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*Original Article*

# Performance of Black Cotton Soil Stabilized with Silica Sand and Lime for Use as Road Subgrade

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***Abstract -*** *Designing foundations, particularly highway pavements, on black cotton soil has consistently posed a delinquent for engineers, as structures supported by this type of black cotton soil are prone to unexpected cracking and settlement. The issue this study aims to solve is the lack of appropriate performance materials for use as road subgrade in regions with black cotton soil. This study aims to inspect if a mixture of silica sand and lime can be used to advance the mechanical properties of black cotton soil, thereby improving its performance for road subgrade construction. The initial step involves evaluating natural soil's qualities using various tests such as Unconfined Compressive Strength (UCS), Atterberg limits, Californian Bearing Ratio (CBR), and Compaction tests. Subsequently, the soil sample is blended with silica sand in incremental amounts ranging from 0% to 12% of the soil sample's dry weight at intervals of 2%. Through this experimentation, it was determined that the ideal amount of silica sand for treating the soil is 8%. At this content level, the corresponding values for UCS and soaked CBR were 181.23 kPa and 6.9%, respectively. The results obtained did not meet the targeted strength; hence, it was necessary to add some lime content in order to meet the targets. After adding lime in steps of 2%, the characteristics of targeted strengths were met at 2% inclusion of lime, and the corresponding soaked CBR and UCS values were 12.3% and 188.39 kPa, respectively. These values were in line with the recommended standard for treated soil characteristics to be used in subgrade material. In conclusion, an optimal mixture of 8% silica sand and 2% lime is selected.*

***Keywords -*** *Black cotton clay soil, Road subgrade, Lime, Silica sand, Stabilization.*

## 1. Introduction

The development of transportation infrastructure is widely recognized as a significant driver of growth, as exemplified by the saying, "Wherever a road is built, progress follows." [1] Developing road infrastructure is imperative for empowering rural communities' economic and social progress in Africa by extending reach to markets, health care, education, and other basic amenities and services.

African countries, in the process of growth and advancement, present a substantial challenge for governments seeking to enhance road connectivity due to typically high construction costs. Connectivity helps link underserved populations to essential resources and opportunities that can alleviate hardship and support community thriving [2].

Black cotton soils expand and contract with changes in moisture content. When they absorb water during the rainy season, they swell and exert upward pressure, potentially causing damage to structures constructed on them [3].

On the other hand, during dry seasons, they lose water and contract, creating voids even without external loads. The most substantial damage occurs when there are frequent fluctuations in moisture content. To tackle the challenges posed by expansive clay soils, various treatment approaches have been proposed. These methods encompass adjusting the road design to align with the particular site conditions, the substitution and removal of existing soil materials, and the application of soil stabilization techniques.

Clay soil has been previously used as the subgrade or base material to construct roads [4]. With evolving requirements and a growing scarcity of suitable soils, black cotton soils are finding increased utilization in several civil engineering applications [5].

Lime and cement emerge as the predominant stabilizing materials for soil. Moreover, the use of such calcium-based additives faces growing concerns about Carbon Dioxide ($CO_2$) emission and climate change.

Therefore, there is a need for more sustainable soil stabilization techniques [6, 7]. The issue of soil stabilization presents a pressing challenge, necessitating the exploration of innovative, cost-effective approaches and stabilizing agents that align with global goals [8].

Nevertheless, these materials exhibit inadequate performance when subjected to challenging traffic and moisture conditions, especially if they have a lot of clay in them, which can lead to swelling or cracking [9]. Therefore, in some cases, especially in road construction, there is a need to stabilize these materials before application.

Research has shown that lime can strengthen the mechanical and physical characteristics of soils, making it a potentially effective stabilizing agent for black cotton soils [10]. Nevertheless, the suitability of these materials for stabilizing black cotton soils for subgrade construction is not well understood [11]. Therefore, it is necessary to investigate the performance of silica sand and lime when used as stabilizing agents for these soils.

Hydrated lime (Calcium Hydroxide, $Ca(OH)_2$), Quicklime (Calcium Oxide, CaO), or lime slurry can be employed for the purpose of stabilizing clay soils. Hydrated lime is produced through the chemical reaction between Quicklime and water [12].

