

**THE COMBINED EFFECT OF PARTICLE SIZE AND
STABILIZER OF BOFS ON HIGH-SULFATE BEARING
KAOLIN CLAY**

Aliya Abzal, B.Sc.

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



**School of Engineering and Digital Sciences Department of Civil &
Environmental Engineering Nazarbayev University**

53 Kabanbay Batyr Avenue,
Astana, Kazakhstan, 010000

Supervisors: Chan-Seon Shon

Alfredo Satyanaga

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DECLARATION FORM

I hereby, declare that this manuscript, entitled “The Combined Effect of Particle Size and Stabilizer of BOFS on High-Sulfate-Bearing Kaolin Clay ”, is the result of my own work except for quotations and citations which have been duly acknowledged.

I also declare that, to the best of my knowledge and belief, it has not been previously or concurrently submitted, in whole or in part, for any other degree or diploma at Nazarbayev University or any other national or international institution.



Name: Aliya Abzal

Date: 28.03.2025

ABSTRACT

Stabilization of high-sulfate-bearing soils with traditional calcium based stabilizers have been used by researchers over the years. However, recent failures in structures like heaving and the formation of expansive minerals have raised concerns about the long-term stability of calcium-based stabilizers in sulfate-rich environments. Given these limitations, alternative stabilizing agents have gained attention. One of them is Basic Oxygen Furnace Slag (BOFS), which has emerged as promising alternatives due to their pozzolanic properties and ability to mitigate sulfate-induced reactions.

The study aims to evaluate the performance of Basic Oxygen Furnace Slag (BOFS) as an alternative to traditional calcium-based stabilizers. Correspondingly, the primary goal of this research is to study the combined effect of particle size and stabilizer effect of BOFS on the mechanical properties and durability characteristics of stabilized soil. Further, the developed experimental program consisted of geotechnical characterization, unconfined compressive strength (UCS), one-dimensional swelling, and mineralogical examination using X-ray Diffraction (XRD) and Scanning Electro Microscopy (SEM).

Kaolin clay which is made artificially with high sulfate content was stabilized mechanically using BOFS of different particle size fractions, and the effects of curing days, particle sizes, and volumetric and mass-based BOFS addition were evaluated. Unconfined compressive strength (UCS) test results demonstrated a significant increase in compressive strength, particularly samples with finer particle size fractions. 1D-Swelling test also proved the hypothesis that BOFS as stabilizer can effectively reduce volume changes, with the finest BOFS fractions minimizing the expansiveness of the soil. XRD and SEM analyses confirmed the formation of cementitious compounds such as calcium silicate hydrates (CSH), contributing to strength enhancement and reduced swelling as well as formation of expansive ettringite minerals.

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Chapter 1 - Introduction

1.1. Overview

This master's of science (MSc) degree thesis comprises a comprehensive literature review, key research concepts, test results, a future work plan, and other detailed information on the master's thesis. It covers introducing steel production by-products, particularly Basic Oxygen Furnace Slag (BOFS), its main properties, and its applications as a stabilization material. Information on the unique characteristics of working with sulfate-bearing soil is also outlined. Laboratory tests evaluate the strengths and weaknesses of BOFS as a stabilizing material and its particle size effect on the mechanical properties such as unconfined compressive strength and one-dimensional swelling for sulfate-bearing kaolin clay. The research aims to fill the gap in the existing literature by testing these parameters on sulfate-bearing kaolin clay soil, as similar studies have not been conducted on this type of soil before.

1.2. Problem Statement

Soils with high sulfate content pose significant challenges in highway pavement construction by causing severe damage to the subgrade layer. Traditional calcium-based stabilizers like lime and cement have been proven ineffective in stabilizing this soil type. They cause ettringite formation between chemical reactions between sulfates and alumina in soil and calcium components in the stabilizer. In soil stabilization, ettringite formation is unfavorable as it causes expansive swelling, cracking, and reduced strength and durability values. This ettringite-induced pavement distresses can become the least favorable when exposed to moisture and temperature variations. The continuous process of renovating and fixing these damaged pavements is costing a severe amount of money to road construction companies and governments [1]. Therefore, innovative subgrade soil modification methods are needed to address this issue to prevent roadway damage, increase its strength, and minimize the changes in its content and volume in different weather conditions [2]. One of these methods is exploring the BOFS, a steel production residue, as a potential stabilizing material. Considering that calcium-based stabilizers are proven to have environmental, resource utilization, and economic drawbacks, BOFS is attracting particular attention due to its extensive global production [3]. For example, in Brazil, 3.4 Mt of BOFS are generated from roughly 80% of the 33.9 Mt of steel annually. Furthermore, employing BOFS as

an essential construction material diminishes its disposal volume by minimizing the impact on ecosystems and mitigating the environmental consequences of waste materials [4].

Moreover, previous research using BOFS to stabilize problematic soil indicates that BOFS can be an alternative stabilizing material replacing traditional stabilizers like cement and lime. For example, researchers [5] reported that finer particle size of BOFS and extended curing period increased unconfined compressive strength (UCS). Others also reported that adding BOFS to kaolin clay singularly or combined with lime increased UCS and freezing and thawing (F-T) resistance [6].

However, the effect of BOFS as a stabilizer and its particle size interaction with high-sulfate-bearing soil remains under-researched. This thesis investigates the combined impact of BOFS particle size and its stabilizing properties on the mechanical behaviors and durability of high-sulfate-bearing kaolin clay. As a result, the thesis work contributes to developing more effective soil stabilization techniques for sulfate-bearing soils.

1.3. Objectives

The thesis aims to achieve the outlined objectives as follows:

- Introduction to high - sulfate bearing soil modification, Basic Oxygen Furnace Slag (BOFS) as a stabilizer, existing strength prediction methods, and swelling behavior of saline soil.
- The experimental program plans to evaluate the combined effect of particle size and BOFS stabilizer on soil's mechanical behavior.
- Execution of the experimental program according to the experimental plan design and collection of the data from the laboratory tests as planned: (i) material characterization, (ii) engineering properties of stabilized kaolin clay, (iii) evaluating mechanical properties of mixtures
- Analysis of collected data to identify trends and test the hypotheses of the thesis
- Forming conclusions on the effectiveness of BOFS as a stabilizer and its particle size effect on saline soil
- Discussion of the applications and future developments of the research work.

1.4. Hypothesis

Based on the research objectives and through reviewing the existing literature, the following hypotheses are formulated:

Hypothesis 1: Dual Function of BOFS in Stabilized Clay

BOFS is hypothesized to exhibit a dual functionality that contributes to both strength improvement and swelling reduction in stabilized high-sulfate-bearing kaolin clay.

- Chemical Function

Free calcium oxide (CaO) in reaction with water forms Ca(OH)_2 , which initiates pozzolanic reactions with the clay matrix, resulting in the formation of cementitious compounds. This chemical reaction strengthens the soil and helps prevent swelling by filling in the gaps and improving its overall structure.

- Physical Function

The possibility of coarse BOFS particles act as aggregates that can enhance the soil matrix and water movement in voids, which also can results in enhancing the volume stability and reduced swelling.

Hypothesis 2: The BOFS Effect on Compressive Strength

With the addition of BOFS, the stabilized soil is expected to show a significant increase in compressive strength.

- Effect of Particle Size

The particle size of BOFS is expected to have an influence on the UCS values of the stabilized mixtures. Finer particles are expected to improve strength by promoting better particle bonding and increasing pozzolanic activity, as they fill voids more efficiently. In contrast, the role coarser particles may contribute less to strength development.

- Time-Dependent Strength Gain

The strength of BOFS-stabilized clay is expected to increase gradually over the curing period as a result of series of reactions.

Hypothesis 3: Swelling Control by BOFS

BOFS particles are expected to reduce swelling, and improve soil stability in sulfate-rich environments.

- Chemical Reactions

The hydration of free CaO in BOFS forms Ca(OH)_2 , which in reaction with clay's silicate and illuminant phases, leading to the formation of CSH and CAH. These products fill voids and densify the soil matrix, and minimizes the water absorption.

- BOFS Particle Size Effect

The BOFS's particles will affect the water movement and can reduce void spaces within the soil. As it limits the ability of the soil to expand, it is expected that the formation of expansive minerals will also be prevented.

Chapter 2 - Literature Review

2.1. Overview

This chapter provides an extensive literature review. The primary goal of this review is to collect relevant data that will establish a strong background for the research area and offer a foundation for analyzing laboratory test results. This is achieved by gathering information from secondary sources, including published research articles, books, laboratory reports, specifications, and guidelines. The central focus of this review will be on stabilizing sulfate-bearing clay using a BOFS as a stabilizer and analyzing its particle size effect. Furthermore, in-depth information on topics such as high sulfate-bearing kaolin clay, the industrial significance of BOFS as a stabilizer, the importance of particle size, and existing strength prediction models based on particle size will be presented.

2.2. Cement-Based Soil Stabilization Techniques

Traditionally, soil science was focused primarily on optimizing the usage of nutrients in agriculture. This emphasis on soil as a biological system for plants and other living organisms has made it challenging to find data for its application as a subgrade material in road infrastructure. Recognizing this gap in the literature, some researchers suggested the collaboration between road engineering and soil science as it will result in the best road design and better pavement performance [7].

Soil stabilization is a critical process in road infrastructure, as the chemical and physical properties of the subgrade soil significantly influence roadways' final quality and durability. The main goal of soil stabilization is to enhance the engineering properties of soil and develop its strength characteristics. Nowadays, soil stabilization can be explained as modifying soil properties using biological, mechanical, and chemical methods [8].

Among these methods, one of the most popular and widely used approaches has been mechanical stabilization with calcium-based materials such as lime and cement. Lime stabilization, in particular, is an excellent method to improve soil strength, enhance its resistance to moisture, decrease swell, and make it more resilient. It is mainly used in highway construction [9]. The overall process of lime stabilization is shown in Figure 2.1.

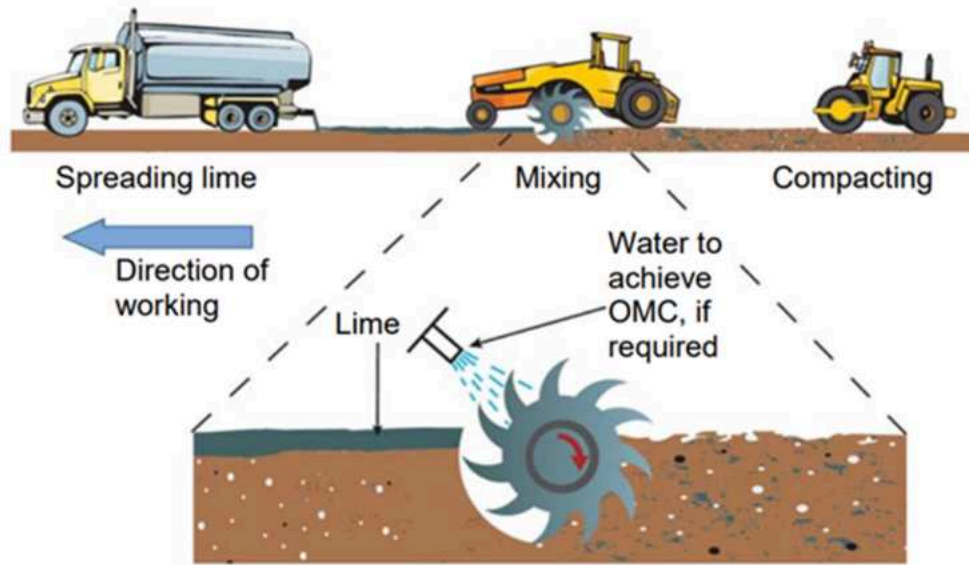


Figure 2.1. Schematic illustration of the lime stabilization process [9].

2.3. Ettringite Formation

Recent road infrastructure failures made engineers doubt the sustainability of calcium-based stabilizers, particularly in high-sulfate soils [10]. High sulfate soils pose significant challenges in highway pavement construction due to adverse chemical reactions between soil components (alumina, gypsum, and sodium sulfate) and calcium-based stabilizers (lime or cement). These reactions can lead to the formation of ettringite, as presented in Figure 2.2. This mineral causes “ettringite/sulfate-induced heaving,” resulting in severe pavement distress when this ettringite formation reaction is exposed to varying moisture levels, humidity, and temperature, where ettringite-induced heaving is highly problematic [9]. The chemical structure of ettringite is given in Figure 2.3

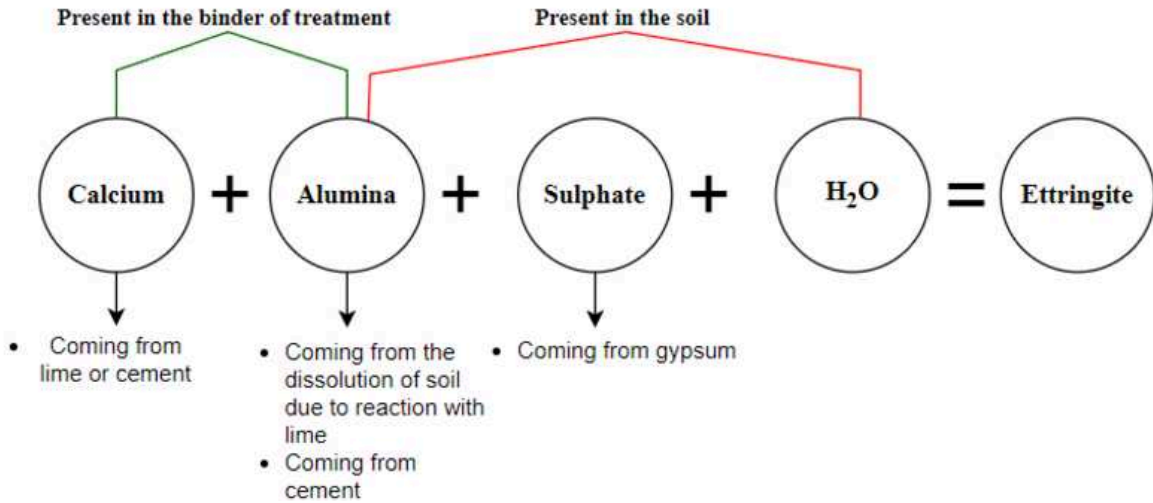


Figure 2.2. Ettringite formation mechanism in sulfate-bearing soil treated with cement and lime [9].

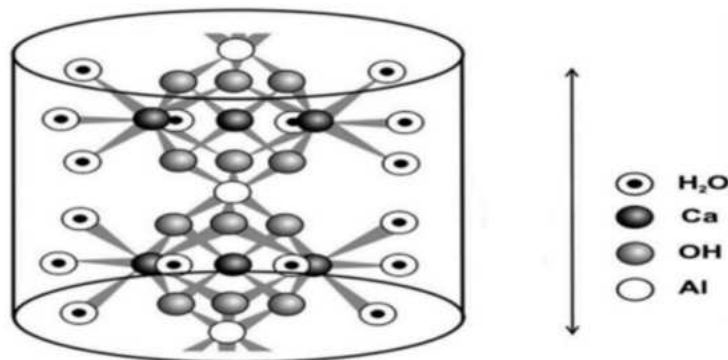


Fig 2.3. Chemical structure of ettringite [9].

Ettringite behavior is controlled by many factors such as water content, pH, sulfate content, and temperature. As mentioned above, minerals like ettringite and thaumasite are products of the hydration process, in which access to inadequate amounts of water can cause swelling. Swelling in soil consequently results in soil heaving.

Given the limitations of traditional calcium-based stabilizers due to ettringite formation, alternative materials like basic oxygen furnace slag (BOFS) have been explored. The next section discusses BOFS properties and its potential role in mitigating sulfate-induced swelling.

2.4. Basic Oxygen Furnace Slag (BOFS) as a Stabilizer

Steel slag is indeed a significant by-product of the steelmaking process. It is formed during the steelmaking process due to the separation of molten steel from any impurities. A detailed description of steel production routes is shown in Figure 2.4.

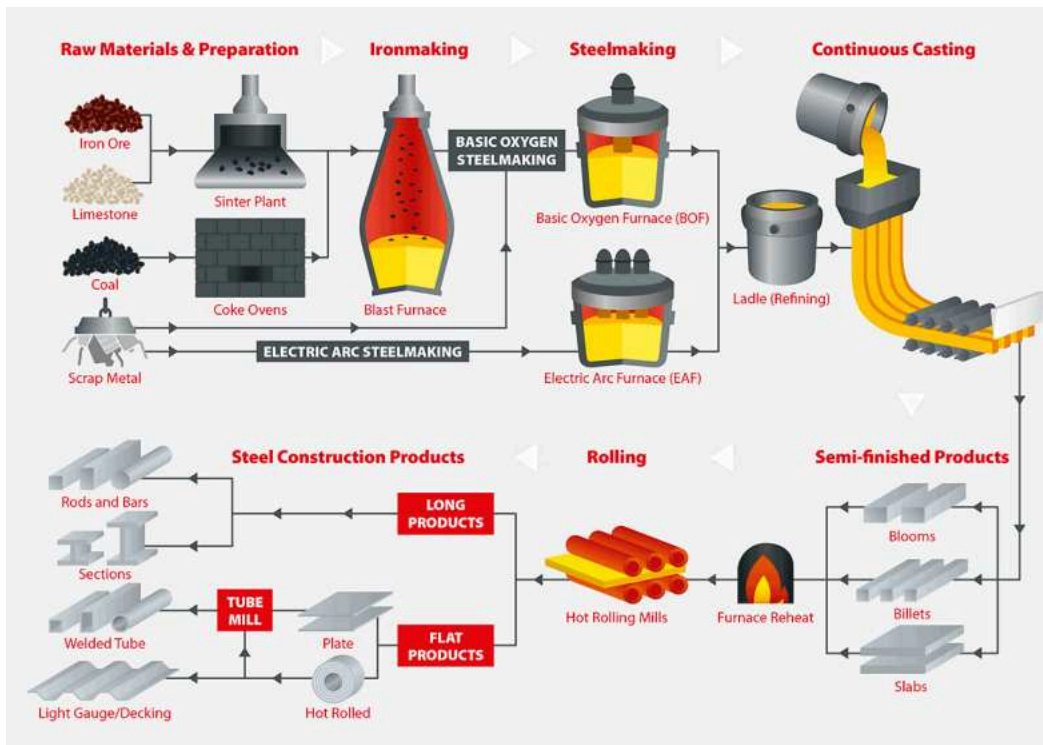


Figure 2.4. Steelmaking processes [11].

The global output of steel slag is estimated to be 1600 million tons annually. Due to its large volume and potential negative environmental impact, steel slag, particularly BOFS, is a major environmental challenge. The fact that such volumes are generated worldwide underlines the need for effective management strategies to minimize its impact on the environment, although it can be used in a variety of applications including road construction, cement production, and agricultural use [12].

The characteristics and composition of BOFS can vary widely depending on the location and production time. These variations are primarily due to the differing nature of the ores and scrap materials used in the process and the unique chemical reactions and mechanisms involved [13]. The typical elemental and molecular composition of BOFS is illustrated in Figure 2.5,

where calcium oxide (CaO) is the most abundant component, followed by iron-containing compounds and silicon dioxide (SiO₂). Additionally, magnesium oxide (MgO) is also present in BOFS, and, along with calcium and silicon-containing compounds, it gradually dissolves to produce silicon hydroxide (Si(OH)₄), contributing to the alkaline properties of the solution.

These components collectively play a crucial role in elevating the pH and increasing the alkalinity of BOFS solutions, which are essential characteristics that make BOFS effective as a soil stabilizer [14].

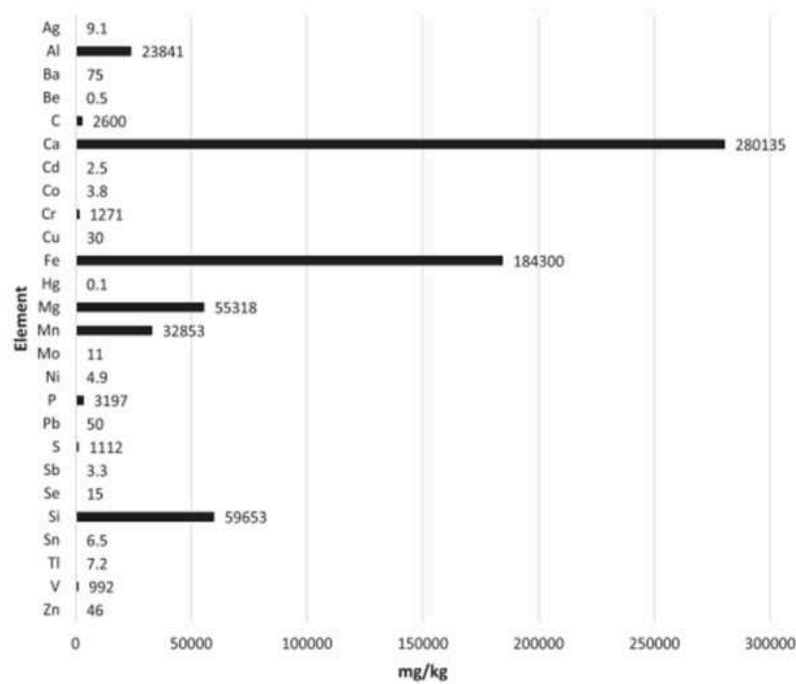


Figure 2.5. Average Elemental composition of BOFS [15].

