Indian journal of
Engineering

Stabilization of black cotton soil in Chittur region in Palakkad using lime, rice husk ash, coir fibre

Jayakrishnan R[1]*, Johnpaul V[2], Balasundaram N[3], Senthilkumar S[4]

To Cite:
Jayakrishnan R, Johnpaul V, Balasundaram N, Senthilkumar S. Stabilization of black cotton soil in Chittur region in Palakkad using lime, rice husk ash, coir fibre. *Indian Journal of Engineering*, 2026, 23, e3ije1709
doi: https://doi.org/10.54905/disssi.v23i59.e3ije1709

Author Affiliation:
[1]Research scholar, Department of Civil Engineering, Karpagam Academy of Higher education, Coimbatore, Tamilnadu-641021, India. Email: jayan1615@gmail.com; Orcid: https://orcid.org/0009-0008-9848-3704
[2]Department of Civil Engineering, Karpagam Academy of Higher education, Coimbatore, Tamilnadu- 641021, India. Email: johnpaulv2490@gmail.com; Orcid: https://orcid.org/0000-0002-2150-0181
[3]Department of Civil Engineering, Karpagam Academy of Higher education, Coimbatore, Tamilnadu- 641021, India. Email: balasundaram49@gmail.com; Orcid: https://orcid.org/0000-0002-4831-1209
[4]Department of Civil Engineering, K,S.R College of Engineering, Trichengode, Tamil Nadu- 637215, India. Email: senthil.env@gmail.com; Orcid: https://orcid.org/0000-0003-1628-6210

***Corresponding author:**
Jayakrishnan R,
Research scholar, Department of Civil Engineering, Karpagam Academy of Higher education, Coimbatore, Tamilnadu-641021, India. Email: jayan1615@gmail.com; Orchid: https://orcid.org/0009-0008-9848-3704

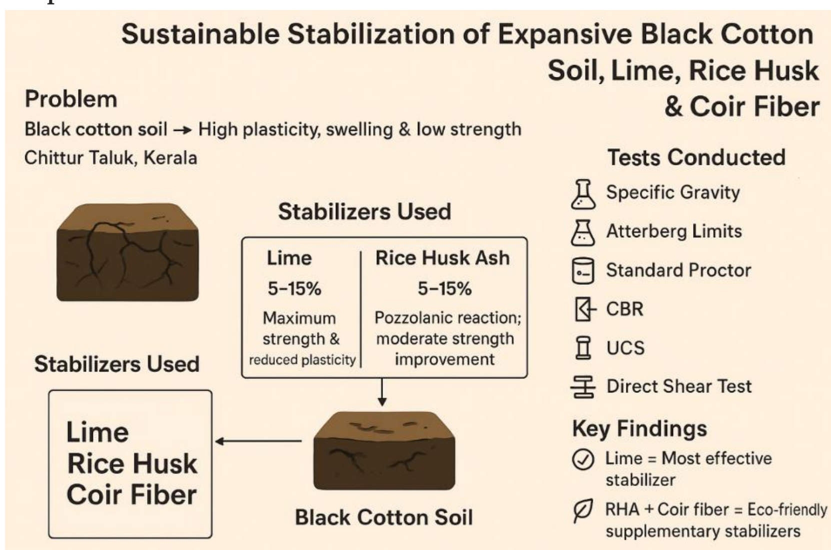
Peer-Review History
Received: 29 July 2025
Reviewed & Revised: 12/August/2025 to 16/February/2026
Accepted: 27 February 2026
Published: 07 March 2026

Peer-Review Model
External peer-review was done through double-blind method.

Indian Journal of Engineering
pISSN 2319–7757; eISSN 2319–7765

DISCOVERY SCIENTIFIC SOCIETY

Graphical Abstract



ABSTRACT

The effectiveness of lime, rice husk ash, and coir fibre as environmentally friendly soil stabilizers in enhancing the engineering qualities of black cotton soil is one of the most extensive and troublesome soils found in Chittur Taluk, Kerala is examined in this study. The experimental program involved determining physical, index, compaction, and strength characteristics of soil treated with various proportions of lime (5-15%), RHA (5-15%), and coir fibre (0.25-1%). Relative density, Fineness Modulus, Atterberg Limits, Standard Proctor Test, CBR, UCS, and Direct Shear Test are some of the tests conducted. Results showed that lime was highly effective in reducing plasticity and improving compaction and strength characteristics, although the maximum improvement, with the highest MDD, CBR, UCS, and shear strength, was obtained for 15% lime. Because of the pozzolanic reactions, RHA showed a moderate improvement in soil properties, including increased workability and stability. The best results were seen at a 15% replacement level. By decreasing the brittleness of the stabilized soil matrix, coir fibre greatly improved ductility while only slightly increasing strength. Finally, lime is found to be the most effective stabilizer, and RHA and coir fibre provided some supplementary eco-friendly benefits. The combined findings show the potential of these locally available stabilizers in providing cost-effective, durable, and sustainable solutions for expansive soil improvement.