The stabilization of clay with lime results in long-lasting changes to its properties. Lime and wet clay react in a number of ways, including pozzolanic reaction, cation exchange, and carbonation [13]. The exchange of cation is accountable for the accumulation of soil fragments, which ensues in early strength development. The slow-moving pozzolanic response is what leads to development at the late strength.

According to references [14, 15], Silica Dioxide ($SiO_2$) is the predominant mineral composition of quartz, which makes up the majority of the tiny particles or grains of rock and minerals that make up silica sand. This composition makes silica sand rich in silica, which is crucial for soil stabilization [16]. Silica sand is widely utilized due to its physical and chemical characteristics. It finds applications in various industries, including glass production, foundries for casting molds, ceramics, shale hydrocarbon extraction, polymers, paints, rubber, water filtration, and more [17].

Incorporating silica sand as an admixture in soil stabilization applications has shown improved strength performance and the utilization of locally available materials for sustainable subgrade road construction. Though many researchers focused on the characteristics of stabilized clay soil (black cotton) with lime, only a few have attempted to investigate a blend of silica sand with lime to stabilize black cotton soil.

This study aims to use silica sand combined with lime-stabilized black cotton soil to optimize mix proportions and improve mechanical properties for stabilized subgrade road construction.

## 2. Materials and Methods

### *2.1. Materials*

The study included silica sand, lime, and black cotton clay soil as its materials. The black cotton soil was sourced from the Juja area of Kiambu County, Kenya. The silica sand and hydrated lime were purchased locally (Kenya). Silica sand was crashed and then sieved using a 0.6mm BS sieve before being used.

### *2.2. Sample Preparation*

The samples of hydrated lime, silica sand, and black cotton soil were taken to the Kenya Ministry of Mining laboratory in Nairobi for chemical analysis. The material's chemical composition was ascertained using the X-Ray Fluorescence (XRF) analysis. This was done to gain a more profound understanding of how silica sand and lime could potentially interact chemically when blended with black cotton soil.

X-Ray Diffraction (XRD) analysis was used to determine the oxide compositions of lime, silica sand, and black cotton soil were described. However, the materials were sieved through a 75 µm sieve before being scanned in an X-Ray Diffractometer (XRD) apparatus using the DB PHASER portable XRD equipment to estimate the molecular composition of the material. As the X-rays activated the sample, it produced variable-frequency diffraction peaks when it was scanned in the XRD device. Using the peaks of the X-ray emission spectra, the various compounds in the samples were identified.

The engineering properties included particle size distribution, specific gravity, moisture content, consistency limits, and free swell, which were performed according to British Standard BS1377:1990, ASTM-962-15, ASTM D-423-61T/D424-59/854. Additionally, the soil was categorized according to the guidelines of the Unified Soil Classification System (USCS). AASHTO M145-91 and BS 1377-1924-13 and 15, ASTM D2487.

The black cotton soil was treated with varying amounts of silica sand at 0%, 2%, 4%, 6%, 8%, 10% and 12% of the dry weight of the soil sample. The optimum amount of silica sand that had the highest performance was then selected. The soil was further treated using lime varying at 0%, 2%, 4%, 6%, and 8% blended with the optimum percentage of silica sand (Figure 1). The Atterberg limits, compaction, free swell, Unconfined Compression Strength (UCS), and California Bearing Ratio (CBR) tests were performed according to standard procedures.

