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Original Article

Performance of Sodium Chloride Blended with Silica Fume for Stabilizing Expansive Soils in Road Subgrade Applications

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***Abstract** - Expansive soils present considerable challenges in constructing road subgrades due to their elevated plasticity, swelling potential, and low strength. This study investigates the stabilization efficacy of Sodium Chloride (NaCl) and Silica Fume (SF) on such soils, aiming to improve performance for infrastructure applications. Initial soil characterization included Atterberg limits, compaction, and California Bearing Ratio (CBR). The research adopted a phased approach. NaCl was introduced in increments ranging from 2% to 10% at 2% intervals, resulting in a notable decrease in Plasticity Index (PI) and an increase in CBR values, with the optimal NaCl concentration identified as 6%. Subsequent experimentation explored the synergistic effects of this optimal concentration of NaCl in combination with varying amounts of SF, from 5% to 15% in 5% increments. It was found that a combination of 6% NaCl and an appropriate concentration of SF, which was determined based on the soil properties, further enhanced soil stabilization, reducing PI to a desirable level and increasing the soaked CBR value to an impressive 8%. This triphasic approach, considering the expansive soil, NaCl, and SF, illustrates the potential of combining these components to significantly improve the stability of expansive soils, thereby offering a viable, sustainable, and economical option for constructing road subgrades and presenting a promising solution to a pervasive challenge in civil engineering and construction industries.*

***Keywords** - Expansive soil, Road subgrade construction, Sodium chloride, Silica fume.*

1. Introduction

In the dynamic realm of civil engineering, managing expansive soils, particularly Black Cotton Soils (BCS), poses a significant challenge to infrastructure stability. Characterized by their high plasticity and swelling properties, BCS is notorious for causing structural issues like differential settlement and cracking, threatening the integrity of road subgrades and building foundations, a concern well documented in the literature [1, 2]. Their widespread presence, especially in regions like Africa, poses a considerable challenge for nations striving to enhance their road networks amidst growing traffic and infrastructural constraints [3].

Against this backdrop, the search for sustainable and cost-effective soil stabilization methods is paramount. Traditional stabilization techniques, like cement usage, are effective but face scrutiny over environmental concerns, particularly CO_2 emissions [4]. The industry's shift towards alternative stabilizers reflects a commitment to eco-friendly and efficient solutions [5]. The use of Sodium Chloride (NaCl) and Silica Fume (SF) emerges as a promising approach, suggesting a synergistic strategy that could significantly enhance the geotechnical properties of expansive soils [6].

This study proposes that integrating NaCl and SF can substantially alter the behavior of expansive soils reducing plasticity and increasing strength providing a sustainable stabilization solution for road subgrade applications [7]. By leveraging the pozzolanic reactions of SF and the osmotic effects of NaCl, this research explores a novel triphasic stabilization method. This approach aligns with global environmental goals while addressing the pressing need for durable infrastructure in areas affected by problematic soils [8]. Thus, this investigation adds to the ongoing discussion on sustainable civil engineering practices, highlighting cost-effective and environmentally conscious soil stabilization methods.

2. Materials and Methods

2.1. Materials

The advancement of civil engineering practices is perpetually challenged by the presence of expansive soils like Black Cotton Soil (BCS), particularly prevalent in regions of Africa. These soils are characterized by high plasticity and swelling properties that pose risks to structural integrity, leading to issues like differential settlement and cracking that affect roads and building foundations [1, 2]. Such geotechnical constraints are more pronounced in developing nations where the improvement of road networks is critical in addressing traffic and infrastructure deficiencies [3].

In response to these challenges, this study focuses on sustainable and cost-effective soil stabilization methods that circumvent the environmental impact associated with traditional cement-based stabilization, known for its significant carbon dioxide emissions [4].

Innovative and eco-friendly alternatives are investigated, with Sodium Chloride (NaCl) and Silica Fume (SF) being identified as promising materials to improve the geotechnical properties of expansive soils [5, 6]. This research explores the potential of a novel triphasic stabilization method that utilizes the pozzolanic reactions of SF and the osmotic effects of NaCl to enhance soil stability [7]. This aligns with global sustainability targets and addresses the urgent requirement for durable infrastructure in areas affected by problematic soils [8].

The study leverages materials sourced with precision to ensure consistency and relevance to local conditions. Black cotton soil samples were meticulously extracted from specified depths ranging from 0.5 to 2 meters below the surface at designated locations surrounding the Jomo Kenyatta University of Agriculture and Technology (JKUAT), Juja. The varied depths ensure a comprehensive understanding of the soil profile, reflecting the heterogeneity of in-situ conditions. These samples were then air-dried and prepared for testing in the civil engineering laboratory at JKUAT.

(a)

(b)

(c)

Fig. 1 (a) Expansive soil, (b) Sodium Chloride, and (c) Silica Fume

The role of Sodium Chloride in soil stabilization is scrutinized for its impact on the electrochemical properties of the soil, which contributes to reduced water uptake and improved compaction by flocculating the clay particles, leading to decreased plasticity and increased strength.

Silica Fume, on the other hand, is evaluated for its pozzolanic reactivity. Being a byproduct of silicon production, SF is known to enhance soil strength and mitigate shrink-swell behaviour by reacting with calcium hydroxide in the presence of water to form cementitious compounds that densify the soil matrix [9].

2.2. Methods

X-ray Fluorescence (XRF) tests were performed at a recognised laboratory to analyse the chemical composition of the expanding soil, Sodium Chloride (NaCl), and Silica Fume (SF) in order to determine their elemental content. To determine the physical and mechanical properties of the soil, a series of tests were performed, including determining the distribution of particle sizes, measuring the specific gravity, evaluating the Atterberg limits, conducting compaction tests, and assessing the soaked California Bearing Ratio (CBR), all in accordance with the most current ASTM standards relevant to the timeframe from 1990 to 2023.

The Atterberg Limits Test involved the use of several equipment, including a cone penetrometer, spatula, balance, and oven, in accordance with the ASTM D4318 standard. The Compaction Test employed a Standard Proctor compaction mould and hammer, along with mixing tools and a device for moisture determination, in line with ASTM D698. The CBR Test was carried out using a CBR testing machine equipped with the necessary moulds, weights, and measurement gauges, consistent with applicable ASTM guidelines. The stabilization treatment was methodically applied in stages:

Sodium Chloride (NaCl) Treatment: The soil was treated with varying concentrations of NaCl (2%, 4%, 6%, 8%, and 10% by dry weight) to identify the optimal content for soil improvement.

Silica Fume (SF) Integration: After determining the optimal NaCl concentration, SF was introduced in increments (5%, 10%, and 15% by dry weight) based on the established NaCl content to enhance the stabilization effect.

Combined NaCl and SF Treatment: Soil samples treated with the optimal mix of NaCl and SF were subjected to additional testing, including revised Atterberg limits, compaction, and CBR tests, in compliance with the referenced ASTM standards.

This investigative approach seeks to validate the efficacy of NaCl and SF as sustainable stabilizing agents, enhancing the geotechnical properties of expansive soils for improved road subgrade construction.

2.3. XRD and SEM Tests

XRD (X-Ray Diffraction) is a technique used to identify the crystalline structure of materials by measuring the pattern and intensity of X-rays scattered by the crystals in the material. It is useful for determining crystal structure, size, and orientation.

SEM (Scanning Electron Microscopy) is a method for creating detailed images of the surfaces of materials by scanning them with a high-energy beam of electrons. It reveals the topography and composition of the material's surface at very high magnifications.

XRD provides a detailed look at the mineralogical composition by identifying crystalline phases within a sample. The diffraction patterns produced can pinpoint the presence of specific minerals like quartz or muscovite in soils, which helps in understanding the soil's structural and chemical behavior.

SEM offers a microscale view of the sample's surface topography. It reveals the morphology of soil particles, their distribution, and the interaction between different components. This can show how soil aggregates, pores, and potential cementing materials come together to form the soil's structure.

XRD and SEM are valuable in the field of geotechnical engineering to understand the properties of soil and how it will interact with various stabilization treatments. XRD provides the mineralogical framework of the soil, which is essential for predicting how it will react chemically and physically to stabilizers. In contrast, SEM gives a close-up view of the physical changes in the soil's microstructure post-treatment.

