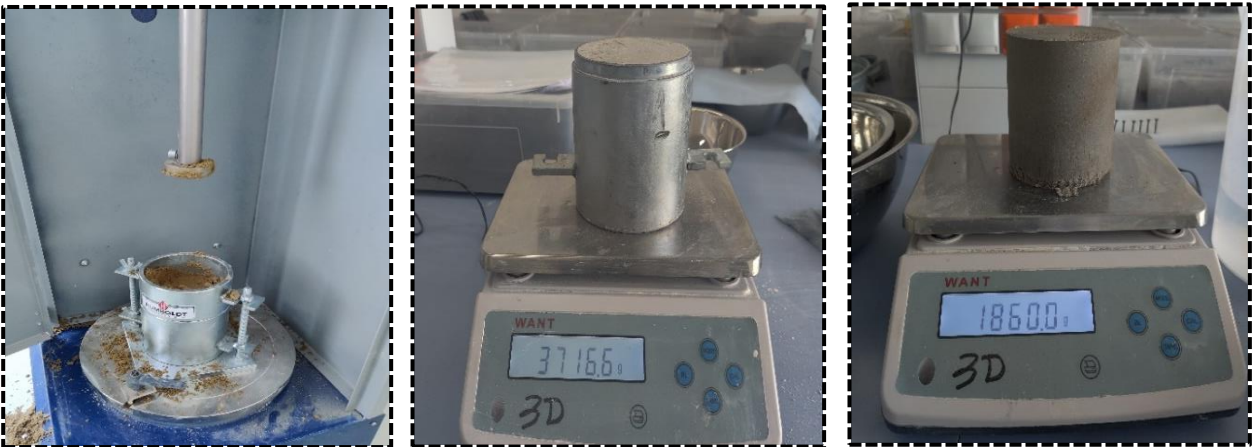


Figure 3.7 Set up of Proctor Compaction Test for the determination of OMC and MDD relationship.

Soil pH

pH test is another physical property technique used to determine the alkalinity and acidity of soil samples. The results of the above tests were obtained and illustrated in the next chapter and were carried out according to Tex-128-E [65].

Sulfate Content Test

This is a test for determining the soluble salt concentration in the soil. This test was determined using the colorimetric method following Tex-145-E [66]. Figure 3.8 illustrates the procedure involved in conducting sulfate content determination using colorimetric apparatus.



Figure 3.8 Set up of Colorimetric test for determination of soluble sulfate concentration.

3.3.3 Mechanical Property Tests

Unconfined compressive strength (UCS) tests

Unconfined Compressive Strength was performed on saline soil (control group) and other mixtures in unconfined conditions with its setup illustrated in Table 3.2. The test as shown Figure 3.9 was performed according to ASTM D2166 [67] to determine the maximum strength ($q_{u\max}$) with its strain failure for both untreated saline soil and stabilized soils. Also, the UCS test was performed for these soils with different types of binders, and different percentages at varying curing durations (3, 14, and 28 days). Prior to the UCS test, the soils were compacted with OMC in different layers and extruded afterward. After that, cling film was put sufficiently around the soil specimens to prevent the escape of moisture. A continuous 1 mm/min loading rate was adopted to compress cylindrical test specimens with dimensions of 50 mm in diameter and 100 mm in height. Each mixture was tested four (4) times to provide more precise data, and the average UCS value was computed and analyzed.

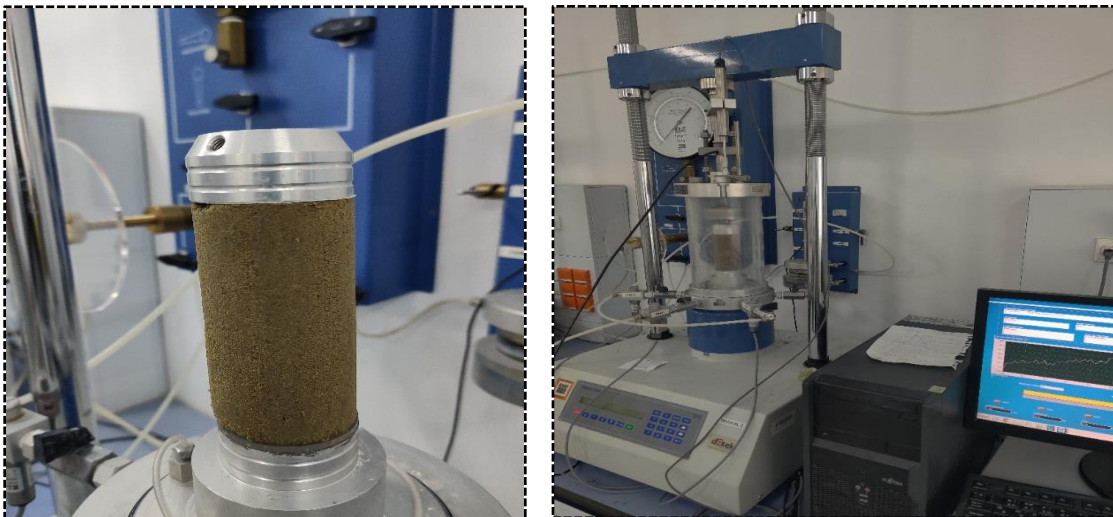


Figure 3.9 Set up of Unconfined Compressive Strength

3.3.4 Durability Property Tests

Soil Mellowing

At OMC, saline soil with a sulfate level of 12,000 ppm was mixed with 6 percent lime to start the mellowing process. This process was given 60 days to complete. Figure 3.10 shows the soil mellowing process when it was mixed with lime at different intervals (1,2 and 4 days). Bowls containing soil-lime combinations were covered with plastic sheets to stop moisture from evaporating. The mixture was reworked with extra water to preserve OMC because water is necessary for chemical interactions between calcium ions from lime and sulfates in soil. After being mellowed, the samples were carefully homogenized and compacted. The samples of compacted soil were subjected to engineering testing [24]. Table 3.1 shows the soil mellowing program critical for the development of other stabilizing mixtures for investigating their mechanical and durability properties.

Table 3.3 Testing variables for soil mellowing program

Description	Variable
Saline Soil	Three (Only soil, ternary II mixtures)
Stabilizer	Lime
Dosage	One (6%)
Compaction moisture contents	One (OMC)



Figure 3.10 Soil Mellowing Process.

Three-Dimensional Test

The three-dimensional test was performed on saline soil (control) and other soil mixtures (binary, ternaries) as given in Table 3.1. This 3D test was critical for understanding the swelling and shrinkage behaviors of various soil mixtures. This test was performed in accordance with the directives of the Texas A&M Transportation Institute. Prior to the test, two sets of soil specimens were prepared by compacting in three layers with the OMC for each soil mixture then extruded using an automatic extruder after weighing using a weighing scale. Following the specimens demolding, the two specimens for each soil mixture were weighed and measured (diameter, D , & height, H). These specimens were air-cured for three days after being wrapped in cling film to prevent moisture loss and then subsequently oven-dried at 60°C for 1-day after the cling films were removed.

Before oven drying, the dielectric constant test was performed on each soil specimen, and after oven drying, all specimens were carefully enclosed with moist paper in a rotational manner and finally enclosed with a synthetic rubber skin or membrane. On the top and bottom of the soil specimens that have been covered are pieces of filter paper and porous stone. These appropriately dressed soil samples' initial height and diameter were measured and documented before being carefully immersed into the water container for capillary action to observe the swelling characteristics of the mixtures. Adequate moisture is necessary for the sulfate soils to undergo the required reactions that facilitate the formation of ettringite crystals and their subsequent hydration [21, 55]. Therefore, during and after the 3D-swelling process, the assembled and soaked soil samples' height was measured using a digital caliper at three points at regular intervals. Similarly, the radial diameter of the soil sample was determined at the marked top, middle, and bottom and explicitly, the procedure is shown in Figure 3.11. The samples' volume was then determined based on the average height and diameter values. The expansion of the soil sample was then obtained by determining the rate of change of its volume to the original volume. By calculating the average values for height and diameter, the volume of the soil sample was determined, which explains the observed changes during the 28-day 3-D swelling test. This test is essential to verify the maximum point at which soil heaving can take place. After the 3D-swelling process and oven drying of all 3D samples, the dielectric constant was performed again.

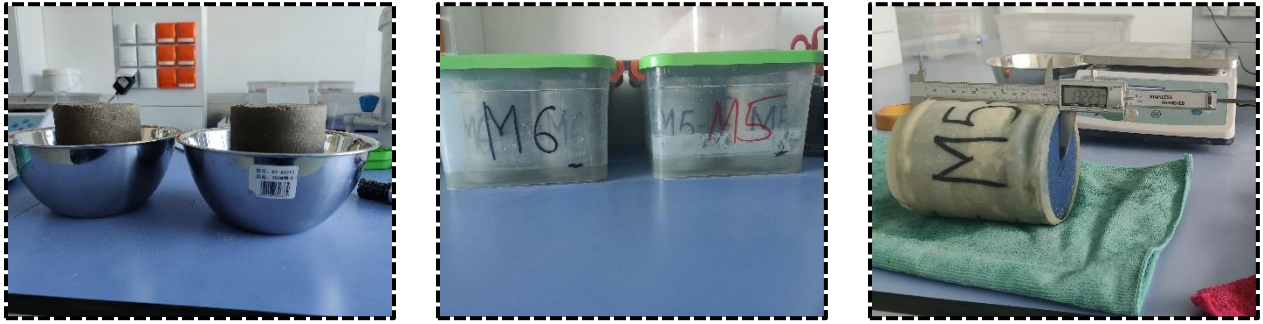


Figure 3.11 Setup for Three-Dimensional procedure for swell-shrink determination

Dielectric Test

Material can be categorized as "good," "marginal," or "bad" depending on how susceptible it is to moisture based on its dielectric constant. The "tube suction test" procedure specified in Tex-144-E [68] standard was employed to calculate the dielectric constant value. The test entailed placing a specimen having a 4in (101.1 mm) diameter and 4.5in (116.80 mm) high on an arranged filter paper and a porous stone at the bottom and enclosed with yellow rubber skin. Each filter paper, plastic sheet, and porous stone were placed on top of the specimen before being placed under continuous capillary suction conditions inside a container. Figure 3.12 shows the percometer measurements of the dielectric constant values for each specimen.



Figure 3.12 Setup of Dielectric Constant Test for moisture susceptibility determination.

Freeze-Thaw Test

According to the ASTM D560-16 [69], this test would be conducted in a freezing-thawing controlled chamber with a standard temperature of between -25°C and 20°C as well as under 60

cycles. This standard is used to assess the susceptibility of hardened compacted soil specimens to frequent freezing and thawing. The resistance criteria are based on the volume changes and soil-additive losses caused by frequent freezing and thawing [37]. All soil specimens obtained from the 3-D swelling action (as shown in Figure 3.13) were carefully placed into the F-T chamber to undergo F-T cycles (10, 20, 30, 40, 50, and 60). An open system that was used throughout the test while the specimens' containers were filled with water to the bottom porous stone level for capillary action for only the 5 cycles. The duration of one cycle of freezing and thawing was 12 hours.



Figure 3.13 Setup of Freezing-Thawing Test for 60 cycles action.

Ultrasonic Pulse Velocity

The Ultrasonic Pulse Velocity (UPV) technique is a non-destructive testing technique for determining the stress waves' compression velocities in solid materials. These velocities are driven by the density and elastic properties of the materials [50]. The UPV test was conducted using a PUNDIT device as shown in Figure 3.14 and was performed following standard ASTM C597 [70]. Before using this PUNDIT device, it was calibrated by attaching two transducers to the cylindrical block and the double readings were similar (25.4 μ s).



Figure 3.14 Setup for Ultrasonic Pulse Velocity (UPV) Test.

The UPV value was then determined by measuring the time required for the stress wave to travel the full length of the soil specimen after the two transducers had been attached to both ends of each specimen. Meanwhile, the resilient modulus (E_R) measures a soil's capacity to withstand deformation [71] and they are computed using UPV data.

3.3.5 Mineralogical and Microstructural Tests

X-Ray Diffraction (XRD)

X-ray diffraction (XRD) was instrumental in identifying the mineralogical components of all soil samples, which was completed using a RIGAKU Smart Lab X-Ray diffractometer as shown in Figure 3.15. The fine or powdered samples passing #325 (45 μm) sieve were run and determined through a scan axis of 2theta ranging from 5 to 70 with a step of 0.01 and integrated at the duration time of 3.0 counts per second speed. The findings from the experiment was analyzed using MDI Jade 6 software and the computational analysis of the generated values were completed using Origin Pro 2022.



Figure 3.15 Setup for X-Ray Diffraction Test

Scanning Electron Microscope (SEM)

Scanning electron microscopy (SEM) was utilised to analyse and describe the surface morphology of both untreated and treated soil samples. This experiment was completed using Scanning Electron Microscope Jeol JSM-IT200(LA) as shown in Figure 3.16 and stabilizers used for this experiments are the one with volumetric expansion behaviours and the images obtained will be analyzed for identify the elements that may be responsible for such behaviors.



Figure 3.16 Scanning Electron Microscope

Energy Dispersive Spectroscopy

Energy Dispersive Spectroscopy (EDS) was used to assess the chemical nature of the elemental composition of various soil samples. The experiment was performed in conjunction with SEM as shown in the immediate above figure (3.16) to identify different elements to verify findings from SEM.

Chapter Four – Results and Analysis

4.1 Introduction

The results on the strength and quality of the stabilized saline soil are holistically presented and analyzed.

4.2 Soil Characterization

The characterization of soils for this study are grouped into physical, chemical, and mineralogical properties. The findings of both properties are presented in the subsequent subheadings to understand the properties of both untreated soil and treated soil, where applicable.

Table 4.1 Physical Properties of High-Sulfate Saline Soil

Property	Value
Liquid limit (LL)	37.2
Plastic limit (LP)	17
Plasticity Index (PI)	20.2
Specific gravity	2.48
pH	9.08
<i>Grain Size distribution</i>	
Gravel (> 4.75)	0.14
Sand (0.075- 4.75)	96.89
Silt and Clay (<0.075)	2.97
USCS Soil Classification	CL
Maximum Dry Density (MDD) (kg/m ³)	1916
Optimum Moisture Content (OMC) (%)	10.6

4.2.1 Soil Gradation Test

The soil gradation findings for this study indicate that the soil used had a particle size distribution as shown in Figure 4.1, revealing gravel, silt and clay, and sand contents of 0.14%, 96.89%, and 2.97%, respectively.