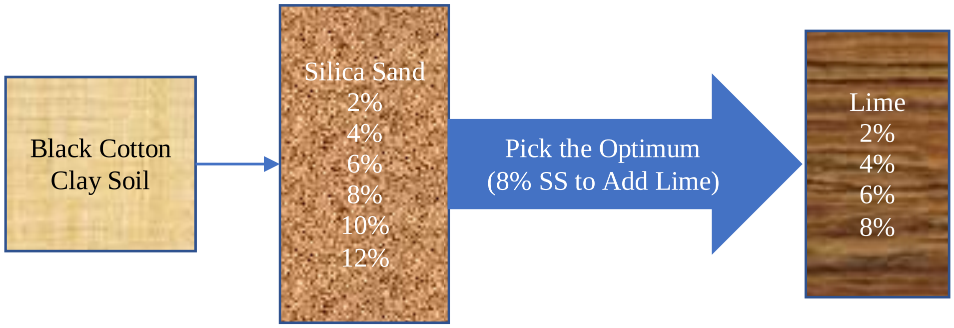


**Fig. 1 Schematic layout of treatment of black cotton soil**

## 3. Results and Discussion

### *3.1. Chemical Characterization of Black Cotton Soil, Silica Sand, and Lime*

The X-Ray Fluorescence (XRF) analysis findings for the samples are shown in Table 1. The analysis revealed that the black cotton soil was primarily composed of Silica ($SiO_2$) and contained a notable amount of iron oxide. This composition suggests that the presence of swelling clay minerals could cause shrink-swell behavior like smectite and illite, which are rich in iron. On the other hand, as indicated in Table 1, silica sand was predominantly composed of Silicon Dioxide ($SiO_2$) at 96.080%.

In the case of lime, calcium oxide exhibited the highest content, followed by aluminum and iron oxide, as shown in Table 1. According to the chemical characterization, there may be a way to improve metal cation exchange, which would take the place of the expanded clay minerals' drained double layer and improve flocculation, as suggested by [19]. The elemental makeup of lime results in the creation of gels such as Calcium Silicate Hydrate (CSH), Calcium Aluminate Hydrate (CAH), and Calcium Alumina Silicate Hydrate (CASH). These amorphous gels undergo crystallization over time, which involves the production of cementitious compounds that successfully combine clay particles [20].

**Table 1. The chemical composition of the silica sand, black cotton, and lime**

| Oxides | Amount Oxides in Clay Soil Black Cotton (%) | Amount Oxides in Lime (%) | Amount Oxides in Silica Sand (%) |
|---|---|---|---|
| Magnesium Oxide (MgO) | - | 3.393 | 1.148 |
| Aluminium Oxide ($Al_2O_3$) | 9.883 | 2.550 | 1.491 |
| Silica ($SiO_2$) | 78.543 | - | 96.080 |
| Phosphorus Pentoxide ($P_2O_5$) | - | 0.696 | 0.094 |
| Sulphur (S) | - | 0.647 | - |
| Chlorine (Cl) | - | - | - |
| Potassium Oxide ($K_2O$) | 0.652 | - | 0.340 |
| Calcium Oxide (CaO) | 1.347 | 92.262 | 0.287 |
| Titanium (Ti) | 0.931 | 0.045 | 0.022 |
| Chromium (Cr) | - | - | - |
| Manganese (Mn) | 0.535 | 0.027 | 0.009 |
| Iron Oxide ($Fe_2O_3$) | 7.752 | 0.300 | 0.517 |
| Copper (Cu) | 0.004 | 0.031 | 0.002 |
| Zinc (Zn) | 0.017 | - | 0.002 |
| Strontium (Sr) | 0.014 | 0.026 | - |
| Zirconium (Zr) | 0.117 | 0.003 | 0.003 |