3. Results and Discussion

3.1. Characterization of Expansive Soil (BCS)

Table 1 presents the engineering properties of natural Black Cotton Soil (BCS), which highlight the challenges it poses for construction. With a dark grey appearance, the soil's high plasticity and expansion potential are evident from its high Liquid Limit (LL) of 64.86% and Plasticity Index (PI) of 26.4%. Most of its particles are fine-grained, passing through a 75-micron sieve, and it has a specific gravity of 2.29.

The soil is categorized as A-7-6 according to AASHTO, which suggests a significant clay content and a tendency for considerable volume changes, as indicated by its 14.61% linear shrinkage. Additionally, a low California Bearing Ratio (CBR) value of 2.1% after soaking signifies the need for effective soil stabilization measures.

Figure 2 shows the particle size distribution of Black Cotton Soil, identifying it as expansive due to its high silt content and moderate sand presence, with minimal gravel. This distribution is key to understanding the soil's tendencies to expand and shrink, affecting foundation designs and construction on such soil.

Table 2 shows the stabilization mix designs for Black Cotton Soil (BCS) with varying percentages of Sodium Chloride (NaCl) from 2% to 10% and subsequent Silica Fume (SF) additions at 5%, 10%, and 15% combined with the optimal NaCl amount. The aim is to determine the most effective concentrations for soil improvement.

Chemical composition analyses, as detailed in Table 3, indicate that Black Cotton Soil (BCS) has high levels of Silicon Dioxide (SiO_2), Aluminum Oxide (Al_2O_3), and Iron (Fe). In contrast, Sodium Chloride (NaCl) is mainly Chlorine, and Silica Fume (SF) consists largely of Silicon Dioxide, which contributes to its pozzolanic characteristics, useful in stabilizing soils.

SEM and EDS analyses provide insights into the soil's microstructure and elemental composition. SEM micrographs reveal clay soils with agglomerated, irregular-shaped particles, contributing to their expansive nature and high plasticity.

EDS graphs offer a quantitative elemental analysis, highlighting the dominance of Oxygen (O) and Silicon (Si), with the presence of Aluminum (Al), Iron (Fe), and traces of Calcium (Ca), Magnesium (Mg), Potassium (K), indicative of the mineral composition.

Table 1. Engineering properties of the natural Black Cotton Soil

Properties	Proportion/Value
Observation of Color	Dark Grey
Natural Moisture Content	8.28%
%Passing through BS Sieve 75µ	90%
Classification (AASHTO)	A-7-6
Specific Gravity	2.29
Free-Swell	105%
Liquid Limit (LL)	64.86%
Plastic Limit (PL)	38.46%
Plasticity Index (PI)	26.4%
Linear Shrinkage	14.61%
Maximum Dry Density	1.269g/cm³
Optimum Moisture Content	25%
CBR Value (7 days Cure + 7 Days Soaked) %	2.1%

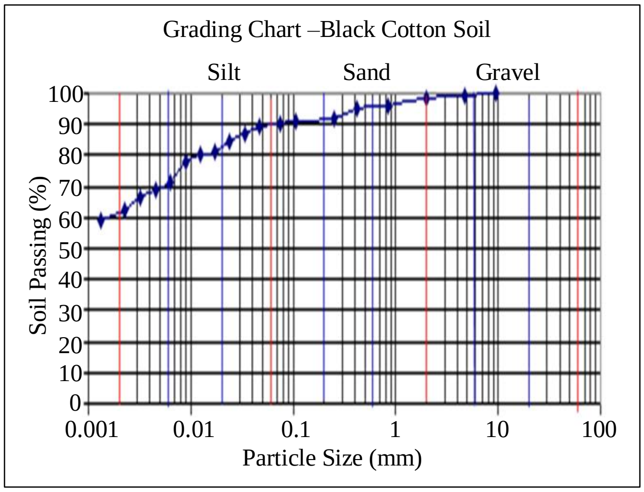


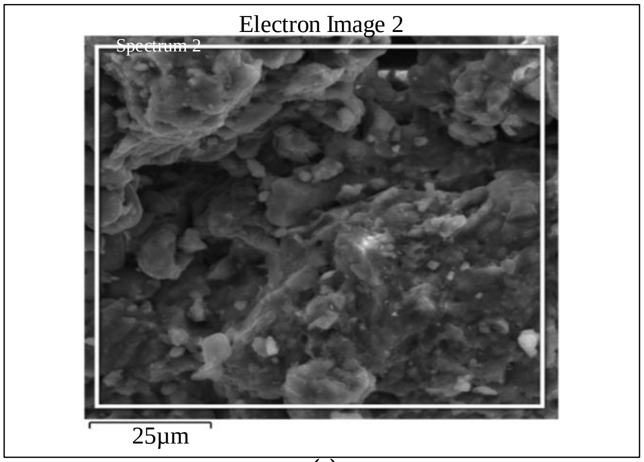
Fig. 2 Soil's grain size distribution curve

Table 2. Expansive soil (BCS) treatment mix design

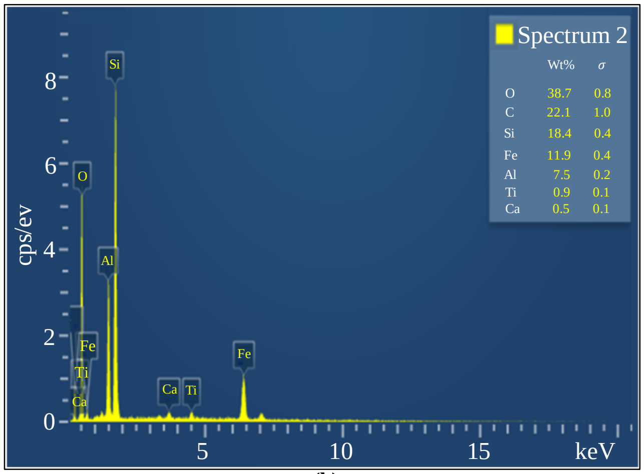
Percentages of the Mixed Design Proportions	
BCS + Varying NaCl (%)	**100% BCS + Optimal NaCl% + Varying SF (%)**
2	-
4	-
6	-
8	-
10	-
-	5 (with Optimal NaCl%)
-	10 (with Optimal NaCl%)
-	15 (with Optimal NaCl%)

Table 3. Chemical composition of the BCS, NaCl, and SF

Element	Percentage (%)		
	BCS	**NaCl**	**SF**
MgO	0.00	0.000	--
Al_2O_3	9.672	0.801	0.070
SiO_2	76.898	0.057	98.555
Fe	8.328	0.079	0.070
CaO	1.183	0.00	0.732
K_2O	0.803	0.00	0.262
Ti	0.973	0.019	0.008
Mn	1.518	0.012	0.015
Cr	0.000	0.041	0.000
P_2O_5	0.000	--	0.076
S	0.000	0.00	0.151
Cl	0.260	94.174	0.000
Cu	0.005	0.003	0.012



(a)



(b)

Fig 3. (a) SEM micrograph of Black Cotton, and (b) EDS graph of Black Cotton.