Keywords: Black cotton soil; Soil stabilization; Lime; Rice husk ash (RHA); Coir fibre.

1. INTRODUCTION

Black cotton soil is mainly composed of montmorillonite clay minerals, and its volumetric instability with fluctuations in moisture content is relatively high. During wet seasons, black cotton soil swells significantly; during dry seasons, it shrinks significantly and cracks. These volumetric changes causes the low bearing capacity, differential settlements, and frequent structural distress or failure (Jayakrishnan et al., 2025). Due to its expansive nature, the untreated black cotton soil is not appropriate for engineering properties in its natural state, particularly for foundations in the lightweight structures and road pavements (Ramesh and Manjunatha, 2023). Because of this only, the soil stabilization have emerged a crucial technique in recent decades for altering the physio-mechanical properties of expansive soils and their enhancing suitability of construction (Goutham and Krishnaiah, 2025).

Because lime stabilization can cause cation exchange, pozzolanic reactions, and flocculation–agglomeration of clay particles, it is a tried-and-true technique for treating expansive soils. By adding lime, soil plasticity is decreased, strength is increased, workability is improved, and swelling potential is greatly decreased (Mai-Bade et al., 2021). Numerous studies conducted in the region of Chittur has reported significant improvements in California Bearing Ratio (CBR) and Unconfined Compressive Strength (UCS), as well as reduced shrinking behavior at optimal lime contents (Ramesh and Manjunatha, 2023; Sajeev et al., 2025). However, the stabilized soils often exhibit enriched brittleness and limited resistance to tensile stresses under cyclic loading and volumetric changes (Domphoeun et al., 2023). New cementitious compounds are produced when it combines with lime and rice husk ash (RHA), an agricultural by-product rich in amorphous silica (Pande et al., 2023). The addition of RHA enrich the strength, lowers the plasticity index, and reduces differential free swell by promoting a denser and more stable soil structure (Annamalai et al., 2025a). By adding 10–20% RHA and roughly 5% lime stabilizes expansive soils under favorable outcomes (Konai et al., 2024). By utilizing agricultural waste that would otherwise contribute to waste accumulation and pollution, RHA not only improves the geotechnical properties of the treated soil but also benefits the environment (Annamalai et al., 2025b).

A natural, biodegradable reinforcing material made from coconut husk is called coir fibre. Coir considerably improves the ductility, toughness, crack resistance, and post-peak behavior of stabilized soil while providing only a modest increase in compressive strength when used alone (Jayakrishnan et al., 2022). Coir fibre improves tensile and flexural performance by mitigating the brittleness of lime-stabilized soils when combined with lime or lime-RHA blends (Singh and Kalita, 2021). According to earlier studies, the best results are obtained with 1% coir fiber (by weight) and an aspect ratio of roughly 20 (Arathi et al., 2022). Coir fibers increase the flexibility and durability of the soil composite while lime and rice husk ash (RHA) participate in pozzolanic reactions to create a strong cementitious matrix. California Bearing Ratio (CBR), Unconfined Compressive Strength (UCS), optimal moisture content, and overall soil stability all significantly improve as a result of this tri-component stabilization (Khalak and Juremalani, 2022). There is a clear synergistic effect when coir fibre, lime, and RHA are used together. Because of the mix's increased strength and ductility, it is especially well-suited for low-cost sustainable construction and subgrade upgrades in road pavements (Arya et al., 2023). In places like Chittur, where coconut and rice husk are more, this approach is in line with green building techniques and effective for the use of local resources (Anbarasu et al., 2024).

The literature review states that a hybrid stabilization strategy that combines coir fiber, lime, and RHA greatly enhances the geotechnical behavior of black cotton soil through increased ductility, decreased swelling potential, improved durability, and synergistic strength enhancement. This makes the strategy more economically and environmentally suitable than traditional soil stabilizers (Bhowmik et al., 2023). The ideal ratios of 1% coir fiber, 10–20% RHA, and 5% lime have shown improved properties (Konai et al., 2024; Behera, 2022). This study examines stabilization methods for black cotton soil, focusing on the effects of lime, rice husk ash (RHA), and coir fiber, separately as well as with a combination, on the geotechnical characteristics of expansive soils (Chethan and Ravi Shankar, 2022). Applicability and sustainability of these materials in the regions like Chittur, Palakkad, where they are locally available. Laboratory test are conducted and found that the Atterberg limits, compaction, CBR, and UCS tested and evaluated for the relevance of its practical field application.