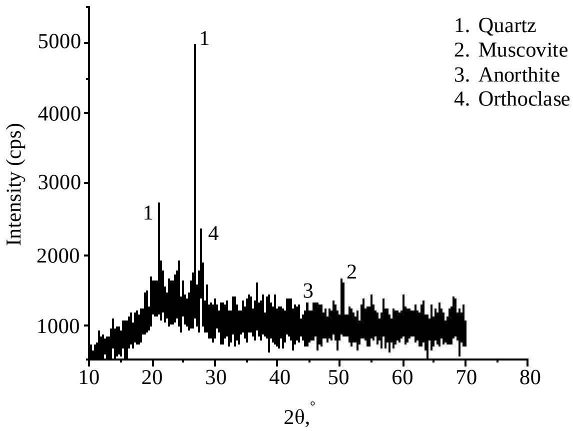


**Fig. 2 X-Ray Diffractogram (XRD) patterns of black cotton**

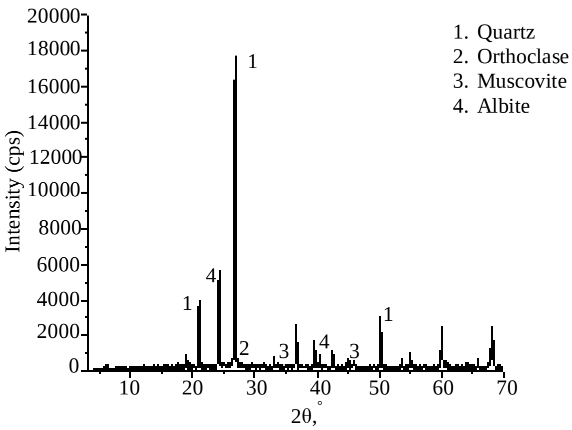


**Fig. 3 X-Ray Diffractogram (XRD) patterns for silica sand**

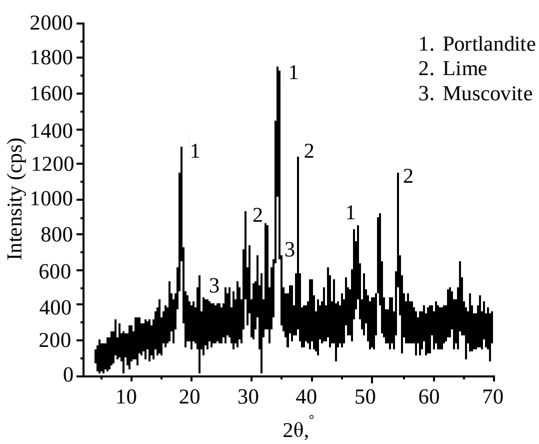


**Fig. 4 X-Ray Diffractogram (XRD) patterns of Lime**

Analyses using XRD were performed on processed Black Cotton (BC), Silica Sand (SS), and lime to determine the mineralogical properties of these materials, as illustrated in (Figures 2, 3, and 4) respectively. The results showed that both BC and SS contained significant quantities of quartz, which is consistent with the observations made by [21, 18]. Muscovite and orthoclase were similarly detected in substantial amounts in both BC and SS.

Furthermore, the lime sample exhibited the presence of portlandite, which aligns with the results obtained from the chemical composition analysis as reported by [22].

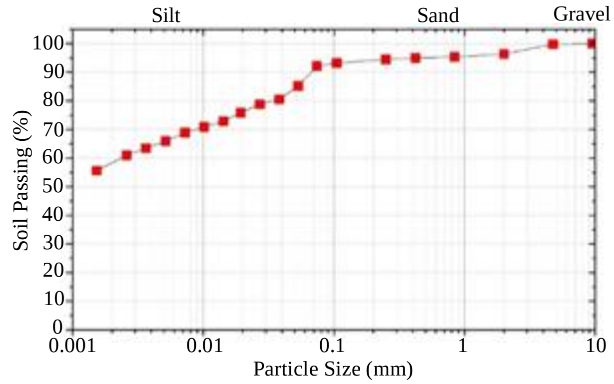


**Fig. 5 Particle size distribution of black cotton soil**

### *3.2. Physical and Mechanical Properties of Black Cotton Soil*

The primary mechanical and physical characteristics of lime, silica sand, and untreated black cotton clay soil are compiled in Tables 2, and 3.

#### *3.2.1. Particle Size Distribution*

Figure 5 illustrates the distribution of particle sizes in the black cotton soil. Based on the characteristics exhibited from the tests, the soil was categorized under the AASHTO criteria as A-7-6 and ASTM D422-98 [23]. It was indicated that black cotton soil contained 3.44% gravel, 7.67% sand, 30% silt, and 58.30% clay [24].

### *3.3. Effect of Silica Sand and Lime Stabilization on the Consistency Limits of Black Cotton Soil*

The percentage of silica sand rose from 0 to 12% by dry mass (Figure 6). As the amount of silica sand rose, the Plastic Limit (PL) and Liquid Limit (LL) both decreased. The best modification was achieved, as seen in (Figure 7), when 8% silica sand was added, and the dry mass lime percentage was raised from 0% to 8%, gradually decreasing the Plasticity Index (PI) to 2.31% from 30.39%. While Liquid Limit (LL) initially decreased slightly with lime proportions of 0-8%, Plastic Limit (PL) showed a small rise (Figure 7) enhancing soil consistency [25].

As silica sand content increased from 0% to 12%, this led to a decrease in linear shrinkage from 15.71% to 12.14% (Figure 6). Varying lime content from 0 to 8% further decreased linear shrinkage from 15.71% to 5.71% (Figure 7) [26].

As noted by [27], lime contributes to soil strength through cation exchange and pozzolanic reactions, forming cementitious compounds. The combination of silica sand and lime, therefore, facilitated the formation of cementitious bonds, decreasing PI and improving consistency. This modification curbed soil expansion, which is suitable for road construction. Consequently, the study concludes that combining 8% silica sand and 2% lime effectively modified the soil's consistency for cost-effective road construction while curbing expansion and reducing shrinkage [28].