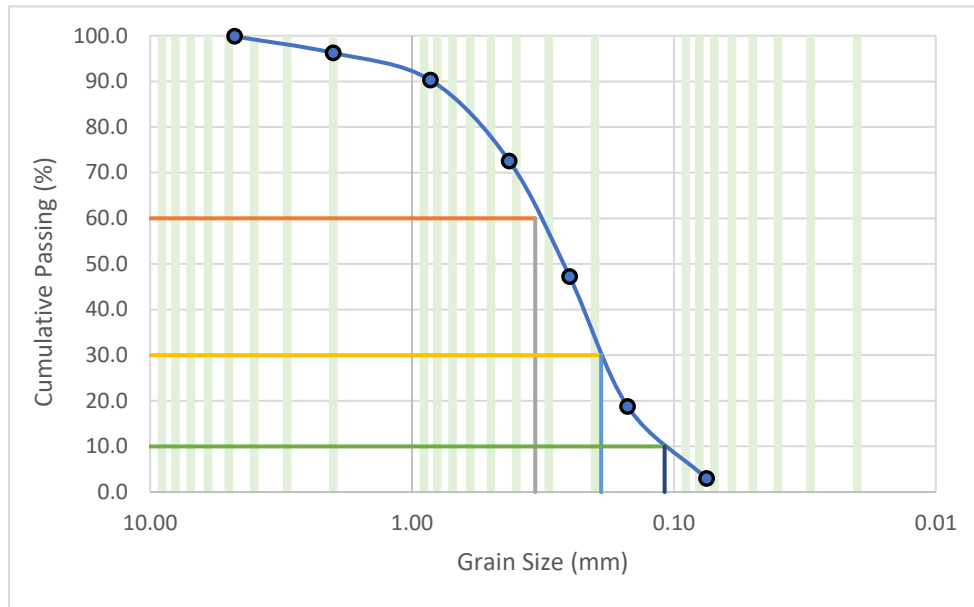


Figure 4.1 Particle Size Distribution

4.2.2 Atterberg Limits Test

Table 4.1 presents the outcomes of the Atterberg limits test encompassing the liquid limit, plastic limit, and plasticity index. The liquid limit (LL) was determined by conducting three trials of the cone penetration test, guided by the Tex-105-E [72], and the liquid limit was determined to be 37.2% through the corresponding moisture content value for 20mm penetration. The plastic limit was found to be 17.2%, resulting in a plasticity index of 20%. These parameters, namely LL, PL, and PI, are recognized as valuable indicators of moisture affinity changes in soil engineering properties and offer useful estimates of soil swell potential, as previously noted by Chen [73].

4.2.3 Edge-Grim Test

Figure 4.2 presents the soil pH of saline soil treated with lime, which accelerates the pH to 12.4 causing calcium to release, clay alumina and silica to dissolve, and pozzolanic compounds to develop as a result.

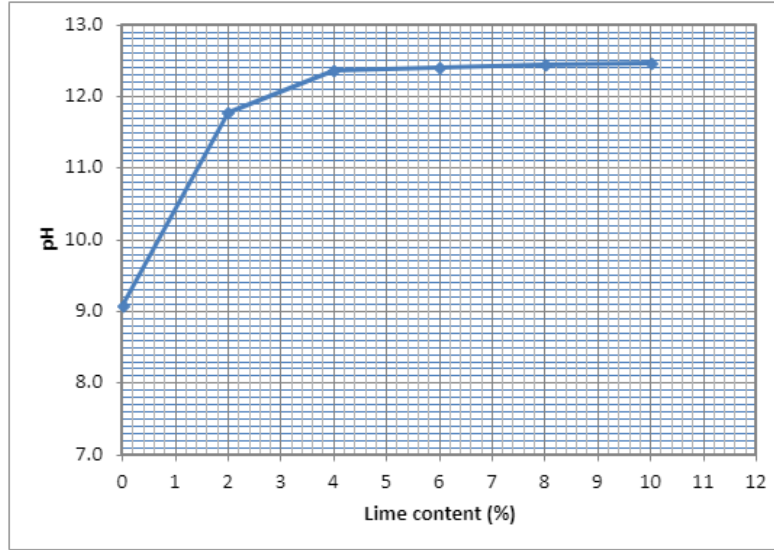


Figure 4.2 Eades-Grim Test Result for Saline Soil and Lime

4.2.4 Sulfate Content Test

Based on the directives provided in Tex-145-E [66] to evaluate the sulfate concentration of soil mixtures, the values (in parts per million) are summarized as shown in Table 4.2. The tests were performed aftermath unconfined compressive strength at fixed durations for all soil mixtures, mellowing inclusive. Figure 4.3a and Figure 4.3b represent the trends of sulfate level in soil for all soil mixtures prior to mellowing and after mellowing. In the case of soil mixtures, as shown in Figure 4.3a, all soil samples had very high sulfate levels at three days before decreasing in 14 days, albeit temporarily. This is due to the noticeable increment in the sulfate levels of soil mixtures except soil stabilized with 4 percent of lime and 2% (50%G:50%B).

Following the pre-compaction mellowing procedure (other methods of stabilization), the concentration of soluble sulfates declined, as was expected. During the first three days, they had the lowest sulfate level compared to the regular soil combinations (un-mellowed soil mixtures). The reduction in sulfate of the mellowed soils is highly apparent when compared to the control soil before and after mellowing, which supports the essence of soil mellowing, to lower sulfate levels in soils. Other soil blending mixes showed a similar phenomenon. These can be explained by the optimum amounts of lime and water addition, which increases the concentration of free calcium in the system, critical for the formation of ettringite crystals. This phenomenon of sulfate level reduction could be due to the calcium's availability.

Table 4.2 Summary of Soluble Sulfate Concentrations of Soil Mixtures (in ppm)

Soil Mixture	3-d	14-d	28-d
	Soluble Sulfate content (ppm)		
Saline Soil	17040	14000	14720
4% Lime	15840	10240	11840
6% Lime	13600	9440	11120
8% Lime	13040	9920	10000
Soil + 4%L + 2% (50%G:50%B)	14240	10480	9360
Soil + 4%L + 4% (50%G:50%B)	12800	7920	9440
Soil + 4%L + 2% (70%G:30%B)	12560	9840	11520
Soil + 4%L + 4% (70%G:30%B)	11680	7280	7480
MS + 4%L + 2% (70%G:30%B)	9120	8640	10880
MS + 4%L + 4% (70%G:30%B)	8080	7840	10160
Mellowed Soil (MS) (C)	9920	11600	10400

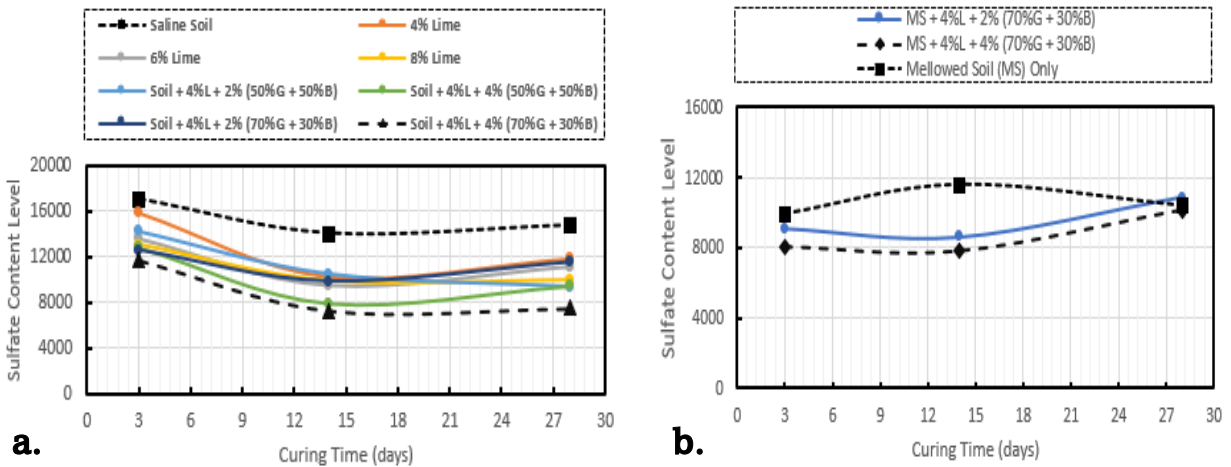


Figure 4.3 Sulfate Content with respect to their curing period (a) stabilized soil mixtures (b) mellowed soil mixtures.

4.2.5 Standard Compaction Test

Following the examination of the behaviors of different stabilizers on the compaction characteristics of saline soil, Figure 4.4 depicts the relationship between optimum moisture content (w_{opt}) and maximum dry density ($\gamma_{d,max}$) for different mixtures under the same compaction effort. This test was performed to satisfy one of the conditions for performing soil stabilization: ensuring that water content is controlled to facilitate maximum dry density [74]. The untreated soil showed a maximum dry density (1916 kg/m^3) and an optimum moisture content (10.6%). The addition of lime in binary mixtures (4%, 6%, and 8%) affected the compaction characteristics, resulting in a slight decrease in the MDD (1867 kg/m^3 , 1862 kg/m^3 , and 1844 kg/m^3 , respectively) and subsequent highest OMC (12%, 11.7%, and 12%). This accompanies an orderly and slightly declining maximum dry density. Afterward, the introduction of different proportions of GGBFS and BOFS to the fixed 4% lime (in ternary mixtures I) showed an increase in MDD (1889 kg/m^3 , 1890 kg/m^3) and a relative decrease in moisture content (10.5%, 11.2%) as compared to the binary mixtures. However, increasing the proportion of GGBFS over BOFS to the fixed 4% lime in ternary mixtures II resulted in a slightly lower MDD (1879 kg/m^3 , 1875 kg/m^3) and a higher OMC (11.4%, 11.5%) compared to the ternary mixture I.

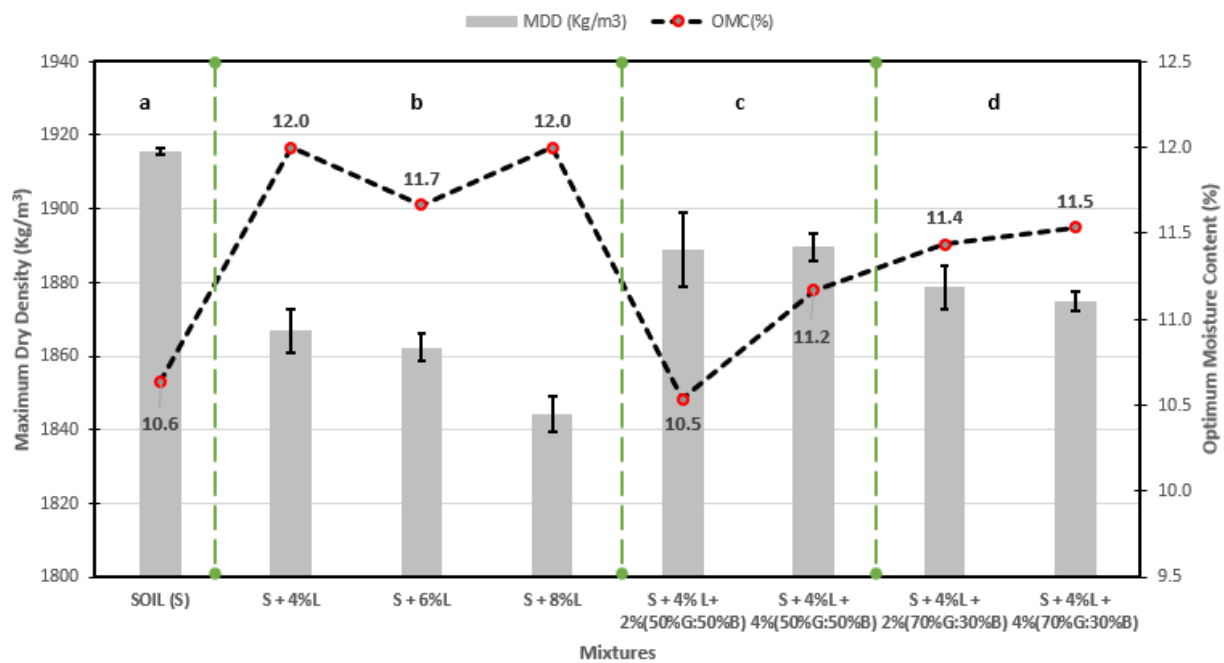


Figure 4.4 MDD and OMC determination of the control and the stabilized soils.

Generally, as compared to plain saline soil, the increasing content of stabilizers reduces the MDD and conversely increases the OMC, except in the ternary mixture I. The decline in MDD of all stabilized mixtures is attributed to the resistance to compaction triggered by “flocculated and agglomerated soil particles” established in cation exchange activity from stabilizers and the surrounding soil surface [33, 75]. Conversely, the increase in OMC could be a result of the exothermic reaction between soil and additives, which requires some water for hydration [76], and the increased void ratio caused by flocculated particles taking up more space in the soil matrix. Therefore, the results of this study are in line with the results found in previous studies on sulfate-contained soils [77-79].

4.3 Mechanical Property

4.3.1 Unconfined Compressive Strength

Figure 4.5 shows the effect of various stabilizer content on the compressive strength of stabilized saline soils. Comparing stabilized mixtures to saline soil (control), the unconfined compressive strength of all mixtures is substantially higher, thus corroborating the rationale for conducting soil stabilization. The unconfined compressive strength (UCS) of most mixtures, apart from the binary mixture containing 4% lime and two ternary mixtures (2% of 50% GGBFS: 50% BOFS and 2% of 70% GGBFS: 30% BOFS), showed a significant increase in strength after 3 days of curing when compared to natural soils.

In comparing the UCS of soil stabilized mixtures without being mellowed, only two lime-and-slag-based mixtures 4% of (50%G + 50% B) and 4% of (70% GGBFS + 30% BOFS) at a fixed 4% lime showed a significant increase in UCS values in all durations when compared with other mixtures, including the untreated soil. Thus, this suggests that an increased lime and slag combination leads to increased strength gain in all durations. Moreover, this consolidates the suitability of slag-based materials in stabilizing high-sulfate saline soils.

Effect of stabilizer content on the UCS Test

A UCS experiment was completed to assess the effect of various chemical binders on enhancing the compressive strength of saline soil. The chemical binders studied were standalone lime and various mixtures of lime with GGBFS and BOFS in various proportions. The results of the study are significant in terms of identifying effective strategies for enhancing the mechanical properties of sulfate-bearing saline soil. In binary mixture, lime of all proportions except 8% did

a substantial enhancement, increasing from 61.89 kPa to 160.35 kPa, in comparison to specimens aged for 14 days. The UCS increase at 28 days was 2.59 times higher than that observed in the 14-day specimens. 6% lime stabilized soil increased from 93.67 kPa (3-day) to 218.51 kPa (28-day), showing that the UCS gain was about 2.33 times whereas, the 8% lime stabilized specimens increased from 133.35 kPa (3-day) to 406.06 kPa (28-day) summarizing that the UCS gain was about 3.05 times. However, there is only a significant increment in the UCS values of 8% lime-based, unlike other lime-treated soil specimens which had no significant UCS gain between 14 to 28 days. This may be explained by the flocculation/agglomeration reactions [31].