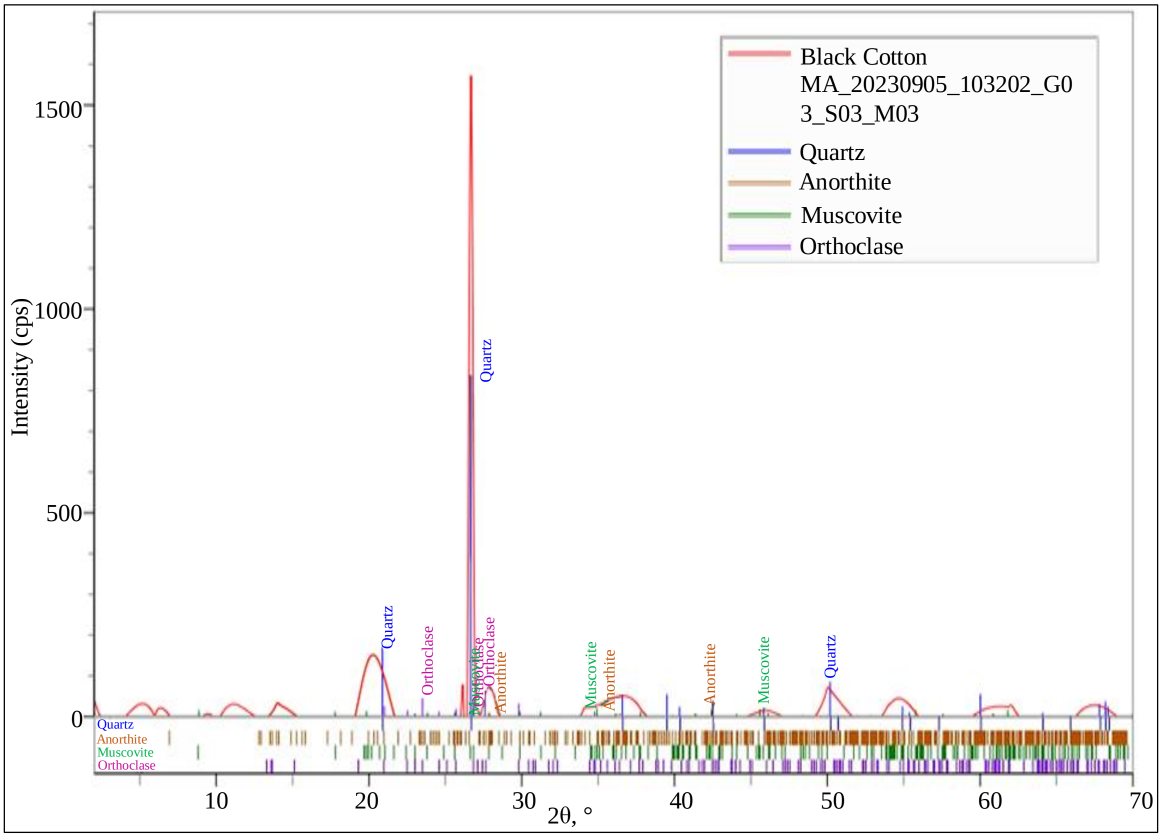
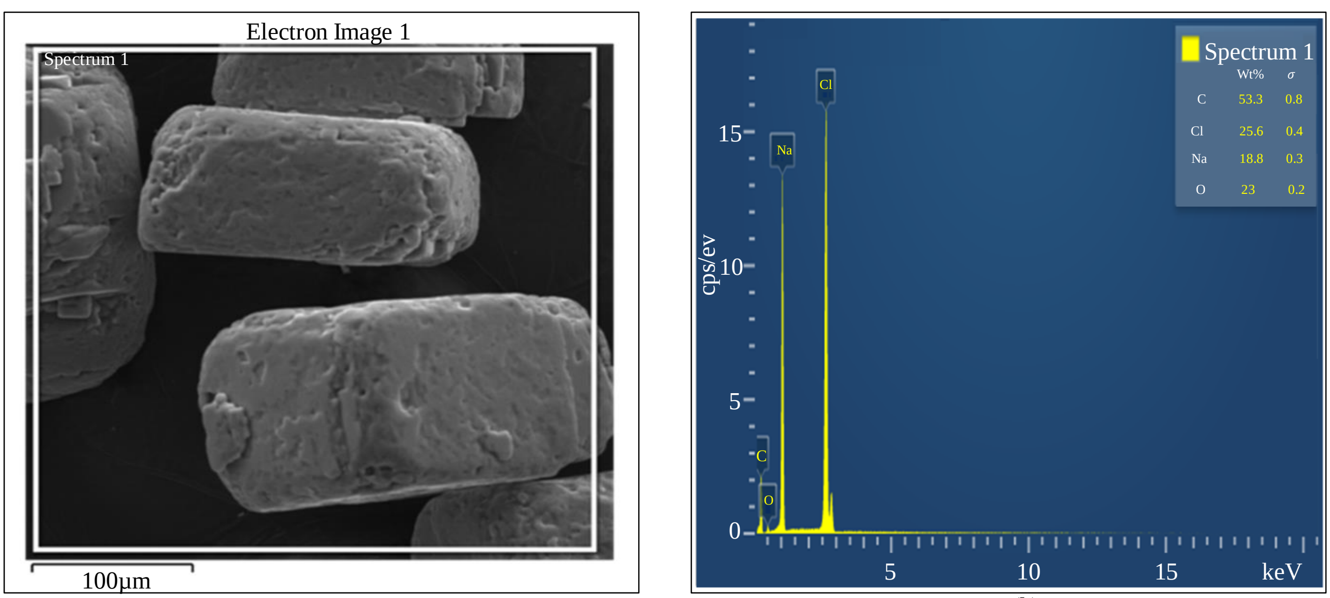


Fig. 4 Pattern of Black Cotton

In Figure 4, the X-Ray Diffraction (XRD) pattern for Black Cotton Soil is showcased, revealing its complex phase composition. The pronounced peak situated around 27 degrees 2θ is indicative of a significant quartz content, a mineral ubiquitously found in various soil types. Quartz, known for its durability and hardness, often governs the soil's mechanical stability. Accompanying this peak are several other peaks, each signifying the presence of distinct minerals such as Anorthite, Muscovite, and Orthoclase, which are integral to the soil's clay fraction.



(a) (b)

Fig. 5 (a) SEM micrograph of sodium chloride, and (b) EDS graph of sodium chloride.

