

Research Article

Effect of Adding Blast Furnace Slag on Shrinkage and Swelling Behavior of Clayey Soil

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Article Info	Abstract
Article History	The challenge of mitigating soil swelling and shrinkage has driven geotechnical engineers and researchers to seek effective, sustainable, and cost-efficient stabilization methods. One promising approach is using industrial by-products, such as blast furnace slag (BFS), as stabilizing agents. This study investigates the effect of BFS on soil's shrink/swell properties by incorporating it in three different percentages (5%, 10%, and 15%). Soil characteristics, including Atterberg limits, linear shrinkage, compaction parameters (maximum dry density and optimum moisture content), and consolidation parameters (compression index (Cc), swelling index (Cs), recompression index (Cr), and swelling strain (ϵ)), were evaluated. The results indicate that BFS significantly improved soil properties. Linear shrinkage was reduced by approximately 50%, while the compression index, swelling index, recompression index, and swelling strain improved by 96.1%, 97.1%, 95.6%, and 50.7%, respectively. These findings suggest that BFS is an effective stabilizing agent for mitigating shrink/swell behavior in soils, making it a viable option for geotechnical applications.
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1. Introduction

Currently, soil improvement encompasses a vast array of geotechnical research areas and techniques to address the weak engineering properties of soils. This concept is not new; according to historical references, soil stabilization was employed by several ancient human civilizations in the construction of their roads and buildings [1]. According to McDowell [2], the history of soil stabilization is long. References note that the concept was used 5,000 years ago by ancient civilizations and empires, including the Tibetans, Mongolians, Mesopotamians, and Romans, for their constructions, such as roads and pyramids. Returning to historical information, the ancient Egyptians used lime with clay and compacted the mixture to construct their magnificent structures; the pyramids are living examples of these constructions in today's world [2]. The religious books also support this fact; for example, in our Holy Quran, specifically in Surah Al-Qasas,

Ayah 38, Almighty Allah said, 'Pharaoh said, "Counsellors, you have no other god that I know of except me." Haman, light me a fire to bake clay bricks, then build me a tall building so I may climb up to Moses' God; I am convinced he is lying" [3].

Another example is the Roman roads, known as the "Appian Way". These roads were created by using an extremely strong technique: excavating the subgrade layer of the soil and placing four layers upon it so that each layer is the completion of the other [4]. Together, they made a strong kind of road that lasted for centuries. Furthermore, Alshareef and Hamed [5] claim that the practice of reinforcing soil dates back to ancient civilizations, particularly in Babylon, highlighting its enduring significance.

Shrinkage and swelling are the means of volume change in clays. When soil is subjected to the gain and/or the absorption of water, as usually happens during the rainy season, the water particles will fill the voids inside the soil mass [6]. As a result of the continuation of the water absorption, the particles of water will be spread freely inside the soil mass, and since the soil particles have reached their complete absorbing ability, the soil package will be compelled to increase in volume [7]. This phenomenon of volume increment is known as "Soil Swelling" [8]. Eventually, as the dry season approaches, this process will be reversed, from the gaining and absorbing of water to its removal and evaporation; the other means of volume change will occur. In this case, water loss within the soil mass will decrease its volume, and subsequently, some cracks will form, which can be easily observed on the soil surface [9]. The production of such cracks will make considerable and perceivable space inside the soil mass; these cracks are known as "shrinkage cracks," and the overall process of decrease in the soil volume is referred to as "soil shrinkage [10]. As a result of continual shrinkage and swelling, the soil will weaken until it causes considerable and dangerous damage to the overlying structure, leading to definite structural failure [11].

Iraq's climate varies across its three main regions. The northern Kurdistan region, characterized by mountainous terrain, experiences cold, wet winters and dry, rainless summers. In contrast, the southern region, particularly the southeast, has an arid climate with minimal rainfall, sometimes experiencing years of drought [12]. The central region exhibits a mix of northern and southern weather patterns. These climatic differences influence soil behavior, with the Kurdistan region experiencing soil swelling during rainy seasons and shrinkage in dry periods due to continuous water absorption, which can lead to plasticity-related soil damage [13]. Furthermore, swelling and shrinkage of soil lead to the formation of cracks, enhancing the soil's permeability. Soils that exhibit high permeability tend to have reduced strength, making them less capable of resisting sliding and other failures [14-16].

Additionally, Iraq generates significant amounts of metallic waste, including 390 tons of iron and steel daily, some of which remain unrecycled [17]. BFS, a by-product of iron production, has been used in construction for decades [18]. This study examines the potential of BFS for enhancing soil quality, thereby contributing to waste management and recycling efforts in Iraq.

The primary objectives of this study are to enhance the plastic properties of soil, specifically addressing shrinkage and swelling, and to introduce a novel approach to stabilize problematic soils in various regions of Iraq, ultimately benefiting the country. Additionally, the study proposes using BFS as an economical alternative to traditional stabilizers such as cement, lime, and fly ash, which are commonly used in the area. Another goal is to encourage the Iraqi engineering community to explore the use of local waste materials, particularly BFS, in engineering applications. Finally, the study aims to support waste management and recycling efforts by reducing metallic waste, thus preserving natural resources and promoting sustainable waste disposal practices.