In this matter, steel industry by-products, ground granulated blast furnace slag (GGBFS), and BOFS are getting more attention. Using these materials is the best way to utilize them. Using the waste materials for other purposes will give waste management opportunities and decrease the environmental impact of cement production [4]. Through different tests and methods, scientists proved that BOF slag is nontoxic and environmentally harmless [15]. Even though lime and cement stabilization methods are prevalent in roadway engineering, they have recently been reconsidered due to high environmental and economic costs. For instance, Portland cement

manufacture causes much damage to the environment through CO₂ emissions and the use of natural resources, and its limited source is one of the problems that should be considered [16].

2.5. Particle Size Effect of BOFS

In materials engineering, the particle size of granular materials plays an important role as it is one of the many factors that affect a material's mechanical behavior. Surface texture, angularity, and overall shape of materials determine their mechanical response [17].

Cikmit et al. in their research specifically investigated the effect of the particle size distribution of BOFS in the stabilization of dredged marine clay, and they obtained such outcomes [16]:

- According to its particle size distribution, BOFS can be divided into two categories: fine particles (<9.5 mm) that have more cementitious properties and coarse particles (>9.5 mm) that behave similarly to aggregates.
- The different improvements in strength were due to variations in specific surface areas
- The influence extends beyond particle size distribution alone. The impact of the curing period on the outcome is noteworthy. The subsequent figure, Figure 2.6, distinctly illustrates this. As can be seen, a longer curing time and smaller particle sizes make the samples stronger and more fragile simultaneously.

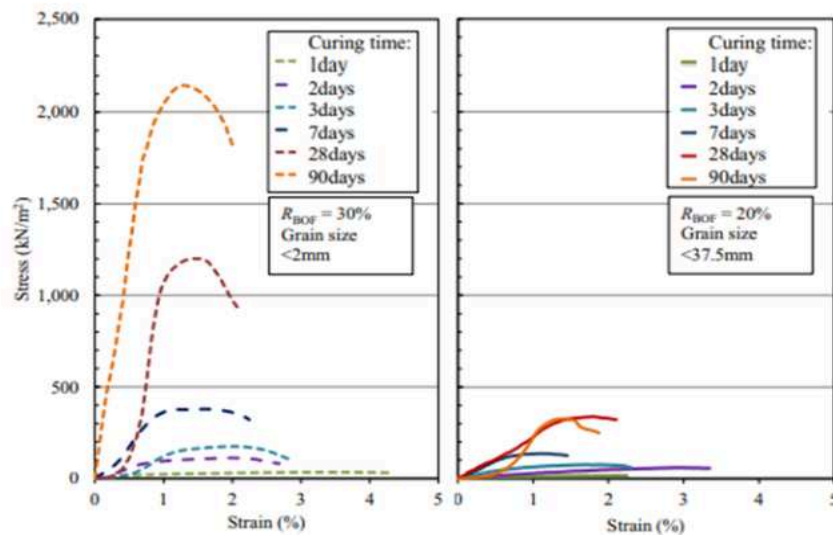


Figure 2.6. UCS Test results for soils stabilized with maximum 2 mm and 37.5 mm particle sizes [16].

Figure 2.7 shows that stabilized soils generally have a higher flow value with the same initial moisture content when stabilized with larger maximum particle sizes, excluding the 37.5mm maximum grain size case. This also contributes to the conclusion that material's particle sizes significantly affect their behavior.

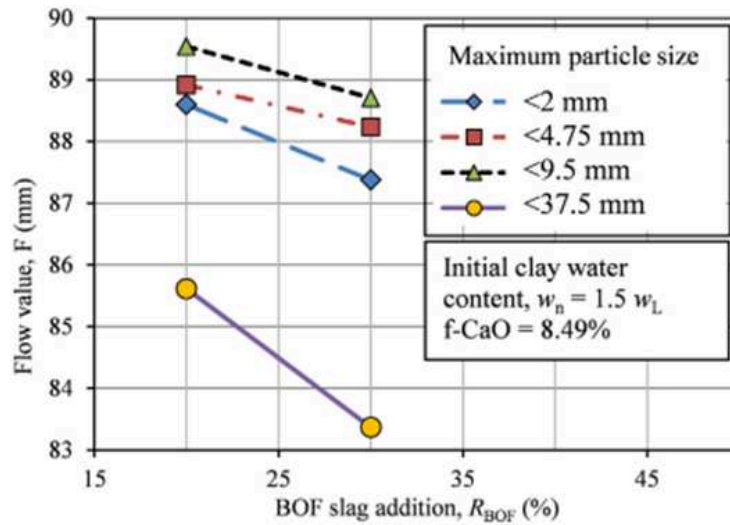


Figure 2.7. Flow value of stabilized dredged marine clay with different BOFS maximum particle sizes [16].

2.6. Kaolin Clay Behavior in Stabilization

Kaolin clay, also known as China clay, primarily comprises kaolinite mineral, a hydrous aluminosilicate ($Al_2Si_2O_5(OH)_4$). In its natural form, kaolin clay is characterized by its softness and white, powdery appearance resulting from kaolinite crystals. The flattened kaolin crystals vary from 0.1 to 10 micrometers or even larger in size. While kaolinite is the predominant mineral in kaolin, it often contains other minerals such as muscovite, quartz, feldspar, and anatase. Kaolin clay is considered a crucial mineral with diverse industrial applications, including pottery, the paper industry, paints, pharmaceuticals, and many others [18]. Kaolin is a hydrated aluminum silicates' weathering product that widely occurs in nature and has a chemical composition.

Kaolin clay is chemically unreactive under everyday conditions [19]. Minimal

shrink-swell capacity is one of the defining properties of kaolin as it absorbs water quickly, and immediate shrinkage occurs when the water drifts away [20]. Kaolin is becoming more popular in the engineering construction industry. It can be used as an additive product in concrete mixtures and a super filler in cement systems. In concrete mixtures, it gives an aesthetically pleasing white color to the mixture, helps to increase the strength, and prolongs the design life of concrete. In cement mixtures, kaolin clay can increase the compressive strength and other mechanical properties of concrete products because of its high pozzolanic activity, accelerating the hydration process. External water content is a significant contributor to stabilized saline soil's devastation. Various water delivery methods lead to varying failure patterns. Erosion will not be noticeable without external water, but UCS will progressively decline as the frequency of freeze-thaw cycles increases [21].

In recent years, kaolin clay usage in pavement construction has gained increasing attention due to its potential to enhance the engineering performance of soil, particularly in concrete mixtures [22]. It has been found effective in reducing cracking and improving durability, making it a valuable material in road construction.

Recently, laboratory experiments have begun using kaolinite by dosing it with varying levels of gypsum to produce an artificial sulfate clay system. This approach has become increasingly common as researchers aim to better understand the behavior of sulfate-bearing soils under stabilization. Studies have shown that clay soils containing 1–10% sulfates by mass tend to exhibit significant swelling when treated with calcium-based stabilizers. This swelling is most pronounced within the first 28 days of curing, particularly in artificial kaolinite–gypsum systems, which showed noticeable volume increases [23]. These findings highlight the challenges involved in stabilizing sulfate-rich clays.

Kaolin clay, known for its moderate plasticity, often requires stabilization to meet the performance requirements of construction applications. Researchers have found that using stabilizers such as cement and fly ash (FA) can significantly improve the strength of kaolin clay [24]. Their study emphasized the importance of soil stabilization in enhancing the engineering properties of kaolin, making it more suitable for use in construction projects.

Taken together, these findings highlight the importance of understanding how kaolin clay behaves under different stabilization conditions, especially when sulfates are present. As research

in this area continues to advance, it becomes increasingly clear that developing effective stabilization strategies is key to optimizing the use of kaolin in construction.

2.7. Strength Estimation Methods

Shear strength is one of the most critical engineering parameters in the design of pavement subgrade layers. To predict the strength development of stabilized soils, a variety of models have been developed—ranging from simple empirical equations to advanced machine learning algorithms. The primary motivation behind creating these models is the need for accurate strength estimation, which is vital for optimizing material performance and ensuring long-term durability of construction projects. One notable method that has gained attention is the strength estimation equation proposed by Arlyn Cikmit et al. (2019). Their model offers a systematic approach for estimating the strength of BOFS-stabilized soils by considering the specific surface area associated with various BOFS particle sizes. The process for estimating the strength of soil stabilized with BOFS is outlined as follows:

Step 1. Determine the particle size distribution

The grain size distribution of BOFS is determined according to the ASTM E11 Test Sieves. The weight of material retained in each sieve size should be determined.

Step 2. Unconfined Compressive Strength (UCS) Test #1

In this study, the first unconfined compressive strength will be carried out to determine the effective grain size boundary of BOFS. The BOF slag addition rate will be used:

$$R_{BOFS(volumetric)} = \frac{V_{BOFS}}{V_{soil} + V_{water} + V_{BOFS}} \times 100 \quad (\%)$$

Where:

V_{soil} - a solid volume of soil

V_{water} - a volume of water

V_{BOFS} - a solid volume of BOF slag

After that, the UCS test will be carried out.

Step 3. Unconfined Compressive Strength (UCS) Test #2

Mix design proportions of samples for UCS test #2 should be created according to the rate of addition using the next equation:

$$R_{BOFS (mass)} = \frac{M_{BOFS(GB)}}{M_{soil} + M_{water} + M_{BOFS}} \times 100 \quad (\%)$$

Where:

$M_{BOFS(GB)}$ - a mass of chemically active BOFS [boundary was taken as 9.5 mm]

M_{soil} - the mass of soil

M_{water} - the mass of water

M_{BOFS} - the mass of BOFS

4. Calculate Specific Surface Area (SSA)

To calculate the SSA of BOFS, Cikmit et al. (2019) used Herdan's (1953) ball-shape-like assumption equation for granular materials, as shown below:

$$SSA = \frac{6}{\rho} \sum_{i=1}^n \left(\frac{w_i}{x_i} \right)$$

n - the number of intervals in the grain size distribution

w_i - weight of retained fraction size I

x_i - harmonic mean size distribution

ρ - density of material

Harmonic mean size distribution is calculated using the following equation below:

$$x_i = \left(\frac{(x_h^2 + x_j^2) * (x_h + x_j)}{4} \right)^{1/3}$$

Where:

x_h - upper grain size interval (*mm*)

x_j - lower grain size interval (*mm*)

Chapter 3 - Experimental Program

3.1. Overview

The experimental program plays a vital role in identifying the optimal combination of stabilizer type and BOFS particle size for effective soil stabilization in sulfate-rich environments. This study was designed to address the challenges of stabilizing high-sulfate-bearing kaolin clay and to explore the combined effects of the physical and chemical characteristics of BOFS on the soil's mechanical strength and durability. BOFS was selected as the stabilizing agent due to its environmental and economic benefits. The research includes material characterization of both soil and BOFS, along with a series of mechanical and durability tests—such as Unconfined Compressive Strength (UCS), one-dimensional swelling (1D-swelling), and mineralogical analysis. For a systematic investigation, the experimental program is organized into four main stages.

1. Material selection and characterization: Evaluate physical and chemical properties of kaolin clay, gypsum, and BOFS
2. Soil stabilization analysis: Examine optimal addition rates and particle sizes of BOFS
3. Strength and durability Testing: Include unconfined compressive strength (UCS) and One-Dimensional (1-D) swelling tests
4. Mineralogical and microstructural analysis: Uses X-ray diffraction (XRD) and scanning electron microscopy (SEM) to assess microstructural and phase diagrams

In theory, the research concludes with the development of a strength prediction model that incorporates both the mass-based and volumetric addition rates of BOFS.

3.2. Methodology

The experimental methodology adopts a systematic approach to evaluate the effectiveness of BOFS as a stabilizer for high-sulfate-bearing kaolin clay. The study encompasses geotechnical characterization, mechanical strength testing, swelling behavior assessment, and mineralogical

analysis. Figure 3.1 presents an overview of the methodology, detailing each step of the experimental process.

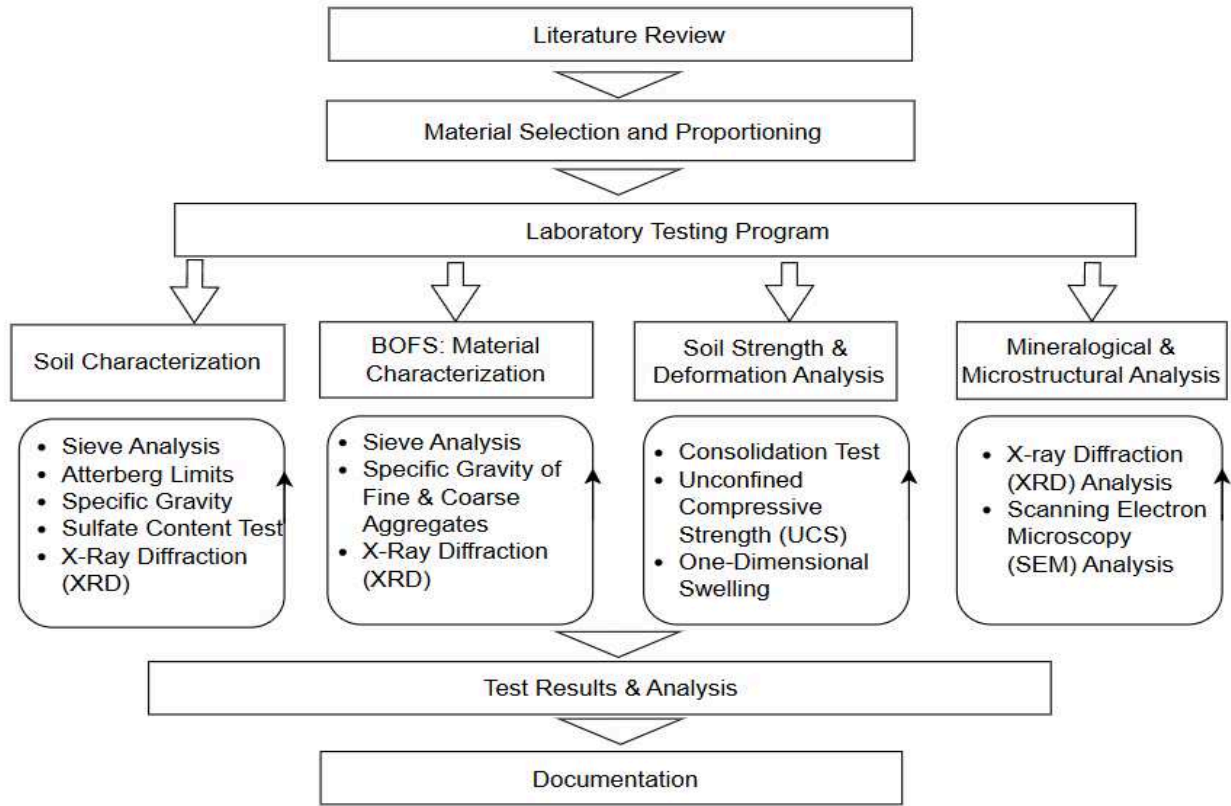


Figure 3.1. Methodology flowchart of the experimental program.

1. Material selection and preparation: This phase involved selecting materials, including high-sulfate-bearing kaolin clay and Basic Oxygen Furnace Slag (BOFS). The appropriate mix designs and proportions were determined based on preliminary studies and laboratory tests.

2. Mix Design and sample preparation: This phase includes pre-mix design to determine an optimum BOFS replacement (volumetric) ratio based on the consolidation test and optimal particle size classifications based on the UCS test. Based on the obtained test results using pre-mx design tests, the BOFS particle sizes and replacement ratio were determined for the specified experiments, such as soil strength, swelling, mineralogical and microstructural analyses, and strength prediction model.

3. Laboratory Testing Program: This phase includes the laboratory testing program, which was divided into three main categories:
 - Geotechnical characterization: for material characterization, geotechnical evaluation included sieve analysis, Atterberg limits, cone penetration, sulfate content determination, specific gravity measurement, and standard proctor compaction tests.
 - Mechanical strength and deformation analysis: To assess the resistance and durability of stabilized high-sulfate-bearing kaolin clay, consolidation, unconfined compressive strength (UCS), and one-dimensional swelling tests were conducted.
 - Mineralogical and microstructural Analysis: XRD and SEM Analyses were chosen for this stage to understand the stabilized soil's microstructural changes after the swelling test.

4. Data Analysis and Interpretation: The experimental program results obtained from the laboratory tests were analyzed to evaluate the effectiveness of BOFS as a stabilizing agent. The data were interpreted to determine improvements in strength, durability, and resistance to sulfate-bearing soil conditions. At last, all findings were compiled and documented systematically for documentation. This phase included the preparation of graphs, tables, and other data visualization aids for a clear presentation of results.

3.3. Materials

The materials used in this study include kaolin clay, gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$), BOFS, and water. Each material was carefully selected for its geotechnical properties and its relevance to sulfate-rich soil stabilization.

Kaolin clay, a high-plasticity soil, serves as the primary material in this research. It was selected due to its common use in stabilization studies and its known sensitivity to sulfate-induced swelling, making it well-suited for evaluating the effectiveness of BOFS as a stabilizer. The kaolin clay used was sourced from a commercial supplier and classified as high

plasticity clay (CH) based on Atterberg limits and sieve analysis. Its fine-grained nature ensures consistency in the testing environment, enabling precise assessment of the stabilization outcomes.

Gypsum was incorporated to replicate a high-sulfate soil condition. Based on findings from previous studies, a 10% gypsum content was selected to provide sufficient sulfate levels to induce ettringite formation—one of the main challenges in stabilizing sulfate-bearing soils.

The sulfate concentration in the artificial soil mixture was set at 25,560 ppm, classifying it as a Level 3 sulfate soil, representing extreme sulfate conditions commonly found in problematic subgrade soils.

BOFS, an industrial by-product from the steelmaking process, is the primary stabilizing agent in this study. It was sourced from JSC ArcelorMittal Temirtau, Kazakhstan, where six different types of BOFS were analyzed. These included:

- Batch 2 fresh BOFS (aged up to 6 days)
- Batch 2 stockpiled BOFS (aged 3 months)
- Top BOFS (6-10 years aged)
- Middle BOFS (up to 20 years old)
- Bottom BOFS (over 20 years old)
- Batch 2 fresh BOFS (aged 3 months under wet/dry cycles)

Fresh BOFS was chosen for this experiment due to its higher reactivity and cementitious properties, which are essential for effective soil stabilization. To evaluate the influence of particle size on strength development and swelling reduction, the BOFS was sieved and categorized into various size fractions, ranging from 25 mm to #100 mesh. Its chemical composition was also analyzed, revealing significant amounts of calcium oxide (CaO), iron oxide (Fe₂O₃), silica (SiO₂), and magnesium oxide (MgO)—key components that contribute to pozzolanic activity and stabilization reactions.

Tap water was used for preparing the test specimens and carrying out the lab experiments. The water content was controlled carefully, and specific ratios were used during the soil mixing and testing process. The water-to-soil ratio was decided based on the Atterberg limit test—the water content used was 1.5 times of the liquid limit ($1.5 \times LL$).

Using these materials together helps create a controlled setup to check how well the BOFS-stabilized clay performs in terms of strength, swelling, and durability.

3.4. Materials & Geotechnical Characterization

The baseline properties of kaolin clay and BOFS, sieve analysis, Atterberg limits, sulfate content measurement, specific gravity tests, and XRD analysis were performed.

3.4.1. Basic Oxygen Furnace Slag (BOFS)

The testing methods for sieve analysis, specific gravity, XRD, and XRF analysis for BOFS are presented below.

3.4.1.1. Sieve Analysis

Sieve analysis was performed to assess the gradation of BOFS per ASTM C136, the Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates [25]. The primary purpose of this method was to evaluate the coarser fraction of the material and its suitability for working with large sizes of material. For that matter, the high-capacity sieve shaker was used to sieve BOFS, which is shown in Figure 3.2 below.



Figure 3.2. High-Capacity Sieve Shaker used for BOFS Sieving.

For this analysis, 67 kilograms of BOFS was sieved using the high-capacity sieve shaker. The particle size distribution graph for BOFS is presented in Figure 3.3. The BOFS samples contained a balanced mix of fine and coarse particles. The weight of BOFS retained on each sieve was later utilized in strength prediction calculations. The particle size distribution of BOFS

is critical in influencing its stabilization potential. According to different studies, larger particles are expected to primarily contribute to mechanical reinforcement, while finer particles enhance chemical reactivity.

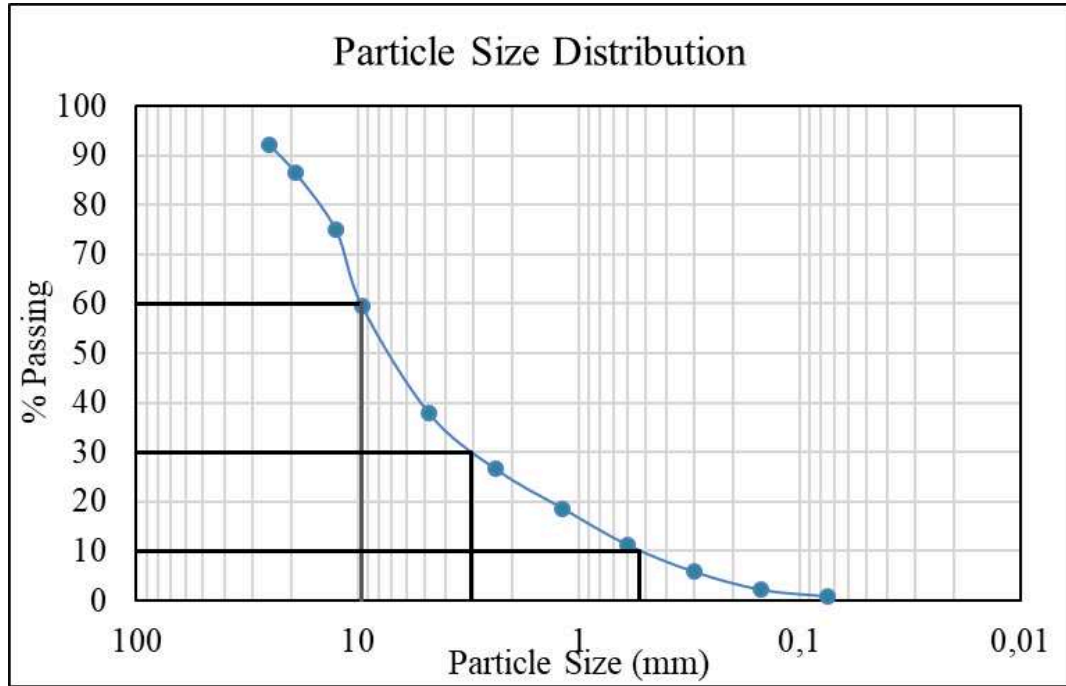


Figure 3.3. Particle Size Distribution of BOFS.