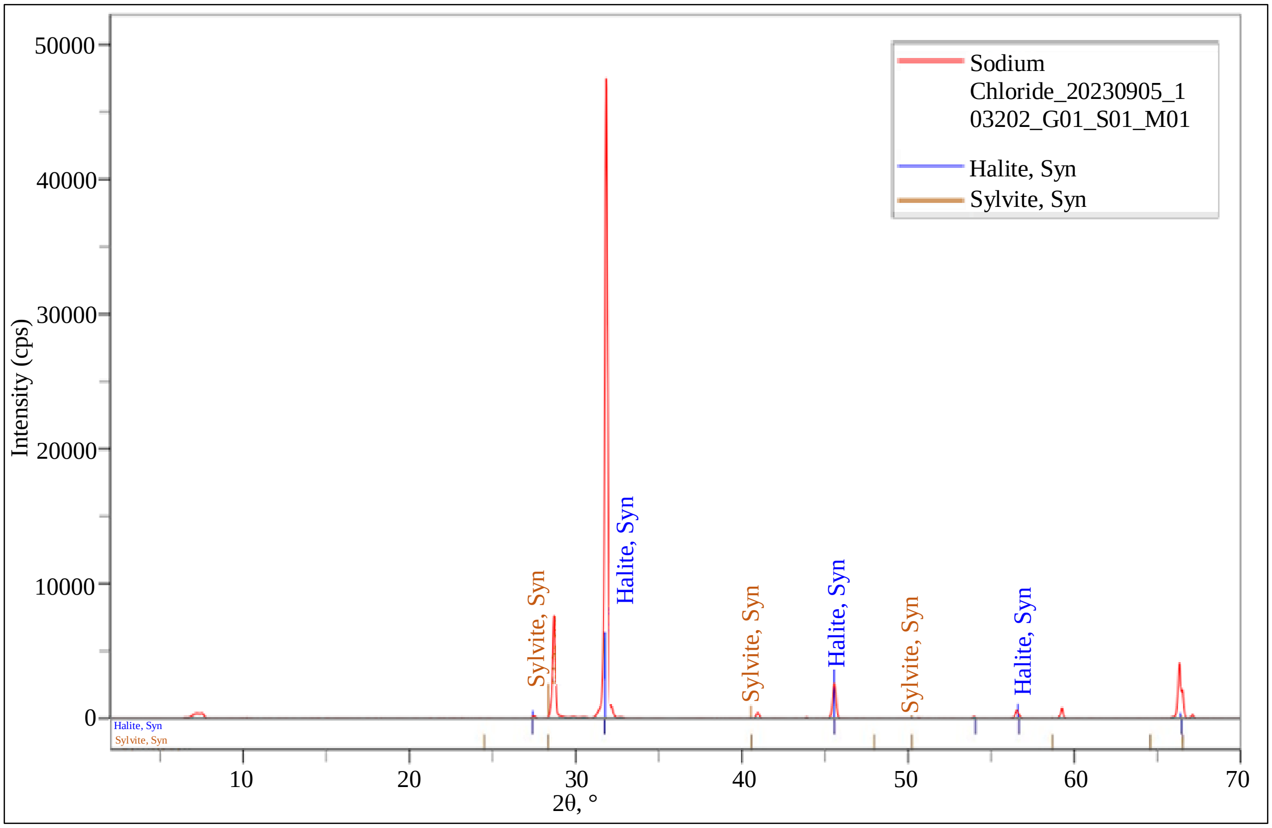
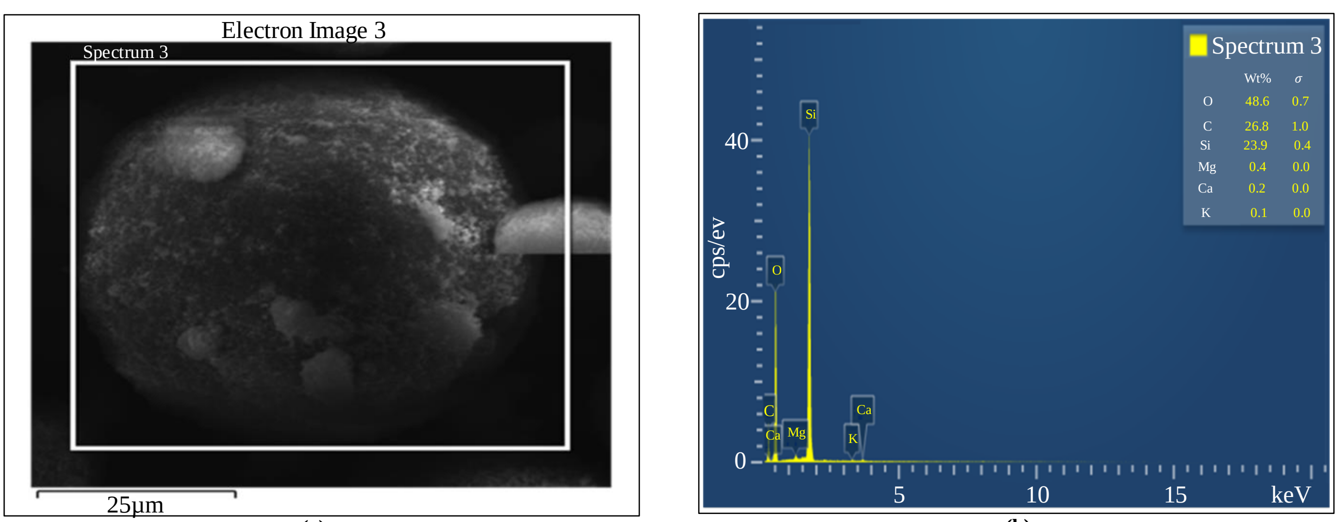


Fig. 6 Pattern of Sodium Chloride

The XRD pattern depicted in Figure 6 illustrates the crystalline structure of Sodium Chloride (NaCl). The prominent peak is characteristic of the (200) plane of halite, the natural crystalline form of NaCl, indicating a high degree of crystallinity. The sharp and high peak suggests a pure and well-ordered lattice typical of halite. The presence of other smaller peaks further confirms the crystalline nature of the Sodium Chloride in the sample. The XRD pattern presented in Figure 8 displays the characteristic peaks of Silica Fume. The prominent peak was indicative of the amorphous nature of silica and is centered around 20-30° 2θ, which is typical for amorphous materials like Silica Fume. This peak, along with other minor peaks, suggests the presence of crystalline phases, such as Quartz, within the Silica Fume. This XRD profile is what one would expect from Silica Fume, confirming its use as a pozzolanic material in various applications.



(a) **(b)**

Fig .7 (a) SEM micrograph of Silica Fume, and (b) EDS graph of Silica Fume.

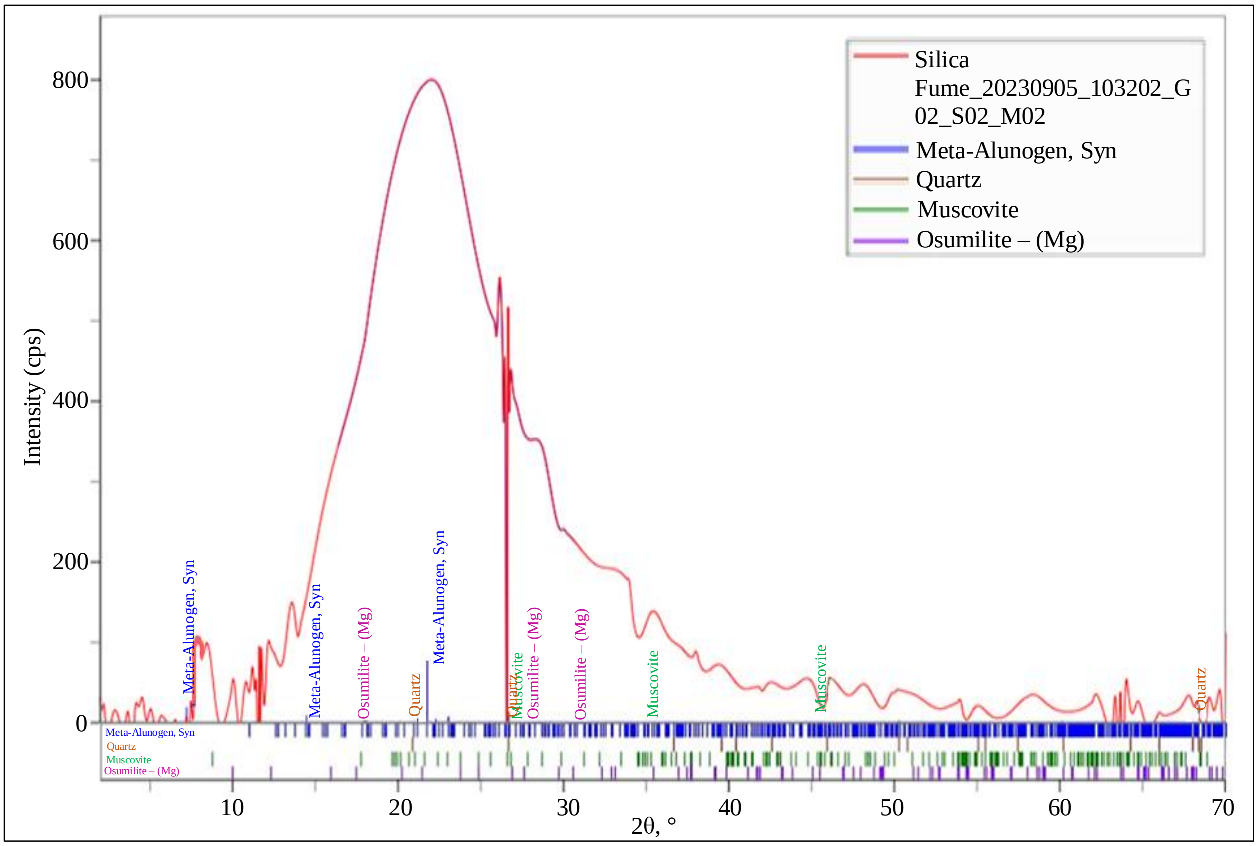


Fig. 8 Pattern of Silica Fume

3.2. Stabilization of the Expansive Soil (BCS) with Sodium Chloride

3.2.1. Consistency Limits and Workability

The incorporation of Sodium Chloride (NaCl) into Black Cotton Soil, ranging from 0% to 16%, has been shown to significantly improve the soil's workability and decrease its flexibility. Initially, the soil's Plasticity Index (PI) is at a considerable 26.4%, but as NaCl is introduced, the PI notably decreases, reaching as low as 10.36% at the highest NaCl content.

This reduction in PI, evidenced in Figure 9, is indicative of the efficacy of NaCl in altering the soil's consistency limits, thereby enhancing its workability and lessening its vulnerability to changes in moisture attributes that are critical in the context of soil stabilization for construction purposes [14, 15].