A considerably high UCS increment is prevalent in some of the combined lime-and-slag stabilized soil mixtures such as 4% (50% GGBFS and 50% BOFS) and 4% (70% GGBFS + 30% BOFS). For example, the former (ternary mixture I) had significantly higher UCS values (172.61 kPa, 472.32 kPa, and 996.78 kPa) after 3-day, 14-day, and 28-day, respectively, which summarizes that the UCS gain was 5.77 times in 28-day as compared to 3-day. Whereas the latter (ternary mixture II) had the highest UCS values in all mixtures (133.55 kPa, 534.64 kPa, and 1115.80 kPa) after 3-day, 14-day, and 28-day, which summarizes that the UCS gain was 8.35 times in 28-day as compared to 3-day.

In general, the compressive strength of the soil treated with lime demonstrated notable enhancement within a 3-day curing period as compared to the untreated natural soils. However, the unconfined compressive strength (UCS) of other stabilized soils subjected to the same curing duration did not exhibit significant improvement. This could be ascribed to the inability of the lime to produce insufficient Ca^{2+} for cation exchange and pozzolanic reactions [7], but it is only natural for the UCS of stabilized soil to increase with increasing curing time [80]. Contrarily to the behavior of saline soil, the UCS of combined lime-and-slag soil mixtures significantly increased with time, although the increase in UCS for soil treated with 6% lime was relatively slow between 14 to 28 days. Remarkably, the protracted improvement observed in 28 days for the UCS of combined lime-and-slag base (GGBFS and BOFS) stabilized soils reflects the development of “calcium aluminate hydrate (C-A-H) and calcium silicate hydrate (C-S-H) gel” from pozzolanic activity [81, 82].

4.4 Durability Properties

4.4.1 Three-Dimensional Swelling

Figure 4.6 illustrates the volumetric change behavior of untreated and treated soil specimens of different compositions subjected to 28 days of continuous capillary suction. The untreated soil (control), when subjected to soak action, expanded rapidly until 6 days slowing down the expansive phenomenon for the rest of the duration. However, the binary blending of the soil with three percentages of lime stabilizers (such as 4%, 6%, and 8%), drastically reduced the volumetric expansion of the soil. For instance, soil stabilized with 4% lime exhibits shrinkage behavior for up to 8 days, after which it resists both steady resistance to shrinkage and swelling afterward. The soil treated with 6% lime showed steady increases in expansion up to 8 days then resumed increasing swelling which peaked at 1.3% corresponding to 24 days. The volume expansion of soil treated with 8% lime peaked early before showing varying declining trends until the end of the 3D test. From the binary mixture standpoint, it can be concluded that an increase in the lime content increases the swelling behavior of the soil with respect to the capillary suction duration.

In the case of ternary mixture II, soil stabilized with 2% (70% GGBFS + 30% BOFS) at fixed 4% is characterized by shrinkage at an early age, albeit it started exhibiting swell behavior from day 10 which rapidly rises and eventually peaking at 1.5% corresponding to 28 days. Conversely, soil treated with 4% of (70% GGBFS + 30% BOFS) is marred by inconsistent volumetric expansion throughout the continuous capillary suction despite peaking early at 1.4% (6 days). The presence of CaO in the GGBFS may have triggered the formation of ettringite minerals. The former mixture had the second-highest expansion rate of 1.5% at 28 days after 6 days, unlike the latter mixture which recorded 1.4% during the same period.

The addition of 2% and 4% by weight of equal proportions of ground granulated blast furnace slag (50% GGBFS) and basic oxygen slag (50%), respectively, is characterized by fluctuating shrinkage behavior at an early stage, with the former mixture showing resistance to both swelling and shrinkage at later stages. Conversely, the latter mixture (4% of 50G:50B) showed fluctuating swelling behavior between 6 days and 21 days where it peaked at 1.1% corresponding to 21 days. Thus, the presence of ettringite minerals may explain this behavior disparity due to the addition of lime in sulfate-containing soils. It is noteworthy that these mixtures

had the highest shrinkage, indicating that the equal addition of both GGBFS and BOFS provides resistance to volumetric expansion between the ternary mixture I and II. Overall, the saline soil treated with 4% lime exhibited the greatest resistance to volumetric expansion and shrinkage throughout the full 28-day capillary suction test. In terms of final swelling percentage for all mixtures, Table 4.3 summarizes the soil mixtures with Maximum swell and shrink values.

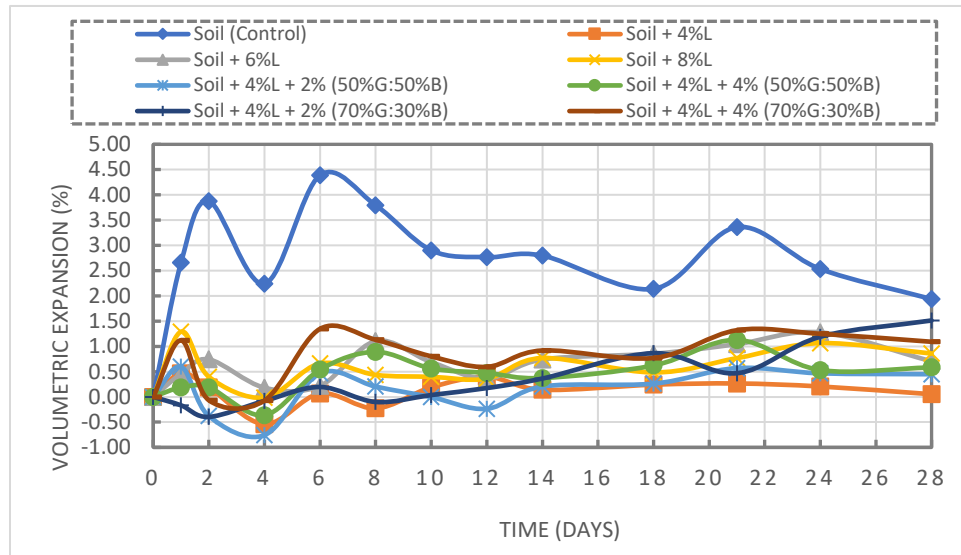


Figure 4.6 3-D Volumetric Swell-Shrink Measurement.

Table 4.3 Summary of the final volumetric swell behavior of stabilized soil samples

	Maximum Swell	Duration (days)	Ranking	Maximum Shrink	Rank
Soil (Control)	4.39	6	8	NA	NA
4%L	0.47	1	1	-0.53	5
6%L	1.28	24	3	NA	NA
8%L	1.29	1	4	-0.01	1
4%L+ 2% (50G:50B)	0.60	1	2	-0.76	6
4%L + 4% (50G:50B)	1.13	21	5	-0.36	3
4%L + 2% (70G:30B)	1.51	24	7	-0.40	4
4%L + 4% (70G+30B)	1.35	6	6	-0.07	2

The moisture content change during the 3-D swelling test on stabilized soil mixtures was evaluated and presented in Figure 4.7. All soil specimens experienced an increase in moisture content change over the initial two days, attributed to the capillary action. Among the dried soil specimens, the

ternary mixture I (2% (50% GGBFS and 50% BOFS)) showed the highest water absorption without any signs of slowing down until 28 days. Although it is only natural for the control soil (untreated soil) to absorb excess water due to its properties, it slowly reduces the water absorption later on. Conversely, the soil mixture stabilized with 4% lime showed the lowest water absorption of all the pre-mellowing categories. Moreover, ternary mixture II, such as soil stabilized with 2% (70% GGBFS and 30% BOFS) and the soil stabilized with 4% (70% GGBFS and 30% BOFS) exhibited the second and third lowest moisture content, respectively, throughout the capillary soak action.

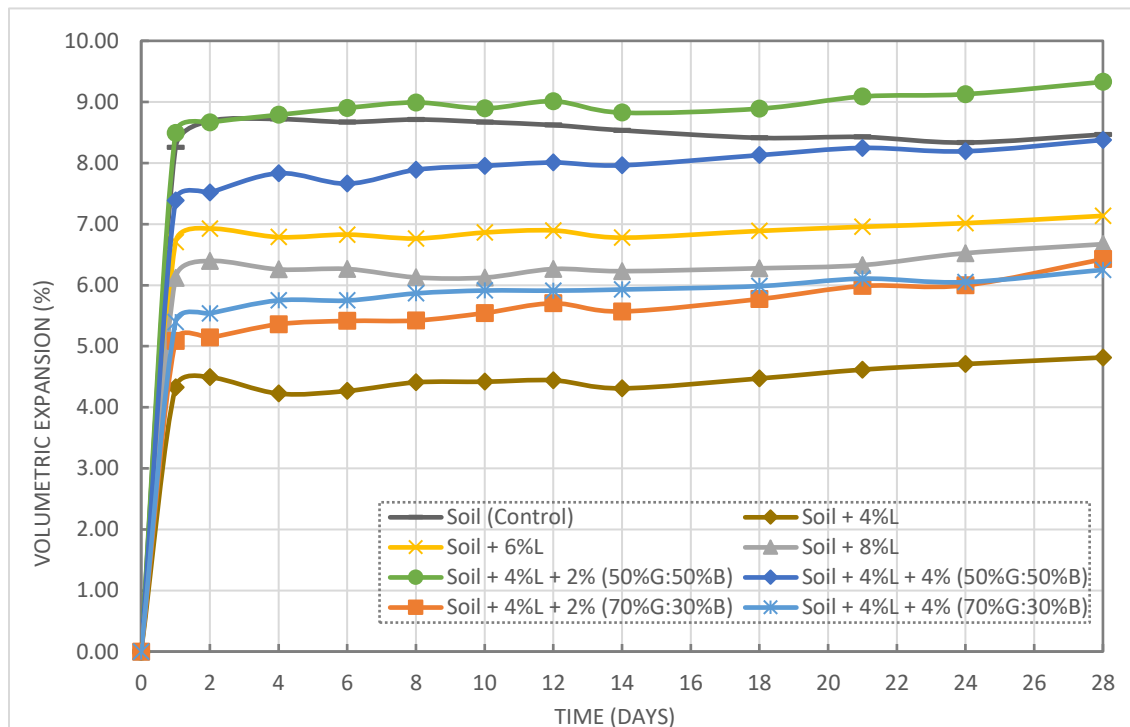


Figure 4.7 Moisture content change determination.

4.4.2 Dielectric Constant

Figure 4.8 demonstrates the dielectric constant (DC) values which highlight the moisture susceptibility of all soil mixtures within a specified duration. Compared with the untreated soil (control), the stabilized soils before 3-D swelling presented increasing DC values but drastically reduced DC values after the 3-D swelling test. The presence of lime drastically reduces the DC values at 28 days, but the introduction of slag increases the DC values within the same period.

Surprisingly, increasing the slag materials content increases the DC values, whereas the presence of lime reduces the DC values.

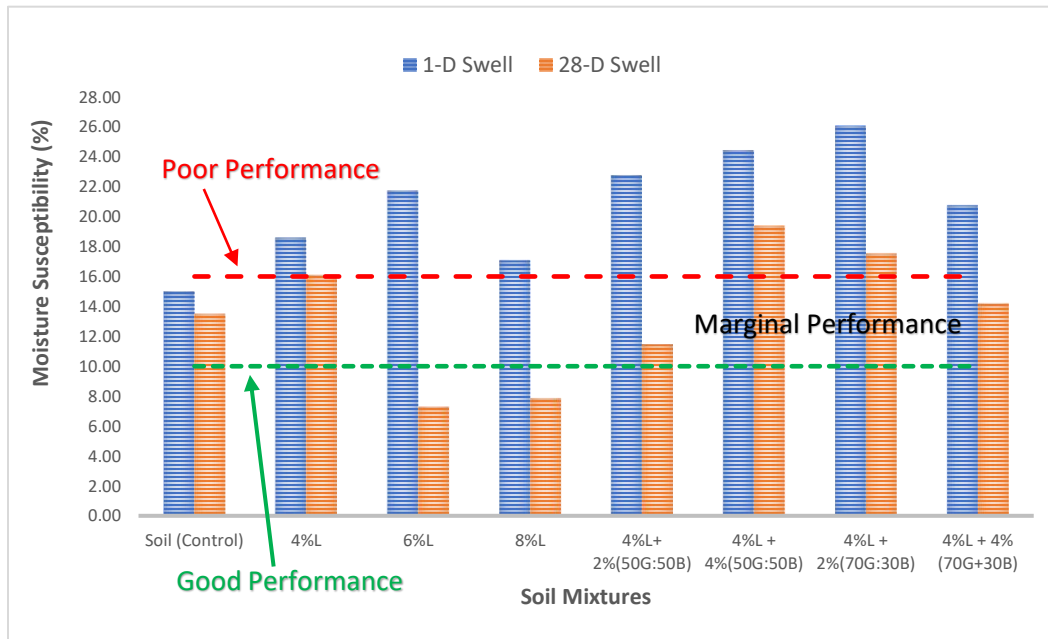


Figure 4.8 Dielectric Constant measurement for all soil mixtures

4.4.3 Soil Mellowing

Following the soil mellowing process conducted on ternary II mixtures, (see ternary III mixtures), various tests such as UCS test, 3D swelling test, DC test, and F-T test were conducted to understand their effects on the strength and durability behaviors as compared to treated soils that were not mellowed. The following sub-headings are results obtained, respectively with analyses.

Effect of Soil Mellowing on the UCS Test

The strength behavior of mellowed soils throughout 3, 14, and 28 days are presented and compared as shown in Figure 4.5. Generally, the mellowed soil stabilized with a proportion of 4% (70% GGBFS + 30% BOFS) recorded the highest compressive strength (814 kPa, 891.21 kPa, and 1425.90 kPa) in 3-day, 14-day, and 28-day, respectively, when compared to other mellowed soils and even other soil mixtures (not-mellowed). However, the only difference is that the UCS gain of 2% (70% GGBFS + 30% BOFS) was much higher for 14 days as compared to 4% (70% GGBFS

+ 30% BOFS). Also, the strength gain was not as significantly higher (1.75 times in 28 days) with respect to the curing time as compared with not-mellowed soil mixtures of similar mix proportions.

Effects of Soil Mellowing on the 3-D Test

Figure 4.9 depicts the variations in the behavior of mellowed soils (ternary mixture III) under 3D-swelling action over 28 days. After immersing the mellowed soil (control) specimens in water for two days, a maximum volumetric expansion of 1.2% was observed, followed by a steep increase in the expansion of the soil until day eight. The trend fluctuated and resisted expansion for the remainder of the duration. On the other hand, the mellowed soil stabilized at 2% (70% GGBFS + 30% BOFS), reached a peak of expansion (1.5%) at 10 days and fluctuated until 28 days. Meanwhile, the mellowed soil stabilized with a higher proportion of additives, i.e., 4% (70% GGBFS + 30% BOFS), which dramatically and consistently increased to a peak of 1.1% in 18 days. Since then, it has decreased rapidly until 24 days and then steadily. Overall, this soil mixture can withstand shrink and swell behavior during soak action.