Gaps in the previous research are the non-availability of any standardized mix proportions for lime-RHA-coir combinations, because the optimum dosage in different studies varies widely, and region-specific guidelines based on actual soil conditions need to be implemented. Most of the literature refers to laboratory investigations. Long-term durability assessments under realistic field conditions are scarce, taking into account the processes of weathering, wet-dry cycles, fluctuations in groundwater, and sustained loads of traffic or other structural loads.

2. LITERATURE REVIEW

Chittur Taluk, in the southeastern part of the Palakkad district in the state of Kerala, faces soil related issues that creates severe engineering difficulties in both construction and agricultural purposes. Black cotton soil is major in different areas like alluvial plains, terrains, and undulating areas (Bharti et al., 2025). Elevation in Chittur Taluk varies from 100 to 300 m above mean sea level (MSL), and it has sloping landforms that are moderately gentle. This largely affects drainage and retains soil moisture (Manaviparast et al., 2025). It is clay loam to heavy clay soil that contains a large amount of fine material, which makes it less permeable and less draining. It drains very slowly (Tamassoki et al., 2022; Abhishek et al., 2025). Thus, it experiences extreme shrinkage and swelling naturally throughout seasons. However, in the case of Chittur Taluk, one can notice that black cotton soil experiences extreme shrinkage and swelling cycles, which are largely contributed by montmorillonite clay (Syed et al., 2022). These water-sensitive clay minerals cause the soil to swell upon wetting and shrink intensely upon drying, often resulting in deep surface cracks several centimeters wide (Nair, 2020).

Chittur Taluk, within the south-eastern region of Palakkad district, Kerala, is confronted with troublesome soils that pose grave challenges to construction and agricultural activities. Black cotton soil is mainly affected by its extensive occurrence in alluvial plains, terraces, and undulating areas. These soils have mixed properties and are thus difficult to handle in terms of their expansive nature (Bharti et al., 2025). The height of Chittur Taluk ranges from 100 to 300 meters above Mean Sea Level and has some gently to moderately sloping areas, which affect water drainage, pattern of drainage, and maintenance of soilheld moisture in the soil (Manaviparast et al., 2025). Black cotton soil in this region tends to vary in texture from clay loam to clay and is dominated by fine soil components, making it less permeable and drained slowly into the subsoil, specifically in Tamassoki (Tamassoki et al., 2022; Abhishek et al., 2025). Hence, it experiences huge expansion and contraction seasonally, making it very dangerous from an engineering perspective. One prominent feature of the black cotton soil in Chittur Taluk is the enormous shrink–swell potential owing predominantly to montmorillonite clay minerals (Syed et al., 2022). Water-loving clay minerals make the soil swell upon moisture and shrink violently upon drying. When dried, deep cracks may develop, often several centimeters in width (Nair, 2020). These cracks bring foundations, roads, and other civil structures into instability, leading to structural distress, differential settlement, and collapse.

On the other hand, water seeping deeply into the ground during the monsoon causes swelling, which transfers lateral pressure on building foundations, resulting in building heaving or rising. This cycle of swelling and shrinking poses a risk to nearby construction projects and calls for appropriate soil stabilization techniques. In addition to these characteristics, black cotton soil from Chittur Taluk has poor load-bearing capacity and cannot support heavy structures in view of the apparently large settlement. Due to the low shear strength and pronounced compressibility of the soil, direct construction cannot be implemented without pre-treatment. Due to some additional limitations associated with drainage properties, this type of soil shows waterlogging and contributes to the subsequent weakening of the soil structure, thus enhancing susceptibility to erosion and instability. Because of these challenges, there is an increasing need for soil stabilization techniques that can improve the strength, durability, and usability appreciably in this area. As a result of these challenges, this study attempts to investigate the effectiveness of the stabilization methods, i.e., with lime, coir fibre, and rice husk ash. Lime stabilizes the soil and, at the same time, shows improvements in both soil strength and plasticity, thus the capacity for load bearing increases.