Concurrently, the Plastic Limit (PL) and Liquid Limit (LL) follow descending paths, further validating the role of NaCl as a stabilizing agent. Such modifications in Atterberg limits are significant in the effort to improve the soil's mechanical behaviour and durability as a foundation material. This aligns with current research that seeks to address the pressing need for sustainable construction materials and practices, contributing to the broader objective of building infrastructure that is both resilient and environmentally responsible [7, 9, 16].

3.2.2. Limits on Shrinkage and Stable Volume

The treatment of Black Cotton Soil with Sodium Chloride (NaCl), as demonstrated in Figure 10, has yielded significant improvements in soil stability. By increasing the NaCl content to 16%, the soil's shrinkage limit has been markedly reduced from 18.34% to 5.32%.

This substantial decrease underscores the efficacy of NaCl in enhancing the structural integrity of the soil and mitigating shrinkage issues, which are pivotal in overcoming the challenges posed by the expansive nature of Black Cotton Soil. Such advancements are instrumental in rendering the soil more conducive for construction endeavours, thereby aligning with sustainable soil management practices and offering an economical approach to the stabilization of expansive soils [14, 15].

3.2.3. Compaction Characteristics

The compaction characteristics of Black Cotton Soil, particularly Maximum Dry Density (MDD) and Optimum Moisture Content (OMC), are essential in evaluating its construction applicability. As shown in Figure 11, the strategic addition of Sodium Chloride (NaCl) in varied proportions significantly alters these properties. The MDD notably increases upon NaCl treatment, reaching an optimal value of 1.75 g/cm³ at a 6% NaCl concentration, indicative of a denser and more stable soil structure. Yet, extending NaCl content to 10% slightly reduces the MDD to 1.68 g/cm³. Meanwhile, the OMC remains relatively unchanged, suggesting a moderate influence of NaCl on soil moisture affinity. These observations highlight NaCl's pivotal contribution to soil stabilization, emphasizing the necessity of fine-tuning NaCl amounts to achieve the best compaction outcomes for subgrade construction, which is crucial for the structural integrity of construction projects [14, 15].

3.2.4. Getting Stronger (Soaked CBR for 7 Days)

The application of Sodium Chloride (NaCl) to Black Cotton Soil leads to a notable enhancement in the California Bearing Ratio (CBR) values, which are important indicators of soil strength and stability for road construction. This improvement is clearly seen in Figure 12.

CBR values rise with NaCl addition, peaking at an optimal concentration that balances soil stability and NaCl content, then slightly decline beyond this point, highlighting the importance of accurately determining NaCl percentages for soil stabilization [14, 15]

