# Laboratory study on the soil stabilization of expansive soils using quick lime

[1]Patara.Divya Sasikala, [2]B. Ganesh
[1]M. Tech Student, [2]Associate professor
[1,2]SOIL MECHANICS AND FOUNDATION ENGINEERING, DEPARTMENT OF CIVIL ENGINEERING,
[1,2]LENORA COLLEGE OF ENGINEERING, RAMPACHODAVARAM – 533288, E.G. District, Andhra Pradesh

**ABSTRACT**

Expansive soils, commonly found in arid and semi-arid regions, present significant challenges to civil engineering due to their tendency to undergo substantial volume changes with variations in moisture content. These soils are prone to swelling during wet seasons and shrinking during dry seasons, leading to differential settlements and structural damage. This study investigates the effectiveness of lime stabilization in enhancing the engineering properties of expansive clay soils. Laboratory experiments were carried out to evaluate the impact of varying lime content on Atterberg limits, unconfined compressive strength (UCS), and swelling potential. Quicklime was mixed with the expansive soil at varying percentages (2%, 4%, 6%, and 8% by dry weight), and specimens were cured for 7, 14, and 28 days. The untreated soil exhibited a liquid limit of 68%, plastic limit of 36%, and a plasticity index (PI) of 32%, which indicates high plasticity. With 6% lime content, the PI reduced to 18%, showing a significant decrease in soil plasticity. The swelling potential dropped from 12.5% in the natural soil to 2.1% with 6% lime treatment, indicating a major improvement in volume stability. Unconfined compressive strength tests revealed that the UCS of untreated soil was 120 kPa, while the strength increased to 460 kPa with 8% lime after 28 days of curing. The optimal improvement in strength and reduction in swell potential were observed at 6% lime content, beyond which the gains became marginal. These results demonstrate that lime effectively modifies the physicochemical properties of expansive soils, making them suitable for use as subgrade and foundation materials. In conclusion, lime stabilization is a proven, economical, and environmentally sustainable method for improving the performance of expansive soils in geotechnical and pavement engineering applications.

***Keywords:*** *Expansive soils, Moisture content, Quicklime, Swelling, Stabilization, environmentally sustainable.*

## 1. INTRODUCTION

Expansive soils, predominantly composed of clay minerals such as montmorillonite, are known for their high shrink–swell potential due to moisture variations. These soils undergo considerable volumetric changes when exposed to fluctuating environmental conditions, causing serious distress to civil infrastructure, including pavements, foundations, embankments, and pipelines [1]. The adverse behavior of such soils, particularly in semi-arid and arid regions, demands effective stabilization techniques to ensure long-term durability and performance of structures.

Among the many soil stabilization methods available, lime stabilization has proven to be one of the most cost-effective and widely adopted solutions for modifying expansive clays. When lime (usually quicklime or hydrated lime) is mixed with clayey soil, a pozzolanic reaction occurs, forming cementitious compounds such as calcium silicate hydrates (CSH) and calcium aluminate hydrates (CAH), which significantly enhance the strength and durability of the treated soil [2]In addition to reducing plasticity and swell potential, lime also improves the workability and compaction characteristics of the soil [3]. Several studies have demonstrated the efficacy of lime stabilization in improving the engineering behavior of expansive soils. For example, [4] reported that lime-treated fine-grained soils exhibited higher strength and lower compressibility. Similarly, [5] observed a substantial reduction in plasticity index and increase in unconfined compressive strength (UCS) upon adding lime and fly ash to clayey soils. [6] further reinforced this by showing that lime-treated fly ash composites could be effectively used in pavement base courses due to their strength and stability.

The optimum lime content varies depending on the soil's mineralogical composition and initial properties, but typically ranges between 4% and 8% by dry weight of soil. [7] reported that a 6% lime addition to black cotton soil led to a 60–70% reduction in swelling potential and a two-fold

increase in UCS after 28 days of curing. [8] found that combining lime with cement and silica fume produced a significant synergistic effect in stabilizing expansive clays.In addition to traditional stabilizers, modern research has focused on the combination of lime with other industrial by-products, such as fly ash [9], lime sludge [10], and geopolymer binders [11], aiming to reduce environmental impact and improve long-term performance. [12] demonstrated that lime-fly ash blends could substitute a significant portion of cement in soil stabilization applications, offering both environmental and economic benefits.

The current study aims to investigate the effect of lime stabilization on the geotechnical properties of expansive soils, with particular emphasis on Atterberg limits, swell potential, and unconfined compressive strength. The research provides valuable insights into the optimum lime content required to achieve substantial improvements in soil behaviour, thereby contributing to the development of more sustainable ground improvement strategies.