**Table 2. Engineering properties of black cotton soil**

| Property | Value | Standard |
|---|---|---|
| Colour Observations | Dark Grey | |
| Moisture Content | 8.07% | BS 1377-2,1990 |
| Classification (AASHTO) | A-7-6 | BS 1377-2-1990, ASTM D 4318 |
| Plastic Limit (PL) | 29.03% | |
| Plasticity Index (PI) | 30.39% | |
| Liquid Limit (LL) | 59.42% | BS 1377-2,1990 |
| Linear Shrinkage | 15.71% | ASTM D427 and BS 1377-2-1990 |
| Free-Swell | 110% | BS 1377-2,1990 |
| Specific Gravity | 2.23 | BS 1377-2,1990 |
| Maximum Dry Density | 1.335g/cm³ | ASTM D698-00 a, BS 1377-4-1990 |
| Optimum Moisture Content | 28.0% | |
| Soaked CBR (4 Days Soaking) | 1.41% | AASHTO T193-93, BS 1377:1990, ASTM D 4429/D1883 |
| UCS | 50.11 kPa | BS1377:1990, ASTMD2166/D2166M |

**Table 3. Specific gravity properties for black cotton soil, lime, and silica sand**

| Sample | Specific Gravity Value | Code Limits | Standard Code |
|---|---|---|---|
| Black Cotton | 2.23 | 2.6- 2.75 | ASTMD854-02, ASTM C128(2001), BS 1377-2,1990 |
| Lime | 2.32 | 2.0-2.3 | BS 1377-2,1990 |
| Silica Sand | 2.66 | 2.55-2.75 | ASTM C 128, (2001) |

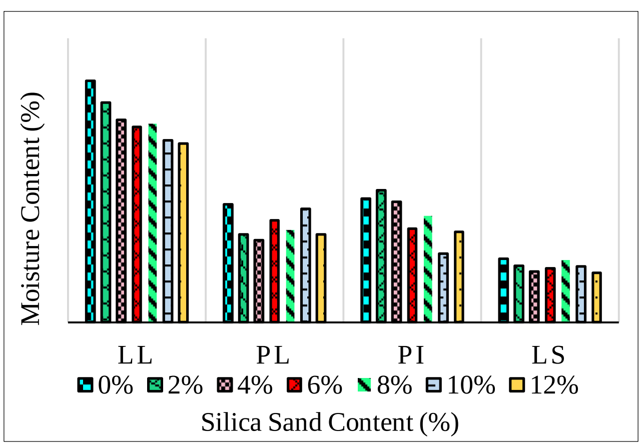


**Fig. 6 Black cotton's consistency limits when treated with silica sand content**

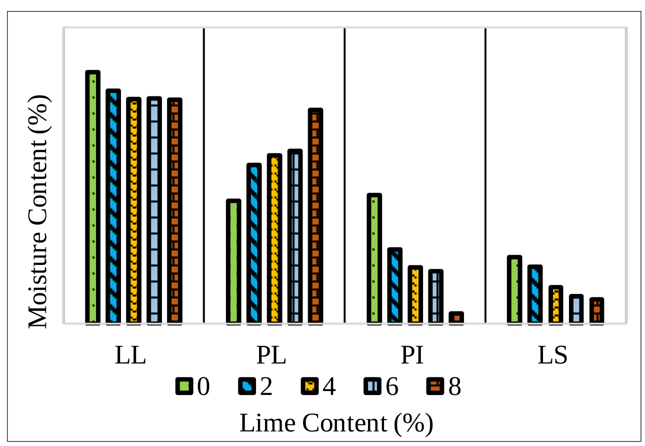


**Fig. 7 Black cotton's consistency limits when treated with 8% silica sand and different amounts of lime content**

### *3.4. Effect of Silica Sand and Lime Stabilization on Free-Swell of Black Cotton Soil*

The untreated black cotton soil exhibited a high free swell index of 110%, demonstrating its distinctive characteristics. However, the free swell was significantly reduced when silica sand concentration was increased from 0% to 12%, the range between 65% to 30%, as shown in (Figure 8) [29]. According to [30], a free swell index greater than 50% is considered very high. Furthermore, when 0% to 8% lime content was added to the optimum 8% silica sand, it further decreased the free swell, as depicted in (Figure 9).