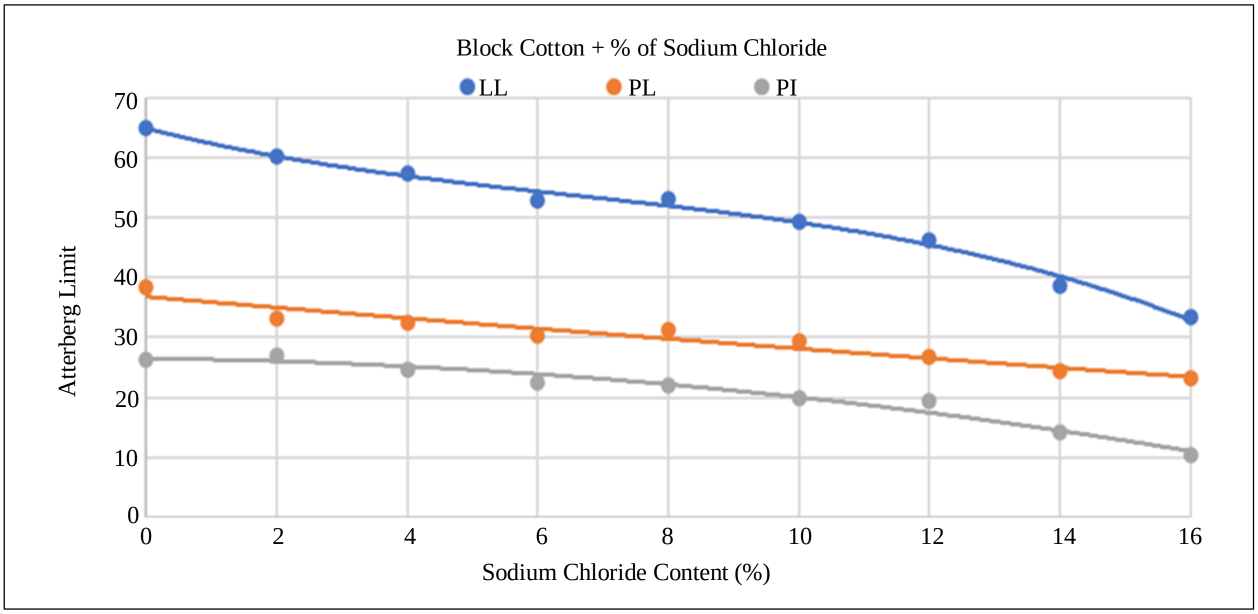


Fig. 9 Effect of Sodium Chloride on Atterberg limits of the Black Cotton Soil

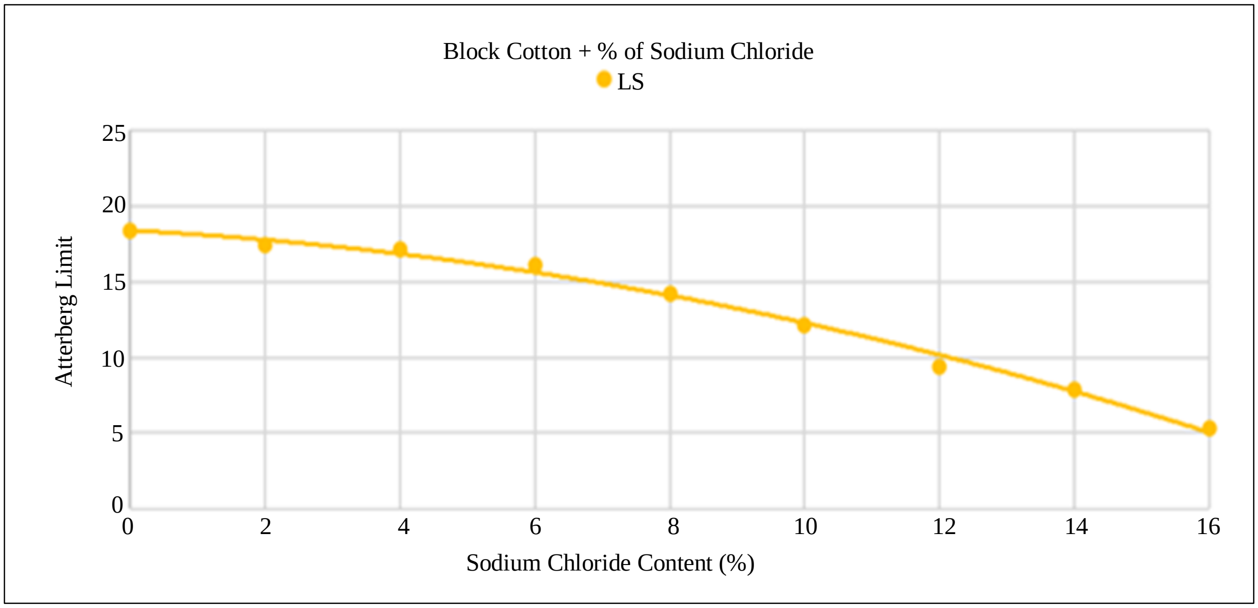


Fig. 10 Effect of Sodium Chloride on shrinkage of the Black Cotton Soil

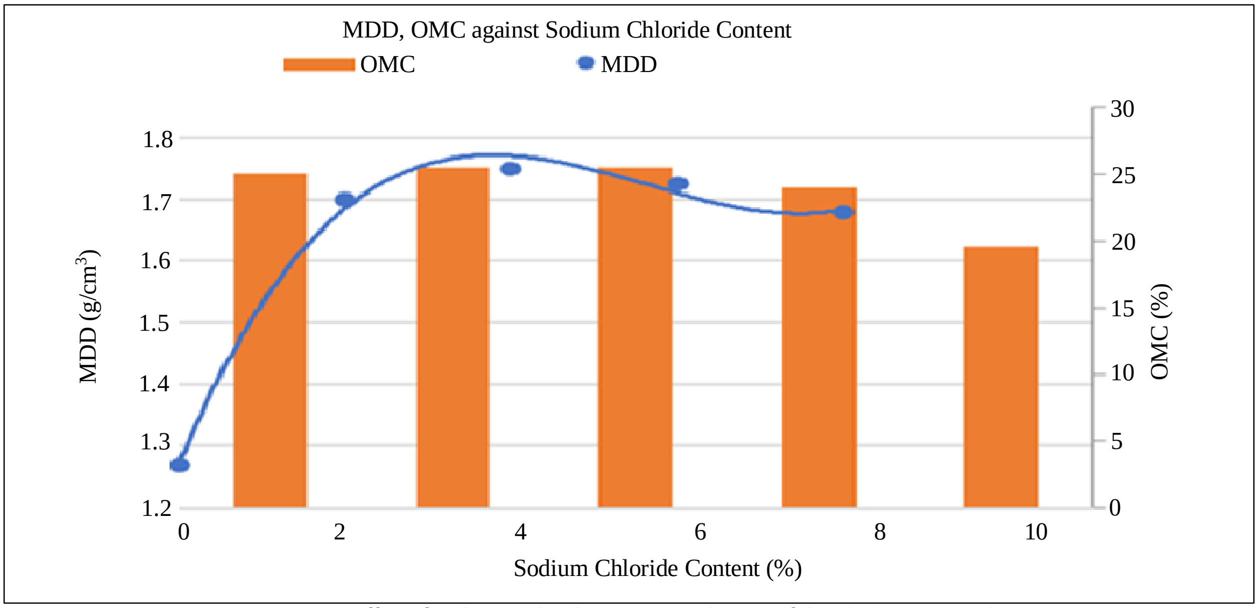


Fig. 11 Effect of Sodium Chloride on MDD and OMC of the Black Cotton Soil

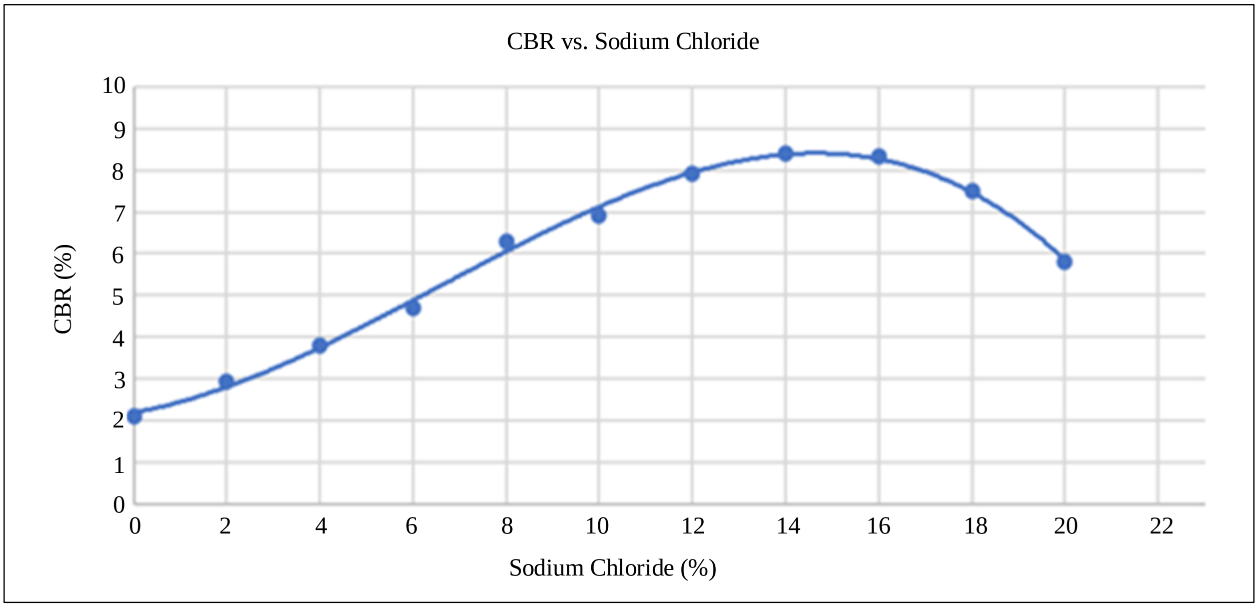


Fig. 12 Impact of Sodium Chloride on CBR value of the expansive soil

3.3. Stabilization of the Expansive Soil (BCS), Sodium Chloride, and Silica Fume

During this stage of the research, Sodium Chloride (NaCl) was added to Black Cotton Soil in gradual amounts in order to enhance its mechanical characteristics and attain certain strength parameters. Adjustments were made in precise 2% increments of NaCl, aiming to systematically enhance the soil's load-bearing capabilities as reflected in the stabilization and strength test results.

3.3.1. Consistency Limits and Workability

Building on the workability improvements provided by Sodium Chloride (Figure 13) showcases the additional effects of incorporating Silica Fume (SF) into Black Cotton Soil, already treated with a baseline of 6% NaCl.

The study methodically introduced SF in 5% increments, ranging from 5% to 30%. This strategic addition demonstrates a clear trend: as SF content escalates, the soil's Atterberg limits-Liquid Limit (LL), Plastic Limit (PL), and Plasticity Index (PI)-experience a marked decrease. This trend signifies not only enhanced workability but also a notable reduction in soil plasticity, particularly pronounced at higher SF concentrations. These observations underscore the synergistic potential of NaCl and SF in soil stabilization, optimizing soil properties for construction readiness [9, 7, 16].

3.3.2. Shrinkage Limits

Figure 14 illustrates the significant impact of adding Silica Fume (SF) in increments to Black Cotton Soil treated with a steady 6% Sodium Chloride (NaCl). Beginning with a 5% SF addition and progressing up to 30%, the soil's shrinkage limit markedly decreases from an initial 14.61% to just 2.5%.

This considerable reduction points to enhanced volume stability and a diminished likelihood of shrinkage with increased SF content. Such a trend underscores the pivotal role of SF, alongside NaCl, in bolstering the soil's structure as it dries, suggesting a synergistic effect between these additives in stabilizing expansive soils [9, 7, 16].

3.3.3. Compaction Characteristics (MDD and OMC)

Figure 15 details the impact of integrating Sodium Chloride (NaCl) and Silica Fume (SF) on the compaction characteristics of Black Cotton Soil.

The Maximum Dry Density (MDD) achieves its peak at the incorporation of 10% SF, suggesting this concentration is the most effective for optimizing soil compaction. However, adding SF beyond this point, particularly at 15%, leads to a reduction in MDD, indicating there's a limit to the beneficial effects of SF on soil density.

Concurrently, the Optimum Moisture Content (OMC) experiences a slight uptick with increased SF levels, implying a greater need for moisture to achieve optimal compaction at higher SF concentrations. This nuanced response to the combined treatment underscores the importance of careful calibration of NaCl and SF amounts to attain the best compaction results for construction applications [9, 7, 16].

3.3.4. Strength Improvement (CBR for 7 Days Soaked)

Figure 16 exhibits the impact of Silica Fume (SF) incorporation, in increments from 5% to 30%, on the California Bearing Ratio (CBR) of Black Cotton Soil, preconditioned with a consistent 6% Sodium Chloride (NaCl).

This graph reveals a positive correlation between the SF content and the soil's CBR values, affirming SF's efficacy in soil stabilization. Notably, the CBR values ascend with each 5% increase in SF, peaking at an optimal SF concentration, beyond which the CBR values start to taper off. This trend underscores the existence of an ideal SF percentage for maximizing soil strength, beyond which additional SF may not yield further benefits and could potentially detract from the soil's structural integrity. Identifying the precise SF percentage for optimal stabilization is therefore paramount, ensuring enhanced load-bearing capacity without compromising the soil's condition [9, 7, 16].