3.4.1.2. Specific Gravity

The specific gravities of BOFS were determined separately for its coarse and fine BOFS particles according to AASHTO T 85 and AASHTO T 84, respectively [26,27]. The specific gravity values of BOFS materials ranged from 3.22 to 2.98. The average value of 3.1 for specific gravity and 5.30 g/cm^3 for absolute dry density were used further. The fragments of the test process for specific gravity test are shown below in Figure 3.4.



Figure 3.4. Specific gravity test of BOFS materials.

3.4.1.3. XRD Analysis

The XRD analysis was performed on BOFS to determine the mineralogical compositions, focusing on calcium oxides, silicates, and iron compounds. The high content of lime, hematite, and quartz in crystalline phases was found in BOFS material.

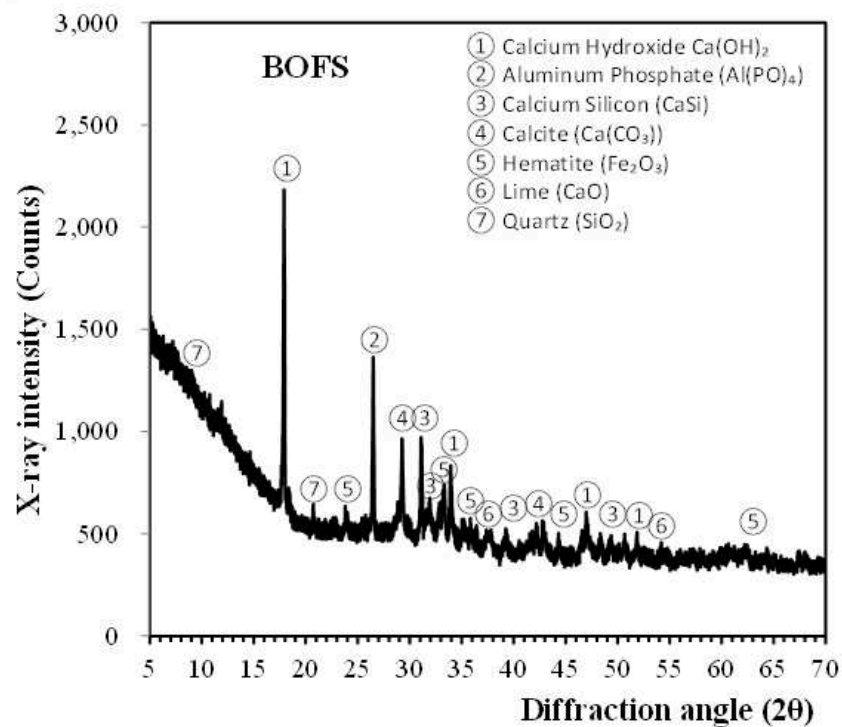


Figure 3.5. Crystalline phases of BOFS materials.

3.4.1.4. XRF Analysis

The chemical composition of BOFS material was analyzed by PANalytical Epsilon 4 machinery, as presented in Table 3.1. SiO₂, Fe₂O₃, and CaO are the primary chemical elements of BOFS materials. These findings are consistent with the XRD examination.

Table 3.1. Chemical composition of BOFS materials.

	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	K ₂ O	MnO	P ₂ O ₅	MgO	SO ₃
BOFS	7.39	1.53	29.39	52.38	-	4.33	-	3.13	0.23

3.4.2. Soil Characterization

3.4.2.1. Sieve Analysis

The sieve analysis for the soil sample in this study was conducted following the guidelines of ASTM D6913, *Standard Test Methods for Particle-Size Distribution of Soils Using Sieve Analysis* [28]. This method is primarily used for soil classification and focuses on determining the fine content of the soil. The analysis employed sieves with the following sizes: #4, #10, #20, #40, #60, #100, #140, #200, and a pan. For each trial, a soil sample of 500 grams was used.

Figure 3.6 illustrates the sieve shaker used for the soil.



Figure 3.6. Mechanical sieve shaker used for soil sieving.

Cumulative particle size distribution curves for kaolin clay and BOFS were plotted and are shown in Figure 3.7. Most kaolin clay particles were retained in finer fractions like #140 and #200, indicating a predominance of fine-grained material. In contrast, BOFS shows a flatter curve, meaning a broader distribution of particle sizes. This contrast in size gradation highlights the complementary of kaolin clay and BOFS in stabilization applications.

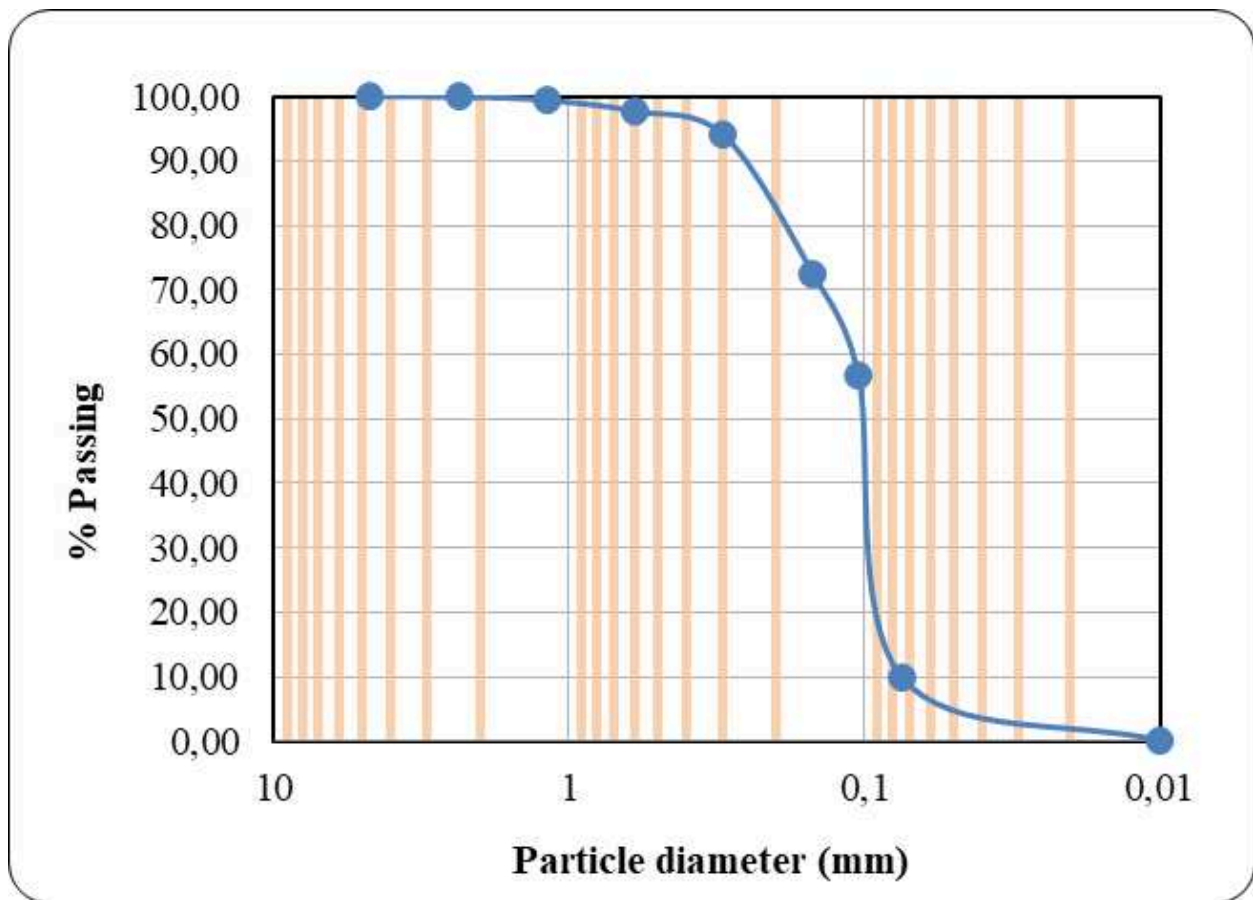


Figure 3.7. Particle size distribution of kaolin clay.

3.4.2.2. Atterberg Limits

The liquid limit (LL), plastic limit (PL), and plasticity index (PI) of the soil were determined per ASTM D4318, Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils [29]. LL indicates the water content at which clay transitions to a liquid state, whereas PL is the water content at which it transitions to a semi-solid state. Casagrande Apparatus was utilized to establish the LL value. All the other test apparatus used are shown in Figure 3.8. The

numerical values for LL and PL were 56.51 and 34.83, respectively. The difference between these values is known as the Plasticity Index (PI):

$$PI = LL - PL = 56.51 - 34.83 = 21.68$$

Kaolin clay with a PI of 21.68 can be considered high-plasticity clay.



Figure 3.8. Atterberg limits apparatus.

3.4.2.3. Soil Classification

The soil classification was based on the results from grain size distribution and Atterberg limits, which were performed using the Unified Soil Classification System (USCS) and AASHTO Soil Classification System.

According to USCS:

- The percentage passing No.200 (0.075 mm) is 92.74%, meaning the soil is fine-grained
- The liquid limit value obtained from the Atterberg limits test is equal to 56.51, which is above 50, so the soil is of high plasticity
- According to the USCS Plasticity Chart, the point where the values of LL and PI intersect lies in the CH zone. Soil is Clay of High Plasticity.

According to AASHTO Soil Classification

- Fines passing through the No.200 sieve indicate fine-grained soils from A-5 to A-7 range
- The LL value of 56.51 falls in the range for A-7 soils
- PI value is 21.68, meaning $PI > LL - 30$ and soil is A-7-5, Clay with high plasticity

Therefore, kaolin clay used in this study was classified as follows: CH (High-Plasticity Clay) in USCS Classification and A-7-5 (Clay with High Plasticity) in AASHTO Classification. These classifications indicate that kaolin clay has high plasticity and explain why stabilization is essential for improving its engineering properties.

3.4.2.4. Sulfate Content

The Tex-145-E Sulfate Content Test was carried out to determine the sulfate concentration in the soil sample [30]. The solubility ratio of 1:240 was used as the sulfate concentration was much higher than the sulfate content test apparatus' limit of 150. The test apparatus, the sulfate content test kit, is shown in Figure 3.9.



Figure 3.9. Sulfate content measurement test kit.

Soils can be divided into three types according to their sulfate concentration: less than 3000 ppm (Level 1), more than 3000 ppm and less than 8000 ppm (Level 2), and finally, more than 8000 ppm (Level 3). The sulfate concentration for this study's soil samples varied from 21,360 to 29,760 ppm. It is presented in Table 3.2. Based on soil sulfate concentrations, the soil used in this study can be classified as Level 3 soil of unacceptable risk.

Table 3.2. Soil sulfate concentration in ppm.

Trials	Ratio	Total Sulfate Concentration (ppm)	Level Risk
1	1:240	21,360	Level 3
2	1:240	29,280	Level 3
3	1:240	29,760	Level 3
Average:		25,560	

3.3.2.5. Specific Gravity

The specific gravity (G_s) of high-sulfate-bearing kaolin was determined following ASTM D854, The Standard Test Methods for Specific Gravity of Soil Solids by Water Pycnometer [31]. The tools used for this test are shown in Figure 3.10. The calculated SG values' average was 2.54 kg/m^3 . The results are shown in Table 3.3.



Figure 3.10. Specific gravity test procedure of kaolin clay.

Table 3.3. Specific gravity results of kaolin clay.

Parameter	Trial 1 (g)	Trial 2 (g)	Trial 3 (g)
Pycnometer	160.9	160.3	160.1
Pycnometer with Dry Soil	191.0	190.0	190.0
Pycnometer with Dry Soil and Water	675.6	675.1	676.6
Pycnometer + Water	658.1	657.1	657.8
Specific gravity (dimensionless)	2.39	2.51	2.69

3.4.2.6. XRD Analysis

XRD analysis determined the mineralogical compositions of kaolin clay treated with gypsum (Figure 3.11). Kaolinite, quartz, and gypsum were found in crystalline phases.

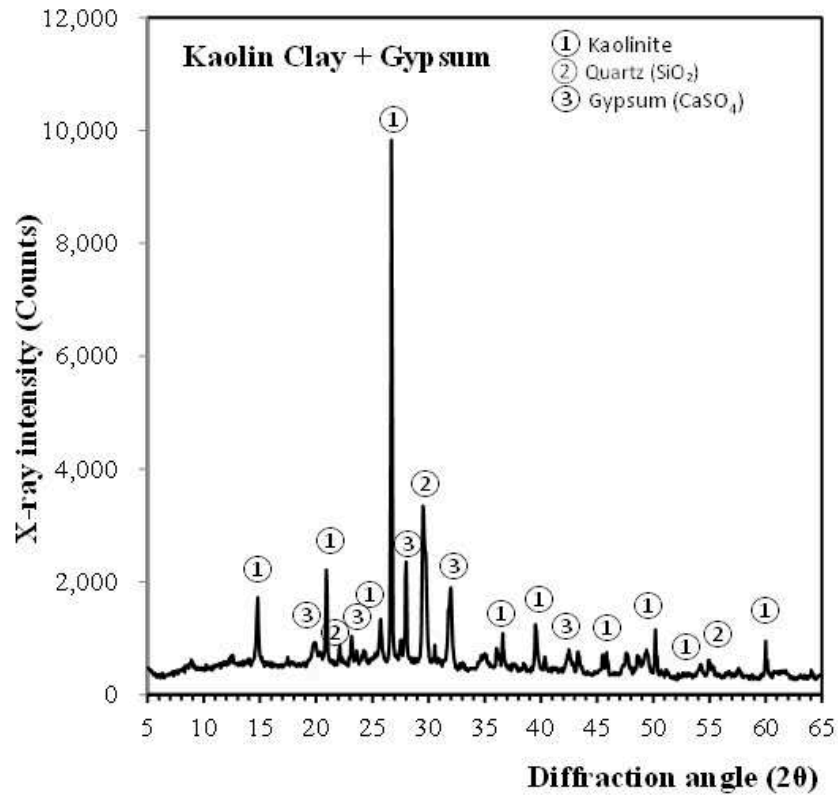


Figure 3.11. XRD analysis of kaolin clay treated with gypsum.

All the properties of kaolin clay used in this study are summarized in Table 3.4.

Table 3.4. Summary of soil characteristics for kaolin clay.

Property	Value
Liquid Limit, (w_L) %	56.51
Plastic Limit, (w_P) %	34.83
Plastic Index, (PI) %	21.68
Specific gravity (G_s)	2.54
Coarse-grained soil (>75 μm), %	4.58

Fine-grained size (<75 μm), %	95.42
USCS Classification	CH (High Plasticity Clay)
AASHTO Classification	A-7-5 (Clay with High Plasticity)

3.5. Engineering Tests

The engineering tests for this study consist of Unconfined Compressive Strength (UCS), One-Dimensional (1-D) Swelling, and Consolidation tests. The UCS and swelling tests were conducted twice to evaluate the impact of BOFS addition based on volumetric and mass proportions. An additional UCS test was conducted to determine the active BOFS particle size range. The following section provides comprehensive details on mix proportions and test procedures for these tests.

3.5.1. Consolidation (Oedometer) test

The oedometer test was carried out according to ASTM D2345, Standard Test Methods for One-Dimensional Consolidation Properties of Soils Using Incremental Loading [32]. The consolidation test is established to test soil particles' settlement and compressibility properties under manual incremental loading. The main principle of the oedometer test is applying hydrostatic pressure to compress the soil by gradually pouring out the excess water. Carrying out an oedometer test on clays stabilized with BOFS is less common than testing the pure clay samples. However, this study conducted this test to gain valuable insights into the consolidation of stabilized soils. Moreover, it provided essential data for determining the optimal BOFS addition rate for the experiment. The tabletop consolidation apparatus, fixed consolidation rings, different weighted loads, computer, and other equipment were used in this laboratory experiment. The leading equipment in performing consolidation tests is the tabletop consolidation test apparatus. The details of it can be seen in Figure 3.12.

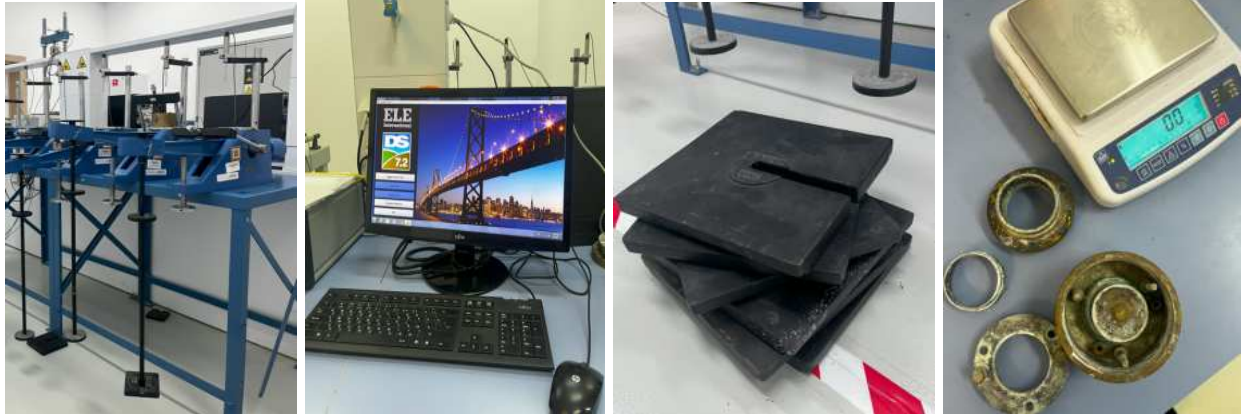


Figure 3.12. Consolidation test apparatus

As mentioned before, the consolidation test was carried out on samples of kaolin clay stabilized with BOFS. The samples were prepared based on the volumetric addition of BOFS. The percentages were chosen for 20%, 30%, and 40%. The mix design for the pre-test consolidation test can be seen in Table 3.5.

Table 3.5. Pre-mix design for optimum BOFS replacement (volumetric) determination.

Mixture	BOFS Addition Rate ($R_{BOFS(volumetric)}$, %)	BOFS Particle Size	Test Type	Water Content
1	20	All sizes combined (#4-#200)	Consolidation Test	1.5 x LL
2	30			
3	40			

The samples were manually compacted into cylindrical molds with a diameter of 50 mm and a height of 100 mm to match the internal diameter of the consolidation ring. After compaction, the samples were placed in the consolidation ring and trimmed to a height of 20 mm for testing. The process is shown in Figure 3.13.



3.13. Sample preparation for consolidation test.

The ELE international DS 7.2 software on the computer was turned on to start the loading. The first stage of loading was begun by applying a 5 kg load. The overall loading stages proceeded to five-step increments: 5, 10, 20, 40, and 80 kgs. In standard procedures, each load is typically maintained for a fixed duration. For example, in the case of ASTM D234, it takes 24 hours to complete the primary consolidation. However, this study modified the test to utilize real-time settlement monitoring via the software. This approach resulted in significantly longer test durations (3–5 days), reflecting the slower consolidation response of BOFS-stabilized clay compared to untreated clay. After reaching the final load of 80 kg, the sample was unloaded directly to 0 kilograms to assess rebound behavior.

3.5.2. Unconfined Compressive Strength (UCS) test

The Standard Test Method for Unconfined Compressive Strength (UCS) of Cohesive Soil, the ASTM D 2166 method, was employed. The test on high sulfate-bearing kaolin clay stabilized with BOFS of different particle sizes and percentages was conducted under unconfined conditions. The water was added to the mix of dry materials, and the mixture was compacted into cylindrical molds 50 mm in diameter and 100 mm in height. After compaction, the specimens were extruded carefully and sealed with plastic wrap to prevent moisture loss. They were unwrapped and tested in a UCS testing machine at definite curing periods. The peak compressive strength value was recorded for analysis. The test details can be seen in Figure 3.14.



Figure 3.14. Unconfined compressive strength test process.

The UCS tests were performed to comprehensively assess the strength behavior of stabilized kaolin clay, focusing on the influence of BOFS particle size variation, replacement percentage, and curing time. The first UCS test evaluates the strength development of kaolin clay stabilized with coarse BOFS fractions. The primary objective was determining the optimal BOFS particle size distribution to improve compressive strength. To achieve it, the particle size ranges of BOFS like 4.75–25.0 mm, 0.85–4.75 mm, 0.425–4.75 mm, 0.25–4.75 mm, and 0.150–4.75 mm were selected. BOFS was added based on volumetric replacement, and the specimens were cured for 1,3,7,28, and 90 days. The mix design for the preliminary UCS test is given in Table 3.6.