## 2. MATERIALS AND METHODOLOGY

### 2.1 MATERIALS

#### A) Black Cotton Soil

Black cotton soils (BCS) are a type of expansive clay soil predominantly found in tropical and subtropical regions, especially across central and southern India. These soils are derived from the weathering of basaltic rocks, particularly from the Deccan Traps, which give them their distinctive black color due to the presence of iron and magnesium-rich minerals such as titaniferous magnetite. A key feature of black cotton soils is their high content of the clay mineral montmorillonite, which is responsible for their excessive shrink-swell behavior. This property leads to significant volume changes depending on the moisture content—expanding during the wet season and shrinking in dry periods—posing serious challenges to civil engineering and construction.

Geographically, black cotton soils are prevalent in Indian states like Maharashtra, Madhya Pradesh, Gujarat, Andhra Pradesh, and Tamil Nadu. Internationally, similar expansive soils are also found in parts of Africa, Australia, and the southern United States. From an engineering perspective, BCS typically exhibit high plasticity and liquid limits (often exceeding 50%), low permeability, and poor compaction characteristics. Their bearing capacity is low, making them unsuitable for supporting structures without appropriate ground improvement techniques. During wet conditions, they can cause upward heaving of structures, and in dry periods, excessive cracking and settlement can occur.Construction on black cotton soil requires careful attention, as these soils can cause structural failures if not properly treated. Several methods are used for stabilization. Chemical stabilization with lime or cement is one of the most common approaches, as these additives reduce plasticity and enhance strength. Additionally, industrial by-products like fly ash can be used to improve soil properties. Mechanical stabilization, such as mixing with coarse aggregates or sand, helps reduce the shrink-swell potential. More recently, bio-enzyme stabilization (e.g., using TerraZyme) has gained attention for its environmentally friendly approach, showing improvements in strength and moisture stability of black cotton soils. Reinforcement using natural or synthetic fibers is also employed to increase the tensile strength and minimize cracking.

Fig. 1 Black Cotton Soil

**Table 1** Properties of Black Cotton Soil

| S. No | Property | Description |
|---|---|---|
| 1 | Plasticity Index | High |
| 2 | Liquid Limit | High |
| 3 | Shrink-Swell Potential | Very High |
| 4 | Bearing Capacity | Low |
| 5 | Permeability | Low |
| 6 | Compaction Behaviour | Poor |

#### B) Quick Lime

Quicklime (Calcium Oxide, CaO) is a highly reactive, alkaline chemical derived from the thermal decomposition of limestone ($CaCO_3$)

at high temperatures (~900°C), releasing carbon dioxide and forming CaO. It is commonly used in geotechnical engineering to stabilize problematic soils such as black cotton soil, which are rich in montmorillonite clay minerals and exhibit high swelling and shrinkage behaviour.

**Properties of Quicklime:**

- Chemical Formula: CaO
- Molecular Weight: 56.08 g/mol
- Specific Gravity: ~3.3
- Bulk Density: 900–1350 kg/m³
- Solubility in Water: Reacts exothermically
- Heat of Hydration: ~65 kJ/mol
- Appearance: White or grayish-white, odorless powder or lumps
- pH in Soil: Raises pH to 12.4 or higher, ideal for pozzolanic reactions

Quicklime undergoes an exothermic hydration reaction with soil moisture, forming calcium hydroxide (slaked lime):

$$\mathrm{CaO} + \mathrm{H_2O} \rightarrow \mathrm{Ca(OH)_2} + \mathrm{Heat}$$

This reaction generates heat, which accelerates drying and initial strength gain. The resulting alkaline environment promotes pozzolanic reactions between $Ca(OH)_2$ and the siliceous/aluminous compounds in the soil, forming cementitious products like calcium silicate hydrate (CSH) and calcium aluminate hydrate (CAH). These products bind soil particles, reducing plasticity and enhancing strength and durability.

Fig. 2 Quick Lime

## 2.2 METHODOLOGY

The methodology outlines a systematic approach to evaluating the effectiveness of quicklime in stabilizing expansive black cotton soil. It involves collecting soil and lime, conducting preliminary tests to determine the soil's natural properties, preparing soil-lime mixtures in varying proportions, curing them over specified durations, and performing strength and index tests to assess improvements.