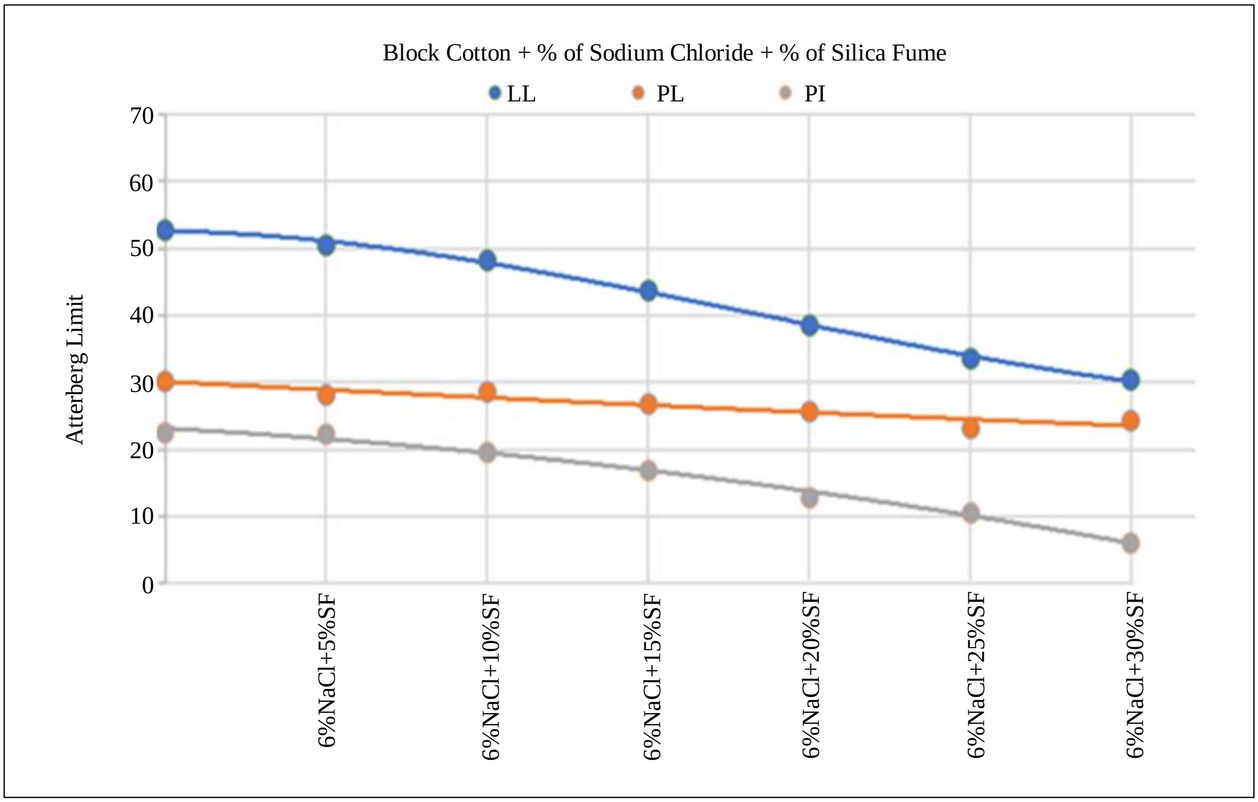


Fig. 13 Effect of Sodium Chloride + Silica Fume on Atterberg limits of the Black Cotton Soil

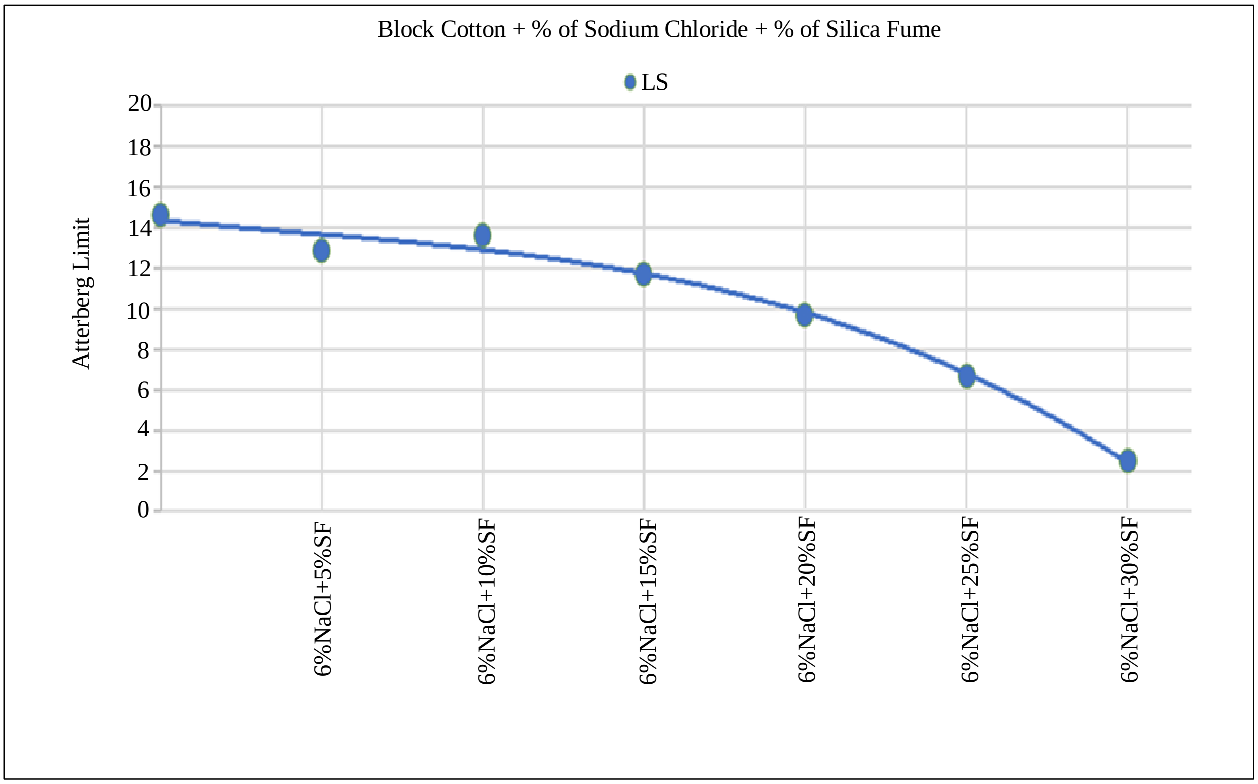


Fig. 14 Effect of Sodium Chloride + Silica Fume on shrinkage limit of the Black Cotton Soil