2. Literature Review

Since BFS is a strong material, it has been thought that it may be used as a soil stabilizer, perhaps to a reasonable degree [19]. That is why numerous studies can be found in engineering journals that utilize BFS as a stabilizing agent, either individually or in combination with other materials to form a stabilizer. Therefore, this section will provide a brief review of these studies.

Yadu and Tripathi [20] have investigated the effects of BFS on the engineering behaviors of soft soil. In the study, a low-plasticity clay was used, and the BFS was blended with the soil in different proportions (3%, 6%, 9%, and 12%) by weight of the soil. The behaviors investigated were Atterberg limits, compaction properties, swelling behavior, UCS, and CBR. As a result, adding BFS has caused the MDD to increase and the OMC to decrease; it has also caused an increase in the UCS and CBR values of 400% and 28%, respectively. Regarding swelling behaviors, the results indicated decrements of 67% in the free swelling index and 21% in swelling pressure. Eventually, the optimal BFS content was found to be 9% [20].

Moreover, Kumar Sharma and Sivapullaiah [21] have also used BFS in their study to improve the strength of the soil. The study was conducted using black cotton soil having USCS classification of CH, and the BFS has been used in different soil proportions such as (9:1, 4:1, 7:3, 3:2, 1:1, 2:3, 3:7, 1:4, and 1:9), and the properties like MDD, OMC, UCS, and initial tangent modulus were examined. Conclusively, both the MDD and OMC decreased after the addition of BFS, and according to the authors' statement, it was due to the predominant effects of reduced clay content and increased frictional resistance, respectively. However, the UCS has been increased at different rates for different curing periods (7, 14, and 28 days). The maximum increment was observed in the case of 28 days, where it reached its peak after adding 40% BFS, and the increment rate was 100%. Finally, it was observed that the initial tangent modulus improved by almost 200% after adding 40% of BFS [21].

Furthermore, Sharma and Sivapullaiah [22] also performed another investigation. However, this time, the BFS was used with fly ash to form a stabilizing agent, and then added to the soil-bentonite mixture in a proportion of 80%-20%. Behaviors such as Atterberg limits, compaction properties, and UCS have been

studied. Consequently, it was clarified that after the binder insertion, the OMC decreased by 10%, and MDD increased by 1.10 kN/m³. Also, the UCS was increased in all curing periods (7, 14, and 28 days) until the binder percentage reached 20%, but after further additions, the UCS was reduced slightly, which was, according to the authors' clarification, due to a lack of pozzolanic reaction in some certain contents of the stabilizers [22].

These researchers published another study using the same method and proportions for the same soil-bentonite mixture. However, this time, the investigation process was modified to focus on swelling behavior, and the study included the addition of 1% lime to the binder [23]. As a result, it was clarified that the incorporation of the binder caused the soil-bentonite mixture to improve in swelling characteristics in which the free swelling index decreased from 7.25% to 4.75%, the swell potential has also decreased from 6.5% to 1%, and similarly, the swelling pressure decreased from 400 kPa to 100 kPa. It is worth mentioning that the addition of lime has further improved the swelling characteristics, in which the swelling behavior has shown a considerable improvement compared to the case without lime [23].

As the last instance, a closer as well as more recent study can be taken, which is the study of Abdalqadir, et al. [24], in which they have investigated the effect of incorporating BFS on a high plasticity soil in the Bakrajo district of Sulaymaniyah governorate, and the properties like Atterberg limits, swelling characteristics, UCS, and bearing capacity have been examined. Consequently, integrating the BFS caused considerable improvements in UCS by more than 45%, swelling pressure by almost 25%, swelling pressure by nearly 27%, and the bearing capacity of the soil by approximately 10% [24].

Usually, when BFS is added to clay soil, a chemical reaction occurs primarily between the calcium compounds in the slag (like calcium silicates and calcium aluminates) and the silicate and alumina content in the clay [25, 26]. This reaction forms calcium silicate hydrate and calcium aluminate hydrate, binding agents that improve the soil's strength and stability. The stabilization mechanism when adding BFS to clay soils involves several processes, such as Cementation, reduction of Poisson's ratio, and improvement of drainage [27].

While the findings of this study largely align with previous research, showing a consistent reduction in shrink/swell potentials and an increase in MDD, there are discrepancies in the observed trends for OMC. While many studies report either an increase or no change in OMC with soil stabilizers, Saidasadq's soil displayed a distinct trend, with OMC decreasing as BFS was added. This observation introduces an important gap in understanding BFS's impact on soil properties, particularly OMC. This study aims to further explore and clarify these inconsistencies, investigating the behavior of BFS in varying soil compositions. This research bridges this gap and contributes to the growing body of evidence supporting BFS as a cost-effective, sustainable, and robust solution for soil stabilization. Given the widespread availability, strength, and economic feasibility of BFS, the findings from this study are significant for advancing its application in both civil engineering and geotechnical fields.

3. Materials and Methods

3.1. Materials

This study used clayey soil, and its stabilizing agent was BFS. In the following two sections, the details of each one will be presented.

3.1.1. Soil

This study uses a clayey soil type to investigate its properties before and after the treatment. The soil was collected from Saidaq, Sulaymaniyah, Iraq (35° 22' 9" N, 45° 53' 13" E), at a depth of 1-2 meters. After air-drying for 72 hours, it was used in the experimental testing process. Table 1 provides the main characteristics of the Saidaq soil.