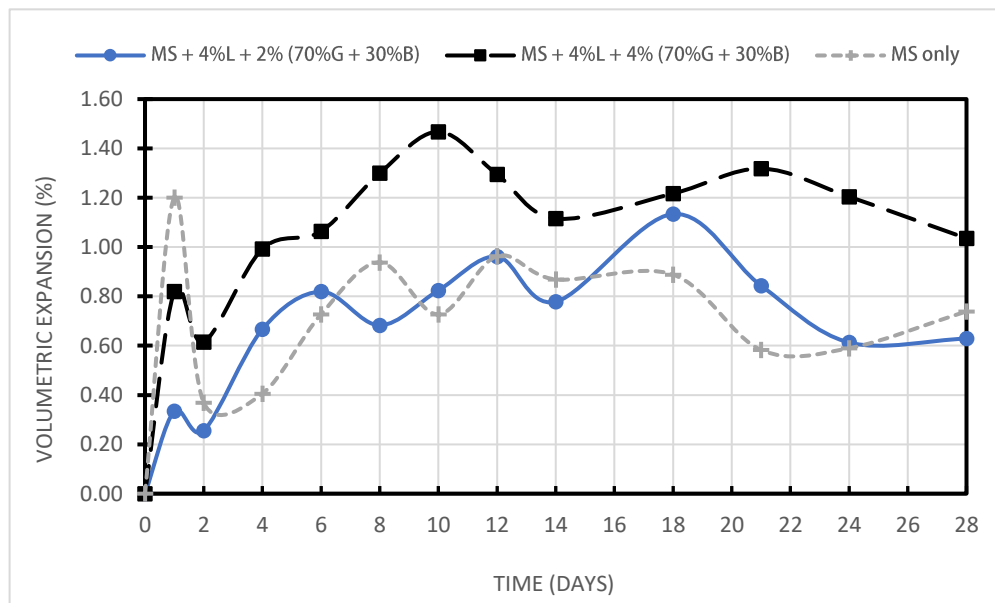


Figure 4.9 Three-Dimensional Swell test determination for mellowed soil samples

As shown in Figure 4.10, the mellowed soil samples with the proportion of 4% (70% GGBFS + 30% BOFS) dramatically exhibit the highest water absorption compared to all other soil mixtures, both before and after mellowing. Whereas the mellowed soil samples comprising 2% (70% GGBFS + 30% BOFS) had the second highest moisture change throughout all the 3D-

Swelling procedures. Overall, these results highlight the impact of different stabilization treatments on soil moisture content and their behavior during the mellowing process.

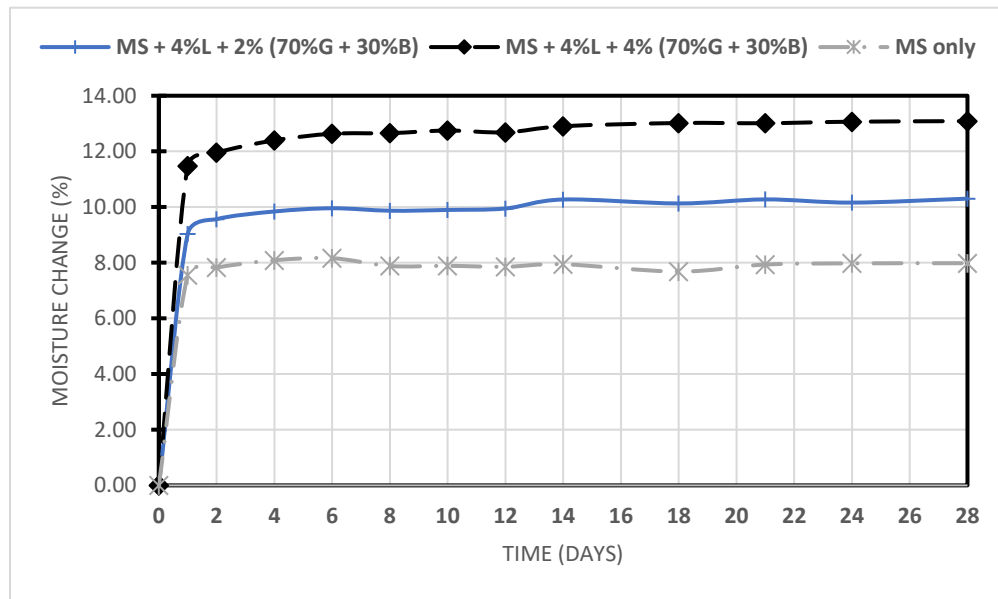


Figure 4.10 Moisture content change determination of mellowed soils mixtures.

Effect of Soil Mellowing on Moisture Susceptibility

In assessing the moisture susceptibility of different mixtures of mellowed soils, a dielectric constant test was performed, and the result is displayed in Figure 4.11. None of the mellowed soil samples showed any significant resistance to moisture susceptibility.

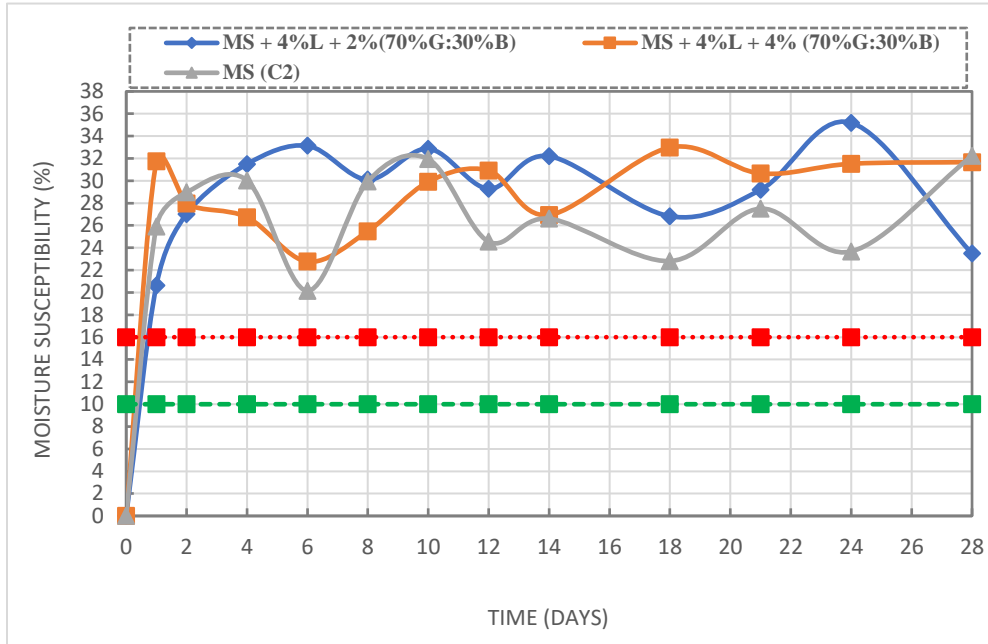


Figure 4.11 Dielectric Constant measurement for all mellowed soil mixtures

4.4.4 Freeze-Thaw Resistance

Relative Dynamic Modulus of Elasticity (RDME) of soil mixtures

RDME is the ratio of strain to stress at the time when the stress is at its minimum point under dynamic loads [83]. Estimating the relative dynamic modulus of soil samples is paramount, especially under extreme weather condition (Freezing and thawing). For instance, as the soil specimens experience F-T cycles, they progressively loses their ability to be elastic, causing the RDME to decrease, surface scaling to gradually grow, and the strength of the material to decrease [84]. Thus, RDME determination of soil mixtures that undergo F-T cycles is crucial for understanding the frost resistance of stabilized soil mixtures. However, due to the huge time commitment and the need for sophisticated laboratory facilities associated with conducting this kind of test, drawing inferences from the concrete parameters reported in the study by Shon et al. [84] could suffice.

$$P_s = v_f^2 / v_0^2 \dots \dots \dots \text{Eqn. 5}$$

Where: v_f symbolizes the UPV after final cycles of freezing and thawing; v_0 symbolizes the UPV at the initial cycles and P_s symbolizes the percentage of RDME at the end of the cycles.

The above equation 5 details how the relative dynamic modulus of elasticity was computed, and the findings are given in the form of an illustration as shown in Figure 4.12. Surprisingly, all soil mixtures except only 4% of the ternary mixture II did not show any signs of RDME throughout the freeze-thaw cycles. The RDME value of 4% of the ternary mixture II slowly increases from 30 cycles and stops at 50 cycles. In contrast, all mellowed soils in ternary mixture III had increasing RDME values with increasing freezing-thawing cycles until 30 cycles, after which the RDME started declining. This could be a result of a drastically declined hydration rate during the F-T cycles, especially given the mass losses in those soil samples. Thus, the higher the slag content, the higher the RDME of all soil samples.

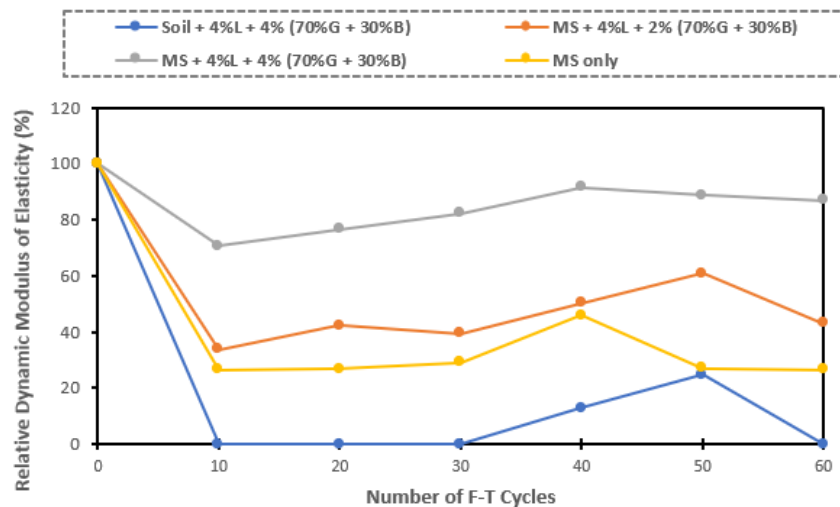


Figure 4.12 The Relative Dynamic Modulus of Elasticity of soil samples

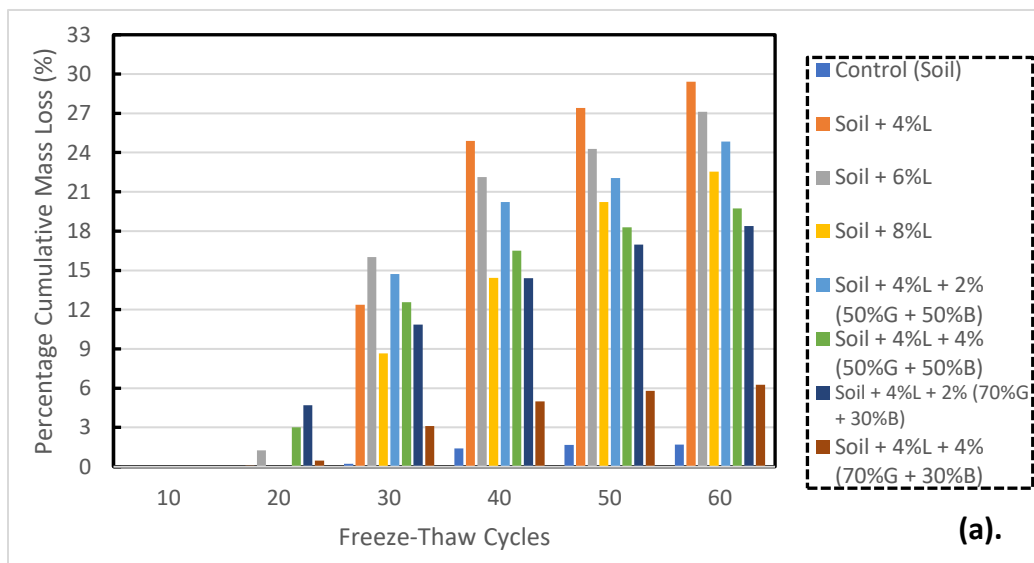
Effect of F-T Actions on soil specimens

The durability performance of all soil mixtures was assessed through the Freezing-Thawing (F-T) test and the findings are shown in Figure 4.13a and Figure 4.13b. The test involved using specimens that have been subjected to 28 days of wetting and drying actions before 60 cycles of freezing and thawing (corresponding to 2 cycles per 24 hours) in accordance with the American Standard D 570. The specimens, stabilized with different proportions of binders, were evaluated in terms of soil-binder mass loss and volume changes. To measure the impact of different binders such as lime, ground granulated blast furnace slag (GGBFS), and basic oxygen furnace slag (BOFS), the weight of the specimens was recorded before and after the F-T cycles. The difference in the masses can be computed as a percentage of the initial dry mass and was referred to as the

percentage cumulative mass loss (PCML) from the freeze-thaw conditions [50]. The PCML is a critical indicator for understanding the resistance of soil specimens to F-T cycles [85].

The findings showed that, during the initial stages of the freeze-thaw action (first 10 cycles), all soil specimens experienced a dramatic increase in mass, due to water absorption, with no mass loss observed. At 20 cycles, mass loss was observed in all specimens except the untreated soil, 8% lime, and 2% of (70% GGBFS + 30% BOFS). Rapid mass loss was observed in all specimens, except the untreated soil and 4% (70% GGBFS + 30% BOFS), starting from 30 cycles. The highest mass losses were observed in 4% lime (16.02%) and 6% (12.38%). The soil specimens in the ternary mixture I and II had mass losses of 14.72% and 12.58%, and 10.85%, respectively. A similar phenomenon was observed until the end of the whole F-T cycle (from 40-60 cycles). With the exception of untreated soil and ternary mixture II [4% (70% GGBFS + 30% BOFS)], the PCML of soil binders increased rapidly, persisting until the conclusion of the freeze-thaw cycles, whereas the latter mixtures showed resistance to mass loss. This showed that the augmentation in slag content in the ternary mixtures had a destructive impact on the soil specimens' mass loss.

In the case of the mellowed soil mixtures (ternary mixture III), Figure 4.13b shows that there was only a gain in mass at 10 and 20 cycles, except for the mellowed soil (Control) with a mass loss of 1.99%. Unlike the non-mellowed soils, the mellowed soil specimens showed higher resistance to mass loss, with the highest mass loss of 6.2% at 60 cycles.