Table 3.6. Pre-mix design for optimal particle size classification (pre-UCS test).

Mixture	BOFS Particle Size	BOFS Addition Rate ($R_{BOFS(volumetric)}$, %)	Water content
1	25mm - #4 (25mm, 19mm, 9.5mm, & 4.75 mm)	30	1.5 x LL (Liquid Limit)
2	#4 - #20		

	(4.75 mm, 2.00mm, & 0.85mm)		
3	#4 - #40 (4.75 mm, 2.00mm, 0.85mm, & 0.425mm)		
4	#4 - #60 (4.75 mm, 2.00mm, 0.85mm, 0.425mm, & 0.25 mm)		
5	#4 - #100 (4.75 mm, 2.00mm, 0.85mm, 0.425mm, 0.25mm & 0.15mm)		

The mix proportions used in the second UCS test were determined based on the results of the first UCS test, which indicated that finer BOFS particles contributed more effectively to strength development. Therefore, this stage evaluated fine BOFS fractions' impact on compressive strength. Similar to the previous stage, BOFS was added using volumetric addition, but here, both 20% and 30% replacement levels were considered. This is to assess the influence of the BOFS replacement ratio on strength development. In this stage, the UCS tests were performed at 3,7,14,28,56, and 90 days of curing.

The last UCS test followed the same proportions and particle size ranges as the second test, where fine BOFS particles were used. However, the key difference in this stage was the method of BOFS addition- instead of volumetric addition, BOFS was added based on mass replacement at 20% and 30% levels. This test aimed to compare the influence of mass-based and volumetric-based BOFS additions on compressive strength improvement. The mix design parameters for the main UCS tests are shown in Table 3.7.

Table 3.7. Mix design for soil strength, deformation, and durability analysis.

Mixture	BOFS Particle Size	BOFS Addition Rate	
		$R_{BOFS(volumetric)}$, %	$R_{BOFS(mass)}$, %
1	#100 -#4 (0.15mm, 0.25mm, 0.425mm, 0.85mm, 2.00mm, & 4.75mm)	20 & 30	20 & 30

2	#100 - #10 (0.15mm, 0.25mm, 0.425mm, 0.85mm, & 2.00mm)		
3	#100 - #20 (0.15mm, 0.25mm, 0.425mm, & 0.85mm)		
4	#100 - #40 (0.15mm, 0.25mm, & 0.425mm)		

*The same mix design was applied for the 1D-Swelling test.

3.5.3. One-Dimensional (1-D) Swelling test

As presented in Figure 3.15, the one-dimensional (1-D) swelling test was performed on the compacted samples with 101.6 mm (4 inches) in diameter and 114.3 mm (4.5 inches.) in height dimensions. For mass addition, samples compacted using the Proctor compaction method were de-molded after 24 hours, air-cured at 23°C for 2 days, and then oven-dried at 40°C for 1 day before being tested for swelling. In contrast, volumetric addition samples were prepared using a Superpave gyratory compactor and only underwent 3 days of air curing before further processing the swelling test.



Figure 3.15. (a) Manual compaction mold with tools used to prepare cylindrical swelling test samples. (b) Automated compaction equipment (Galileo) used for uniform sample preparation in the swelling test setup.

For the test, soil samples were placed by placing a porous stone at the bottom, followed by a layer of filter paper, the soil sample, another layer of filter paper, and another porous stone on top. This assembly was then enclosed in a membrane. The membrane size was 101.6mm in diameter and 0.635mm in thickness. Then, this was placed into a plastic container containing 2 cm water at the bottom, as shown in Figure 3.16.



Figure 3.16. Sample installation procedure for the swelling test.

Before the installation process, the samples' initial height, diameter, and weight were measured. The same parameters were recorded right after the swelling process finished. These were used to calculate the volumetric swelling percentage of samples in 14 days. Besides volumetric swelling, the vertical swelling was measured using a dial gauge to precisely evaluate the stabilized kaolin clay's swelling characteristics. The dial gauge was set up to record the changes in height, with the top porous stone serving as a stable base for accurate measurement, as shown in Figure 3.17. Dial gauge readings were recorded regularly over 14 days, precisely at 2, 4, 6, 8, 12, 16, 24, 32, 40, 48, 72, 96, 144, 192, 240, 288, and 336 hours. The summary of test parameters for engineering tests is presented in Table 3.8.



Figure 3.17. Dial gauge setup for vertical expansion measurement.

Table 3.8. Test methods for soil strength, deformation, and durability analysis.

Test Type	Test Standard	Sample Dimensions	Curing Days	Aim/Purpose
Consolidation (Pre-Test)	ASTM D2435	Ø50 mm × 20 mm	-	Evaluate the compressibility and consolidation behavior of BOFS stabilized clay; Determine optimal volumetric BOFS addition rate.
Unconfined Compressive Strength (UCS) Test (Pre-Test)	ASTM D2166 [33]	Ø50 mm × 100 mm	1,3,7,28,90	Assess the strength gain and identify the most effective BOFS particle size range.
Unconfined Compressive Strength (UCS) Test			3,7,14,28,56,90	<ul style="list-style-type: none"> ● Evaluate the impact of fine BOFS fractions and replacement levels on strength. ● Compare mass-based and volumetric-based BOFS addition methods on strength improvement.
One-Dimensional (1D) Swelling	Modified ASTM D4546 [34]	Ø101.6 mm × 114.3 mm	2-336 hours (14 days)	<ul style="list-style-type: none"> ● Evaluate free swelling potential in BOFS-stabilized high-sulfate bearing clay. ● Compare mass and volumetric-based additions on soil expansion.

3.6. Mineralogical & Microstructural Analysis

The primary materials of this study are the sulfate-bearing kaolin clay and BOFS, which contain calcium oxides and calcium silicates which form calcium hydroxide in excess water. Hydration increases the pH in soil matrix systems, aluminum compounds, and sulfate ions from clay to form ettringite minerals. Two different tests were conducted to confirm the ettringite formation and analyze the mineralogical composition and microstructural characteristics of the stabilized kaolin clay after the 1D-Swelling test. This includes X-ray diffraction (XRD) and scanning electron microscopy (SEM). The samples for the analysis should be in powder form; for that, they were dried in an oven at 40°C for 24 hours.

3.6.1. X-ray Diffraction (XRD) Analysis

The XRD analysis was conducted on kaolin clay stabilized with BOFS after 14 days of a 1D-swelling test. The primary objective was to detect the crystalline phase formation of ettringite, calcium silicate hydrates (CSH), and other sulfate-related compounds. The test equipment used is shown in Figure 3.18. X-ray powder diffraction results were analyzed using MDI Jade 6 software.



3.18. XRD equipment.

3.6.2. Scanning Electron Microscopy (SEM) Analysis

After 14 days of a 1D swelling test on samples, they were used to determine their microstructural morphology by SEM analysis. The test equipment used is shown in Figure 3.19. For this, oven-dried specimens were coated with a thin layer of gold-palladium before being put into sensors. SEM was used to identify the formation of different mineral structures. Additional EDS analysis was performed to detect the key elements and confirm the formation of minerals.



Figure 3.19. SEM analysis equipment.

3.7. Summary

This experimental program provides a systematic approach to evaluating the stabilization of high-sulfate-bearing kaolin clay using BOFS. The study presents geotechnical characterization of materials, mechanical property evaluation, swelling behavior assessment, and microstructural analysis to offer a comprehensive understanding of steel production by-product BOFS. The key aspects of the experimental program include:

- Material Characterization.
- Optimal BOFS Addition Techniques Methods.
- The Evaluation of BOFS Impact on Strength Development and Swelling Reduction
- Microstructural & Mineralogical Analysis

The findings from this experimental program will be used to further assess the BOFS behavior in sulfate-induced environments and develop a strength prediction model.

Chapter 4 - Test Results and Analysis

This chapter provides the consolidation, strength, and swelling characteristics obtained from the oedometer, unconfined compressive strength (UCS), and one-dimensional (1D) swelling tests. It describes and analyzes the impact of particle size and stabilizer content over curing times ranging from 3 to 90 days on the strength and 14 days exposure to water on swelling characteristics of high-sulfate-bearing kaolin clay stabilized with Basic Oxygen Furnace Slag (BOFS). The findings in the discussion are derived from the trends noticed in the oedometer, UCS, and 1D-Swelling tests' results. The following sections discuss the experimental program's outcomes.

4.1. Determination of Optimal BOFS Addition Rate

The consolidation test was conducted to evaluate the potential of the soil to compress and settle under an applied axial load. The primary objective was to assess how the BOFS replacement ratio influences soil compressibility in soil stabilization. BOFS is known to improve soil strength, but excessive amounts may lead to diminishing returns, which could negatively affect the soil's load-bearing capacity. The most effective BOFS replacement rate can be determined by comparing the settlement behavior for further UCS and swelling tests. For that purpose, three different volumetric BOFS addition rates were chosen. The test measured the vertical deformation using a dial gauge under incremental loading and analyzed changes in void ratio, compression index, and coefficient of volume compressibility. The applied stress started at 111 kPa and increased incrementally to 1776 kPa.

The proportions of BOFS, kaolin clay, and water were determined using the next equation:

$$R_{BOFS(volumetric)} = \frac{V_{BOFS}}{V_{soil} + V_{water} + V_{BOFS}} \times 100$$

This equation quantifies the BOFS volume as a percentage relative to the total volume of soil, water, and BOFS combined. The mass of each material was calculated using its specific gravity.

The consolidation test was performed on three different BOFS volumetric compositions: 20%, 30%, and 40%. The measurements derived key soil properties, such as void ratio and coefficient of volume compressibility, which are presented in Table 4.1.

Table 4.1. Consolidation test results for different volumetric BOFS addition rates.

Load increment		$R_{BOFS(volumetric)}^*$					
		20%		30%		40%	
Applied load, kg	Applied stress, kPa	Dial reading at the end of the load, mm	Change in height, mm	Dial reading at the end of the load, mm	Change in height, mm	Dial reading at the end of the load, mm	Change in height, mm
0	0	19.6	0	19.75	0	19.6	0
5	111	18.16	-1.44	18.85	-0.9	18.98	-0.62
10	222	18.03	-0.13	18.723	-0.127	18.78	-0.2
20	444	17.78	-0.25	18.41	-0.313	18.46	-0.32
40	888	17.33	-0.45	17.53	-0.88	18.11	-0.35
80	1776	16.85	-0.48	16.79	-0.74	17.84	-0.27
0	0	17.1	+0.25	16.85	+0.07	17.95	+0.12

* $R_{BOFS(volumetric)}$ -Volumetric addition rate of BOFS

From Table 4.1, it can be observed that higher BOFS content leads to reduced settlement under the same applied stress. The 40% BOFS mixture exhibited the least overall deformation, indicating a significant improvement in soil stability and resistance to compression. However, while higher BOFS content reduces compressibility, an excessively stiff soil matrix can impact long-term performance.

Next, the void ratio was calculated for different stress levels and presented in Table 4.2. The graph in Figure 4.1 was developed to validate the data visually.

Table 4.2. Void ratio values for different BOFS addition rates.

Load increment, kPa	$e = e_i - \Delta e$		
$R_{BOFS(volumetric)}^*$	20%	30%	40%
0	0.56	0.51	0.37
111	0.45	0.44	0.33
222	0.44	0.43	0.31
444	0.42	0.41	0.29
888	0.38	0.34	0.27
1776	0.34	0.28	0.25
0	0.36	0.29	0.26

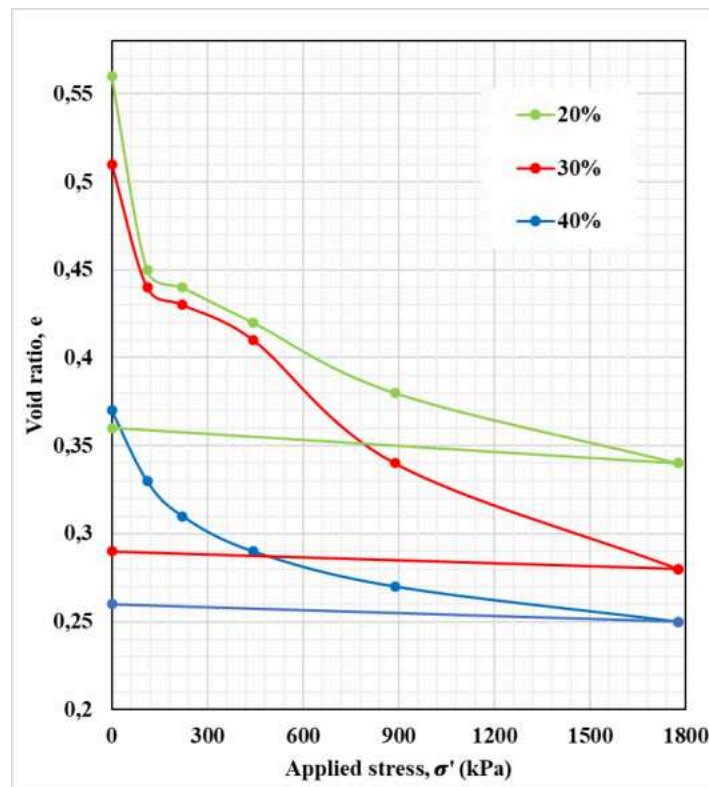


Figure 4.1. Void ratio to applied stress for different volumetric BOFS addition rates.

Table 4.2 shows that higher BOFS content results in a lower final void ratio, suggesting a more compact and stable soil structure. Figure 4.1 illustrates the decline in the void ratio as applied stress increases. It shows that the 40% BOFS curve has the least steep slope, indicating minimum compressibility, while the 20% BOFS curve has a steeper slope, showing greater compressibility. A mixture with a 40% BOFS addition rate experienced the lowest void ratio across all applied stress levels, signifying denser packing and stronger interparticle bonding. The rate of void ratio reduction is steeper in lower stress ranges (0-444 kPa), indicating that most primary consolidation occurs at early stages. For all BOFS addition rates, the void ratio reduction slows down beyond 888 kPa, suggesting completion of primary consolidation and transition to secondary. This shows that BOFS effectively fills soil voids and enhances densification, reducing overall compressibility and improving soil load-bearing capacity.

To further quantify the effect of BOFS stabilization, the coefficient of volume compressibility, consolidation, and compression index were determined. The results are shown in Table 4.3.

Table 4.3. Coefficient of volume compressibility (m_v), compression index (C_c), and coefficient of consolidation (C_v) for different BOFS addition rates.

$R_{BOFS(volumetric)}$	m_v ($m^2/kN * 10^5$)	Compression Index (C_c)	Coefficient of Consolidation, C_v ($m^2/year$)
20%	9.00	0.06	0.85
30%	15.77	0.07	1.05
40%	6.00	0.04	0.92

The coefficient analysis reinforces the consolidation test results, confirming that 20% and 30% BOFS provide an optimal balance of compressibility reduction, strength gain, and workability. In the case of 20% BOFS replacement, there is a moderate reduction in compressibility and settlement. A higher compression index value than a 40% mix means a better drainage capacity and faster primary consolidation. This ensures better workability in field

applications where excessive stiffness could be problematic. The mix that shows the most significant improvement in compressibility reduction with the lowest coefficient of volume compressibility is presented by a 30% addition rate. The highest C_v value is that it will stabilize faster than other replacement rates. The C_v value for the 40% BOFS addition rate decreased compared to the 30% mix, indicating slower stabilization.

Based on these results, both 20% and 30% BOFS addition rates were selected as the optimal contents for further UCS and swelling tests. Whereas the 20% BOFS addition rate ensures better flexibility and workability, the 30% BOFS mix provides enhanced strength, lower compressibility, and faster stabilization, making them the most suitable choices for sulfate-bearing soil stabilization.

4.2. Optimal BOFS Particle Size Classification

To identify the optimal particle size range of BOFS, a 30% BOFS addition rate - previously validated for its effectiveness in enhancing consolidation - was utilized in the UCS test. BOFS particles were classified into finer fractions that contribute to cementitious reactions and coarser fractions that function as aggregates, influencing overall strength development. For this stage, the selected finer fractions included #4 (4.75 mm) to #100 (0.150 mm), #4 (4.75 mm) to #60 (0.250 mm), and #4 (4.75 mm) to #40 (0.420 mm). In comparison, the coarser fractions comprised #4 (4.75 mm) to #20 (0.841 mm) and 25 mm to #4 (4.75 mm), ensuring a comprehensive evaluation of BOFS particle size influence on strength development. The samples were cured and tested at 1, 3, 7, 28, and 90 days. The test results can be seen in Table 4.4 and Figure 4.2.

Based on the UCS values, mixture 1, which contains the coarsest fraction of BOFS, exhibits the lowest average value across all curing times. In contrast, mixtures stabilized with finer BOFS particle fractions like #4 - #40 and #4 - #60 show the highest UCS values at 90 days, reaching 829.01 kPa and 825.70 kPa, respectively. Besides these two, the last, the finest mixture in this program, #4 - #100, also performs well at 806.98 kPa. Additionally, looking at the early strength of mixtures, it is noticeable that these are higher for mixtures with finer particles. At 1 day curing time, the mixture with #4 - #100 fraction of BOFS particles reaches the highest UCS value at 1 day, which is 249.13 kPa. In the long term, at 90 days, the strength is maximized in other #4 - #40 and #4 - #60 fractions.

Table 4.4. Average UCS values (kPa) for different curing times (days).

Mix ture	Description [BOFS Particle size range]	1 Day (kPa)	3 Days (kPa)	7 Days (kPa)	28 Days (kPa)	90 Days (kPa)
1	SBS*+BOFS** [25mm, 19mm, 9.5 mm, #4 (4.75 mm)]	45.48	126.80	138.54	226.61	342.50
2	SBS+BOFS [#4 (4.75 mm), #10 (2.00 mm), and #20 (0.841 mm)]	148.83	211.53	265.23	415.97	514.72
3	SBS+BOFS [#4 (4.75 mm), #10 (2.00 mm), #20 (0.841 mm), and #40 (0.420 mm)]	169.99	182.26	209.64	501.36	829.01
4	SBS+BOFS [#4 (4.75 mm), #10 (2.00 mm), #20 (0.841 mm), #40 (0.420 mm), and #60 (0.250 mm)]	200.95	239.23	279.66	406.72	825.70
5	SBS+BOFS [#4 (4.75 mm), #10 (2.00 mm), #20 (0.841 mm), #40 (0.420 mm), #60 (0.250 mm), and #100 (0.150 mm)]	249.13	245.43	301.93	387.49	806.98

*SBS - Sulfate-Bearing Soil and **BOFS - Basic Oxygen Furnace Slag

The first UCS test focused on analyzing the effect of various BOFS particle sizes on strength development. The results suggest that the particle size of BOFS significantly influences strength development. Finer BOFS particles enhance the UCS values, whereas coarser particles contribute less to strength gain over time. It can also be concluded that the large BOFS particles do not improve the soil stabilization process enough.

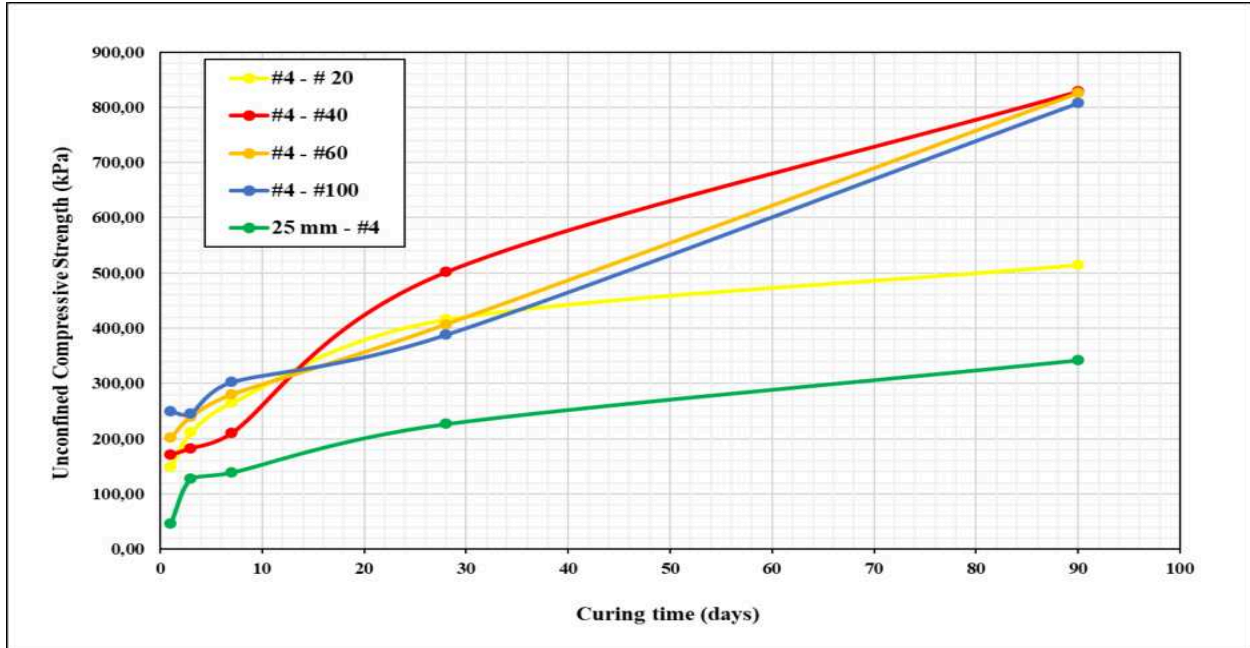


Figure 4.2. UCS curves for optimal BOFS size determination.