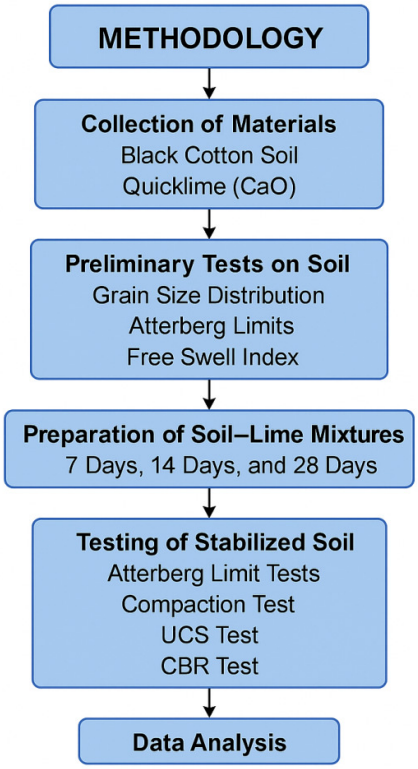


Fig. 3 Methodology

The methodology for this study begins with the collection of black cotton soil, which is known for its expansive characteristics due to the presence of montmorillonite clay minerals. The soil sample is obtained from a representative site and brought to the laboratory for testing.

**1. Preliminary Testing:** Before stabilization, the natural properties of the soil are determined through standard geotechnical tests in accordance with IS codes. These include:

- Atterberg Limits (Liquid Limit, Plastic Limit, and Plasticity Index) to assess the soil's plasticity and behavior with moisture.

- Standard Proctor Compaction Test to determine Maximum Dry Density (MDD) and Optimum Moisture Content (OMC).
- Unconfined Compressive Strength (UCS) and California Bearing Ratio (CBR) to evaluate strength and bearing capacity.
- Free Swell Index (FSI) to quantify the soil's swelling potential.

**2. Preparation of Soil–Lime Mixtures:** Quicklime is mixed with the soil in varying percentages (typically 2%, 4%, 6%, 8%, and 10% by dry weight) to determine the optimum lime content. The mixing is done thoroughly to ensure homogeneity.

**3. Curing Process:** After mixing, the specimens are sealed and cured for predetermined periods (7, 14, and 28 days). Curing allows for the completion of pozzolanic reactions that lead to improved bonding and strength in the soil-lime matrix.

**4. Testing of Stabilized Soil:** After curing, the stabilized samples undergo the same tests (Atterberg limits, UCS, CBR, etc.) to observe the improvements in strength, plasticity reduction, and swelling control.

**5. Data Analysis:** Finally, the test results from untreated and treated soils are compared. Graphs and tables are used to analyze the performance, and the optimum lime content is determined based on maximum strength gain and minimum swelling.

## 3. RESULTS AND DISCUSSION

### 3.1 TESTS ON VIRGIN BLACK COTTON SOIL

**A) Grain Size Distribution:** It is a key parameter in classifying soil and understanding its engineering behaviour. It provides insights into the proportions of sand, silt, and clay present in the soil, which directly influence its plasticity, permeability, and strength. In the case of black cotton soil, grain size distribution typically reveals the following characteristics:

- **Clay Content**: High (often above 50%)
- **Silt Content**: Moderate to high
- **Sand Content**: Low to moderate
- **Gravel**: Negligible or absent

**Table 2** Typical size of particles in soils

| S.No | Particle Size Fraction | Percentage Passing (%) |
|---|---|---|
| 1 | Gravel (>4.75 mm) | 0 – 2% |
| 2 | Sand (4.75 mm – 0.075 mm) | 10 – 25% |
| 3 | Silt (0.075 mm – 0.002 mm) | 20 – 35% |
| 4 | Clay (<0.002 mm) | 40 – 60% |

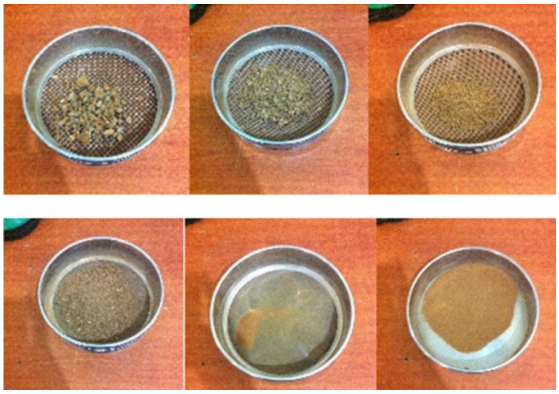

Fig. 4 Sieve Analysis

Grain size analysis is typically performed using sieve analysis for coarser particles and hydrometer analysis for finer particles (silt and clay), providing a complete particle size distribution curve. Understanding this distribution is essential before undertaking any stabilization or ground improvement techniques.