Table 1. Saidaq soil properties

Property	Designation	Quantity	Unit of measurement
Liquid limit	LL	36.2	%
Plastic limit	PL	22.63	%
Plasticity index	PI	13.57	%
Specific gravity	G _s	2.817	-
Passing sieve No.200	-	72	%
Maximum Dry Density	MDD	19.28	kN/m ³
Optimum Moisture Content	OMC	16.16	%
USCS class	-	Group symbol: CL Group name: Lean clay with sand	-
Clay content	-	53.4	%

Figure 1. presents a flowchart (scope of the study) detailing the process of studying the effect of BFS on soil properties. The process begins with selecting a soil location and bringing the soil, specifically Saidaq soil, to the laboratory for testing. An experimental study includes sieve analysis, Atterberg limits, soil classification, specific gravity, compaction testing, linear shrinkage, and one-dimensional consolidation. After obtaining the initial data, BFS is added to the soil, and re-testing is performed to assess changes in soil properties. The re-testing phase includes evaluating the liquid limit, plastic limit, compaction characteristics, linear shrinkage, and one-dimensional consolidation. Finally, the collected data is analyzed to determine the impact of BFS on soil behavior, leading to a clearer understanding of its effects on soil stabilization.

3.1.2. Blast Furnace Slag (BFS)

BFS in this study was brought from the Slemani steel factory in Bazyan City, which has a specific gravity of 3.153. It has been packed, as shown in Figure 2. The BFS has been crushed in a Los Angeles abrasion machine, passed through sieve No. 4, and used as a stabilizing agent at three percentages: 5%, 10%, and 15%. There are different reasons for choosing these percentages. In summary, using BFS as a

stabilizing agent for soils typically falls within a range of 5% to 20% by weight, as studies have shown that these levels can significantly alter the soil's engineering properties without introducing excessive material costs. By testing 5%, 10%, and 15%, one chooses a practical range relevant to typical stabilization practices.

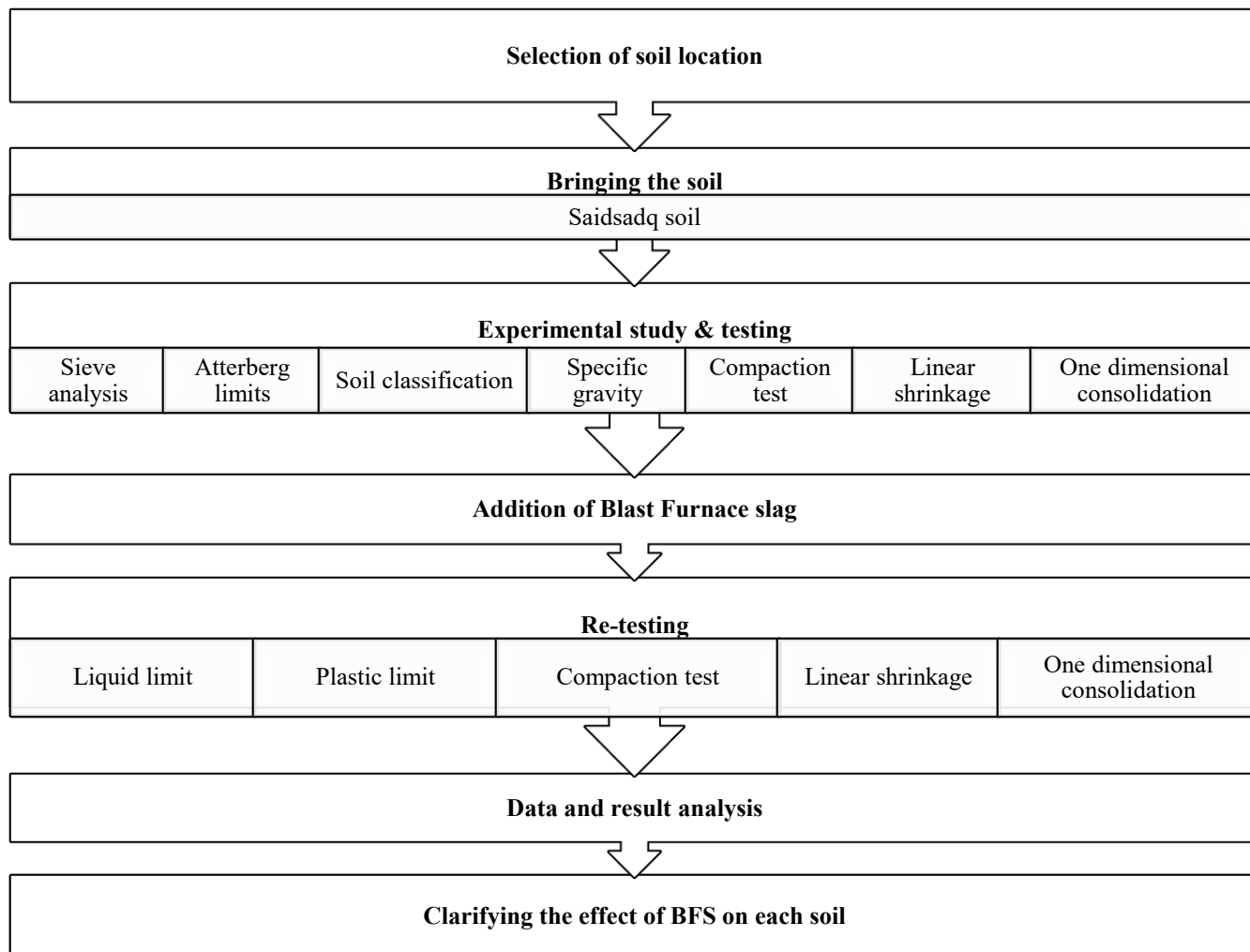


Figure 1. Scope of the study



Figure 2. The packed BFS in the Slemani steel factory [28]