4.3. Unconfined Compressive Strength (UCS) Test Analysis

The first UCS test focused on analyzing the effect of various BOFS particle sizes on strength development. The results showed that mixtures, where sample soil was stabilized with finer BOFS particles, exhibited the highest UCS values. In contrast, ones stabilized with coarser fractions had lower strength development in the long term. Based on these findings, the second UCS test focused on soil stabilization with finer BOFS fractions mixed with 2 different BOFS addition rates: by volume and by mass. For both addition rates, 20% and 30% were chosen based on the consolidation test results. Curing times of 3, 7, 14, 28, 56, and 90 days were chosen. Accordingly, the strength development analysis over time can be divided into three: early-stage strength (3-7 days), mid-term strength (14-28 days), and long-term strength (56-90 days).

4.3.1. Volumetric BOFS Addition Test Analysis

This section presents and analyzes the UCS test results for soil stabilized with BOFS at volumetric addition rates of 20% and 30%. The primary objective is to examine the strength development over time for different BOFS particle size ranges and determine how the particle size influences the overall performance of the stabilized soil.

Tables 4.5 and 4.6 summarize the average UCS values for different curing periods (3,7,14,28,56, and 90 days) at 20% and 30% BOFS volumetric addition rates, respectively. These tables provide insights into the influence of particle size distribution on the mechanical behavior of the stabilized sulfate-bearing soil. Figures 4.3 and 4.4 also illustrate the UCS development trends for the respective BOFS addition rates, allowing for a visual interpretation of strength development. The following sections will provide a detailed analysis of these test results, highlighting key observations, trends, and the impact of BOFS particle size on UCS performance.

Table 4.5. Average UCS values for $R_{BOFS(Volume)} = 20\%$.

Mixture	Description [BOFS Particle size range]	3 Days (kPa)	7 Days (kPa)	14 Days (kPa)	28 Days (kPa)	56 Days (kPa)	90 Days (kPa)
1	SBS* only	70.00	82.50	147.50	212.50	265.25	279.50
2	SBS*+BOFS** [#100 - #40 (20%)]	257.19	287.75	303.03	331.04	399.80	490.20
3	SBS+BOFS [#100 - #20 (20%)]	231.73	241.92	305.58	394.70	499.87	518.89
4	SBS+BOFS [#100 - #10 (20%)]	164.67	26.93	292.85	384.52	503.35	531.11
5	SBS+BOFS [#100 - #4 (20%)]	134.96	166.79	180.80	254.65	323.40	335.12

*SBS - Sulfate-bearing soil and **BOFS - Basic oxygen furnace slag

Table 4.6. Average UCS values for $R_{BOFS(Volumetric)} = 30\%$.

Mixture	Description [BOFS Particle size range]	3 Days (kPa)	7 Days (kPa)	14 Days (kPa)	28 Days (kPa)	56 Days (kPa)	90 Days (kPa)
1	SBS* only	65.00	117.50	185.00	257.50	298.23	324.67
2	SBS*+BOFS** [#100 - #40 (30%)]	229.18	271.20	336.14	507.13	580.09	588.15
3	SBS+BOFS [#100 - #20 (30%)]	182.07	203.72	315.00	388.34	425.26	431.63
4	SBS+BOFS [#100 - #10 (30%)]	175.71	216.45	316.78	438.76	465.16	526.87
5	SBS+BOFS [#100 - #4 (30%)]	216.45	252.10	311.94	337.41	387.06	422.72

*SBS - Sulfate-bearing soil and **BOFS - Basic oxygen furnace slag

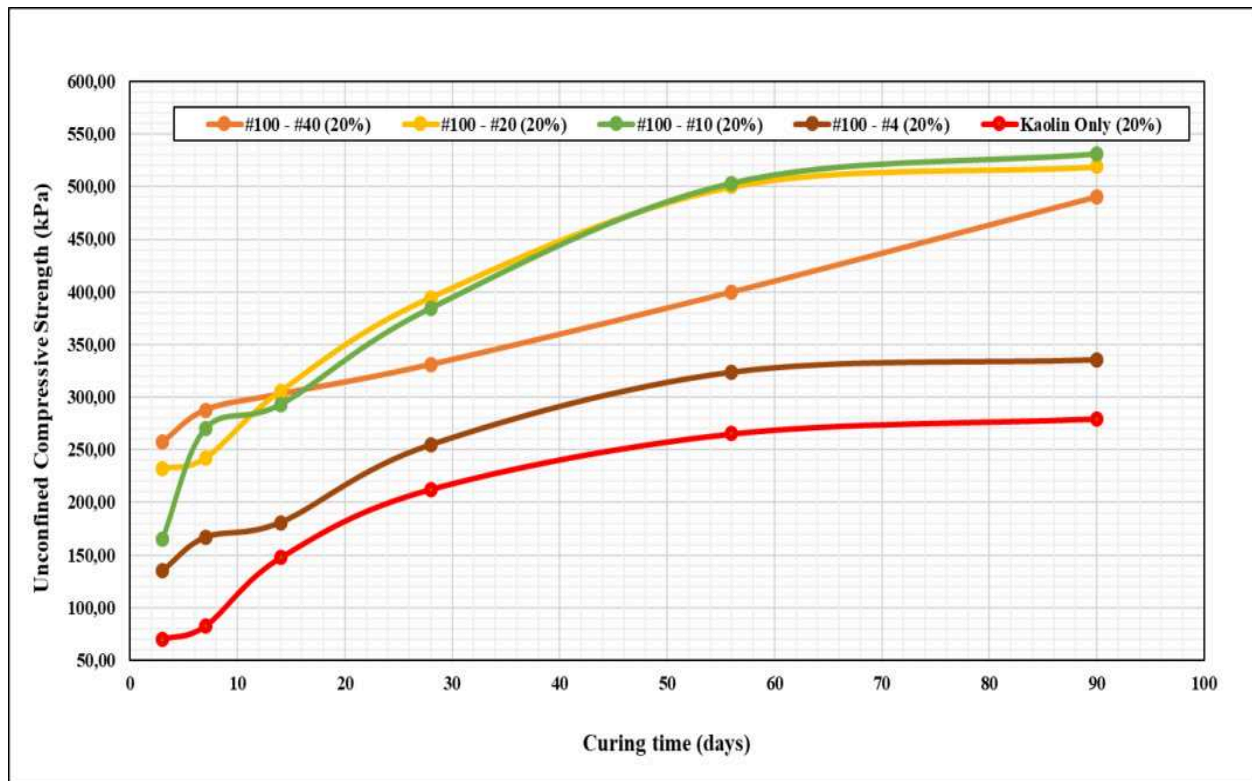


Figure 4.3. UCS curves for $R_{BOFS(volume)} = 20\%$.

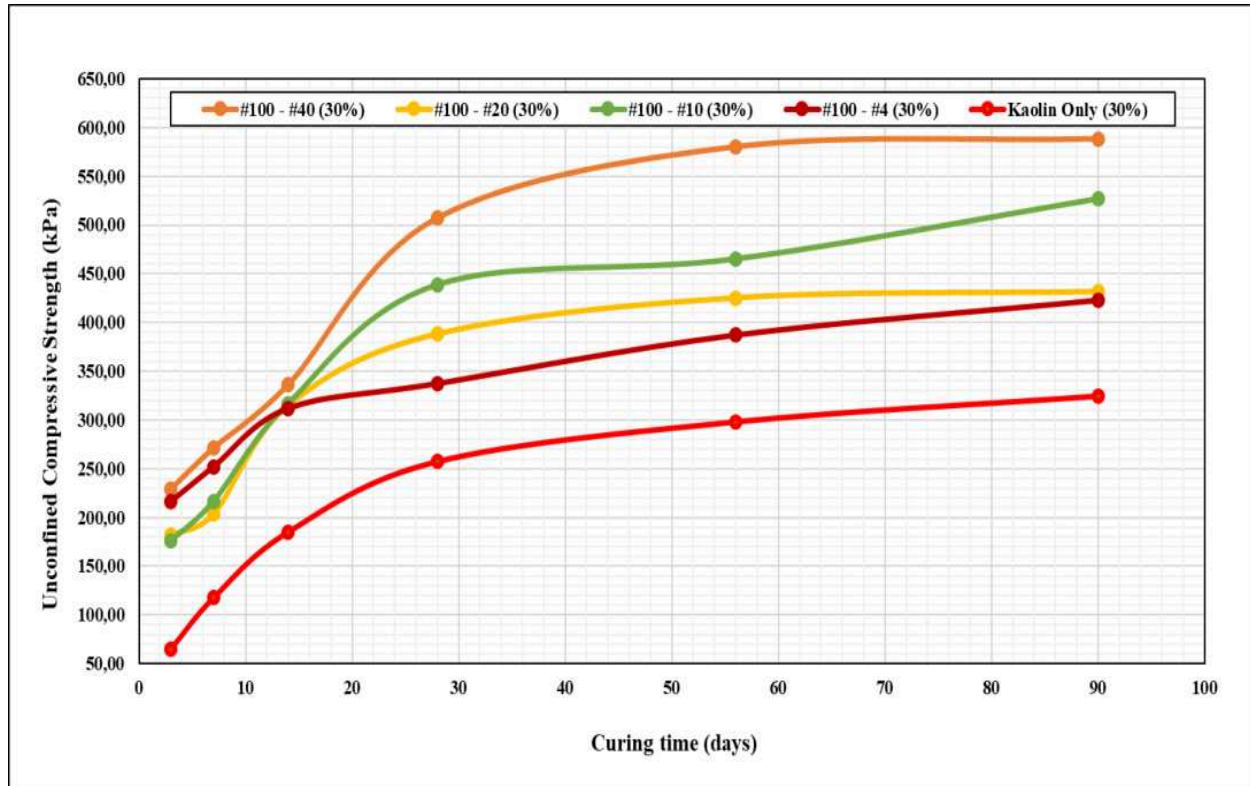


Figure 4.4. UCS curves for $R_{BOFS(volume)} = 30\%$.

Figures 4.3 and 4.4 illustrate the unconfined compressive strength (UCS) development over curing time for kaolin clay stabilized with Basic Oxygen Furnace Slag (BOFS) at volumetric replacement ratios of 20% and 30%, respectively. In both cases, all BOFS-treated mixtures exhibit a positive strength gain over time, confirming the ongoing hydration and pozzolanic reactions contributing to strength development.

The control mixture of kaolin clay only consistently presents the lowest UCS values across all curing durations, emphasizing the beneficial impact of BOFS addition on strength enhancement. At 90 days, the control samples achieved UCS values of approximately 280 kPa ($R_{BOFS(volume)} = 20\%$) and 320 kPa ($R_{BOFS(volume)} = 30\%$), highlighting a moderate increase with higher replacement ratios, yet remaining significantly below stabilized mixtures.

At the 20% BOFS addition rate, the particle size of BOFS plays a critical role in UCS performance. Mixtures incorporating finer BOFS particles (#100-#10 and #100-#20) demonstrated superior strength performance, with UCS values reaching approximately 500 kPa at 90 days. In contrast, coarser particle blends, particularly #100-#4, achieved the lowest UCS among BOFS-treated samples, around 350 kPa at 90 days, though still outperforming the control.

In Figure 4.4, corresponding to the 30% BOFS replacement, all BOFS-stabilized mixtures surpassed the control in UCS performance, with a more pronounced strength gain compared to the 20% case. Interestingly, the #100-#40 particle blend outperformed finer particle mixes at this higher replacement level, achieving the maximum UCS of approximately 600 kPa at 90 days. This suggests that optimal particle packing or improved interaction between particles may enhance strength at higher BOFS contents, even with moderately coarser particles.

Overall, the results underscore the synergistic effect of BOFS particle size and replacement ratio on the strength of stabilized kaolin clay. Finer particles are more effective at lower replacement rates, while moderately fine particles may provide superior strength at higher replacement levels, possibly due to enhanced packing density and hydration dynamics.

4.3.2. Mass BOFS Addition Test Analysis

In this experiment stage, the mass-based addition rate was employed, where the stabilizing materials were added based on their mass relative to the system's total mass. It was achieved using the following rate of addition equation as follows:

$$R_{BOFS(hydrate-mass)} = \frac{M_{BOFS(GB)}}{M_{soil} + M_{water} + M_{BOFS}} \times 100$$

This equation is used to quantify the BOFS mass in the mixture based on the total mass of soil, water, and BOFS combined. $M_{BOFS(GB)}$ is described as a mass of chemically responsive BOFS. According to previous research conducted in this field, grain sizes exceeding 9.5 mm are regarded as non-reactive (Cikmit et al., 2019). The same assumption was applied in this stage, wherein grain sizes exceeding 9.5 mm were considered non-reactive. The largest grain size used in this experiment was 4.75 mm. Therefore, $M_{BOFS(GB)}$ can be considered equivalent to M_{BOFS} .

The water content applied in this study is 1.5 times the soil's LL. As described earlier, the curing period lasted from 3 to 90 days. Tables 4.7 and 4.8 present the UCS test results for two different mass addition rates of 20% and 30%. Figures 4.5 to 4.6 illustrate the relationship between UCS in kPa and curing time (in days).

Table 4.7. UCS test results ($R_{BOFS(mass)} = 20\%$).

Mixture	Description [BOFS particle size range]	UCS (kPa)					
		3	7	14	28	56	90
	Curing time (days)						
1	SBS*+BOFS** [#100, #60, and #40]	11.55	22.09	39.57	111.68	202.70	410.92
2	SBS+BOFS [#100, #60, #40, and #20]	12.76	13.49	38.20	81.45	178.25	269.08
3	SBS+BOFS [#100, #60, #40, #20, and #10]	8.72	15.32	30.56	59.17	149.73	242.76
4	SBS+BOFS [#100, #60, #40, #20, #10, and #4]	7.43	13.75	29.28	48.38	110.01	132.42

*SBS - Sulfate-bearing soil and **BOFS - Basic oxygen furnace slag

Table 4.8. UCS test results for $R_{BOFS (hydrate-mass)} = 30\%$.

Mixture	Description [BOFS particle size range]	UCS (kPa)					
		3	7	14	28	56	90
	Curing time (days)						
1	SBS*+BOFS** [#100 and #60]	17.00	32.08	70.75	165.09	371.79	639.42
2	SBS+BOFS [#100, #60, and #40]	14.91	11.93	53.48	138.15	354.81	503.18
3	SBS+BOFS [#100, #60, #40, and #20]	12.01	27.81	36.28	117.14	247.01	473.14
4	SBS+BOFS [#100, #60, #40 #,20, and #10]	10.08	27.99	25.19	73.34	222.05	297.94
5	SBS+BOFS [#100, #60, #40, #20, #10, and #4]	10.75	14.19	20.37	56.02	205.76	262.29

*SBS - Sulfate-bearing soil and **BOFS - Basic oxygen furnace slag

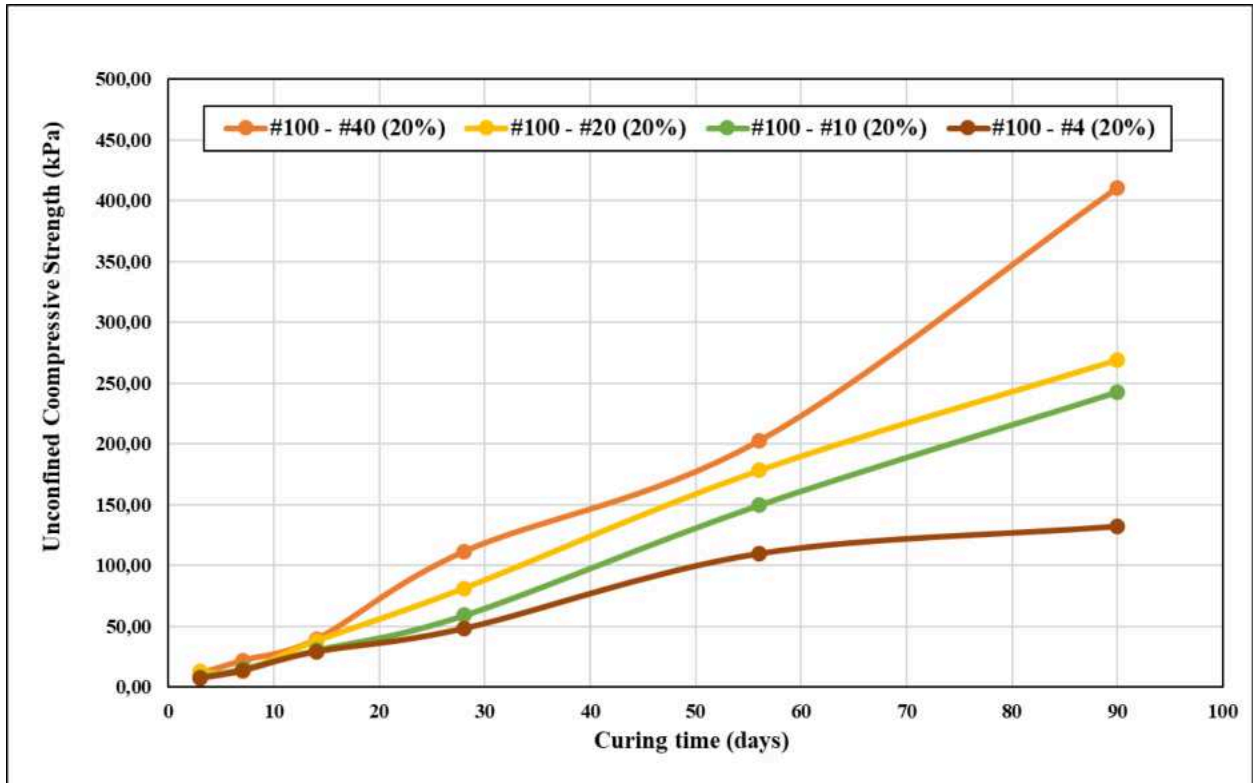


Figure 4.5. UCS curves for $R_{BOFS(mass)} = 20\%$.

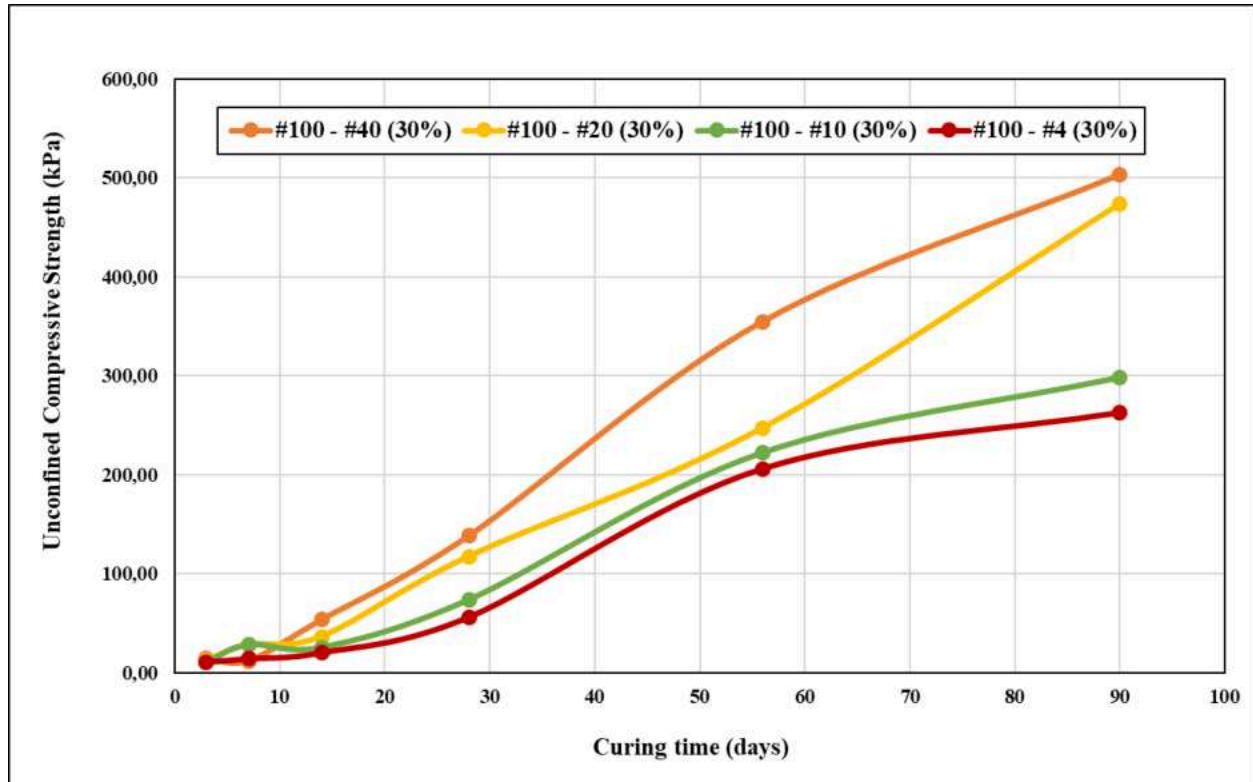


Figure 4.6. UCS curves for $R_{BOFS(mass)} = 30\%$.

The UCS test results show that the UCS strength of high sulfate-bearing kaolin clay stabilized with BOFS increases significantly with curing time. For instance, the UCS strength of mixtures varied from 8.72 kPa to 17.00 kPa in 3 days of curing time, whereas it increased substantially to between 132.42 kPa and 639.42 kPa after 90 days of curing. This represents the impact of curing time on the strength development process.