Coir fibre is also a type of natural fibre. This not only reinforces the soil but also helps in curtailing shrinkage cracks. Rice husk ash, on the other hand, is a pozzolanic material and plays a role in the stabilizing mechanism through a reaction with lime to create additional binding compounds. Overall utilization of these stabilization techniques would improve the overall performance of black cotton soil for making it a good and reliable sub-structure configuration, thus providing a higher level of safety and durability to infrastructural development in Chittur Taluk. Figure 1 and 2 shows the soil maps of Kerala and topography maps of the study area – Eruthempathy.

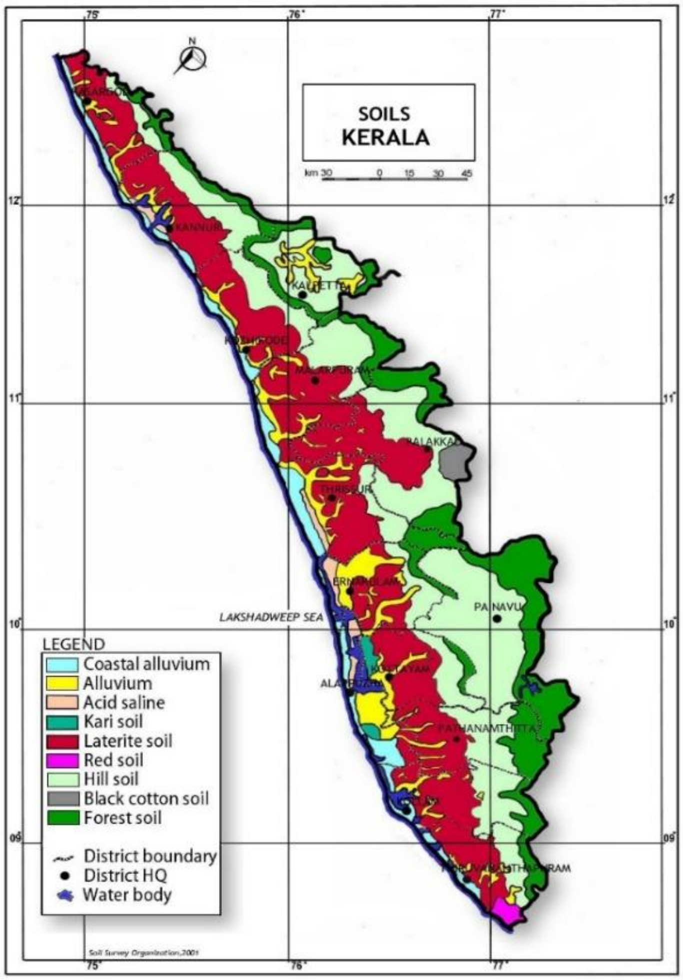


Figure 1. Soil map of Kerala

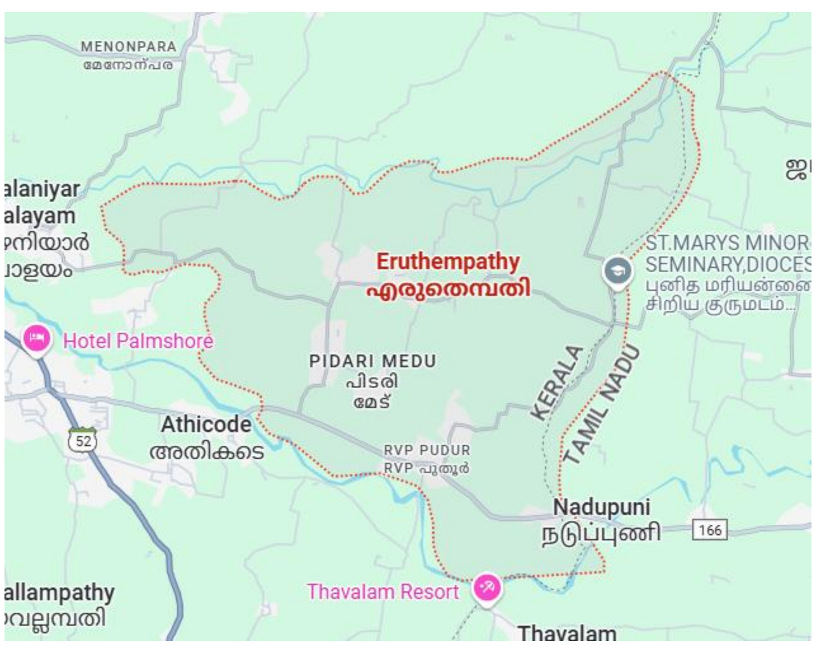


Figure 2. Topography map of study area – Eruthempathy.