**Table 3** Grain Size Distribution test data

| S.No | Sieve Size (mm) | % Weight Retained | Cumulative % Retained | % Passing |
|---|---|---|---|---|
| 1 | 4.75 (coarse sand) | 1.0 | 1.0 | 99.0 |
| 2 | 2.00 | 2.5 | 3.5 | 96.5 |
| 3 | 1.00 | 3.0 | 6.5 | 93.5 |
| 4 | 0.425 | 5.5 | 12.0 | 88.0 |
| 5 | 0.212 | 8.0 | 20.0 | 80.0 |

| | | | | |
|---|---|---|---|---|
| 6 | 0.075 (pan below sieve) | 10.0 | 30.0 | 70.0 |

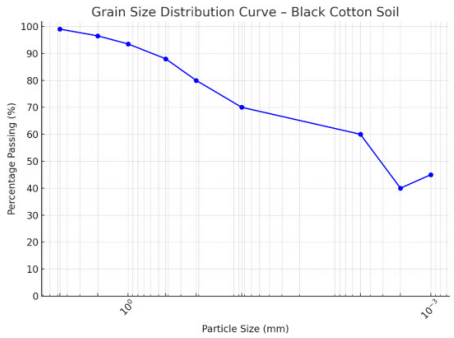


Fig. 5 Grain Size curve for the virgin soil

The grain size distribution curve for black cotton soil provides significant insight into its physical and engineering behaviour. This curve, plotted on a semi-logarithmic graph, shows the percentage of soil particles passing through a range of standard sieves, allowing for the classification and understanding of the soil's texture and gradation.From the curve, it is evident that a large proportion-more than 70%-of the soil particles pass through the 0.075 mm sieve, which marks the boundary between sand and silt. This indicates that the soil is predominantly fine-grained. Further, hydrometer analysis data reveals that approximately 55–60% of the particles are smaller than 0.002 mm, confirming a very high clay content. The presence of such a high percentage of clay-sized particles is characteristic of expansive soils like black cotton soil, which are rich in montmorillonite minerals. These minerals are known for their ability to absorb water and swell significantly, as well as shrink during drying, which causes substantial volume changes.

**Table 4** Atterberg limits for the virgin soil

| S.No | Property | Value (%) | Interpretation |
|---|---|---|---|
| 1 | Liquid Limit (LL) | 68% | Very high – indicates high plasticity |
| 2 | Plastic Limit (PL) | 32% | Moderate – supports plastic behavior |
| 3 | Plasticity Index (PI) | 36% | PI = LL – PL → Highly plastic |
| 4 | Shrinkage Limit (SL) | 14% | Indicates high volume change potential |
| 5 | Flow Index (FI) | 12% (typical) | Represents sensitivity to remolding |
| 6 | Toughness Index (TI) | 3.0 (typical) | PI/FI → High resistance to deformation |

The Atterberg Limits are fundamental indicators of a soil's consistency, plasticity, and potential for expansion and shrinkage. Based on the provided test results, the black cotton soil demonstrates highly problematic behaviour in its natural state.

**B) Atterberg Limits:** Atterberg limits are basic tests used to determine the critical water contents of fine-grained soils. They include the liquid limit (LL), plastic limit (PL), and shrinkage limit (SL). These limits help classify soils and assess their plasticity, consistency, and potential for volume change, which are crucial in geotechnical design.

Fig. 6 Casagrande Test Apparatus

The Liquid Limit (LL) of 68% is significantly high, indicating that the soil requires a large amount of water to reach a liquid state. This reflects the presence of active clay minerals such as montmorillonite, which have a high-water absorption capacity. Soils with such high LL values are typically very compressible and exhibit large volumetric changes upon wetting and drying.

The Plastic Limit (PL) of 32% indicates the moisture content at which the soil begins to behave plastically. The difference between LL and PL, known as the Plasticity Index (PI), is 36%, which categorizes the soil as highly plastic. A high PI is often associated with poor workability, increased swelling potential, and high risk of shrinkage cracks, making the soil unsuitable for load-bearing structures in its natural form.

The Shrinkage Limit (SL) of 14% suggests that the soil retains moisture over a broad range and will undergo considerable volume reduction upon drying. This further confirms the expansive nature of black cotton soil, which can lead to severe foundation issues if left untreated.

**C) Free Swell Index:**The Free Swell Index (FSI) is a measure of a soil's potential to swell when immersed in water compared to a non-polar liquid like kerosene. It helps in identifying expansive soils, particularly those with high clay content such as black cotton soil. A higher FSI value indicates greater swelling potential, which can lead to structural damage in buildings and pavements. Soils with FSI above 60% are considered highly expansive and require stabilization before use in construction.

| Sample | Volume in Water (ml) | Volume in Kerosene (ml) | FSI (%) |
|---|---|---|---|
| Black Cotton Soil | 12.5 | 7.5 | 66.7% |

### 3.2 TESTS ON SOIL MIXED WITH QUICK LIME

**A) Atterberg Limits:**

Liquid Limit (LL) decreases with increasing lime content, indicating reduced water-holding capacity.