The selected percentages (5%, 10%, and 15%) allow for a gradual increase in BFS content, enabling the observation of how the clayey soil's shrinkage and swelling behaviors evolve. This range provides the opportunity to assess the potential threshold at which BFS significantly improves soil properties and to evaluate any diminishing or adverse effects that may occur beyond a certain percentage. In summary, BFS content levels of 5%, 10%, and 15% are suitable for this research because they encompass a practical range for soil stabilization, facilitate clear observation of changes in shrinkage and swelling behavior, and ensure that the findings are relevant and comparable to previous studies in the field. However, the chemical composition of the BFS is shown in Table 2.

Table 2. The composition of the used BFS

Compound Name	Chemical Formula	Content (%)
Calcium oxide (Lime)	CaO	21
Silicon dioxide	SiO ₂	16.5
Sulfur trioxide	SO ₃	14.3
Aluminum oxide	Al ₂ O ₃	6.2
Iron oxide	Fe ₂ O ₃	4.6
Magnesium oxide	MgO	1
Potassium oxide	K ₂ O	0.8
Di-phosphorus pentoxide	P ₂ O ₅	0.8
Sodium oxide	Na ₂ O	0.7
Titanium	Ti	0.2
Others	-	33.9

3.2. Methods and Experimental Working Process

As previously clarified in the scope of the study, after collecting the soil sample, a series of testing processes were conducted to identify the properties of the untreated soil and to establish its classification according to the USCS. The tests conducted before treatment included sieve analysis, Atterberg limits (liquid and plastic limits), specific gravity, modified Proctor test, linear shrinkage, and one-dimensional consolidation. It is worth mentioning that specific gravity and sieve analyses were performed on both the soil and BFS samples.

Table 3. Followed test standards

Test Names	Specification
Sieve analysis	ASTM International [29]
Specific gravity	ASTM International [30]
Liquid limit	ASTM International [31]
Plastic limit	ASTM International [32]
Linear shrinkage	Bureau of Indian Standards [14]
Modified Proctor	ASTM International [33]
One-dimensional consolidation	ASTM International [34]

However, after each addition of the BFS to the soil, the tests of Atterberg limits, linear shrinkage, modified proctor, and one-dimensional consolidation were performed again to determine the effects of the BFS on the shrinkage and swelling properties of the soil. Table 3 below illustrates the standards that were followed to perform each test.

4. Results and Discussions

After completing the experimental investigation and the calculations, the results were analyzed. Eventually, it was clarified that the addition of BFS has caused considerable improvements in the soil's characteristics, particularly in its shrinkage and swelling behaviors. In the following subsections, the results of each test will be discussed, accompanied by graphical illustrations, and statistical regressions will be presented with the corresponding equations for each graph to validate the significance of the change in soil behavior.

4.1. Sieve Analysis

The first test conducted was a sieve analysis. The experiment was conducted on soil and BFS samples to determine their particle sizes. Figures 3 and 4 illustrate the results of particle size distribution for each of the two materials. The soil sieve analysis was done using the wet sieving process, and it was noted that more than 50% of the soil passed through sieve No. 200. As for the BFS, conventional dry sieving was used.