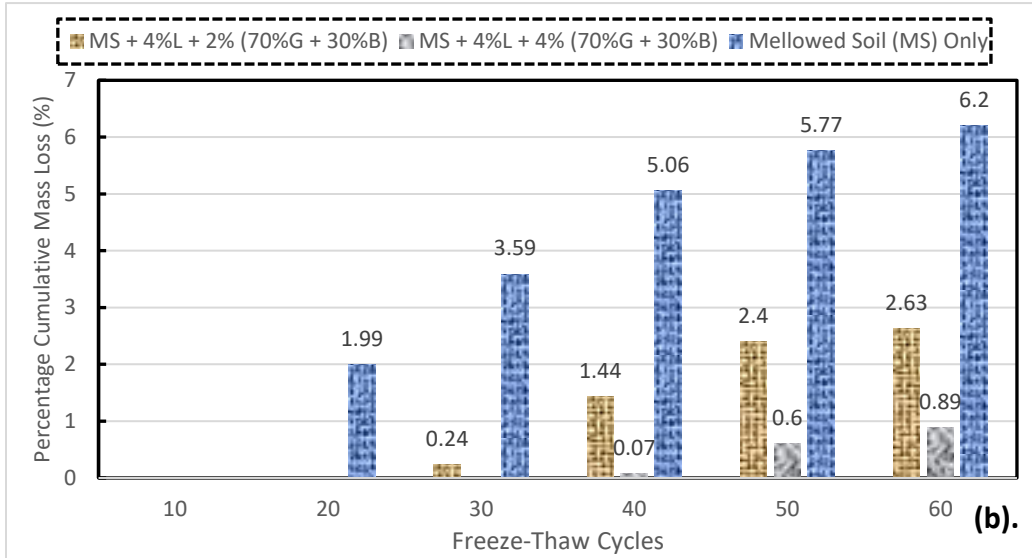


Figure 4.13 PCML of (a). Control soil and stabilized soil mixtures and, (b). Mellowed soil mixtures.

The findings of the study on the impact of freeze-thaw cycles on the volumetric change of stabilized soils are illustrated in Figure 4.14 and Figure 4.15. The study lasted for 30 days (60 cycles) and involved both non-mellowed and mellowed soils. Figure 4.14 indicates that all soil specimens experienced volumetric expansion immediately after the freeze-thaw action, with the highest peak occurring at 20 cycles for all specimens except for the soil specimens containing 2% (70% GGBFS + 30% BOFS), which had the highest volumetric expansion of 7.97% and reached its peak at 40 cycles. Conversely, the lowest volumetric expansion was observed in the ternary II mixture of 4% (70% GGBFS + 30% BOFS), as it demonstrated resistance to expansion up to 30 cycles. After this, it can be seen that all soil sample mixtures exhibited rapid volumetric shrinkage throughout the freeze-thaw cycles. The outcome of the study suggests that the introduction of lime has a minimal effect on controlling swelling and that increasing the proportion of slag, particularly GGBFS has the potential to reduce both expansion and shrinkage during freeze-thaw action.

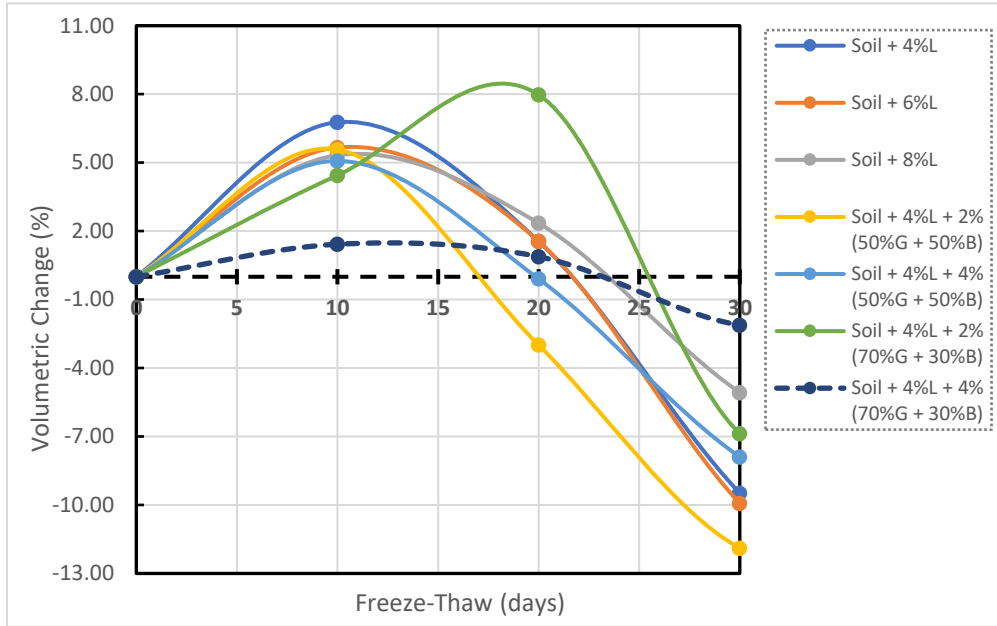


Figure 4.14 3-D Volumetric Swell-Shrink determination of soil mixtures during F-T cycles.

The illustration as shown in Figure 4.15 indicates that all mellowed soil specimens demonstrate resistance to volumetric expansion during the freeze-thaw action. The specimens exhibit slow expansion until 30 cycles, with an expansion rate of less than 0.5% throughout the cycles. Subsequently, these soils exhibit a gradual shrinkage until the end of the freeze-thaw cycle. The highest shrinkage rate was observed in the mellowed soil, reaching 2.55% at 60 cycles. These findings demonstrate the capability of mellowed soils to resist expansion during freeze-thaw cycles, while also undergoing limited shrinkage.

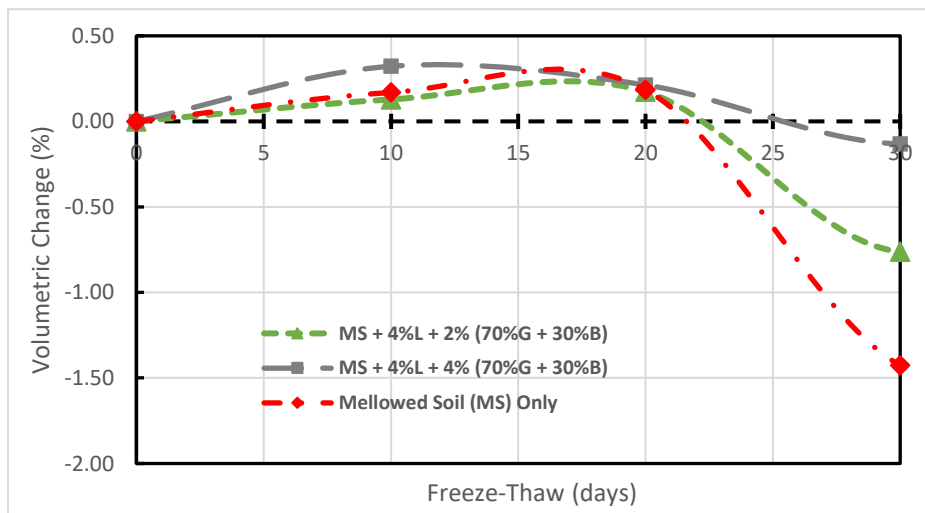


Figure 4.15 3-D Volumetric Swell-Shrink determination of mellowed soil mixtures during F-T cycles.

4.5 Mineralogical and Microstructural Properties

The mineralogical composition of different soil mixtures, acquired subsequent to freeze-thaw (F-T) cycles, was meticulously assessed via X-ray diffraction (XRD), and the corresponding patterns are depicted in Figures 4.16, 4.17 and 4.18. These figures show distinct X-ray diffraction (XRD) patterns of various soil mixtures, wherein XRD of all stabilized soils and mellowed soils displayed akin components (quartz and gypsum) to those found in saline soil. However, a subtle presence of thaumasite was detected in only the mellowed soil (MS). Surprisingly, no significant ettringite or thaumasite, known as expansive minerals, was detected in all the peaks of the XRD patterns. This intriguing finding may potentially provide insight into the underlying mechanisms that drive the observed shrinkage behaviors during the 60 F-T cycles and 3D swell test.

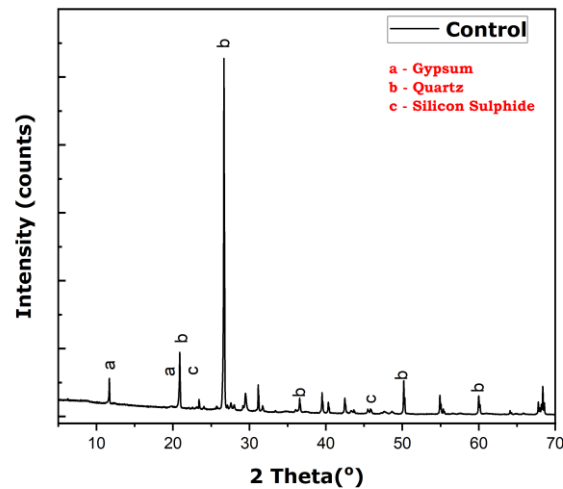


Figure 4.16 XRD Analysis of Saline Soil

The XRD pattern for plain mixture (control) are illustrated in Figure 4.16 and the major components found in the saline soil were predominantly quartz (SiO_2), gypsum ($\text{CaSO}_4\text{H}_2\text{O}$) and some silicon sulphide (SiS_2). The abundance of gypsum in the soil results in a substantial concentration of sulfate ions, showcasing its salinity and precipitating as crystallized salt. This phenomenon significantly diminishes the soil's performance, rendering it inferior in terms of engineering properties, and inflicts deleterious effects that ultimately lead to soil degradation [4].

Figure 4.17 illustrates the diverse X-ray diffraction (XRD) patterns observed in the stabilized soil mixtures. Remarkably, nearly all soil samples displayed similar composition, except for the 4% lime-treated sample, which exhibited a pattern akin to plain soil. Intriguingly, apart

from the 4% lime and 2% (70% GGBFS + 30% BOFS) treated samples, all other soil samples manifested the presence of calcium carbonate, specifically calcite, as revealed by XRD analysis. Notably, the absence of ettringite or thaumasite in any of the soil mixtures is unexpected. This phenomenon may be attributed to constrained moisture circulation during freeze-thaw (F-T) cycles, particularly considering the observed shrinkage behavior in some of the soil specimens. These findings suggest that the F-T action may have resulted in altered mineralogical transformations and reduced the formation of ettringite or thaumasite in the stabilized soil mixtures. This could be because of diminished moisture circulation, especially since there were some shrinkage behaviors among the soil specimens during the F-T cycles.

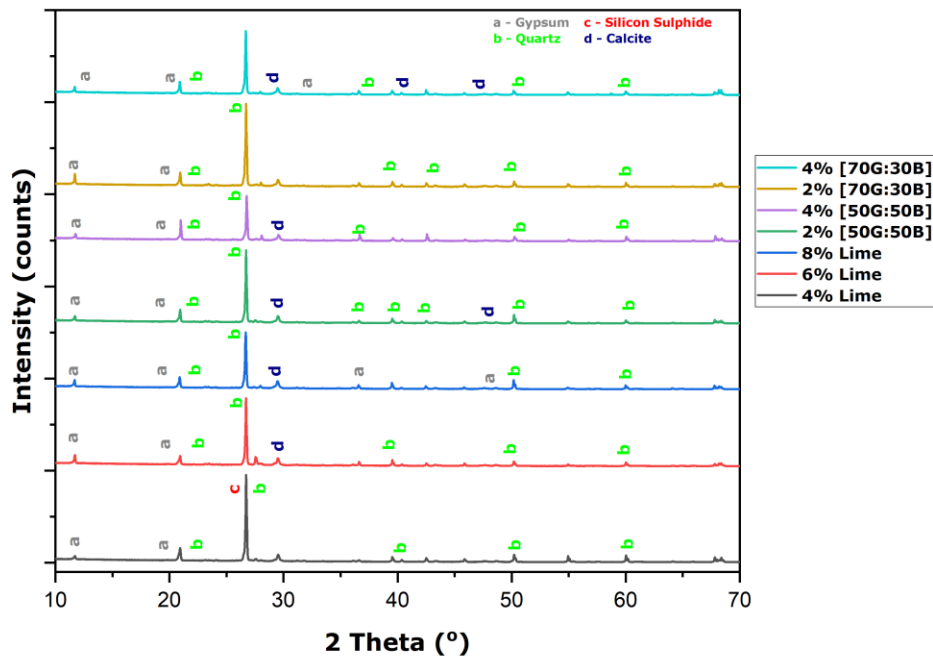


Figure 4.17 XRD Analysis of all Stabilized Saline Soils

Figure 4.18 illustrates distinct X-ray diffraction (XRD) patterns of various mellowed soil mixtures, wherein most soil samples displayed akin components to those found in stabilized soil samples. However, a subtle presence of thaumasite was detected in only the mellowed soil (MS). Furthermore, the XRD patterns shown in the figure succinctly depict that the process of stabilizing mellowed soil samples proved effective, resulting in the complete elimination of gypsum. This

resolute action explains the increased resistance of mellowed soil samples against the detrimental effects of freeze-thaw (F-T) cycles, as corroborated by the durability property findings.

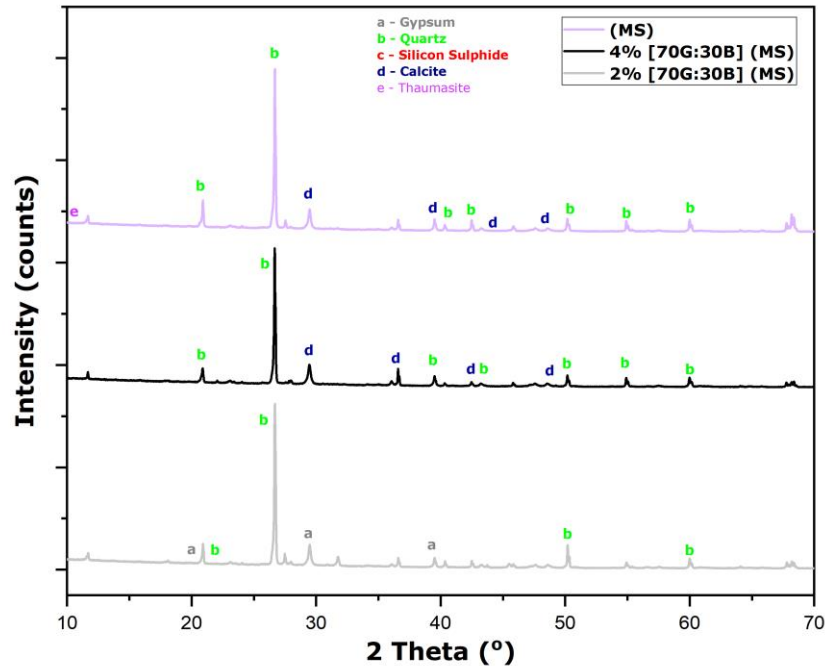


Figure 4.18 XRD Analysis of all Mellowed Soil Samples

4.6 SEM/ EDS Characterization

A scanning electron microscope experiment was performed on selected soil mixtures to investigate their microstructural properties, which are critical for buttressing the durability behaviors exhibited after the F-T cycles. The SEM pictures with accompanying energy dispersive spectroscopy (EDS) were taken after 60 F-T cycles, and the results obtained are summarized in the figures below. Figure 4.19a and Figure 4.19b show the scanning electron microscope and the energy dispersive spectroscopy of control soil and binary mixture (4% lime), respectively.