Figures 4.5 and 4.6 show that the BOFS mass addition rate resulted in different strength gains. The mixtures with finer BOFS particle sizes increased UCS regardless of the percentage of BOFS addition. Between the two addition rates, the 30% mass addition consistently shows better strength development over time than the 20% rate. For example, for a 20% mass addition rate, the maximum strength gain over 90 days was recorded in the mixture with the finest particle sizes (#100-#40), yielding 410.92 kPa. The soil mixture with the same BOFS particle size but with a 30% addition rate over the same period achieved a strength value of 503.18 kPa. This indicates that the finer size in BOFS particles may work as a stabilizer that provides cementing property, enhancing the soil mixture's strength performance.

On the other hand, the lowest strength gain over time was observed in the mixtures with coarser sieve sizes. As with a 30% mass addition rate and 90 days of curing time, the maximum UCS value of 639.42 kPa was achieved in the mixture containing BOFS particles sized between 0.15 and 0.25 mm. In contrast, the UCS value for the mixture with BOFS particles varied between 0.15-4.75 mm and reached only 262.29 kPa. A similar trend was observed at a BOFS mass addition rate of 20%.

4.3.3. Summary of Strength Characteristics

The UCS test results shows that the strength development of high-sulfate-bearing kaolin clay stabilized with BOFS is strongly affected by three main factors: the particle size of BOFS, the amount added, and the curing time. Each of these factors plays an important role in how the stabilized soil performs, influencing both its early and long-term strength.

4.3.3.1. Impact of BOFS Particle Size on Strength Development

The particle size distribution of BOFS had a clear impact on the UCS results. Finer BOFS particles, especially those in the #100 – #40 and #100 – #60 ranges, showed higher strength values at all curing stages. This can be explained by the fact that smaller BOFS particles have more surface area, which improves binding and boosts pozzolanic reactions, making the soil matrix stronger. On the other hand, the mixtures with coarser BOFS particles (#100 – #4) had lower UCS values, meaning that the bigger particles are less reactive and not as effective in stabilizing the soil.

A notable observation was that, while the finer BOFS fractions led to higher early strength, some of the mid-sized ones (like #100 – #10) showed a slower but more steady strength increase as curing time went on. This suggests that while fine BOFS accelerates initial strength development, moderately coarse fractions may contribute to long-term durability due to prolonged hydration processes. However, excessively coarse fractions (e.g., #100 – #4) consistently led to the lowest UCS values, reinforcing the conclusion that large particles in BOFS are less effective in stabilization.

4.3.3.2. Influence of BOFS Addition Rate on Strength Development

The results also demonstrated that increased BOFS content leads to higher UCS values across all curing stages. The 30% BOFS addition rate consistently outperformed the 20% rate, indicating that a higher stabilizer content enhances strength development. For instance, in the mass-based addition approach, the UCS value for the finest BOFS fraction (#100 – #40) increased from 410.92 kPa at 20% BOFS to 503.18 kPa at 30% BOFS after 90 days of curing. Similarly, a higher BOFS content in the volumetric method led to more significant strength improvements, confirming that increasing the higher proportion of stabilizer in BOFS enhances the pozzolanic reactions and overall soil bonding.

Despite these improvements, it is essential to consider the potential limitations of excessive BOFS content, such as workability issues, material segregation, or reduced compatibility. While the 30% addition rate demonstrated superior performance, future studies could explore whether there is an optimal BOFS dosage beyond which additional BOFS particle size charging stabilizer does not contribute significantly to strength gains.

4.3.3.3. Effect of Curing Time on Strength Characteristics

The overall UCS values for 20% and 30% BOFS addition rates increased with curing time across all mixtures, emphasizing the critical role of curing time in the strength development process. This trend is primarily attributed to the progression of chemical reactions, which become more effective over an extended period. The longer the curing duration, the more time is available for these reactions to form stronger bonds between soil particles, improving mechanical performance.

In the early curing stages (1 day to 1 month), the initial strength development is primarily governed by hydration reactions. During this phase, the CaO present in BOFS undergoes hydration, forming calcium hydroxide (Ca(OH)_2) and calcium silicate hydrate (C-S-H). This hydration process is what mainly causes the quick strength gain seen in the first few days. But since hydration by itself can't fully support long-term strength, the later strength improvements are mostly due to pozzolanic reactions, which happen more slowly over a longer period—sometimes months or even years.

In the later curing stages (after about 1 month to 90 days and more), calcium hydroxide reacts with the silica and alumina in the clay, forming calcium silicate hydrate (C-S-H) and

calcium aluminate hydrate (C-A-H). These are well-known pozzolanic compounds that act as the main binding agents in stabilized soils. The presence of C-S-H and C-A-H helps the cementation process, which boosts UCS values, just like what the test results showed. That's why strength keeps increasing over time, even after the initial hydration phase is done.

4.3.4. Conclusion

The UCS trends seen in this study confirm that curing time, BOFS particle size, and how much BOFS is added are the main factors affecting strength development in stabilized high-sulfate-bearing kaolin clay. Early strength gain mostly comes from hydration, while the longer-term strength is mainly controlled by pozzolanic reactions, which take more time to develop. Finer BOFS fractions showed faster strength development early on, while the coarser ones contributed more slowly as time went on. Additionally, replacing a higher proportion of BOFS helped improve the overall strength, and accordingly, more reactive materials were available.

These results highlighted how important it is to find the right balance between particle size fractions used and the addition rate of BOFS added to get good values of both early and long-term strength. In future studies, UCS values at even longer curing periods, beyond 90 days, could be studied to see whether pozzolanic reactions develop strength further, and to better understand how BOFS-stabilized soil behaves over time.

4.4. One-Dimensional Swelling Test Analysis

The one-dimensional swelling test was included to investigate the expansiveness of high-sulfate-bearing kaolin clay stabilized with BOFS. The main objective of this test was to analyze the effect of particle size distribution of BOFS on the volumetric and vertical swelling strain of the soil. The results provide insights on the advantages and disadvantages of stabilization with BOFS in mitigating the swelling potential of high-sulfate environments.

4.4.1. Volumetric BOFS Addition Test Analysis

The volumetric addition rate of BOFS was looked into to see how it affects the swelling potential of high-sulfate-bearing kaolin clay. This method involves replacing a percentage of the total soil

volume with BOFS. Table 4.9 presents the volumetric swelling percentages for two different volumetric BOFS additions: 20% and 30%.

Table 4.9. Volumetric swell for volumetric BOFS addition.

Mixture	Description [BOFS particle size range]	Volumetric Swell, %	
	$R_{BOFS(Volume)}$	20 %	30 %
1	SBS* only	15.76	14.70
2	SBS+BOFS [#100,60, (]	13.79	11.23
3	SBS+BOFS [#100,60,40,]	14.20	14.16
4	SBS+BOFS [#100,60,40,20,
]	17.70	16.69
5	SBS+BOFS [#100,60,40,20,10, & #4]	19.07	18.77

*SBS - Sulfate-bearing soil and **BOFS - Basic oxygen furnace slag

The results indicate that the untreated sulfate-bearing soil (SBS) exhibited the highest swelling potential. The stabilization with BOFS replacement at 20% and 30% volumetric replacement levels led to a noticeable reduction in volumetric swelling. From the results, it is significant that at 20% BOFS addition, the finest BOFS blend, mixture 2, exhibited the lowest swelling at 13.79%, while mixtures with coarser particles resulted in slightly higher swelling values. Whereas at 30% BOFS addition rate, swelling further decreased, mixture 2 achieving the best performance overall at 11.23 %. Even though mixtures 3 and 4 that contain coarser particle sizes, such as #4 and #10, exhibited higher swelling values than finer mixtures, they still reduced expansion compared to untreated soil. Other than volumetric swell over 14 days, the vertical swell strain over this time was also measured. Figures 4.7 and 4.8 illustrate the vertical swell strain over time for 20% and 30% BOFS volumetric replacements.

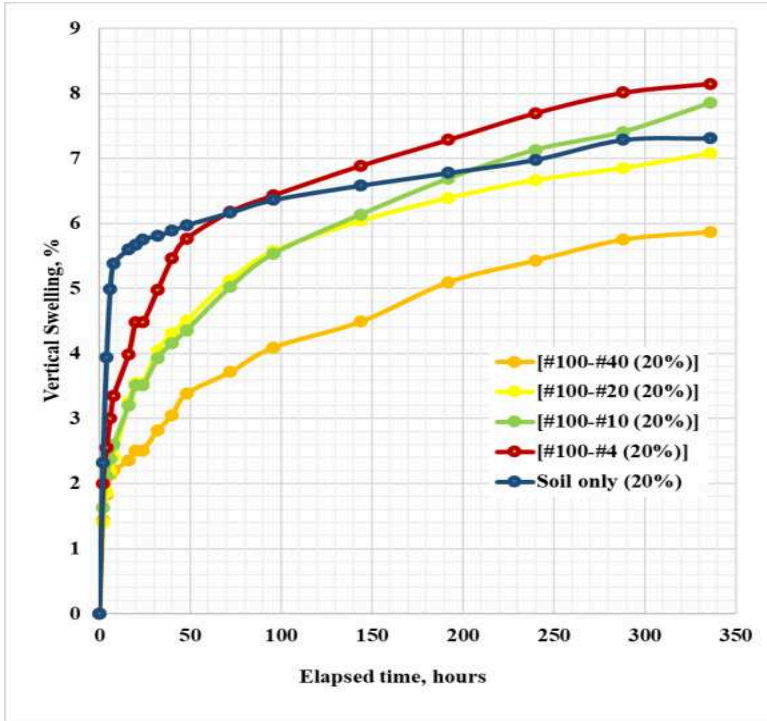


Figure 4.7. Vertical swell strain for $R_{BOFS(Volume)} = 20\%$.

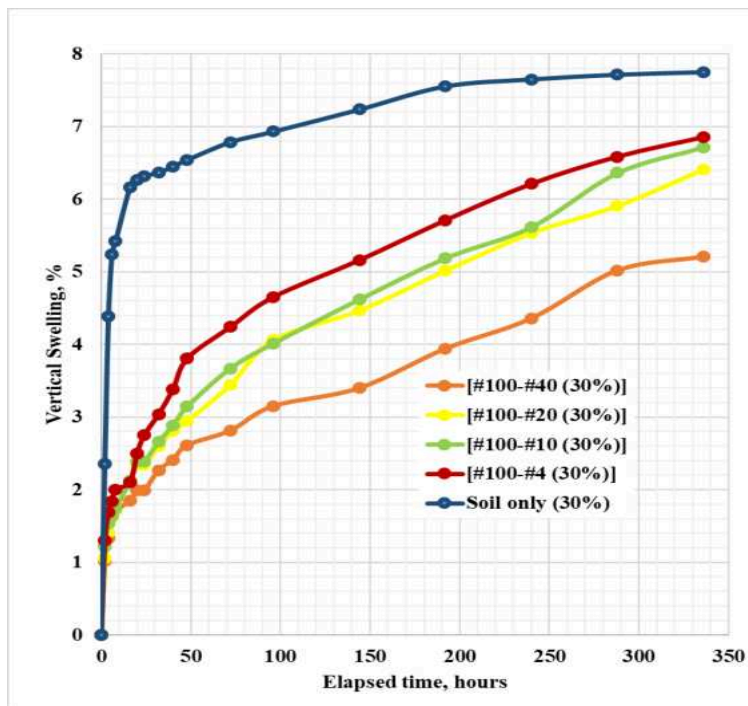


Figure 4.8. Vertical swell strain for $R_{BOFS(Volume)} = 30\%$.

The vertical swell strain curves reveal that the untreated soil samples exhibit the highest swelling strains, reaching almost 8%. Unlike untreated soil, samples stabilized with BOFS swelled much slower, indicating improved moisture absorption resistance. Also, the difference in initial swelling between untreated and untreated soils is significant. The untreated soil exhibited rapid initial swelling within the first few hours, followed by a slower increase in strain over time. In contrast, samples treated with BOFS showed delayed swelling onset, indicating improved resistance to moisture-induced expansion. The samples containing finer BOFS fractions reached equilibrium significantly earlier than those with coarser particles.

4.4.2. Mass-Based BOFS Addition Test Analysis

The mass-based addition rate was also employed to assess the impact of treating with BOFS on swelling. Table 4.10 shows the volumetric swell percentages of sulfate-bearing kaolin clay stabilized with BOFS at different particle sizes and mass addition rates of 20% and 30% at a 14-day swelling period.

Table 4.10. Volumetric swell for mass-based BOFS addition.

Mixture	Description [BOFS particle size range]	Volumetric Swell, %	
	$R_{BOF(hydrate-mass)}$	20 %	30 %
1	SBS* only	15.76	
2	SBS+BOFS [#100, #60, and #40]	12.95	9.78
3	SBS+BOFS [#100, #60, #40, and #20]	9.76	9.12
4	SBS+BOFS [#100, #60, #40, #20, and #10]	7.81	7.29
5	SBS+BOFS [#100, # 60, #40, #20, #10, and #4]	5.97	4.94

*SBS - Sulfate-bearing soil and **BOFS - Basic oxygen furnace slag

A higher BOFS addition ratio leads to better stabilization and less swell. For example, mixture 2 with a 20% mass addition rate caused a 12.95% swell, whereas the mixture with a 30% addition had only a 9.78% swell. Besides the mass addition ratio, the particle size range of BOFS in mixtures also plays a crucial role in reducing the swell potential. The results indicate that as

the BOFS particle size range becomes coarser and more diverse, the volumetric swell potential of samples decreases. In comparison, at a 30% addition rate, the swelling percentage of mixture 1, where kaolin clay was compacted using very fine BOFS with a grain size of 0.15-0.25mm, 9.64%. In contrast, the swelling percentage of mixture 5, with coarser BOFS particle sizes ranging from 0.15 to 4.75mm, was only 4.94%.

Besides volumetric swelling, the vertical swelling was measured using a dial gauge to precisely evaluate the stabilized kaolin clay's swelling characteristics. Dial gauge readings were recorded regularly over 14 days, precisely at 2, 4, 6, 8, 12, 16, 24, 32, 40, 48, 72, 96, 144, 192, 240, 288, and 336 hours. Vertical swell vs. elapsed time charts for kaolin clay stabilized with 20% and 30% BOFS mass addition rates are presented in Figures 4.9 and 4.10, respectively. Regardless of the BOFS addition rate, the vertical swell strain rapidly increases at an early age, which is typical of materials in contact with moisture. However, as the stabilization of kaolin clay starts, the swelling rate gradually increases with elapsed time. Increasing the BOFS content from 20% to 30% enhanced the vertical swelling of the specimens except for mixture 5 (#100 - #4).

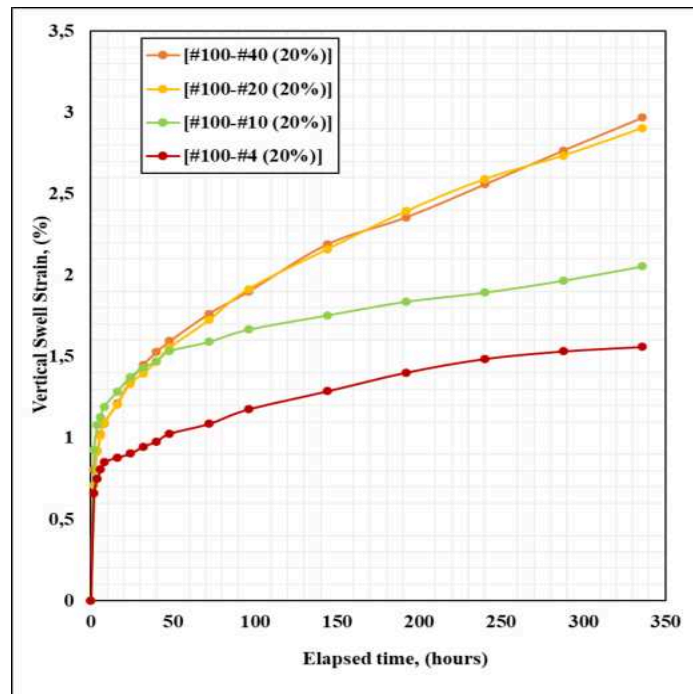


Figure 4.9. Vertical swell strain for $R_{BOFS(mass)} = 20\%$.

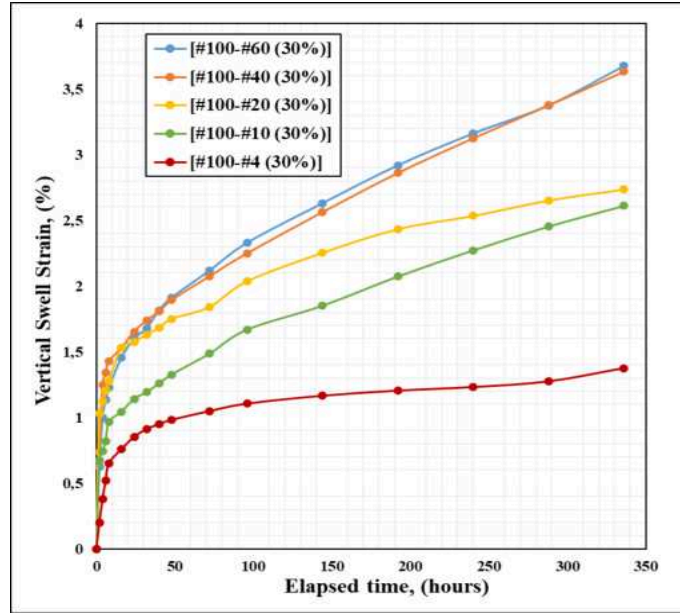


Figure 4.10. Vertical swell strain for $R_{BOFS(mass)} = 30\%$.

4.4.3. Swelling Behavior

The swelling behavior of high-sulfate-bearing kaolin clay stabilized with BOFS was analyzed by examining vertical and volumetric swell over time for both volumetric and mass-based BOFS additions. The results demonstrate an apparent reduction in swelling with BOFS addition, with the extent of reduction being influenced by both particle size distribution and stabilizer content.

4.4.3.1. Impact of BOFS Particle Size on Swelling Behavior

BOFS's particle size played a significant role in swelling mitigation, as seen in both volumetric and mass-based additions. The swelling reduction mechanism varied depending on the distribution of BOFS's fine and coarse particles within each mixture.

Fine BOFS particles significantly reduced swelling, particularly in volume-based additions. The finer particles contributed to a higher degree of pozzolanic reactivity, forming cementitious compounds that reduced swelling potential by improving soil bonding. Additionally, fine particles filled void spaces within the mixture, limiting water penetration and reducing expansive movements.

Coarser BOFS particles were less effective in reducing swelling compared to finer particles. Their primary mechanism of stabilization was through mechanical interlocking, which

helped limit volume change but did not significantly change the soil's chemical compositions. The larger particles created a more open structure, allowing some moisture adsorption and swelling, specifically in the early swelling phase. Moreover, the chemical reaction between coarse particles of BOFS, which is the transformation of free lime (f-CaO) to portlandite ($\text{Ca}(\text{OH})_2$), may also be attributed to higher swelling behavior.

4.4.3.2. Impact of BOFS Content on Swelling Behavior

The stabilizer content also directly influenced swelling behavior, with higher BOFS contents leading to lower swelling percentages. The increase from 20% to 30% BOFS replacement resulted in an additional swelling reduction for most mixtures. However, the effectiveness of increasing BOFS replacement was more significant in mass-based additions than in volumetric additions.

At 20% BOFS replacement, a noticeable decrease in swelling was observed compared to untreated soil, but some expansion still occurred, particularly in samples treated with coarser particles of BOFS. At 30% BOFS replacement, the swelling reduction was more significant, with the finest BOFS mixtures achieving a near-half reduction in swelling strain compared to untreated soil.

4.5. Mineralogical and Microstructural Analysis

Microstructural analyses such as X-ray diffraction (CRD) and scanning electron microscopy (SEM) are important for understanding and improving soil stabilization because they can provide insights into the fundamental properties of soil at the microscopic level. XRD helps identify the mineralogical composition of soils. Different minerals in soils react differently to stabilizing materials. Therefore, knowing the type of minerals in soils makes engineers predict how the soil will behave when treated with stabilizers such as lime, cement, and BOFS used in this study. Moreover, XRD can track the information of new minerals or compounds resulting from soil stabilization treatments. Therefore, XRD helps verify that the desired chemical reaction occurs and that the stabilizers effectively modify the soil. SEM can visualize soil structure. For example, SEM provides high-resolution images of the shape, size, and arrangement of soil particles. Therefore, when stabilizers are used, an SEM image can show how soil particles interact with the stabilizers and how stabilizers modify the soil structure (fabric). SEM can also visualize the

information on the bonding between soil particles and stabilizers. It helps evaluate the effectiveness of soil stabilizations in creating a denser and stronger soil structure, which shows that hydration products fill voids and bind soil particles together. Thus, this section will analyze kaolin clay mixtures treated with BOFS in terms of XRD and SEM analyses.

4.5.1. XRD Analysis

The mineralogical composition of various soil mixtures was analyzed using XRD, and the corresponding patterns are presented in Figures 4.11 and 4.12. These figures show distinct XRD patterns of various mixtures after the swelling test. Regardless of the volumetric BOFS replacement ratio, kaolinite, gypsum, and ettringite minerals were mainly identified. Replacement of kaolin clay with different amounts of BOFS did not affect XRD patterns in spite of different BOFS particle sizes.

Interestingly, the mixtures containing #100 to #4 BOFS particles in both 20% and 30% replacement ratios have strong ettringite picks compared to the mixtures with #100 to #20 and #100 to #10 BOFS particles. This result aligns with the expansion results presented in Figures 4.7 and 4.8. The mixtures containing #100 to #4 BOFS particles had higher expansion than those with #100 to #20 and #100 to #10 BOFS particles.