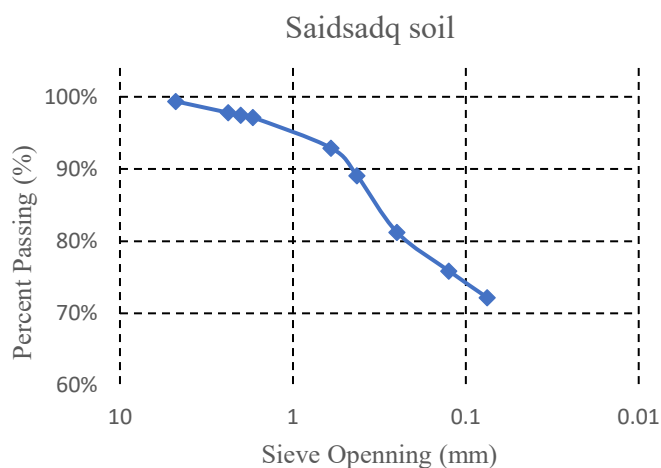


Figure 3. Sieve analysis of Saidsadq soil

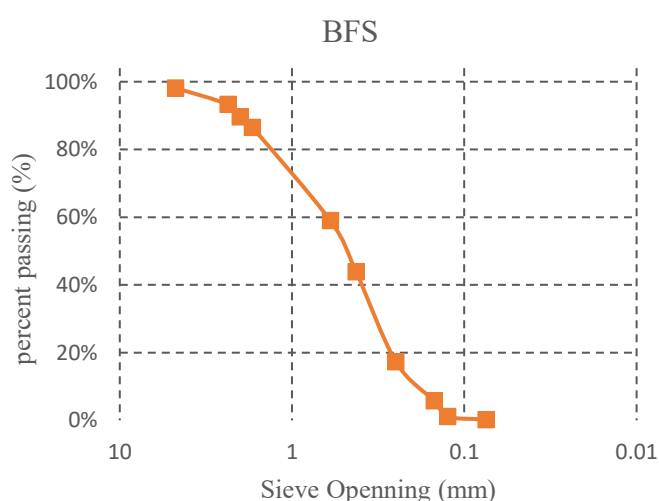


Figure 4. Sieve analysis of BFS

4.2. Atterberg Limits

It is evident that there is a strong relationship between the Atterberg limits and shrink/swell properties of soils. This relationship is such that soil with a higher liquid limit exhibits higher swelling or expansive behavior and vice versa. As for the plastic limit, the higher the plastic limit, the more clay content exists,

and hence, the soil exhibits higher shrinkage, as higher clay content means higher cohesion and loss of moisture during drying. Similarly, the higher the plasticity index is, the more the shrink/swell behavior will be possessed by the soil [35].

In this study, LL, PL, and PI have been included as part of investigating the shrinkage/swell properties of the soil. Figure 5 below explains the variation of LL, PL, and PI with the additions of BFS. It is evident that with the addition of BFS and further increasing its content, the LL has decreased gradually until the decrement reached 81% of the normal soil's LL. Conversely, the PL increased, and as a result, the PI decreased significantly. Conclusively, the decrement of LL means the decrement of swelling, and the decrement of PI means the decrement of shrinkage in the soil.

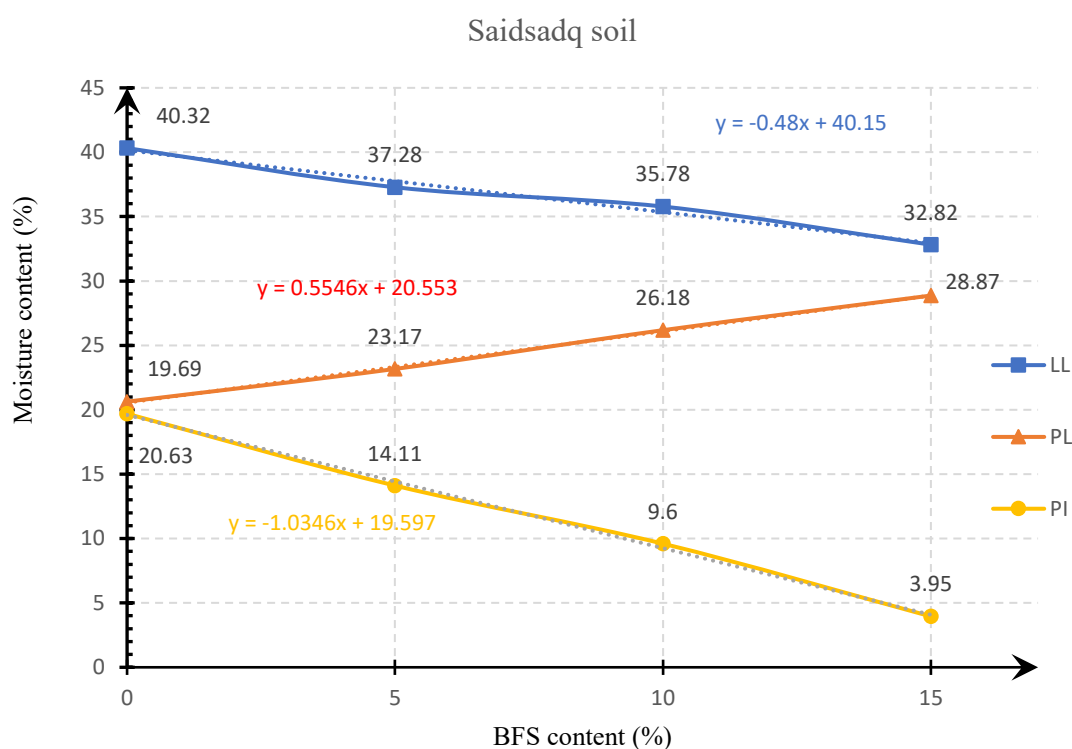


Figure 5. The variation of LL, PL, and PI with the addition of BFS

4.3. Linear Shrinkage

Linear shrinkage is one of those parameters selected to investigate soil shrinkage, and the effect of the three percentages of BFS has been examined. After performing the test procedure, the results were determined and subsequently illustrated in Figure 6. It is conceivable that the addition of the stabilizer caused a decrease in the soil's shrinkage, resulting in a reduction of almost 50% in the original linear shrinkage. Furthermore, nearly 67% of the improvements have occurred after adding the first amount of BFS. This occurrence suggests that the BFS has a significant impact on the soil's shrinkage, making it a reasonable solution for treating shrinkable soils.