This demonstrates the effectiveness of lime in addressing the problematic volume-change tendencies of the soil. Lime can interact with clay soils at a physicochemical level, leading to modifications in the microstructure of the clay. By incorporating silica sand and lime into the soil, they function as pore-fillers, preventing clay from swelling through the establishment of a static interaction between silica sand and clay particles.

Consequently, lime forms a protective coating around and reinforces the surfaces of clay particles. Additionally, the absorbed lime organics disrupt the structured water layer, leading to a denser arrangement of particles, as observed in [31]. These geotechnical additives prove highly effective in reducing swelling to a maximum of 50%, thus fulfilling the stability requirements specified in the Kenya road manual [36].

### *3.5. Effect of Silica Sand Lime Stabilization on Compaction of Black Cotton Soil*

As shown in (Figure 10) Optimum Moisture Content (OMC) decreased while MDD increased with rising silica sand concentrations from 0 to 12%. On adding 8% silica sand as optimum and the lime content increased from 0% to 8%, the OMC decreased from 28% to 24% (Figure 11).

Nevertheless, as a result of incorporating 8% silica sand and 2% lime, the optimum result of compaction, MDD 1.378 gm/cc, and OMC 27.5% at 2% lime (Figure 11) as concluded. The decrease in OMC can be attributed to the hygroscopic nature of lime. In the context of soil stabilization, lime acts as a binding substance that enhances the cohesion and load-bearing capacity of soils. This is typical of silica sand and lime stabilization, as lime reacts with clay minerals, improving soil compaction and reducing the moisture content required for optimal compaction.

### *3.6. Effect of Silica Sand and Lime Stabilization on CBR of Black Cotton Soil*

Black cotton soil's CBR of 1.41% demonstrated that it was incredibly insufficient to be used as a road subgrade to withstand the demands of traffic loads. This discovery was likewise reported by [32]. An optimum of 6.9% was reached by adding 8% silica sand (Figure 12) [33]. This is still below the typical minimum standard, as indicated according to [34-36]. Beyond 8% silica sand, the CBR started decreasing.