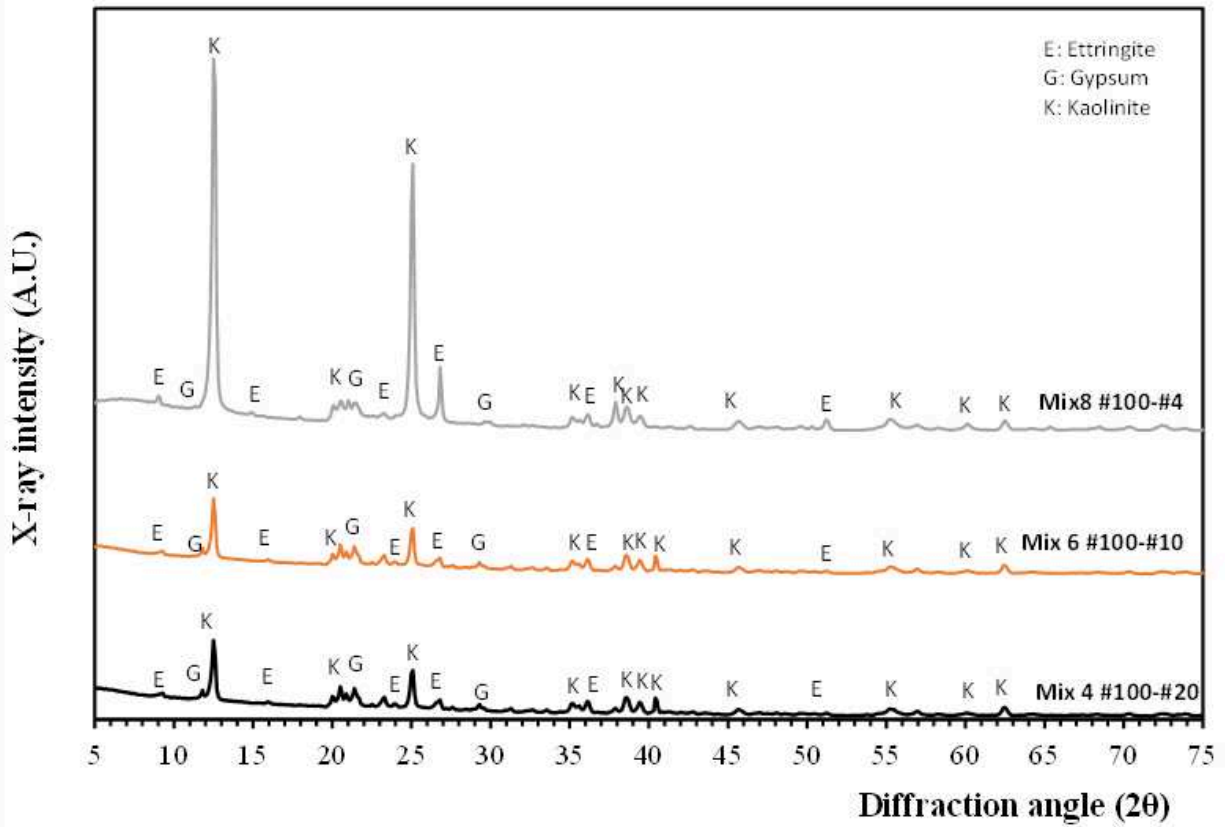


Figure 4.11. XRD Analyses for Mixtures ($R_{(BOFS(vol.))} = 20\%$) after Swelling Test

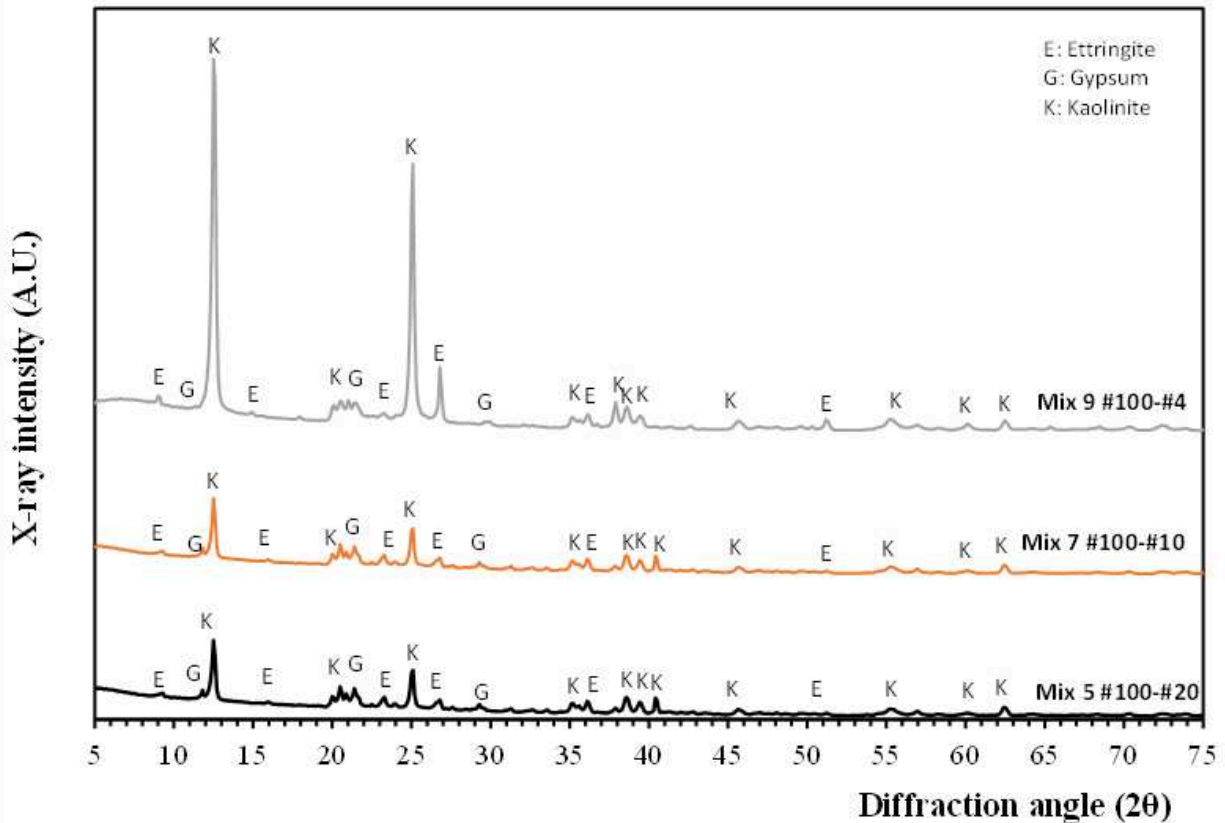


Figure 4.12. XRD Analyses for Mixtures ($R_{(BOFS(vol.))} = 30\%$) after Swelling Test

The XRD analysis highlights the critical influence of BOFS particle size and replacement ratio on the mineralogical behavior of sulfate-bearing kaolin clay mixtures. It is noticeable that mixtures stabilized with coarser BOFS particles caused more ettringite formation, which is the evidence of higher swelling potential. On the other hand, mixtures stabilized with finer particles were in control of the crystal growth better and the expansion was less in volume. These results show the importance of choosing the right BOFS particle size and replacement rate to reduce swelling and improve the long-term durability of stabilized soils.

4.5.2. SEM Analysis

SEM image analysis was performed on selected BOFS-treated kaolin clay mixtures to investigate their microstructural properties after swelling tests. The SEM images, accompanied by energy-dispersive spectroscopy (EDS) results, are presented in Figures 4.13 to 4.16. The SEM

micrographs in all Figures present clay minerals having flakes, gypsum, and ettringite minerals having needle-like crystals. EDS analyses confirmed ettringite minerals. As kaolin clay containing gypsum and BOFS became hydrated, ettringite minerals formed, causing aberrant swelling in the sulfate-bearing soil mixtures.

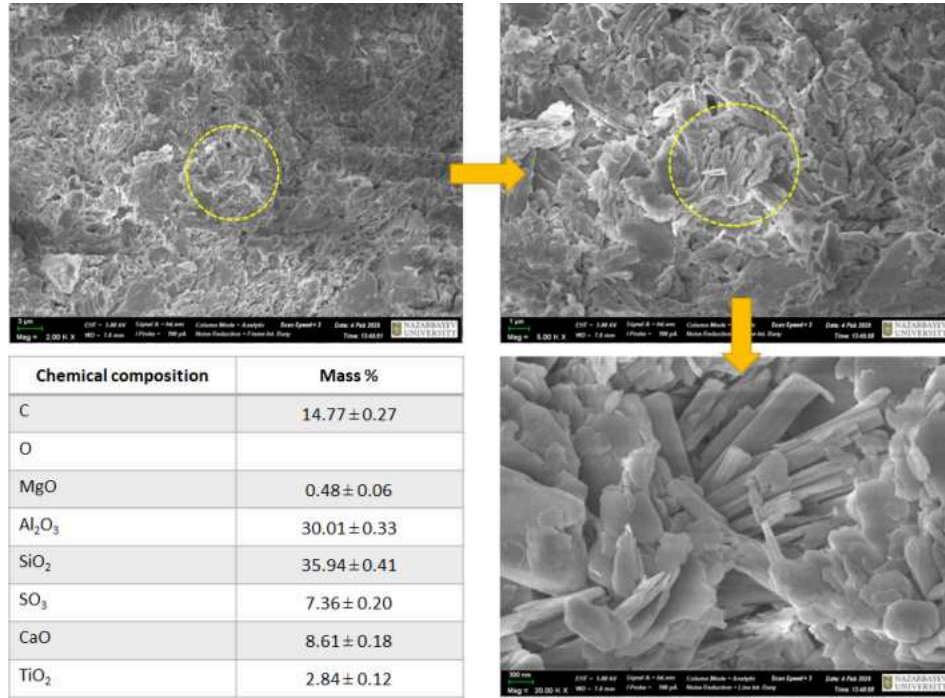


Figure 4.13. SEM Images for Mixtures containing #100 to #20 BOFS Particles ($R_{BOFS(vol.)} = 20\%$) after Swelling Test.

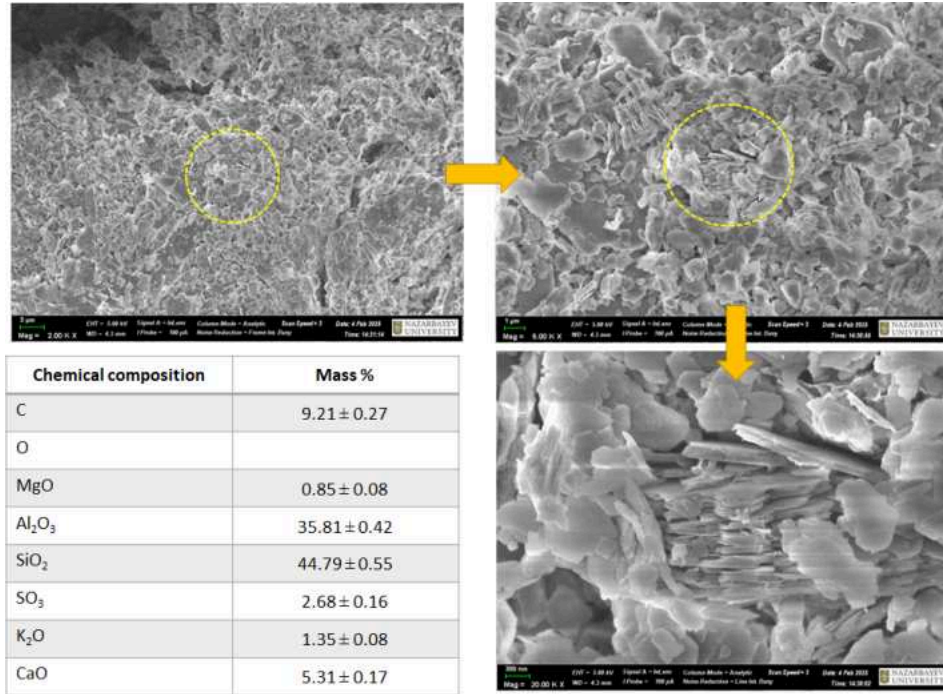


Figure 4.14. SEM Images for Mixtures containing #100 to #4 BOFS Particles ($R_{BOFS(vol.)} = 20\%$) after Swelling Test.

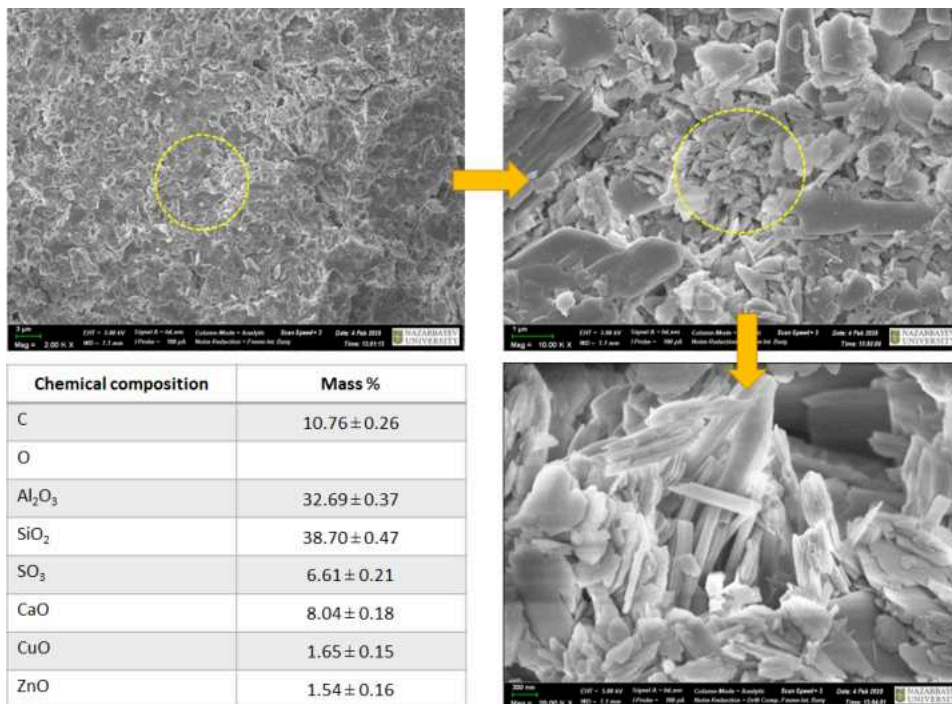


Figure 4.15. SEM Images for Mixtures containing #100 to #20 BOFS Particles ($R_{BOFS(vol.)} = 30\%$) after Swelling Test.

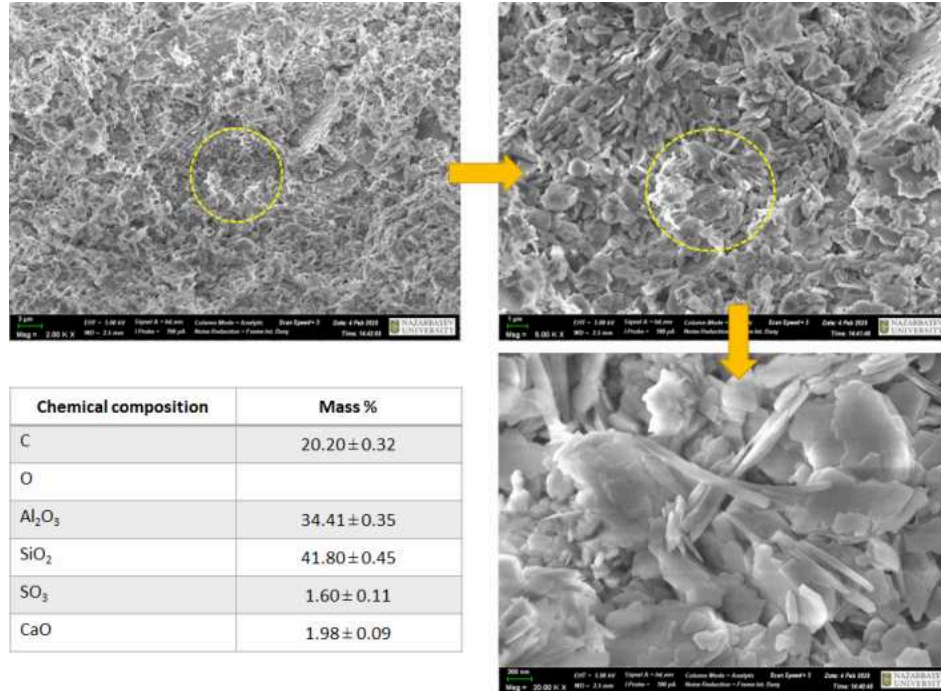


Figure 4.16. SEM Images for Mixtures containing #100 to #4 BOFS Particles ($R_{BOFS(vol.)} = 30\%$) after Swelling Test.

The SEM images presented in Figures 4.13 to 4.16 highlight the microstructural differences between BOFS-treated kaolin clay mixtures with varying particle sizes and replacement ratios. Mixtures containing finer BOFS particles (#100 to #20) demonstrated a denser matrix with minimal voids, indicating improved packing efficiency and reduced porosity. The compact structure not only limited water retention but also slowed down sulfate movement, which helped in minimizing the formation of expansive ettringite crystals.

The effect of BOFS replacement ratio (20% and 30%) on the microstructure was clear across all particle sizes. Soils treated with 20% BOFS showed moderate levels of ettringite crystal formation, and the ones with finer particles developed a denser matrix with more evenly spread crystals. This tighter structure helped reduce sulfate movement and limited swelling. In contrast, the mixtures with coarser particles had a looser structure, which made it easier for water to get in and caused uneven crystal growth.

When the BOFS replacement was increased to 30%, there was a clear rise in ettringite formation in all mixtures, with long, needle-like structures showing up more clearly. The mixtures with finer particles showed more consistent crystal growth, while those with coarser particles had uneven zones of swelling due to patchy crystal distribution. These observations

show that using more BOFS tends to increase the growth of expansive crystals, but finer particles help manage this better by keeping the structure more even and controlled.

From the SEM and EDS analyses it can be concluded that both the size of BOFS particles and the addition rate have a big impact on the microstructure and swelling behavior of high-sulfate-bearing kaolin clay. While finer BOFS particles reduce the amount of ettringite crystals by forming a denser and more stable matrix, coarser BOFS particles are effective in initial stabilization. These results highlight how important it is to choose the right BOFS particle size and replacement ratio to get the best performance in sulfate-rich conditions.

Chapter 5- Strength Prediction Model

The shear strength of soil is one of the most important engineering parameters used when designing pavement subgrade layers. Predicting the strength development of stabilized high-sulfate-bearing kaolin clay is important for understanding how effective BOFS is as a stabilizer. The main reason for this is because estimating strength accurately helps in optimizing how materials perform and making sure the project lasts for a long time.

In this study, a Strength Prediction Model was developed to estimate unconfined compressive strength (UCS) values based on BOFS particle size distribution, specific surface area (SSA), and BOFS addition rate. This model gives useful insights into how strength changes across different curing periods.

To estimate the strength of BOFS-stabilized soil, the following steps were carried out:

$$SSA = \frac{6}{\rho} \sum_{i=1}^n \left(\frac{w_i}{x_i} \right)$$

Where:

SSA - specific surface area (m^2/kg)

n - the number of intervals in the grain size distribution

w_i - weight of retained fraction size I

x_i - harmonic mean size distribution

ρ - density of material

Harmonic mean size distribution is calculated using the following equation below:

$$x_i = \left(\frac{(x_h^2 + x_j^2) * (x_h + x_j)}{4} \right)^{1/3}$$

Where:

x_h - upper grain size interval (mm)

x_j - lower grain size interval (mm)

A strength estimation model was developed to predict unconfined compressive strength (UCS) at different curing times based on the product of SSA and R(BOFS) by mass. The model looks at strength development over 14, 28, 56, and 90-day curing periods. Table 5.1 shows the data collected and demonstrates the relationship between $SSA \times R(BOFS)$ (mass) and the UCS values.

Table 5.1. Strength estimation model results.

Mix ture	Description	SSA (m ² /kg)	$R_{BOFS(mass)}$	SSA * R(BOFS) (mass) (m ² /kg)	14 Days (kPa)	28 Days (kPa)	56 Days (kPa)	90 Days (kPa)
1	SBS+BOFS [#100-#40]	0.9044	20	0.1809	39.57	111.68	202.7	410.92
2	SBS+BOFS [#100-#40]	0.9044	30	0.2713	53.48	138.15	354.81	503.18
3	SBS+BOFS [#100-#20]	1.6932	20	0.3386	38.2	81.45	178.25	269.08
4	SBS+BOFS [#100-#20]	1.6932	30	0.5080	36.28	117.14	247.01	473.14
5	SBS+BOFS [#100-#10]	2.8866	20	0.5773	30.56	59.17	149.73	242.76
6	SBS+BOFS [#100-#10]	2.8866	30	0.8660	25.19	73.34	222.05	297.94
7	SBS+BOFS [#100-#4]	5.7505	20	1.1501	29.28	48.38	110.01	132.42
8	SBS+BOFS [#100-#4]	5.7505	30	1.7252	20.37	56.02	205.76	262.29

A scatter plot in Figure 5.1 below was generated to visualize the relationship between $SSA \times R(BOFS)$ (m²/kg) and UCS (kPa) for different curing periods. A linear regression model was applied to estimate the relationship using the equation:

$$q_u = k(SSA \times R_{BOFS})$$

Where:

k represents the rate of strength increase per unit $SSA \times R(\text{BOFS})$.