- Plastic Limit (PL) increases, suggesting improved workability and reduced plasticity.
- Plasticity Index (PI) drops significantly—from 36% (untreated) to 8% at 10% lime—reflecting effective reduction in swelling and shrinkage behaviour.
- This trend confirms that quicklime stabilization improves the soil's engineering properties, making it more stable and suitable for construction applications.

**Table 5** Atterberg Limit test values for soil with quicklime

| S.No | Lime Content (%) | Liquid Limit (LL%) | Plastic Limit (PL%) | Plasticity Index (PI%) |
|---|---|---|---|---|
| 1 | 0 (Untreated) | 68 | 32 | 36 |
| 2 | 2 | 64 | 36 | 28 |
| 3 | 4 | 59 | 38 | 21 |
| 4 | 6 | 55 | 39 | 16 |
| 5 | 8 | 52 | 41 | 11 |
| 6 | 10 | 50 | 42 | 8 |

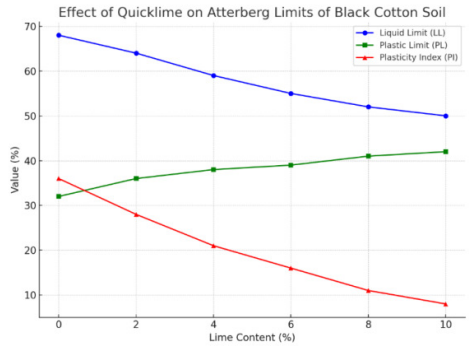


Fig. 7 Graphical representations for LL, PL, and PI

**B) Unconfined Compressive Strength: Unconfined** Compressive Strength (UCS) is a fundamental test used to determine the shear strength of cohesive soils, especially clays, under uniaxial loading without any lateral confinement. It measures the maximum axial stress a soil sample can withstand before failure. The test is simple, quick, and economical, making it widely used in soil stabilization and geotechnical investigations.

Fig. 8 UCS Soil Samples

Fig. 9 UCSEquipment

In the UCS test, a cylindrical soil specimen is placed in a compression testing machine and loaded until it fails. The UCS value is calculated as the peak load divided by the cross-sectional area of the specimen. The result helps in evaluating the stability of soil under foundation loads, the effectiveness of soil improvement techniques, and the bearing capacity of soil.

Higher UCS values indicate stronger soils, which are more suitable for supporting structures. Additives like lime, cement, or fly ash are often used to increase the UCS of weak soils.

**Table 6** UCS Test Data

| S.No | Lime Content (%) | UCS (kN/m²) | Observation |
|---|---|---|---|
| 1 | 0 (Untreated) | 85 | Very low strength, unsuitable for construction |
| 2 | 2 | 145 | Initial increase due to flocculation |
| 3 | 4 | 215 | Moderate strength gain |
| 4 | 6 | 310 | Significant improvement |
| 5 | 8 | 390 | High strength, good bonding |
| 6 | 10 | 425 | Peak strength, optimum lime content |

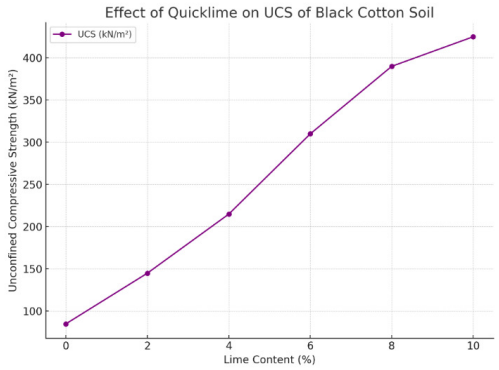


Fig. 10 Graphical Representation of UCS for different Soil Mixes

The Unconfined Compressive Strength (UCS) data reveals a clear and progressive improvement in the strength characteristics of black cotton soil with increasing percentages of quicklime. The untreated soil exhibits a UCS of 85 kN/m², which is considerably low, reflecting the poor load-bearing capacity of expansive clay in its natural state.When 2% lime is added, the UCS increases to 145 kN/m², indicating an initial improvement due to cation exchange and flocculation of clay particles. This early-stage reaction alters the soil structure, reducing plasticity and enhancing particle bonding.

At 4% lime, UCS rises further to 215 kN/m², reflecting continued structural improvement. From 6% to 10% lime, the strength increases significantly—from 310 kN/m² to 425 kN/m². This sharp gain is attributed to pozzolanic reactions, where lime reacts with silica and alumina in the clay to form cementitious compounds like calcium silicate hydrate (CSH) and calcium aluminate hydrate (CAH). These compounds bind soil particles together, greatly improving compressive strength and long-term stability.