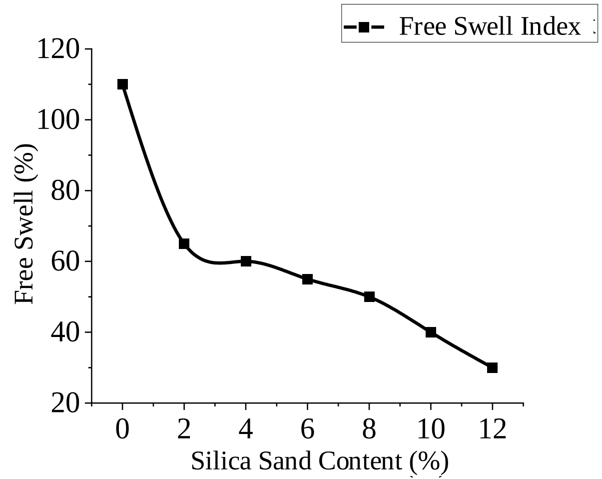


**Fig. 8 Free swell of black cotton soil with silica sand content only**

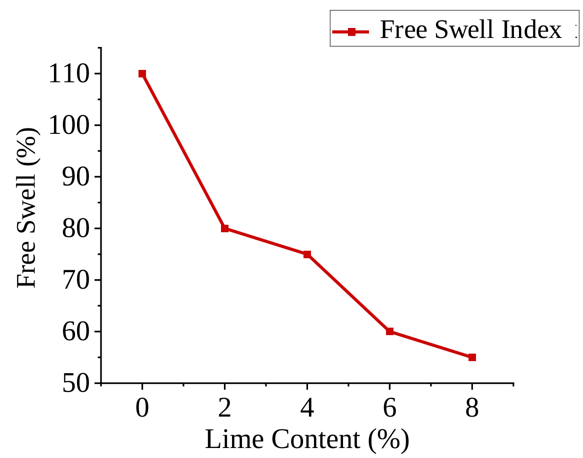


**Fig. 9 Free swell of black cotton soil with 8% silica sand and varying lime content**

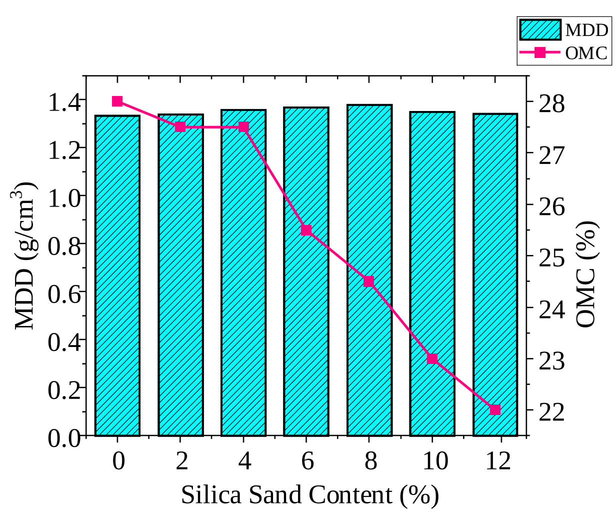


**Fig. 10 OMC and MDD of black cotton only containing silica sands**

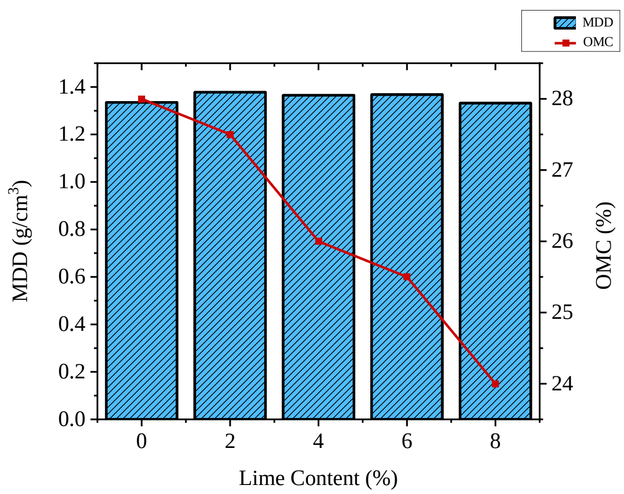


**Fig. 11 OMC and MDD of black cotton treated through 8% silica sand and lime content**

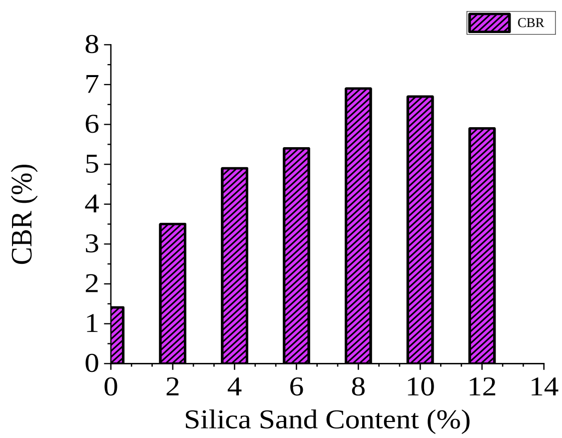


**Fig. 12 CBR of black cotton soil containing only silica sand**

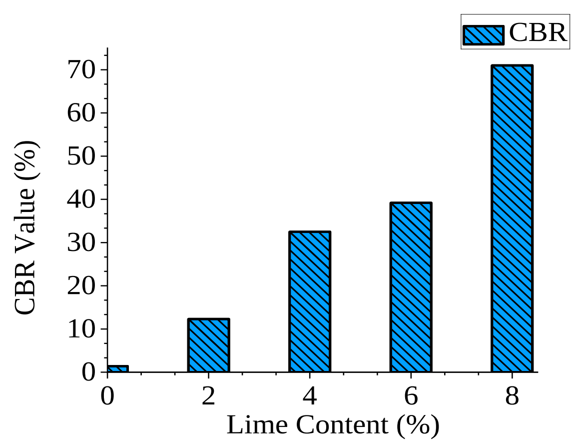


**Fig. 13 CBR of black cotton treated with 8% silica sand and varying lime content**

Adding 0 to 8% lime on an optimum of 8% silica sand. The complementary static interactions with silica sand and lime-treated clay minerals clarify the enhanced strength after adding 2% lime. Modifying mineralogy and pore structure through physico-chemical mechanisms imparted by the optimized 8% silica sand and 2% lime treatment increased the CBR to 12.3% (Figure 13) load-bearing capacity was sufficiently improved to support traffic loads per design requirements.