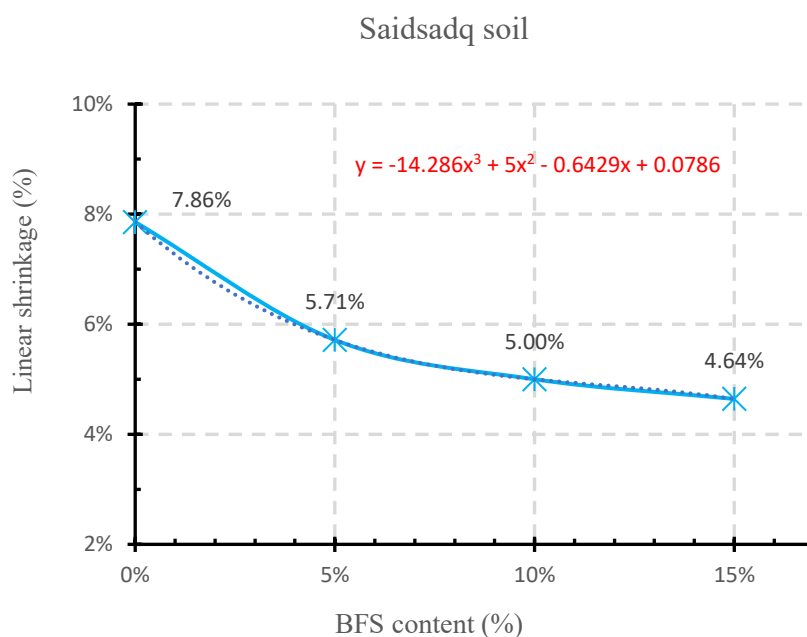


Figure 6. The variation of linear shrinkage with the addition and increment of BFS

4.4. Compaction Characteristics

In this study, a compaction test was performed using the modified Proctor test, a modern method for determining the MDD and OMC. This test is one of the most common and basic tests in the research area of geotechnical engineering, and it is present in almost all studies as an indicator of the strength and mechanical properties of the soil. This is because its OMC is considered a crucial requirement for the preparation of the tests for strength and deformation. Figure 7 (a) shows the variation of MDD after adding different percentages of BFS. It is seen that the addition of 15% BFS caused the increment of MDD from 19.28 kN/m³ to 19.71 kN/m³. Such an increment of MDD describes the ability of BFS to densify the soil and increase its strength. Here, the slight increment declares that the pozzolanic reaction did not occur properly to make a considerable effect, and perhaps it is due to the type of soil or the quality of the BFS and its chemical composition. Figure 7 (b) illustrates the OMC variation after adding BFS. Notably, in contrast to the slight variation of MDD, the variation of OMC is a considerable one in which the OMC has been decreased to the degree that it became 78% of the original OMC. This occurrence provides a clue, indicating that the BFS has absorbed water, which has led to a reduction in the free water available within the soil mass, and hence, the OMC decreases.

4.5. One-Dimensional Consolidation Test Parameters

In one-dimensional consolidation, four different parameters were considered and investigated to determine the effect of the different amounts of slag. The following subsections will briefly describe the amount and nature of changes in each parameter.

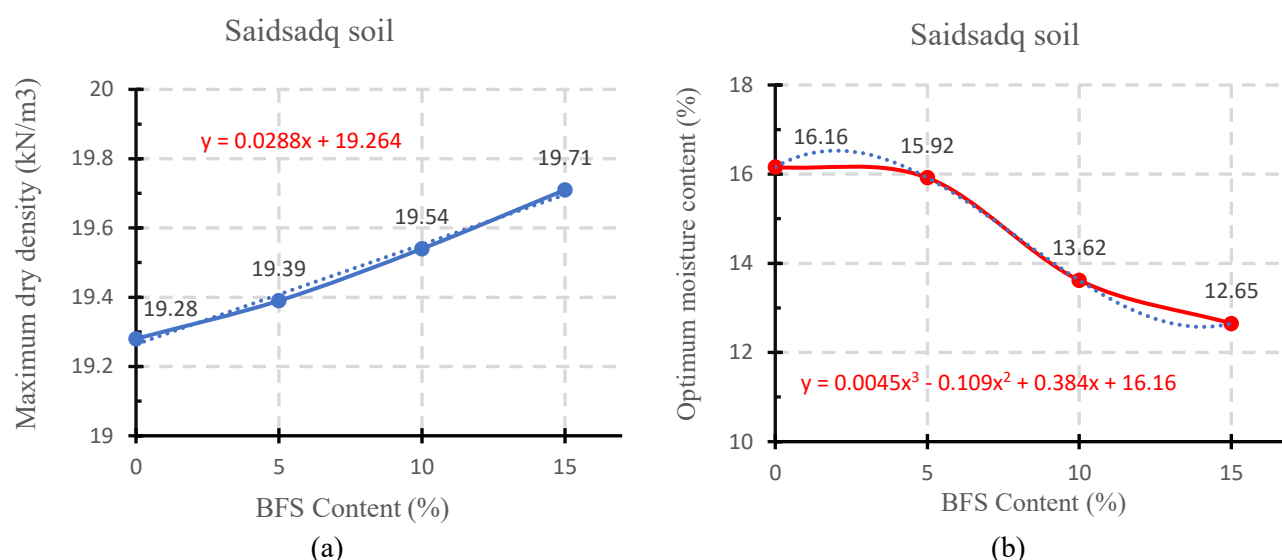


Figure 7. Variation of Compaction parameters with different contents of BFS: (a) MDD and (b) OMC

4.5.1. Compression Index (Cc)

Figure 8 below concludes the results of Cc before and after the addition of BFS.