The SEM micrographs in both figures had similar elements, and there were clay mineral flakes present therein. Moreover, it can be seen that from the SEM illustration that the addition of 4% lime, as shown in Figure 4.20 led to several pores and openings, which could be a direct

consequence of reduced moisture caused by evaporation [38]. However, no formation of ettringite or thaumasite was observed.

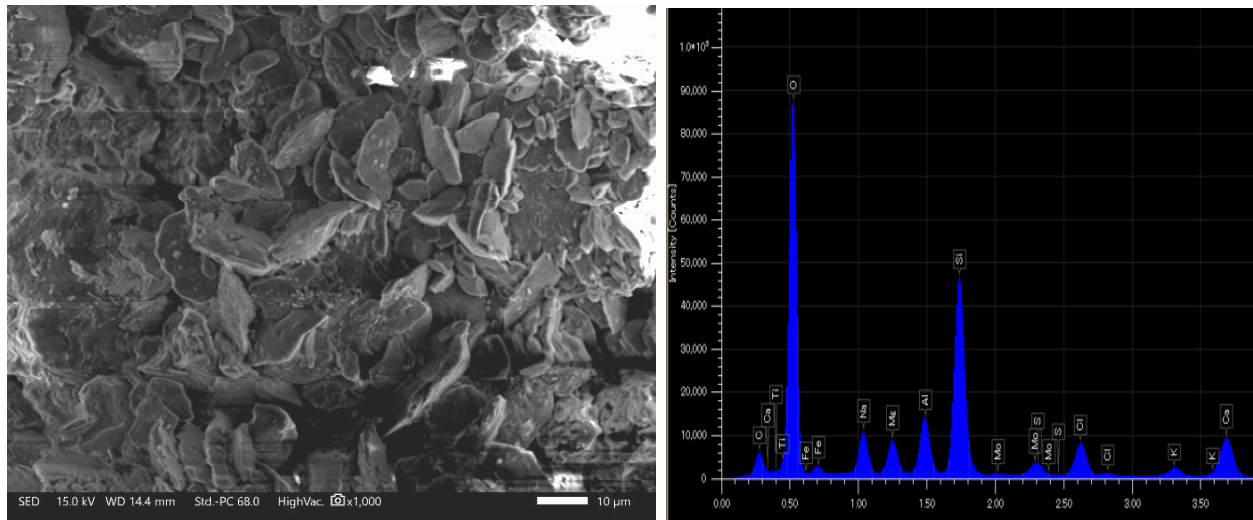


Figure 4.19. SEM/EDS images for high sulfate saline soil (a) SEM image and (b) EDS image.

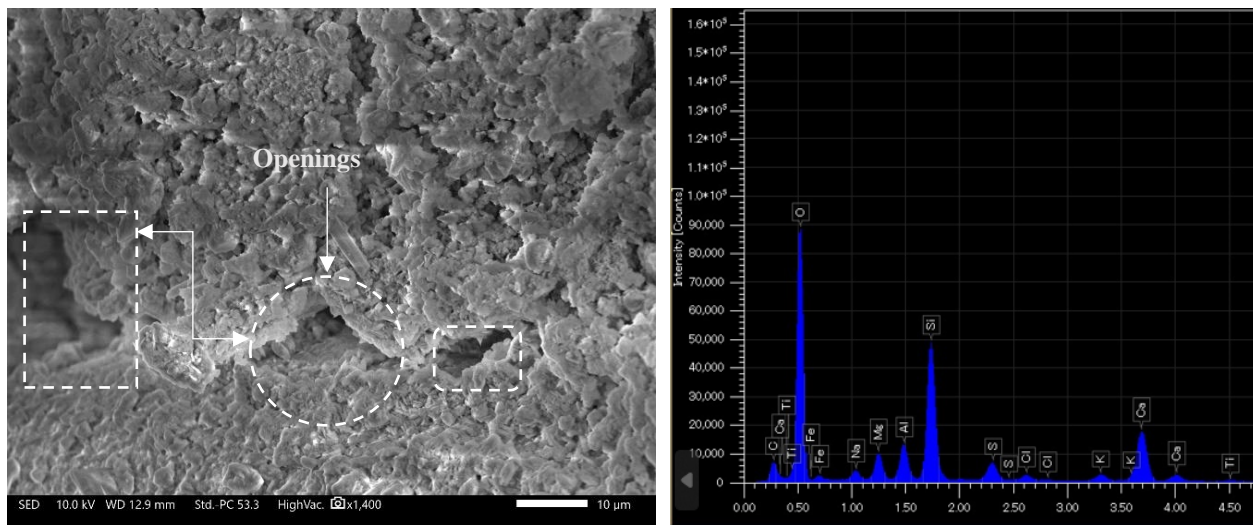


Figure 4.20. SEM/EDS images for 4% lime (a) SEM image of 4% lime and (b) EDS image of 4% lime.

Figure 4.21a and Figure 4.22a illustrate the SEM images of the stabilized sulfate-bearing saline soil of ternary mixture I (2% and 4% of [50% GGBFS and 50% BOFS], respectively), while Figure 4.23a belongs to 4% of ternary mixture II, revealing the scattered and significant quantity of needle-like crystals, otherwise known as ettringite. These crystals in these figures are a sign of the ettringite mineral's formation in the presence of sulfate. It is possible that as the stabilizer and soil mixture hydrated, ettringite minerals formed, causing aberrant swelling in the treated sulfate-

bearing soils [4, 29]. Figure 4.21b, Figure 4.22b and Figure 4.23b, respectively, show similar EDS spectra and elemental components.

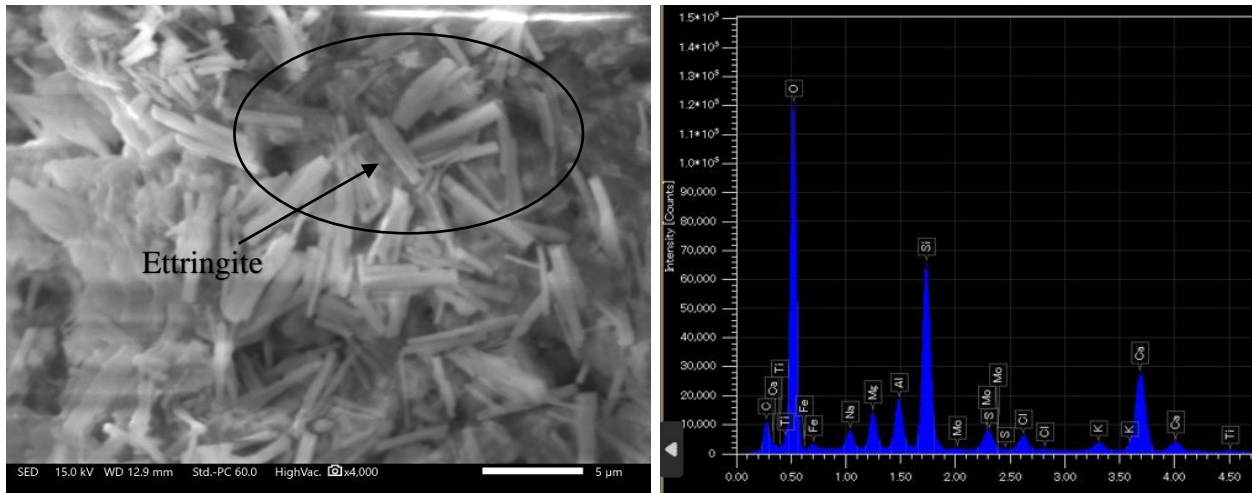


Figure 4.21. SEM/EDS images for 2% of stabilized ternary mixture I (a) SEM image (b) EDS image.

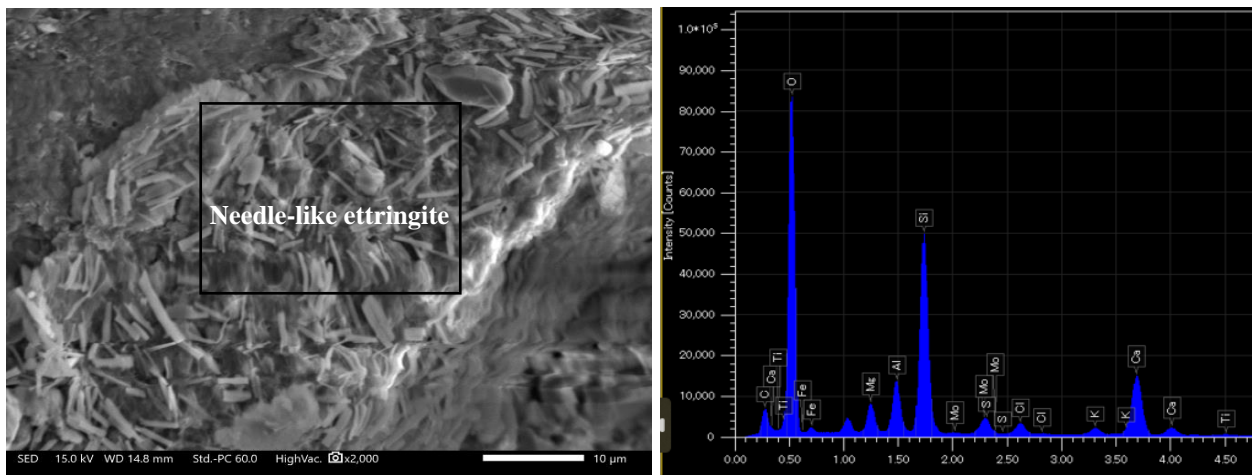


Figure 4.22. SEM/EDS images for 4% of stabilized ternary mixture II (a) SEM image (b) EDS image.

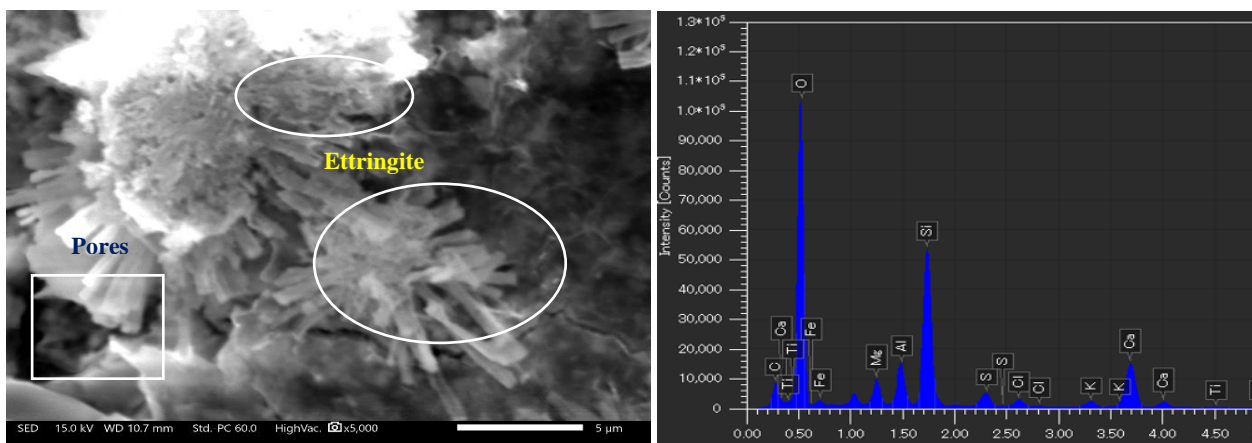


Figure 4.23. SEM/EDS images for 4% of stabilized ternary mixture II (a) SEM image (b) EDS image.

Figure 4.24a and Figure 4.25a show the SEM images of different mellowed soil mixtures (ternary mixture III), comprising 2% of 70% GGBFS and 30% BOFS and only mellowed soil, respectively. It is surprising that there was no significant needle-like ettringite mineral formation in the illustration, which could be a reason why the soil specimens did not collapse like other soil specimens. Moreover, Figure 4.24b and Figure 4.25b show the corresponding EDS spectrum and elemental composition of the ternary soil mixture III, which also share similarity in the elements.

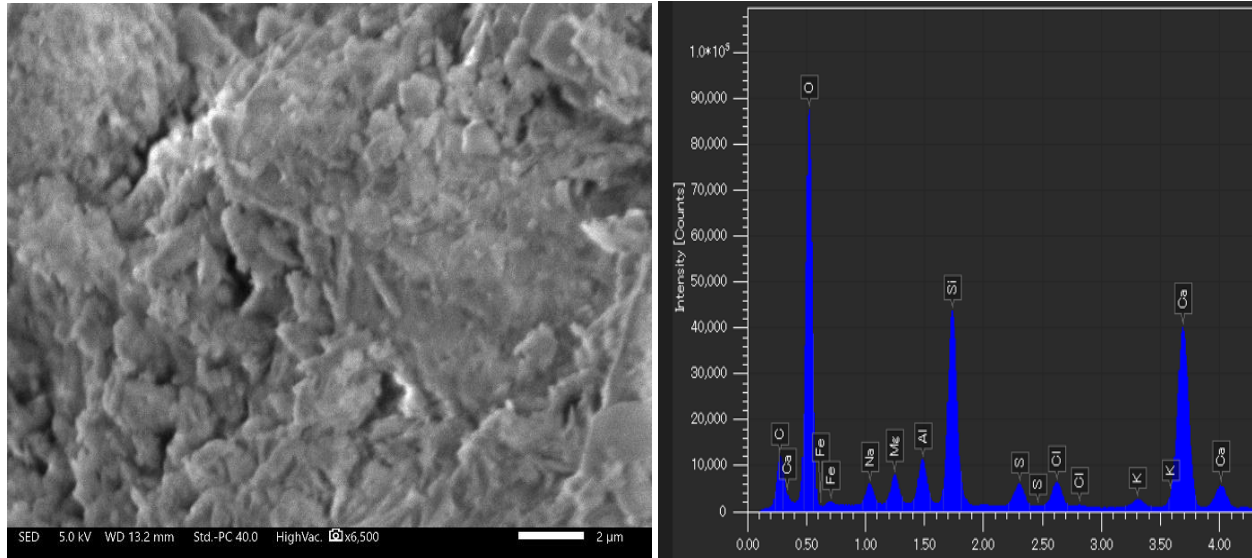


Figure 4.24. SEM/EDS images for 2% of ternary mixture III, *mellowed soil* (a) SEM image (b) EDS image.