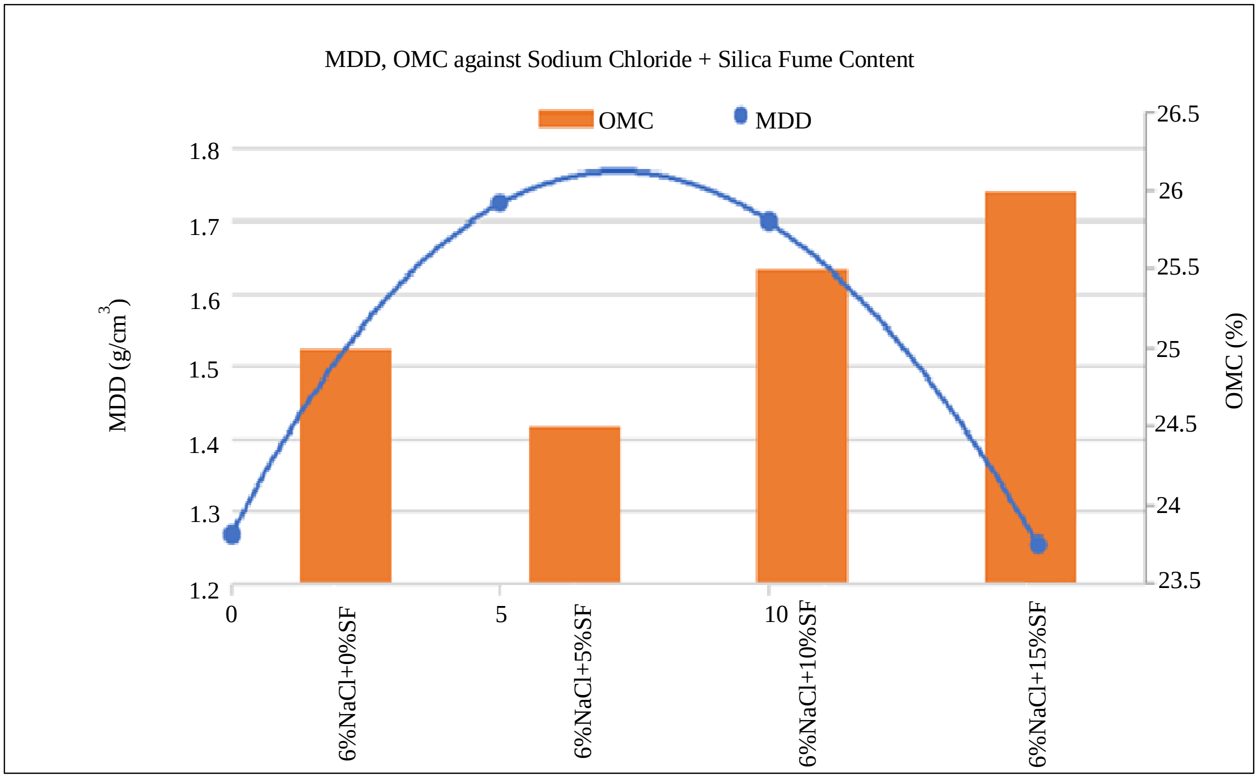


Fig. 15 Effect of Sodium Chloride + Silica Fume on MDD and OMC of the Black Cotton Soil

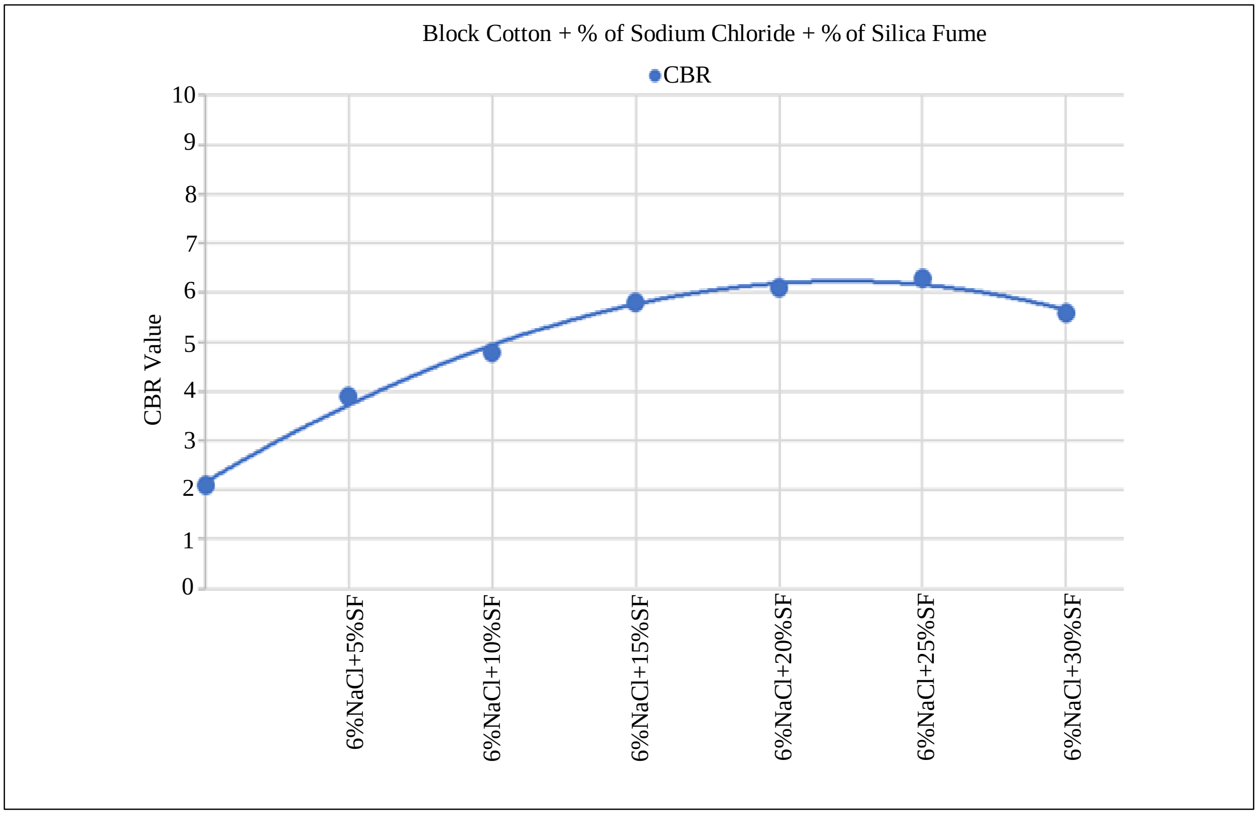


Fig. 16 Effect of Sodium Chloride + Silica Fume on CBR value of the Black Cotton Soil

3.4. Discussion of SEM Micrograph and EDS Graph

The SEM micrograph (Figure 3(a)) provides a detailed visualization of the soil's microstructure at a high magnification, revealing the texture, particle size, and morphology. It shows the agglomerated and irregular-shaped particles typical of clay soils, which contribute to their expansive nature and high plasticity. The accompanying EDS graph (Figure 3(b)) complements the SEM image by providing a quantitative elemental analysis of the same soil sample. The peaks in the EDS spectrum correspond to the elements present in the soil, with their heights indicating the relative abundance. The spectrum shows that Oxygen (O) and Silicon (Si) are the dominant elements, followed by other elements such as Aluminum (Al), Iron (Fe), and smaller amounts of Calcium (Ca), indicative of the mineral composition of the soil which includes silicates and possibly clay minerals.

The SEM micrograph (Figure 5(a)) shows the crystalline structure of NaCl at high magnification. The granules have a characteristic cubic form, which is typical of the crystalline structure of halite, the natural mineral form of sodium chloride. The EDS graph (Figure 5(b)) complements the SEM image by detailing the elemental composition of the sample. The two prominent peaks correspond to Sodium (Na) and Chlorine (Cl), the constituents of NaCl. The weight percentages of these elements confirm the sample is predominantly composed of NaCl, with a minor presence of other elements as impurities or due to the sample preparation or environmental factors during SEM-EDS analysis.

The SEM micrograph (Figure 7(a)) displays the ultrafine particulate nature of Silica Fume, which is a byproduct of silicon or ferrosilicon alloy production. The particles are spherical, which is characteristic of Silica Fume, and they vary in size, indicating a high surface area to volume ratio. The EDS graph (Figure 7(b)) provides an elemental analysis of the Silica Fume.

The predominant peak is for Silicon (Si), confirming the material's primary component as silicon dioxide (SiO2). The presence of Oxygen (O) correlates with the Silicon to form SiO_2. Minor elements such as Carbon (C), Magnesium (Mg), Calcium (Ca), and Potassium (K) are also detected, which may come from the source material or as part of the production process. The high Silicon content makes Silica Fume a valuable pozzolanic material in enhancing concrete's mechanical properties.

4. Conclusion

This comprehensive study on the stabilization of Black Cotton Soil using Sodium Chloride (NaCl) and Silica Fume (SF) underscores the significance of meticulously selected additive percentages for enhancing soil properties. The systematic introduction of NaCl up to a 16% concentration has been shown to notably reduce the Plasticity Index and shrinkage limits of the soil, thereby improving workability and diminishing its vulnerability to moisture-induced volume changes. Furthermore, the incorporation of SF in a range of 5% to 30% has substantially bolstered the soil's strength, with the most significant increases in California Bearing Ratio (CBR) values occurring at intermediate SF levels.

These observations highlight the critical role of precise additive measurement in achieving optimal soil stabilization, paving the way for more resilient construction methodologies and infrastructure longevity [7, 9, 16].

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