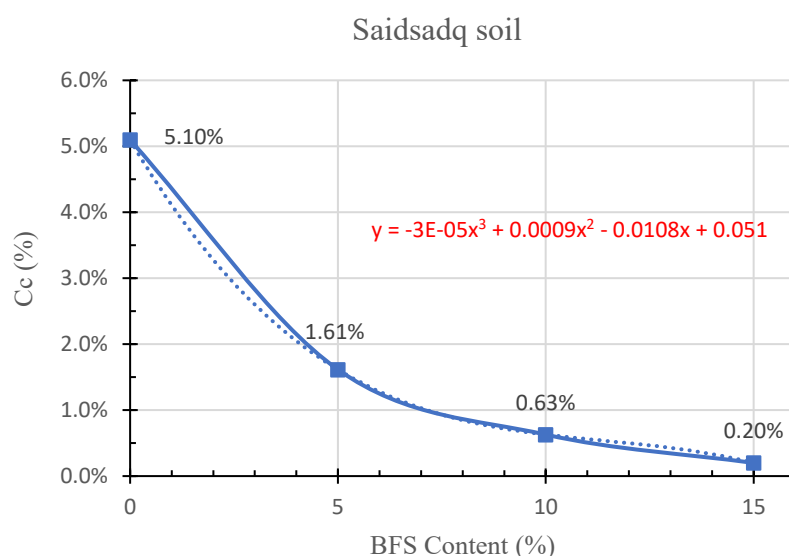


Figure 8. The effect of BFS on the soil's compression index (Cc)

It is clear that after each addition of the slag, the compression index decreased by an amount, and this means that the more the slag was added, the stronger and less compressible the soil became. As is known, the less the Cc is, the less shrinkage will occur after removing the load from the soil, and the same applies to swelling as well. Here, the compression index has been reduced after the addition and further increment of the BFS, in which the nature of the decrements in Cc was such that from nearly 5.1%, it has been reduced to almost 0.2% after adding 15% of BFS (25 times smaller). Most of the reduction occurred after adding 5% of slag, so approximately 70% of the improvement occurred after adding the first amount of BFS, indicating that BFS can be considered a strong soil stabilizer.

4.5.2. Swelling Index (Cs)

The swell index in a soil consolidation test measures the potential for a soil sample to expand or swell when it is saturated with water. The addition of BFS has also caused changes in the swelling index, shown in Figure 9 below.

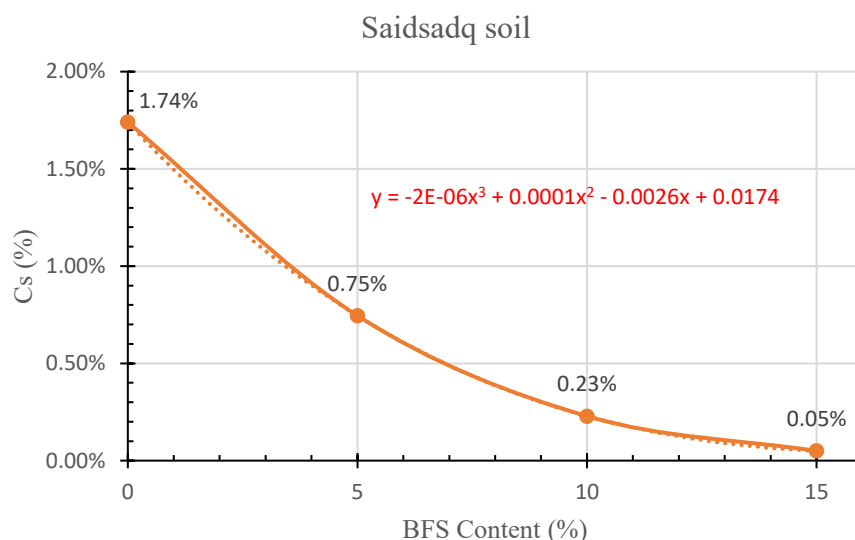


Figure 9. The effect of BFS on the Soil's Swelling index (Cs)

As shown in the figures, the swelling index decreased after adding BFS, and further decreases occurred after additional additions. This outcome indicates that the BFS can improve the soil's swelling properties and make the soil more stable.

It is noticeable that the nature of the improvement is nearly similar to that of C_c ; again, most of the improvement occurred after the first addition of BFS, but this time, nearly 60% of the improvement occurred after the first addition. However, it can be concluded that the addition of 15% BFS caused an improvement in the soil's swelling index from almost 1.75% to nearly 0.05%, which is nearly 35 times smaller than the normal soil's swelling index.

4.5.3. Recompression Index (Cr)

Another parameter considered in this study for the one-dimensional consolidation test is the recompression index. Figure 10 clarifies the changes in C_r after any addition of BFS.

From the previous figure, it can be seen that there has been a significant improvement in the soil's C_r after the addition and increase in the slag amount, as it is evident that soils with higher C_r are often more likely to shrink and/or swell under different water content conditions. Here, the original soil has a recompression index of nearly 13.8%. After each addition of slag, it decreased by an amount until it became 0.61% after the addition of 15% slag, which is approximately 23 times smaller. The percentage of improvement after the first addition is similar to that of C_c and C_s , which is approximately 70% of the total improvement.