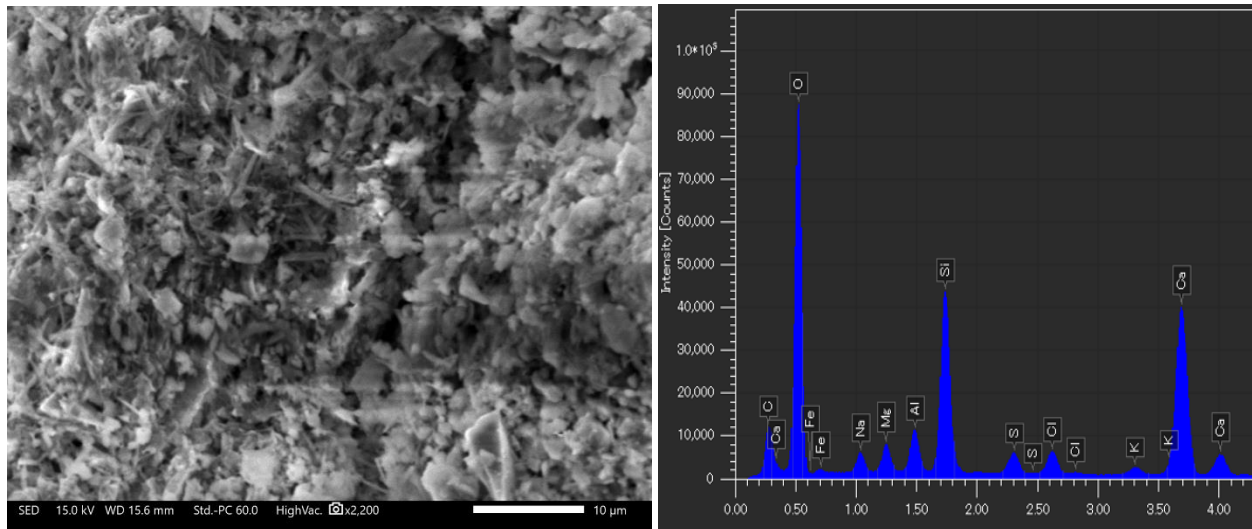


Figure 4.25. SEM/EDS images for ternary mixture III (a) SEM image of *only mellowed soil* (b) EDS image of *only mellowed soil*.

Chapter Five – Conclusion and Recommendation

The primary aim of the research was to investigate and develop supplementary cementitious binders generated from the ternary combination of varying proportions of lime, GGBFS, and BOFS, followed by the assessment of the material characterization, mechanical, and durability properties of sulfate-saline soil stabilized with different blends of materials, especially when under freeze-thaw cycles. Succinctly, the characterization and engineering properties of these different blends were studied to evaluate how they contribute to the performance of sulfate-saline soil. Also, assessing their durability behaviors through various experimental testing guided by experimental programs illustrated in Figure 3.1. To gain a more comprehensive understanding of the enhanced durability performance of the stabilized soils, mineralogical and microstructural experiments such as XRD, SEM, and accompanying EDS were performed and evaluated on treated, untreated, and mellowed soils that had been exposed to severe weather conditions.

5.1 Conclusion

The following important conclusions can be made following the research's findings and further recommendations concerning the study were provided for future research.

- Surprisingly, there was some disparity in the compaction characteristics in accordance with their respective blend. e.g., in the case of the binary blend, there was a relative enhancement in the optimum moisture content with a corresponding reduction in the maximum dry density. In ternary blend I, there was an increase in the OMC with a corresponding slight increase in the MDD, and finally, in ternary blend II, as OMC increases, there was a subsequent slight decrease in the MDD.
- The optimization of the ternary blend binder showed that higher proportions of GGBFS: BOFS (4% of 70:30) was the most sufficient and suitable in reducing the sulfate level in the saline soil.
- Following the mellowing process, which is another method of stabilization, the above blend also proved to be the most effective in reducing the soluble sulfate present in the soil.
- Generally based on respective ternary blends, the proportion of GGBFS: BOFS (4% of 70:30) had the highest compressive strength corresponding to before mellowing and after

mellowing. Moreover, this shows that an increase in the waste slag-based materials results in higher strength gain whether instant or prolonged.

- Untreated soil had the highest volumetric expansion, and all stabilizers were effective in lowering it. However, 4% lime was the most effective in lowering the expansion whereas lowering the slag contents was more effective in lowering the volumetric expansion of all the ternary mixtures (2% of 50%GGBFS:50%BOFS).
- Moisture susceptibility of soil is unsuitable for pavement and thus, only 6% and 8% lime were more effective in providing resistance to the susceptibility than any other binders, especially at a later age (28 days).

Moreover, the durability performance of all soil mixtures was assessed through the measurement of several parameters following their exposure to 30 days of freezing and thawing corresponding to 60 cycles (2 cycles per day). The results and analysis of these parameters were performed and therefore, the following conclusions were derived:

- All soil samples subjected to ultrasonic pulse velocity showed no sign of velocity movement except the higher proportions of GGBFS: BOFS (4% of 70:30) starting at 30 cycles. Thus, the higher the slag content, the higher the velocity of the soil samples.
- Conversely, all mellowed soil samples exhibited UPV values throughout the freezing and thawing cycles even though the higher proportions of GGBFS: BOFS (4% of 70:30) was more encouraging.
- The resulting relative dynamic modulus of elasticity using UPV parameters also had similar outcomes. This concludes that the higher the slag content, the higher the RDME value of the soil samples before and after mellowing.
- Although all specimens before mellowing could not withstand the high volumetric effect of freezing-thawing action beyond 20 days (40 cycles), higher proportions of GGBFS: BOFS (4% of 70:30) was the most effective in lowering the volumetric expansion of all mixtures under extreme weather condition.
- As expected, all mellowed soil specimens exposed to F-T cycles were the most effective in lowering the volumetric expansion even though mellowed proportions of GGBFS: BOFS (4% of 70:30) proved effective in withstanding the expansion for a longer time (25 days).

- At the end of whole cycles, proportions of GGBFS: BOFS (4% of 70:30) before mellowing and after mellowing had the lowest mass loss.

Finally, the mineralogical and microstructural performance of soil samples subjected to 60 cycles of freezing and thawing, equivalent to 30 days at a rate of 2 cycles per day, were assessed. Subsequent to the examination and analysis of the XRD patterns and SEM image observations, the following conclusions were deduced:

- Based on the XRD data, no ettringite and thaumasite minerals was detected in all of the soil samples subjected to the F-T cycles, not noticeably in the peak region. However, a weak thaumasite minerals was detected on mellowed soil (MS) only. This finding concludes that the absence of these minerals may have led to the reduced expansion, but shrinkage behaviors experienced during the 60 F-T cycles and 3D swell test.
- Quartz was predominant in all soil mixtures (I, II & III) whereas, gypsum was presence in only plain soil, all binary and ternary mixtures except ternary mixture III. Thus, it is concluded that gypsum can present detrimental effects on the soil samples.
- The results of the SEM and EDS show that there were several openings and pores after stabilizing the soil with lime without any trace of needle-like ettringite. This perfectly align with the XRD finding on the same soil mixtures.
- The formation of needle-like ettringite can be observed in all of ternary mixture II, while 4% of ternary mixture III also shows some signs of ettringite and pores.
- There was no noticeable ettringite in soil-mellowed mixtures, as shown in the SEM image observation. This almost coincides with the XRD result except for the only mellowed soil.

Based on the investigation of geotechnical and durability performance metrics for sulfate-saline stabilized mixtures, the utilization of a 4% dosage of a ternary mixture consisting of 70% GGBFS and 30% BOFS (for ternary mixtures II and III) demonstrates the most superior overall performance. This novel combination of supplementary cementitious materials exhibits enhanced resistance to F-T cycles. However, it is noteworthy to mention that an alternative stabilization method, known as mellowing, displayed even greater resistance to F-T cycles. Therefore, the utilization of waste slag as a partial replacement for calcium-based materials proves to be the most favorable option in terms of eco-friendliness, cost-effectiveness, and potential for carbon emissions reduction.

5.2 Limitation of the Study

As a result of persistent malfunctions in the core facility laboratory's equipment, coupled with a highly constrained reservation schedule, the study was unable to successfully carry out X-ray fluorescence testing to elucidate the findings derived from X-ray diffraction and Scanning electron microscope. Succinctly, based on the proposed experimental program, XRF was not conducted in this study at this time due to a faulty AxiosmAX XRF spectrometer. However, an Energy Dispersive Spectroscopy (EDS) was used as an alternative approach.

5.3 Recommendation

The following are the key recommendations critical for future research based on the long-term performance of slag-based soil treatment under freeze-thaw action.

- Mellowing of soil samples to reduce sulfate concentration of about 3,000 ppm or less needs to be achieved before compaction and subsequent swell and F-T cycle tests.
- Improvement in the stabilizer contents by adding more slag-based materials can be proposed.
- Perform a CBR test to understand the bearing capacity of the soil mixtures.
- Saline soil stabilization as well as soil mellowing need to be performed for a longer period to verify the possible presence of ettringite or thaumasite formations.
- Considering other alkali-activated wastes with separate ground granulated blast furnace slag and basic oxygen furnace slag for comparing their superior performances.

Reference

- [1] D. Bazarov, A. Kayumov, B. Salimova, R. Khakimova, and A. Kayumov, "Strengthening the roadbed of highways using soil stabilizers," *E3S Web of Conferences*, vol. 264, 2021, doi: 10.1051/e3sconf/202126402012.
- [2] R. Z. Moayed, E. Izadi, and S. Heidari, "Stabilization of saline silty sand using lime and micro silica," *Journal of Central South University*, vol. 19, no. 10, pp. 3006-3011, 2012, doi: 10.1007/s11771-012-1370-1.
- [3] S. Zhang, X. Yang, S. Xie, and P. Yin, "Experimental study on improving the engineering properties of coarse grain sulphate saline soils with inorganic materials," *Cold Regions Science and Technology*, vol. 170, 2020, doi: 10.1016/j.coldregions.2019.102909.
- [4] Y. Zhou, Q. Guan, P. Yan, and T. Zhang, "Investigation of Freeze-Thaw Resistance of Stabilized Saline Soil," *Advances in Civil Engineering*, vol. 2021, pp. 1-13, 2021, doi: 10.1155/2021/5555436.
- [5] G. T. Issanova, J. Abuduwaili, Z. U. Mamutov, A. A. Kaldybaev, G. A. Saparov, and T. A. Bazarbaeva, "Saline soils and identification of salt accumulation provinces in Kazakhstan," *Arid Ecosystems*, vol. 7, no. 4, pp. 243-250, 2017, doi: 10.1134/s2079096117040035.
- [6] E. I. Pankova and M. V. Konyushkova, "Climate and soil salinity in the deserts of Central Asia," *Eurasian Soil Science*, vol. 46, no. 7, pp. 721-727, 2013, doi: 10.1134/s1064229313070065.
- [7] Y. Liu *et al.*, "Experimental investigation of the geotechnical properties and microstructure of lime-stabilized saline soils under freeze-thaw cycling," *Cold Regions Science and Technology*, vol. 161, pp. 32-42, 2019, doi: 10.1016/j.coldregions.2019.03.003.
- [8] X. Zhao, A. Shen, Y. Guo, P. Li, and Z. Lv, "Pavement mechanic response of sulfate saline soil subgrade section based on fluid–structure interaction model," *International Journal of Pavement Research and Technology*, vol. 10, no. 6, pp. 497-506, 2017.
- [9] X. Wan, Q. Hu, and M. Liao, "Salt crystallization in cold sulfate saline soil," *Cold Regions Science and Technology*, vol. 137, pp. 36-47, 2017, doi: 10.1016/j.coldregions.2017.02.007.
- [10] Z. Cheng *et al.*, "Improvement of the Salinized Soil Properties of Fly Ash by Freeze-Thaw Cycles: An Impact Test Study," *Sustainability*, vol. 13, no. 5, 2021, doi: 10.3390/su13052908.
- [11] A. Hotineanu, M. Bouasker, A. Aldaood, and M. Al-Mukhtar, "Effect of freeze–thaw cycling on the mechanical properties of lime-stabilized expansive clays," *Cold Regions Science and Technology*, vol. 119, pp. 151-157, 2015.
- [12] J.-M. Konrad, "Physical processes during freeze-thaw cycles in clayey silts," *Cold Regions Science and Technology*, vol. 16, no. 3, pp. 291-303, 1989.
- [13] T. Kamei, A. Ahmed, and T. Shibi, "Effect of freeze–thaw cycles on durability and strength of very soft clay soil stabilised with recycled Bassanite," *Cold Regions Science and Technology*, vol. 82, pp. 124-129, 2012.
- [14] A. Aldaood, M. Bouasker, and M. Al-Mukhtar, "Impact of freeze–thaw cycles on mechanical behaviour of lime stabilized gypseous soils," *Cold Regions Science and Technology*, vol. 99, pp. 38-45, 2014.
- [15] D.-y. Wang, W. Ma, Y.-h. Niu, X.-x. Chang, and Z. Wen, "Effects of cyclic freezing and thawing on mechanical properties of Qinghai–Tibet clay," *Cold regions science and technology*, vol. 48, no. 1, pp. 34-43, 2007.
- [16] Q. Lv, L. Jiang, B. Ma, B. Zhao, and Z. Huo, "A study on the effect of the salt content on the solidification of sulfate saline soil solidified with an alkali-activated geopolymer," *Construction and Building Materials*, vol. 176, pp. 68-74, 2018, doi: 10.1016/j.conbuildmat.2018.05.013.
- [17] E. Belhadj, C. Diliberto, and A. Lecomte, "Characterization and activation of Basic Oxygen Furnace slag," *Cement and Concrete Composites*, vol. 34, no. 1, pp. 34-40, 2012, doi: 10.1016/j.cemconcomp.2011.08.012.