The peak strength of 425 kN/m² at 10% lime content suggests that this may be close to the optimum lime percentage for this soil type. Beyond this point, the strength gains typically plateau, and excessive lime may not contribute meaningfully to further improvement.

Quicklime significantly enhances the UCS of black cotton soil, making it more suitable for engineering applications such as road subgrades, embankments, and foundations. This data supports lime stabilization as an effective treatment for expansive soils, with 8–10% lime content being ideal for achieving substantial strength improvement.

**C) California Bearing Ratio (CBR)**

The California Bearing Ratio (CBR) test is a crucial geotechnical method used to evaluate the strength and load-bearing capacity of subgrade soil, sub-base, and base layers for road and pavement design. It measures the resistance of soil to penetration under standardized conditions. Black cotton soil, in its natural state, typically exhibits very low CBR values due to its high plasticity and swell-shrink behavior. Stabilization using materials like quicklime significantly improves CBR, enhancing soil performance for construction purposes.

**Table 7** CBR Test Data for different soil samples

| S.No | Lime Content (%) | CBR (%) – Unsoaked | CBR (%) – Soaked | Observation |
|---|---|---|---|---|
| 1 | 0 (Untreated) | 2.1 | 1.5 | Very poor strength, unsuitable for pavement |
| 2 | 2 | 4.3 | 3.2 | Slight improvement due to flocculation |
| 3 | 4 | 7.8 | 5.9 | Moderate improvement |
| 4 | 6 | 13.2 | 9.8 | Significant gain, suitable for subgrade |
| 5 | 8 | 18.4 | 13.7 | High strength, suitable for pavement layers |
| 6 | 10 | 21.1 | 15.9 | Peak performance, ideal lime content range |

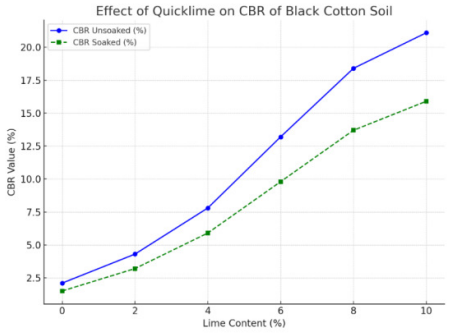


Fig. 11 Graphical Representation of CBR values with different soil mixes

The California Bearing Ratio (CBR) values for black cotton soil demonstrate a marked improvement with increasing quicklime content, highlighting the effectiveness of lime stabilization in enhancing the soil's load-bearing capacity.

Untreated Soil (0% Lime): The unsoaked CBR value is just 2.1%, and the soaked CBR is even lower at 1.5%, which is significantly below the acceptable threshold of 5% for use in subgrade construction. This low value is attributed to the soil's high plasticity, low cohesion in saturated states, and tendency to expand and shrink.

2% to 4% Lime Content: At 2% lime, the CBR begins to improve modestly to 4.3% (unsoaked) and 3.2% (soaked), indicating early-stage reactions like cation exchange and flocculation.
By 4% lime, there is a more noticeable increase (7.8% unsoaked, 5.9% soaked), reaching the minimum standard for subgrade layers. This improvement shows lime's ability to enhance cohesion and reduce water sensitivity.

6% to 10% Lime Content: Significant strength gain occurs in this range:

- At 6%, the unsoaked CBR jumps to 13.2%, and the soaked CBR reaches 9.8%—making the soil suitable for sub-base applications.

- At 10% lime, unsoaked and soaked CBR values reach 21.1% and 15.9%, respectively. This suggests optimum lime content, beyond which the benefits tend to stabilize.

## 4. CONCLUSION

Black cotton soil, in its natural state, possesses poor engineering properties such as high plasticity, low strength, and significant swelling potential, rendering it unsuitable for construction without treatment. This study investigates the effectiveness of quicklime as a stabilizing agent to enhance the geotechnical properties of black cotton soil for civil engineering applications.

Laboratory tests including Atterberg Limits, Unconfined Compressive Strength (UCS), California Bearing Ratio (CBR), and Free Swell Index were conducted to evaluate the impact of varying lime content on soil behaviour. Results indicate that lime stabilization significantly improves the soil's engineering characteristics:

- Atterberg Limits decreased with increasing lime content, demonstrating reduced plasticity and better workability.
- UCS values increased substantially due to pozzolanic reactions forming cementitious compounds, thereby enhancing structural strength.
- Both soaked and unsoaked CBR values exceeded standard requirements at lime contents above 4%, indicating suitability for use in subgrade and pavement layers.
- The Free Swell Index was markedly reduced, confirming a decrease in the soil's expansive nature.