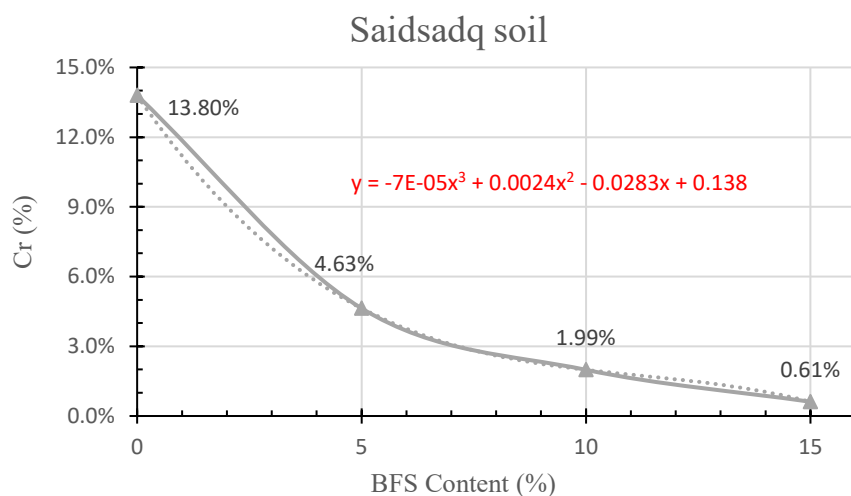


Figure 10. The effect of BFS on the Soil's Recompression index (Cr)

4.5.4. Swelling Strain (ϵ)

This parameter represents the volume change in the soil after absorbing water. When soil is subjected to water, it absorbs an amount of water; hence, its volume increases to a degree. The volume change rate here is referred to as a swelling strain, and its variation with the BFS amount is illustrated in Figure 11.

It is visible that a significant change occurred as soon as the first percentage of slag was added, and then the improvement continued until it reached a minimal swell strain in which the swelling strain of the soil sample having 15% BFS is almost 2 times smaller than the normal soil with no slag. Again, most of the improvement occurred after the first addition of slag (45.5% of the final improvement), and subsequent additions had similar effects to the previous parameters.

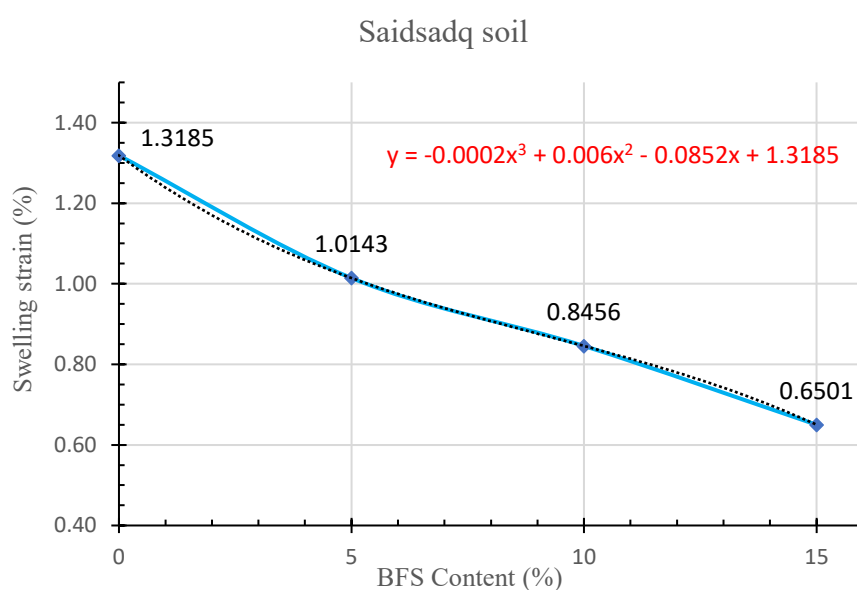


Figure 11. The variation of swelling strain with different percentages of slag

One may consider that the normal soil has a very small swelling strain, and the stabilization caused by BFS is negligible. However, when the rate of change is expressed as percentages, the results are suggestive and provide positive signs and hopeful expectations that BFS should also be tried on high-swell soils.

5. Conclusion

Ultimately, several key points can be drawn from the study. It may be noticeable that the amount of change in the properties of Saidasadq soil is not so tremendous; this is perhaps due to the type of soil, and it was evident from the beginning since the type of soil is low-plastic clay. This type of soil's shrink/swell properties are usually less affected by the stabilizers than by high-plasticity soils because of their structure, such that their volume is somehow more stable than high-plasticity soils. However, even though the changes are small in number when converted to percentages, a significant improvement can be observed. Overall, the plasticity index improved by nearly 81% and linear shrinkage by 41%. However, more significant improvements were noticed in the one-dimensional consolidation parameters C_c , C_s , C_r , and ϵ , with respective improvements of 96.1%, 97.1%, 95.6%, and 50.7%. Finally, it is worth noting that the study's results indicate that BFS can be considered a good stabilizer in improving the swell/shrink properties of soils. Overall, in this study, BFS acted as a soil stabilizer by promoting pozzolanic reactions that enhanced soil structure, strength, and resistance to moisture-related issues, such as shrink/swell behaviors, which is evident in the study's outcome. Ultimately, it is recommended to use BFS in conjunction with other stabilizers, such as lime, cement, or fly ash. Additionally, the mineralogical properties of these materials should be studied to elucidate the chemical reactions between clay, BFS, and lime. To provide better information regarding chemical reactions and improvements in soil properties.

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