### *3.7. Effect of Silica Sand and Lime Stabilization on UCS of Black Cotton Soil*

The Unconfined Compressive Strength (UCS) of silica sand increased from 2 to 8 as the proportion of silica sand varied from 0 to 12% (Figure 14) as reported by [37]. However, the UCS values decreased for proportions of 10% and 12%.

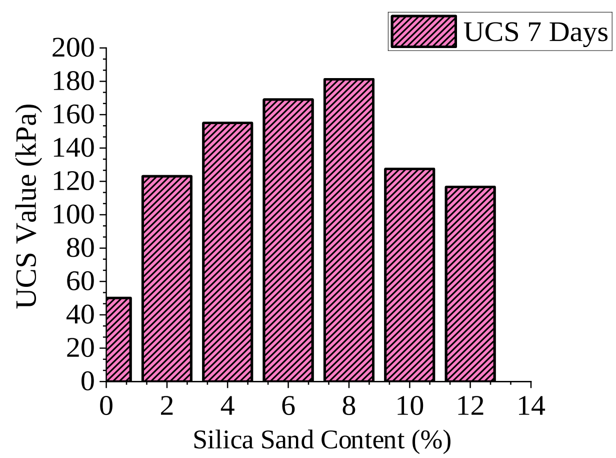


**Fig. 14 UCS of black cotton soil treated with silica sand content**

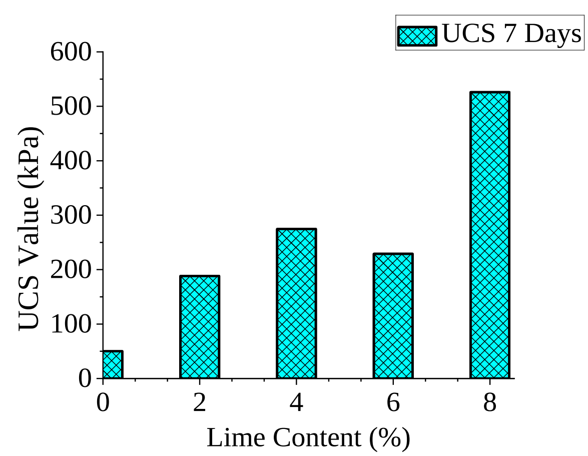


**Fig. 15 UCS of black cotton treated with 8% silica sand and varying lime content**

However, it was found that 8% silica sand was the optimal amount, and 181.23 kPa determined the treated soil's UCS value after seven days [38]. Similarly, an optimal proportion of 8% silica sand was achieved while maintaining a lime content ranging from 0 to 8% in black cotton soil (Figure 15). resulting in enhanced qualities of mechanical strength. With a rise in lime content, the soil exhibited enhanced cohesive properties, leading to a significant increase in axial strain. This indicates that the soil became very stiff, as classified according to [39, 40]. The substantial improvement in strength observed with the reaction can be linked to a higher silica sand content between silica, calcium ions from lime, and clay minerals.

## 4. Conclusion

This study aimed to evaluate the performance of black cotton soil stabilized with silica sand and lime as a subgrade material for road construction. The subsequent conclusions are derived from the results obtained in this study:

- The effect of silica sand alone in black cotton soil is significant in linear shrinkage. However, adding lime does improve the black cotton soil's plastic index. Further, the free swell index can be reduced to a very high degree by adding 8% silica sand in black cotton soil.
- The addition of 8% silica sand, which was determined to be the optimal proportion, along with 2% lime, resulted in an enhancement in contrast to stabilized soil with silica sand and lime in the range of 4% to 8% lime content, the maximum dry density and a decrease in the ideal moisture content increased stabilized black cotton soil.
- The addition of 8% silica sand and 2% lime to black cotton soil leads to 12.03% and 188.39 kPa CBR and UCS values, respectively. Thus, increase in strength.
- The addition of silica sand as a co-stabilizer with lime has a profound effect on the California Bearing Ratio and unconfined compressive strength of black cotton soil. An optimum value of 8% silica sand and 2% lime was realized in this study.

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