- [18] Y. Gao *et al.*, "BOF steel slag as a low-cost sorbent for vanadium (V) removal from soil washing effluent," *Sci Rep*, vol. 7, no. 1, p. 11177, Sep 11 2017, doi: 10.1038/s41598-017-11682-3.
- [19] C. Kambole, P. Paige-Green, W. K. Kupolati, J. M. Ndambuki, and A. O. Adeboje, "Basic oxygen furnace slag for road pavements: A review of material characteristics and performance for effective utilisation in southern Africa," *Construction and Building Materials*, vol. 148, pp. 618-631, 2017, doi: 10.1016/j.conbuildmat.2017.05.036.
- [20] T. S. Naidu, C. M. Sheridan, and L. D. van Dyk, "Basic oxygen furnace slag: Review of current and potential uses," *Minerals Engineering*, vol. 149, 2020, doi: 10.1016/j.mineng.2020.106234.
- [21] N. Talluri, A. J. Puppala, B. C. Chittoori, A. H. Gaily, and P. Harris, "Stabilization of high-sulfate soils by extended mellowing," *Transportation research record*, vol. 2363, no. 1, pp. 96-104, 2013.
- [22] W. Li, R. Li, Y. Chen, and H. Xiao, "Comparison of Two Sulfate-Bearing Soils Stabilized with Reactive Magnesia-Activated Ground Granulated Blast Furnace Slag: Swelling, Strength, and Mechanism," *Buildings*, vol. 13, no. 1, p. 230, 2023.
- [23] R. Ziaie-Moayed, M. Samimifar, and M. Kamalzare, "Improvement of shear strength characteristics of saline soil using cement and polymer," *International Journal of Geotechnical Engineering*, vol. 5, no. 3, pp. 307-314, 2011.
- [24] A. J. Puppala, N. Talluri, S. S. C. Congress, and A. Gaily, "Ettringite induced heaving in stabilized high sulfate soils," *Innovative Infrastructure Solutions*, vol. 3, pp. 1-12, 2018.
- [25] E. Berger, D. Little, and R. Graves, "Technical memorandum: Guidelines for stabilization of soils containing sulfates," *National Lime Association, Arlington, VA*, 2001.
- [26] A. Behnood, "Soil and clay stabilization with calcium-and non-calcium-based additives: A state-of-the-art review of challenges, approaches and techniques," *Transportation Geotechnics*, vol. 17, pp. 14-32, 2018.
- [27] A. R. Goodarzi and M. Salimi, "Stabilization treatment of a dispersive clayey soil using granulated blast furnace slag and basic oxygen furnace slag," *Applied Clay Science*, vol. 108, pp. 61-69, 2015, doi: 10.1016/j.clay.2015.02.024.
- [28] L. C. d. F. L. Lucena, J. F. T. Juca, J. B. Soares, and P. G. T. Marinho Filho, "Use of wastewater sludge for base and subbase of road pavements," *Transportation Research Part D: Transport and Environment*, vol. 33, pp. 210-219, 2014.
- [29] E. Celik and Z. Nalbantoglu, "Effects of ground granulated blastfurnace slag (GGBS) on the swelling properties of lime-stabilized sulfate-bearing soils," *Engineering Geology*, vol. 163, pp. 20-25, 2013, doi: 10.1016/j.enggeo.2013.05.016.
- [30] E. Mansour, J. Kinuthia, J. Oti, and Q. Al-Waked, "Sulfate soil stabilisation with binary blends of lime–silica fume and lime–ground granulated blast furnace slag," *Transportation Geotechnics*, vol. 37, 2022, doi: 10.1016/j.trgeo.2022.100888.
- [31] A. A. Firoozi, C. Guney Olgun, A. A. Firoozi, and M. S. Baghini, "Fundamentals of soil stabilization," *International Journal of Geo-Engineering*, vol. 8, no. 1, 2017, doi: 10.1186/s40703-017-0064-9.
- [32] K. I. A. Ehwillat, M. A. M. Ismail, and A. M. A. Ezreig, "Ettringite Formation and Stabilization Methods of Sulfate-Bearing Soil: A State-of-the-Art Review," *Indian Geotechnical Journal*, vol. 52, no. 4, pp. 927-941, 2022, doi: 10.1007/s40098-022-00619-x.
- [33] D. Barman and S. K. Dash, "Stabilization of expansive soils using chemical additives: A review," *Journal of Rock Mechanics and Geotechnical Engineering*, vol. 14, no. 4, pp. 1319-1342, 2022, doi: 10.1016/j.jrmge.2022.02.011.
- [34] G. Obuzor, J. Kinuthia, and R. Robinson, "Soil stabilisation with lime-activated-GGBS—A mitigation to flooding effects on road structural layers/embankments constructed on floodplains," *Engineering Geology*, vol. 151, pp. 112-119, 2012.

- [35] A. Puppala, E. Wattanasanticharoen, and K. Punthutaecha, "Experimental evaluations of stabilisation methods for sulphate-rich expansive soils," *Proceedings of the Institution of Civil Engineers-Ground Improvement*, vol. 7, no. 1, pp. 25-35, 2003.
- [36] A. J. Puppala, C. Viyanant, A. P. Kruzic, and L. Perrin, "Evaluation of a modified soluble sulfate determination method for fine-grained cohesive soils," *Geotechnical Testing Journal*, vol. 25, no. 1, pp. 85-94, 2002.
- [37] I. Bozbey *et al.*, "Effects of soil pulverization level on resilient modulus and freeze and thaw resistance of a lime stabilized clay," *Cold Regions Science and Technology*, vol. 151, pp. 323-334, 2018.
- [38] M. Keramatikerman, A. Chegenizadeh, and H. Nikraz, "Effect of GGBFS and lime binders on the engineering properties of clay," *Applied Clay Science*, vol. 132, pp. 722-730, 2016.
- [39] M. Salimi and A. Ghorbani, "Mechanical and compressibility characteristics of a soft clay stabilized by slag-based mixtures and geopolymers," *Applied Clay Science*, vol. 184, p. 105390, 2020.
- [40] R. Al-Khafaji *et al.*, "Stabilization of Soft Soil by a Sustainable Binder Comprises Ground Granulated Blast Slag (GGBS) and Cement Kiln Dust (CKD)," *Recycling*, vol. 8, no. 1, p. 10, 2023.
- [41] R. Nidzam and J. M. Kinuthia, "Sustainable soil stabilisation with blastfurnace slag—a review," *Proceedings of the Institution of Civil Engineers-Construction Materials*, vol. 163, no. 3, pp. 157-165, 2010.
- [42] Y. Yi, L. Gu, and S. Liu, "Microstructural and mechanical properties of marine soft clay stabilized by lime-activated ground granulated blastfurnace slag," *Applied Clay Science*, vol. 103, pp. 71-76, 2015.
- [43] A. Seco, L. Miqueleiz, E. Prieto, S. Marcelino, B. García, and P. Urmeneta, "Sulfate soils stabilization with magnesium-based binders," *Applied Clay Science*, vol. 135, pp. 457-464, 2017.
- [44] A. Seco, F. Ramírez, L. Miqueleiz, B. García, and E. Prieto, "The use of non-conventional additives in Marls stabilization," *Applied Clay Science*, vol. 51, no. 4, pp. 419-423, 2011.
- [45] D.-H. Shen, C.-M. Wu, and J.-C. Du, "Laboratory investigation of basic oxygen furnace slag for substitution of aggregate in porous asphalt mixture," *Construction and Building Materials*, vol. 23, no. 1, pp. 453-461, 2009.
- [46] Y. Xue, S. Wu, H. Hou, and J. Zha, "Experimental investigation of basic oxygen furnace slag used as aggregate in asphalt mixture," *Journal of hazardous materials*, vol. 138, no. 2, pp. 261-268, 2006.
- [47] A. A. Cikmit, T. Tsuchida, G. Kang, R. Hashimoto, and H. Honda, "Particle-size effect of basic oxygen furnace steel slag in stabilization of dredged marine clay," *Soils and Foundations*, vol. 59, no. 5, pp. 1385-1398, 2019.
- [48] D. H. Diniz, J. M. F. de Carvalho, J. C. Mendes, and R. A. F. Peixoto, "Blast oxygen furnace slag as chemical soil stabilizer for use in roads," *Journal of materials in civil engineering*, vol. 29, no. 9, p. 04017118, 2017.
- [49] M. R. Abdi, "Effects of basic Oxygen steel slag (BOS) on strength and durability of kaolinite," 2011.
- [50] A. Boz and A. Sezer, "Influence of fiber type and content on freeze-thaw resistance of fiber reinforced lime stabilized clay," *Cold Regions Science and Technology*, vol. 151, pp. 359-366, 2018.
- [51] B. C. S. Chittoori, "Clay mineralogy effects on long-term performance of chemically treated expansive clays," The University of Texas at Arlington, 2008.
- [52] T. Y. Elkady and A. A. Shaker, "Role of cementation and suction in the swelling behavior of lime-treated expansive soils," *Journal of Materials in Civil Engineering*, vol. 30, no. 5, p. 04018073, 2018.
- [53] T. Y. Elkady, "The effect of curing conditions on the unconfined compression strength of lime-treated expansive soils," *Road Materials and Pavement Design*, vol. 17, no. 1, pp. 52-69, 2016.

- [54] D. Wang, R. Zentar, and N. E. Abriak, "Durability and swelling of solidified/stabilized dredged marine soils with class-F fly ash, cement, and lime," *Journal of Materials in Civil Engineering*, vol. 30, no. 3, p. 04018013, 2018.
- [55] N. Talluri, A. J. Puppala, S. S. Congress, and A. Banerjee, "Experimental studies and modeling of high-sulfate soil stabilization," *Journal of Geotechnical and Geoenvironmental Engineering*, vol. 146, no. 5, p. 04020019, 2020.
- [56] C.-S. Shon, T. Scullion, W. Blackmon, D. Zhang, and J. R. Kim, "Characterization of Mellowing Process to Control Expansion in High-Sulfate-Bearing Soil," *Transportation Research Record*, vol. 2676, no. 1, pp. 355-364, 2022.
- [57] W. Zhang, J. Ma, and L. Tang, "Experimental study on shear strength characteristics of sulfate saline soil in Ningxia region under long-term freeze-thaw cycles," *Cold Regions Science and Technology*, vol. 160, pp. 48-57, 2019.
- [58] Y. Han *et al.*, "Effect of freeze-thaw cycles on shear strength of saline soil," *Cold Regions Science and Technology*, vol. 154, pp. 42-53, 2018.
- [59] G. Tebaldi, M. Orazi, and U. S. Orazi, "Effect of freeze—thaw cycles on mechanical behavior of lime-stabilized soil," *Journal of Materials in Civil Engineering*, vol. 28, no. 6, p. 06016002, 2016.
- [60] M. Ding, F. Zhang, X. Ling, and B. Lin, "Effects of freeze-thaw cycles on mechanical properties of polypropylene fiber and cement stabilized clay," *Cold Regions Science and Technology*, vol. 154, pp. 155-165, 2018.
- [61] *Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils*, A. S. f. t. a. m. A. D4318-17, 2018.
- [62] *Standard Test Methods for Specific Gravity of Soil Solids by Water Pycnometer*, A. S. f. t. a. m. A. D854-14, 2014.
- [63] *Soil-Lime Testing Eades_Grim Test*, Tex-121-E, Construction Division, Austin, TX, 2002.
- [64] *Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12,400 ft lbf/ft³ (600 kN-m/m³))*, A. S. f. t. a. m. A. D698-12, 2015.
- [65] *Determining Soil pH*, Tex-128-E, Austin, TX., 1999.
- [66] *Determining Sulfate Content in Soils-Colorimetric Method*, Tex-145-E, Construction Division, Austin, TX, 2005.
- [67] *Standard Test Method for Unconfined Compressive Strength of Cohesive Soil*, A. S. f. t. a. m. A. D2166/D2166M-16, 2016.
- [68] *Tube Suction Test*, Tex-144-E, Materials and Test Division, Austin, TX, 2020.
- [69] *Standard Test Methods for Freezing and Thawing Compacted Soil-Cement Mixtures*, A. S. f. t. a. m. (ASTM)D560/D560M-16, 2016.
- [70] *Pulse Velocity Through Concrete*, A. C-597, US, 2003.
- [71] L. Tang, S. Cong, L. Geng, X. Ling, and F. Gan, "The effect of freeze-thaw cycling on the mechanical properties of expansive soils," *Cold Regions Science and Technology*, vol. 145, pp. 197-207, 2018.
- [72] *Determining Plastic Limit of Soils*, Tex-105-E, Construction Division, Austin, TX, 1999.
- [73] F. H. Chen, *Foundations on expansive soils*. Elsevier, 2012.
- [74] J. Ren, Y. Lai, R. Bai, and Y. Qin, "The damage mechanism and failure prediction of concrete under wetting–drying cycles with sodium sulfate solution," *Construction and Building Materials*, vol. 264, 2020, doi: 10.1016/j.conbuildmat.2020.120525.
- [75] F. Santos, L. Li, Y. Li, and F. Amini, "Geotechnical Properties of Fly Ash and Soil Mixtures for Use in Highway embankments," *World of Coal Ash (WOCA) Conference, Denver, CO, USA*, pp. 125-136, 2011.
- [76] A. M. A. Ezreig, M. A. Mohamad Ismail, and K. I. A. Ehwaitat, "Hydrophobic Effect of Soil Stabilization for a Sustainable Subgrade Soil Improvement," *Materials*, vol. 15, no. 9, p. 3087, 2022.

- [77] L. Sharma, N. Sirdesai, K. Sharma, and T. Singh, "Experimental study to examine the independent roles of lime and cement on the stabilization of a mountain soil: A comparative study," *Applied Clay Science*, vol. 152, pp. 183-195, 2018.
- [78] F. Zhu, Z. Li, W. Dong, and Y. Ou, "Geotechnical properties and microstructure of lime-stabilized silt clay," *Bulletin of Engineering Geology and the Environment*, vol. 78, pp. 2345-2354, 2019.
- [79] M. R. Abdi, A. Askarian, and M. Safdari Seh Gonbad, "Effects of sodium and calcium sulphates on volume stability and strength of lime-stabilized kaolinite," *Bulletin of Engineering Geology and the Environment*, vol. 79, pp. 941-957, 2020.
- [80] Y. Zhu, X. Yu, L. Gao, J. Chen, and M. D. Cotugno, "Unconfined Compressive Strength of Aqueous Polymer-Modified Saline Soil," *International Journal of Polymer Science*, vol. 2019, pp. 1-11, 2019, doi: 10.1155/2019/9137069.
- [81] H. A. Mboya, C. K. King'onde, K. N. Njau, and A. L. Mrema, "Measurement of Pozzolanic Activity Index of Scoria, Pumice, and Rice Husk Ash as Potential Supplementary Cementitious Materials for Portland Cement," *Advances in Civil Engineering*, vol. 2017, pp. 1-13, 2017, doi: 10.1155/2017/6952645.
- [82] C.-S. Shon, Y. s. Jung, and D. Saylak, "Evaluation of synthetic aggregates using off-ASTM specification ashes as road base course materials," *Construction and Building Materials*, vol. 38, pp. 508-514, 2013, doi: 10.1016/j.conbuildmat.2012.08.014.
- [83] H.-S. Shang and T.-H. Yi, "Freeze-thaw durability of air-entrained concrete," *The Scientific World Journal*, vol. 2013, 2013.
- [84] C.-S. Shon, A. Abdigaliyev, S. Bagitova, C.-W. Chung, and D. Kim, "Determination of air-void system and modified frost resistance number for freeze-thaw resistance evaluation of ternary blended concrete made of ordinary Portland cement/silica fume/class F fly ash," *Cold Regions Science and Technology*, vol. 155, pp. 127-136, 2018.
- [85] G.-y. Li *et al.*, "Freeze-thaw resistance of eco-material stabilized loess," *Journal of Mountain Science*, vol. 18, no. 3, pp. 794-805, 2021.