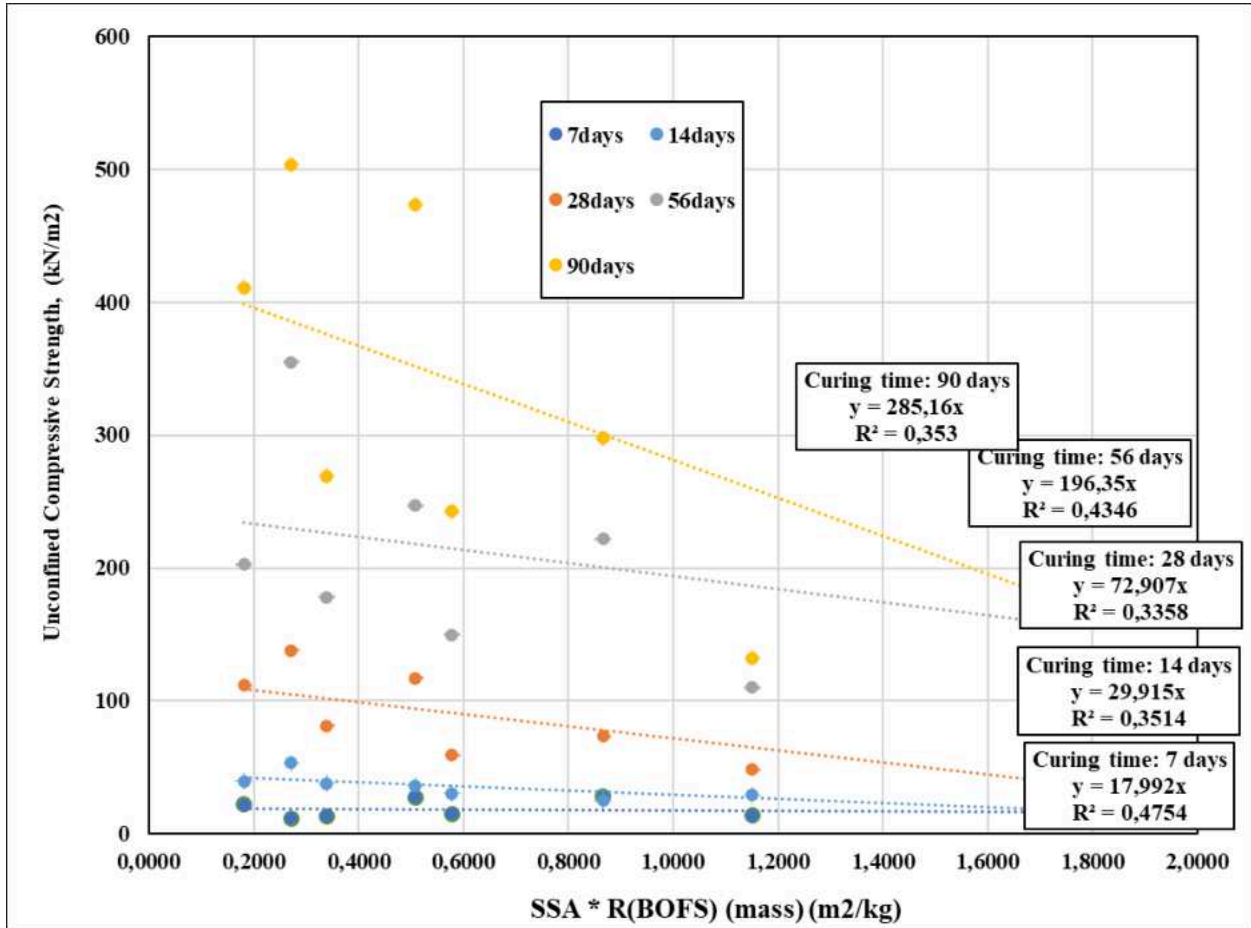


Figure 5.1. Relationship between $SSA \times R(\text{BOFS})(\text{mass})$ and UCS over time.

To quantify this relationship, linear regression equations were derived for each curing age, resulting in the following expressions:

- **7 days:**

$$q_{u(7\text{ days})} = 17.992 \times (SSA \times R_{BOFS})$$

- **14 days:**

$$q_{u(14\text{ days})} = 29.915 \times (SSA \times R_{BOFS})$$

- **28 days:**

$$q_{u(28\text{ days})} = 72.907 \times (SSA \times R_{BOFS})$$

- **56 days:**

$$q_{u(56\text{ days})} = 196.35 \times (SSA \times R_{BOFS})$$

- **90 days:**

$$q_{u(90\text{ days})} = 285.16 \times (SSA \times R_{BOFS})$$

These equations reveal a progressive increase in the regression coefficient (k-value) with longer curing periods, illustrating the cumulative effect of hydration and pozzolanic reactions over time. The steep rise in strength from 28 to 90 days suggests that the majority of strength gain in these stabilized mixtures occurs during the extended curing phase, particularly after the initial 14-day period.

Interestingly, when the same analysis was conducted using volumetric BOFS replacement (Figure 5.2), a similar trend was observed, though with minor variations in slope and data spread. This implies that while both mass-based and volume-based calculations are valid, the mass-based model may offer slightly better precision due to its closer alignment with the actual material behavior during mixing and compaction.

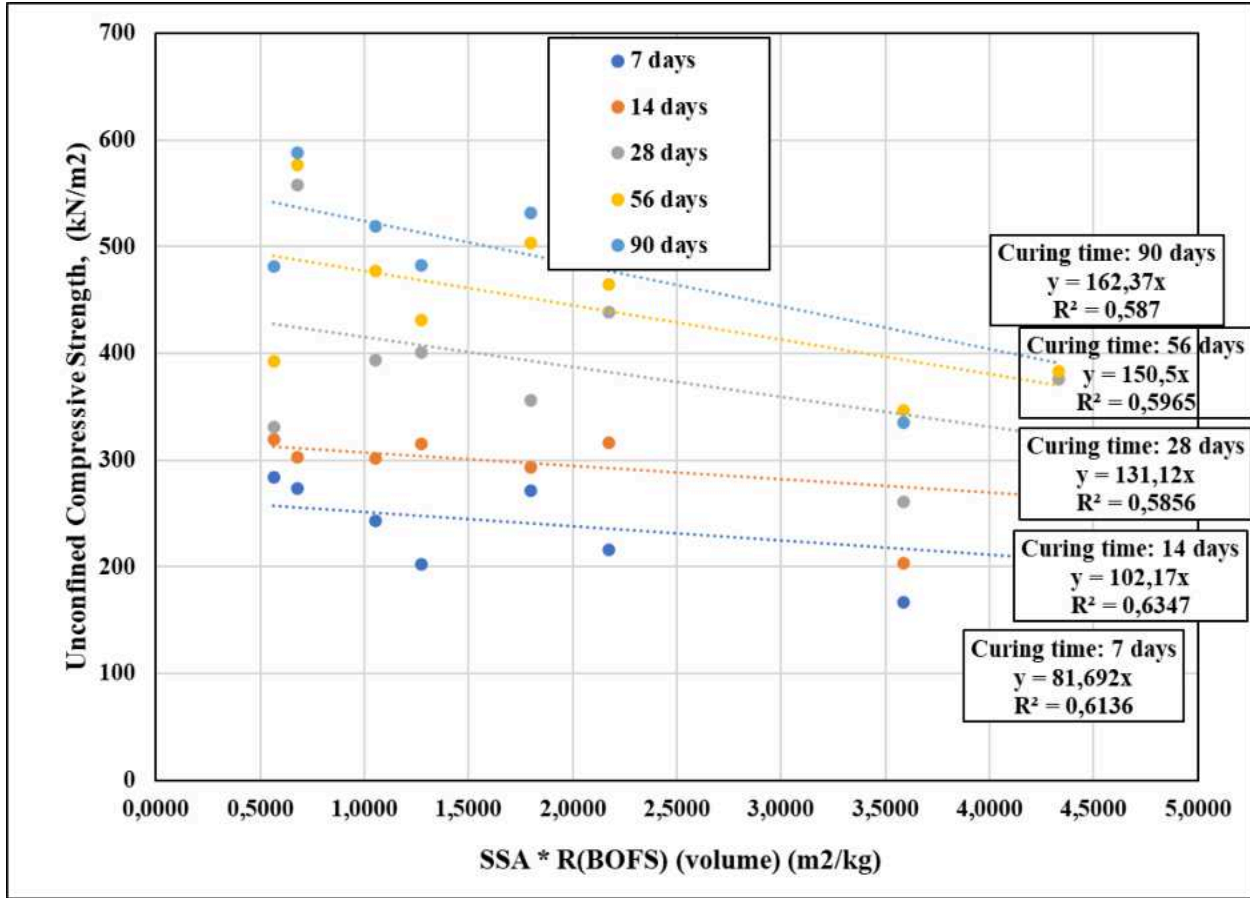


Figure 5.2. Relationship between $SSA \times R(BOFS)(\text{volume})$ and UCS over time.

Similarly, a separate analysis was conducted using volumetric replacement ratios of BOFS instead of mass-based calculations. The results, presented in Figure 5.2, show a set of linear regression equations that relate unconfined compressive strength (q_u) to $SSA \times R(BOFS)$ based on volume. Although the trends remained consistent with the mass-based model, the rate of strength development differed slightly across curing periods.

The regression equation for the

- **7-day** curing period was:

$$q_{u(7 \text{ days})} = 81.692x (SSA \times R_{BOFS})$$

- **14 days**

$$q_{u(14 \text{ days})} = 102.17x (SSA \times R_{BOFS})$$

- **28 days**

$$q_{u(28 \text{ days})} = 131.12x (SSA \times R_{BOFS})$$

- **56 days**

$$q_{u(56 \text{ days})} = 150.50x (SSA \times R_{BOFS})$$

- **90 days**

$$q_{u(90 \text{ days})} = 162.37x (SSA \times R_{BOFS})$$

Compared to the mass-based regression model, the volume-based model produced steeper regression slopes at early curing stages, suggesting a more immediate strength gain when volume is considered. However, the differences between the two methods became smaller as curing continued. These results suggest that while both approaches are valid, the volume-based method might be more sensitive for predicting early-age strength, which could be helpful in time-sensitive construction work.

Chapter 6 - Conclusions and Recommendations

6.1. Summary

This study looked into the combined effect of basic oxygen furnace slag (BOFS) particle size and its stabilizing properties on the mechanical behavior and durability of high-sulfate-bearing kaolin clay. The main goal was to see if BOFS could work as a good alternative to traditional calcium-based stabilizers, which often cause ettringite-related swelling and damage in sulfate-rich soils. To meet these goals, an experimental program was designed and carried out at the Soil Laboratory of Nazarbayev University.

The test results demonstrated the effectiveness of BOFS in improving the unconfined compressive strength (UCS) of sulfate-bearing kaolin clay. It was observed that finer BOFS particles made a bigger contribution to strength gains, thanks to their higher surface area and better pozzolanic activity. The ideal BOFS addition rate by volume was found to be between 20% and 30%, which gave a good balance between strength and workability. Also, extending the curing period had a clear positive impact on UCS values, with the 90-day samples showing the highest strength increases in this experiment.

The swelling test results showed that stabilization of high-sulfate-bearing kaolin clay with BOFS effectively reduces the volumetric and vertical expansion, particularly in mixtures with finer BOFS fractions. Moreover, higher BOFS content of 30% led to greater swelling. The mineralogical and microstructural analyses, XRD and SEM, confirmed the presence of cementitious compounds, which indicates the contribution of chemical reactions to the improved engineering properties of the stabilized soil. In addition, from the SEM images, the needle-like ettringite crystals were noticed, revealing the ettringite formation in excess moisture conditions.

This study successfully developed a strength prediction model to estimate the unconfined compressive strength (UCS) of BOFS-stabilized high-sulfate-bearing kaolin clay, based on the product of specific surface area (SSA) and BOFS addition rate. The model demonstrated a strong linear relationship between $SSA \times R(\text{BOFS})$ and UCS across various curing periods, with regression equations providing reliable estimates of strength development at 7, 14, 28, 56, and 90

days. Notably, the strength gain increased significantly over time, emphasizing the importance of long-term curing in stabilized soil performance.

Based on these observations, the implication of this research is expected to be significant in sustainable soil stabilization techniques, as BOFS is a promising stabilizer for problematic sulfate-bearing soils. By utilizing BOFS, this study supports the sustainable reuse of steel industry by-products, reducing its environmental impact as well as improving the soil performance in construction applications.

6.2. Future Research Recommendations

While this study has provided critical insights into the stabilization of high-sulfate-bearing kaolin clay using BOFS, the following recommendations are required to further enhance the understanding and applicability of this method:

1. One limitation of this study was the absence of a direct comparison between BOFS and traditional stabilizers. In future studies, the mixtures incorporating other stabilizers to assess their combined effect on strength and durability.
2. This study focuses only on BOFS, its particle sizes and addition rates, but in further research, additional mixtures, including cement, GGBFS (Ground Granulated Blast Furnace Slag), or fly ash can be explored.
3. Investigating other BOFS addition rates such as 10%, 15%, 25%, 35% can help us in getting more accurate observations. Other than that, 40% addition rate, which was second best in settlement studies, also should be studied further.
4. As curing period of 90 days showed promising strength gains in mixtures, longer curing durations would be more helpful and accurate in analysing its resistance in real-world applications.

By addressing these areas, future research can present more refined BOFS-based soil stabilization techniques and develop more sustainable, practical solutions for sulfate-rich environments.

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APPENDICES

Appendix A

Table A.1: Sieve Analysis Table of Soil

Sieve Size		Individual Weight Retained (g)	Individual % Retained	Cumulative % Retained	% Passing
No.	mm				
4	4.75	0.00	0.00	0.00	100
10	2	0.50	0.10	0.10	99.90
20	0.85	6.40	1.31	1.41	98.59
40	0.425	15.50	3.17	4.58	95.42
60	0.25	29.10	5.95	10.54	89.46
100	0.15	39.70	8.12	18.66	81.34
140	0.106	108.90	22.28	40.95	59.05
200	0.075	253.10	51.79	92.74	7.26
pan	0	35.50	7.26	100.00	0.00
Total		488.70			

Table A.2: Grain Size Distribution Summary for Soil

% gravel	0	D ₆₀ (mm)	0.114	C _u = D ₆₀ / D ₁₀	1.521
% sand	95.42	D ₃₀ (mm)	0.088	C _c = (D ₃₀) ² / D ₁₀ *D ₆₀	0.901
% fines	4.58	D ₁₀ (mm)	0.075		

Table A.3: Sieve Analysis Table of Basic Oxygen Furnace Slag (BOFS)

Sieve Size		Individual Weight Retained (kg)	Individual % Retained	Cumulative % Retained	% Passing
No.	mm				
4	4.75	31.44	47.33	47.33	52.67

10	2	13.1	19.72	67.05	32.95
20	0.85	8.66	13.04	80.07	19.91
40	0.425	4.628	6.97	87.05	12.95
60	0.25	2.72	4.09	91.15	8.85
100	0.15	2.58	3.88	95.03	4.97
140	0.106	0.86	1.29	96.33	3.67
200	0.075	1.12	1.69	98.01	1.99
pan	0	1.32	1.99	100	0
Total		66.428			

Appendix B

Table B.1: Specific gravity for soil (Trial #1)

Pycnometer	W1	160,9
Pycnometer+Dry soil	W2	191
Pyc+soil+water	W3	675,6
Pycnometer + water	W4	658,1
	Specific Gravity	2,39

Table B.2: Specific gravity for soil (Trial #2)

Pycnometer	W1	160,3
Pycnometer+Dry soil	W2	190
Pyc+soil+water	W3	675,1
Pycnometer + water	W4	657,1

	Specific Gravity	2,54
--	------------------	------

Table B.3: Specific gravity for soil (Trial #3)

Pycnometer	W1	160,1
Pycnometer+Dry soil	W2	190
Pyc+soil+water	W3	676,6
Pycnometer + water	W4	657,8
	Specific Gravity	2,69

Appendix C

Table C.1: Specific gravity for fine aggregates of BOFS

Sam ple	Pycno meter+ Water (g)	SSD sample (g)	Pyc+Wate r+SSD sample (g)	Oven dry sample+bo wl (g)	Oven Dry (g)	G sb-od	G ssd	G sa	Absorpti on
1	7392	505	7716	703	473	2.61	2.79	3.17	6.76
2	7399	461	7694	652	425	2.56	2.78	3.269	8.47
3	7397	454	7688	600	422	2.59	2.78	3.24	7.582
					Average:	2.58	2.78	3.2217	7.61

Table C.2: Specific gravity for coarse aggregates of BOFS

Sam ple	Pycnome ter+Wate r (g)	SSD sample (g)	Pyc+W ater+SS D	Oven dry sample+ bowl (g)	Oven Dry (g)	G sb-od	G ssd	G sa	Absorpti on
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			sample (g)						
1	700,73	1023.2 4	1391.2	1151.3	992.3	2.98	3.07	2.98	3.12
2	700,87	1028.2 1	1395.16	1159.82	997.82	2.98	3.0	2.98	3.04
3	701,34	1047.0 9	1404.25	114.,8	1018.8	2.96	3.04	2.96	2.77
					Average:	2.97	3.07	2.97	2.98

Appendix D

Table D.1.: Strength Estimation Value for Volumetric BOFS addition

#	Mixture description	Harm onic mean size distribution (mm)	SSA (m ² /kg)	R (BOFS) (%)	R(BOFS) (hydrate-mass) (%)	SSA * R(BOFS) (hydrate-mass) (m ² /kg)	qu (7days)	qu (14days)	qu (28days)	qu (56days)	qu (90days)
2	SBS + BOFS [#100-#40]	0.3079	0.9044	20	62.36	0.5640	283.93	319.16	331.04	392.16	481.59
3	SBS + BOFS [#100-#40]	0.3079	0.9044	30	75.31	0.6810	273.75	303.03	558.06	576.52	588.15

4	SBS + BOFS [#100-#20]	0.571 1	1.6932	20	62. 36	1.0560	243. 19	301.76	393.4 3	477.21	518.89
5	SBS + BOFS [#100-#20]	0.571 1	1.6932	30	75. 31	1.2751	202. 45	315	401.0 7	431.63	482.98
6	SBS + BOFS [#100-#10]	1.293 1	2.8866	20	62. 36	1.8001	271. 2	292.85	356.5 1	503.35	531.11
7	SBS + BOFS [#100-#10]	1.293 1	2.8866	30	75. 31	2.1737	216. 45	316.78	438.7 6	465.16	525.72
8	SBS + BOFS [#100-#4]	3.024 5	5.7505	20	62. 36	3.5862	166. 79	203.72	261.0 1	346.32	335.12
9	SBS + BOFS [#100-#4]	3.024 5	5.7505	30	75. 31	4.3305	254. 65	311.94	375.6 1	383.25	429.99

Appendix E

Table E.1.: Volumetric Swell for Mass-Based Addition Rate

#	Mixture description	Air-dry			After 14 days			V swell (%)
		Diameter (mm)	Height (mm)	Volume (cm ³)	Diameter (mm)	Height (mm)	Volume (cm ³)	
1	SBS + BOFS [#100-#40] (20%)	93.72	109.50	755.04	97,50	114.28	852.79	12.95
2	SBS + BOFS [#100-#40] (30%)	95.22	108.44	771.89	97.83	112.78	847.36	9.78
3	SBS + BOFS [#100-#20] (20%)	92.28	109.11	729.34	94.83	113.39	800.50	9.76

4	SBS + BOFS [#100-#20] (30%)	94.72	110.78	780.24	97.94	113.06	851.38	9.12
5	SBS + BOFS [#100-#10] (20%)	95.39	110.78	791.26	96.06	117.78	853.06	7.81
6	SBS + BOFS [#100-#10] (30%)	93.78	108.11	746.35	95.22	112.50	800.75	7.29
7	SBS + BOFS [#100-#4] (20%)	93.17	111.17	757.47	94.78	113.83	802.70	5.97
8	SBS + BOFS [#100-#4] (30%)	94.06	110.89	770.06	95.44	113.00	808.07	4.94

Table E.2.: Volumetric Swell for Volumetric BOFS Addition Rate

#	Mixture description	Air-dry			Final			V swell (%)
		Diameter (mm)	Height (mm)	Volume (cm ³)	Diameter (mm)	Height (mm)	Volume (cm ³)	
1	SBS + BOFS [#100-#40] (20%)	100.00	115.00	902.75	103.33	122.56	1027.27	13.79
2	SBS + BOFS [#100-#40] (30%)	100.00	115.00	902.75	103.22	120.06	1004.15	11.23

3	SBS + BOFS [#100-#20] (20%)	100.00	115.00	902.75	103.61	122.33	1030.93	14.20
4	SBS + BOFS [#100-#20] (30%)	100.00	115.00	902.75	104.67	119.83	1030.54	14.16
5	SBS + BOFS [#100-#10] (20%)	100.00	115.00	902.75	104.67	123.56	1062.55	17.70
6	SBS + BOFS [#100-#10] (30%)	100.00	115.00	902.75	103.89	124.33	1053.41	16.69
7	SBS + BOFS [#100-#4] (20%)	100.00	115.00	902.75	104.50	125.39	1074.88	19.07
8	SBS + BOFS [#100-#4] (30%)	100.00	115.00	902.75	104.83	124.28	1072.17	18.77
10	Soil only - 20%	100.35	113.86	900.02	104.44	121.67	1041.87	15.76
11	Soil only - 30%	103.38	117.54	986.16	105.15	130.33	1131.14	14.70