The optimum lime content was determined to be between 8% and 10%, where maximum improvements in strength and stability were observed. Beyond this range, minimal additional benefits were noted, suggesting an economic threshold for effective stabilization.

In conclusion, quicklime stabilization is a practical, cost-effective, and technically viable method for improving the engineering properties of expansive black cotton soils. It enables safe and durable construction in infrastructure projects such as roads, embankments, and foundations, particularly in regions where such problematic soils are prevalent.

## REFERENCES

[1] Saleh, S. A., Hussein, S. K., & Khoshnaw, G. J. (2020). *Effect of Soil Stabilization on Subgrade Soil Using Cement, Lime and Fly Ash*. Eurasian Journal of Science and Engineering, 6(2), 39–52. https://doi.org/10.23918/eajse.v6i2p39

[2] Al-Gharbawi, A. S. A., Najemalden, A. M., & Fattah, M. Y. (2023). *Expansive Soil Stabilization with Lime, Cement, and Silica Fume*. Applied Sciences, 13(1), 436. https://doi.org/10.3390/app13010436

[3] Krishana, P. B., & Pavan, G. S. (2019). *Soil Stabilization by Using Lime & Fly Ash*. International Journal of Trend in Scientific Research and Development, 3(5), 663–667. https://www.ijtsrd.com/papers/ijtsrd26442.pdf

[4] Hatmoko, D. D., Rifa'i, A., &Ismanti, S. (2024). *Effect of Using Lime and Fly Ash as a Cement Substitute for Soil Stability*. KURVATEK, 9(1), 45–54. https://doi.org/10.33579/krvtk.v9i1.4834

[5] Sahu, V., Srivastava, A., Misra, A. K., & Sharma, A. K. (2017). *Stabilization of Fly Ash and Lime Sludge Composites: Assessment of Its Performance as Base Course Material*. Archives of Civil and Mechanical Engineering, 17(3), 475–485. https://doi.org/10.1016/j.acme.2016.12.010

[6] Wong, B. Y. F., Wong, K. S., & Phang, I. R. K. (2019). *A Review on Geopolymerisation in Soil Stabilization*. IOP Conference Series: Materials Science and Engineering, 495(1), 012070. https://doi.org/10.1088/1757-899X/495/1/012070

[7] Muhammad, S. A., &Jethoo, A. S. (2025). *Harnessing Microbial-Induced Calcite Precipitation for Sustainable Seepage Control in Cohesionless Soil Channels*. Geomicrobiology Journal, 42(2), 147–163.

https://doi.org/10.1080/01490451.2024.2439919

[8] Hang, L., Yang, E., Zhou, Y., Song, W., & He, J. (2022). *Microbially Induced Calcite Precipitation (MICP) for Stabilization of Desert Sand Against Wind-Induced Erosion: A Parametric Study*. Sustainability, 14(18), 11409. https://doi.org/10.3390/su141811409

[9] Wang, Y., & Konstantinou, C. (2024). *A Comprehensive Optimization Study of Microbially Induced Carbonate Precipitation (MICP) for Soil Strength Enhancement: Impact of Biochemical and Environmental Factors*. arXiv preprint arXiv:2409.19358. https://arxiv.org/abs/2409.19358

[10] Wu, Q., & Wang, Y. (2024). *Influence of On-Site Low-Ureolysis Bacteria and High-Ureolysis Bacteria on the Effectiveness of MICP Processes*. arXiv preprint arXiv:2409.17071. https://arxiv.org/abs/2409.17071

[11] Wang, Y., Konstantinou, C., Soga, K., DeJong, J. T., Biscontin, G., &Kabla, A. J. (2020). *Enhancing Strength of MICP-Treated Sandy Soils: From Micro to Macro Scale*. arXiv preprint arXiv:2006.15760. https://arxiv.org/abs/2006.15760

[12] Agate, E. E., Nyomboi, T., Nathaniel, A. O., & Ngassam, I. (2024). *Performance of Expansive Soil Stabilized with Bamboo Charcoal, Quarry Dust, and Lime for Use as Road Subgrade Material*. arXiv preprint arXiv:2403.06669. https://arxiv.org/abs/2403.06669

[13] Dash, S. K., & Hussain, M. (2012). *Lime stabilization of soils: Reappraisal*. Journal of Materials in Civil Engineering, 24(6), 707–714. https://doi.org/10.1061/(ASCE)MT.1943-5533.0000431

[14] Khemissa, M., &Mahamedi, A. (2014). *Cement and lime mixture stabilization of an expansive overconsolidated clay*. Applied Clay Science, 95, 104–110. https://doi.org/10.1016/j.clay.2014.03.017

[15] Jauberthie, R., Rendell, F., Rangeard, D., &Molez, L. (2010). *Stabilisation of estuarine silt with lime and/or cement*. Applied Clay Science, 50(1), 1–400. https://doi.org/10.1016/j.clay.2010.07.002

[16] Sharma, N. K., Swain, S. K., & Sahoo, U. C. (2012). *Stabilization of a clayey soil with fly ash and lime: A micro level investigation*. Geotechnical and Geological Engineering, 30(5), 1197–1205. https://doi.org/10.1007/s10706-012-9532-3

[17] Edil, T. B., Acosta, H. A., & Benson, C. H. (2006). *Stabilizing soft fine-grained soils with fly ash*. Journal of Materials in Civil Engineering, 18(2), 283–294. https://doi.org/10.1061/(ASCE)0899-1561(2006)18:2(283)

[18] Tastan, E. O., Edil, T. B., Benson, C. H., &Aydilek, A. H. (2011). *Stabilization of organic soils with fly ash*. Journal of Geotechnical and Geoenvironmental Engineering, 137(9), 819–833. https://doi.org/10.1061/(ASCE)GT.1943-5606.0000502

[19] Li, H., Ma, W., Wang, K., Feng, Y., Zhang, S., Zhou, S., & Zhang, H. (2024). *Preparation of a Low-Cement-Content Silty Soil Stabilizer Using Industrial Solid Wastes*. Applied Sciences, 14(1), 317. https://doi.org/10.3390/app14010317

[20] Zhang, X., Li, W., Tang, Z., Wang, X., & Sheng, D. (2020). *Sustainable regenerated binding materials (RBM) utilizing industrial solid wastes for soil and aggregate stabilization*. Journal of Cleaner Production, 275, 122991. https://doi.org/10.1016/j.jclepro.2020.122991

[21] Sujatha, E. R., & Saisree, S. (2019). *Geotechnical behaviour of guar gum-treated soil*. Soils and Foundations, 59(6), 2155–2166. https://doi.org/10.1016/j.sandf.2019.11.012

[22] Sujatha, E. R., Atchaya, S., Sivasaran, A., &Keerdthe, R. S. (2021). *Enhancing the geotechnical properties of soil using xanthan gum – an eco-friendly alternative to traditional stabilizers*. Bulletin of Engineering Geology and the Environment, 80, 1157–1167. https://doi.org/10.1007/s10064-020-02010-7

[23] Zhang, T., Liu, S., Zhan, H., Ma, C., & Cai, G. (2020). *Durability of silty soil stabilized with recycled lignin for sustainable engineering materials*.

Journal of Cleaner Production, 248, 119293. https://doi.org/10.1016/j.jclepro.2019.119293

[24] Soon, N. W., Lee, L. M., Khun, T. C., & Ling, H. S. (2013). *Improvements in engineering properties of soils through microbial-induced calcite precipitation*. KSCE Journal of Civil Engineering, 17(4), 718–728. https://doi.org/10.1007/s12205-013-0003-9

[25] Wang, Y., Konstantinou, C., Soga, K., DeJong, J. T., Biscontin, G., &Kabla, A. J. (2020). *Enhancing strength of MICP-treated sandy soils: from micro to macro scale*. arXiv preprint arXiv:2006.15760. https://arxiv.org/abs/2006.15760

[26] Soltani, A., Deng, A., Taheri, A., &Mirzababaei, M. (2018). *Rubber powder–polymer combined stabilization of South Australian expansive soils*. Geosynthetics International, 25(3), 304–321. https://doi.org/10.1680/jgein.18.00009

[27] Fatahi, B., & Khabbaz, H. (2013). *Influence of fly ash and quicklime addition on behaviour of municipal solid wastes*. Journal of Soils and Sediments, 13(7), 1201–1212. https://doi.org/10.1007/s11368-013-0720-4

[28] Saldanha, R. B., da Rocha, C. G., Caicedo, A. M. L., & Consoli, N. C. (2021). *Technical and environmental performance of eggshell lime for soil stabilization*. Construction and Building Materials, 298, 123648. https://doi.org/10.1016/j.conbuildmat.2021.123648

[29] Gonzalez, J., Sargent, P., & Ennis, C. (2021). *Sewage treatment sludge biochar activated blast furnace slag as a low carbon binder for soft soil stabilisation*. Journal of Cleaner Production, 311, 127553. https://doi.org/10.1016/j.jclepro.2021.127553

[30] Gajo, A., Cecinato, F., & Hueckel, T. (2019). *Chemo-mechanical modeling of artificially and naturally bonded soils*. arXiv preprint arXiv:1904.06581. https://arxiv.org/abs/1904.06581