3. METHODOLOGY

3.1. Materials

The appropriate selection of stabilizing materials that could improve the engineering behavior of expansive soils significantly depends upon their physical and chemical characteristics. By virtue of their unique composition and mechanical behavior, lime, RHA, and coir fibre have been recognized as the most effective soil stabilizers. A close review of the physical and chemical properties of lime, rice husk ash, and coir fibre will provide an in-depth understanding of their performances in soil as stabilizing additives individually and in combination, relating to strength gain, durability, and volumetric stability control.

As per its physical properties, lime can be described as a white, fine, powdery substance with bulk density and specific gravity values of around 450 kg/m³ and 2.63, respectively. The primary reasons for the intimate mixture of lime with the clay minerals are its finely divided form, high cementation property, and other related attributes that help in building a stable structure and an optimum cation exchange. Lime is characterized by an absorption of only about 5% water, and it exhibits high durability; therefore, it is a reliable additive for long-term stabilization of expansive soils. RHA is a grey to black finely divided ash with a lower specific gravity, about 2.05, and a bulk density of close to 650 kg/m³. Due to its very porous texture, it has a moderate water absorption capacity of nearly 10%. While it does not have any natural binding properties, it is a highly reactive pozzolanic material and forms substantial cementitious compounds in the presence of lime.

Coir fibre is a natural, lignocellulosic reinforcement material that usually has a brown to golden yellow colour. It has a very low specific gravity, about 1.25, and a low value for density at about 1.15 g/cm³, which expresses its lightweight and organic composition. Coir has a high-water absorption capacity of about 30%, due to its fibrous cellular structure with a high content of lignin and cellulose. The increased flexibility and toughness when mixed with soil, hence leading to an increased resistance against cracking and deformation. While it does not form direct chemical bonds with soil, it enhances soil tensile strength and reduces cracking through mechanical reinforcement. Due to its high lignin content, coir fibre also displays good durability and decay resistance compared to other natural fibres.

Table 1. Physical properties of materials

Physical Properties	Lime	Rice Husk Ash (RHA)	Coir Fibre
Physical Form	Fine powder	Fine ash	Fibrous strands
Colour	White	Grey to black	Brown to golden yellow
Relative density	2.63	2.05	1.25
Density	450 kg/m³	650 kg/m³	1.15 g/cm³
Water Absorption	5%	10%	30%
Binding Property	Strong cementation	Pozzolanic (reacts with lime)	No direct binding, but adds reinforcement
Durability	High	Moderate	High (resistant to decay)

The chemical composition of lime is dominated by calcium oxide (90%), which has minor proportions of magnesium oxide (2%), calcium hydroxide (2%), silica (1%), and alumina (1%). Its high calcium content is the primary source of its reactivity with soil, contributing to flocculation, decreased plasticity, and formation of cementitious gels such as C-S-H and C-A-H. RHA is, in turn, dominated by silica, in a proportion of about 87%, accompanied by smaller proportions of the order of about 2% each, in alumina, iron oxide, and magnesium oxide, and a loss on ignition of 7% to account for residual unburnt carbon. This high amorphous silica composition is indeed responsible for the pozzolanic reaction with lime that improves the strength and reduces the shrink–swell behaviour of the respective soil. By contrast, the chemical composition of coir fibre is somewhat different since this is an organic, lignocellulosic material. It is made up approximately of 43% cellulose, 45% lignin, 4% pectin, and a small ash content of 0.25%, with a loss on ignition of 7.75%. Based on the higher percentage of lignin, there will be greater resistance to microbial attack and a slower degradation in soil, and the cellulose provides strength and flexibility to the fibres.

Various physical and chemical characteristics of lime, RHA, and coir fibre collectively justify their use in soil stabilization. The addition of lime forms the chemical basis for modification in the soil. RHA enhances pozzolanic activity and strength gain, while coir fibre improves ductility and reduces cracking, hence making the combination efficient and sustainable in the stabilization of expansive soils. Tables 1 and 2 show the various physical and chemical properties of materials.

Table 2. Chemical properties of materials

Chemical Properties	Lime	Rice Husk Ash	Coir Fibre
Calcium Oxide	90%	-	-
Magnesium Oxide	2%	-	-
Calcium Hydroxide	2%	-	-
Silica	1%	87%	-
Alumina	1%	2%	-
Iron Oxide	-	2%	-
Magnesium Oxide	-	2%	-
Cellulose	-	-	43%
Lignin	-	-	45%
Pectin	-	-	4%
Ash	-	-	0.25%
Loss on Ignition	4%	7%	7.75%

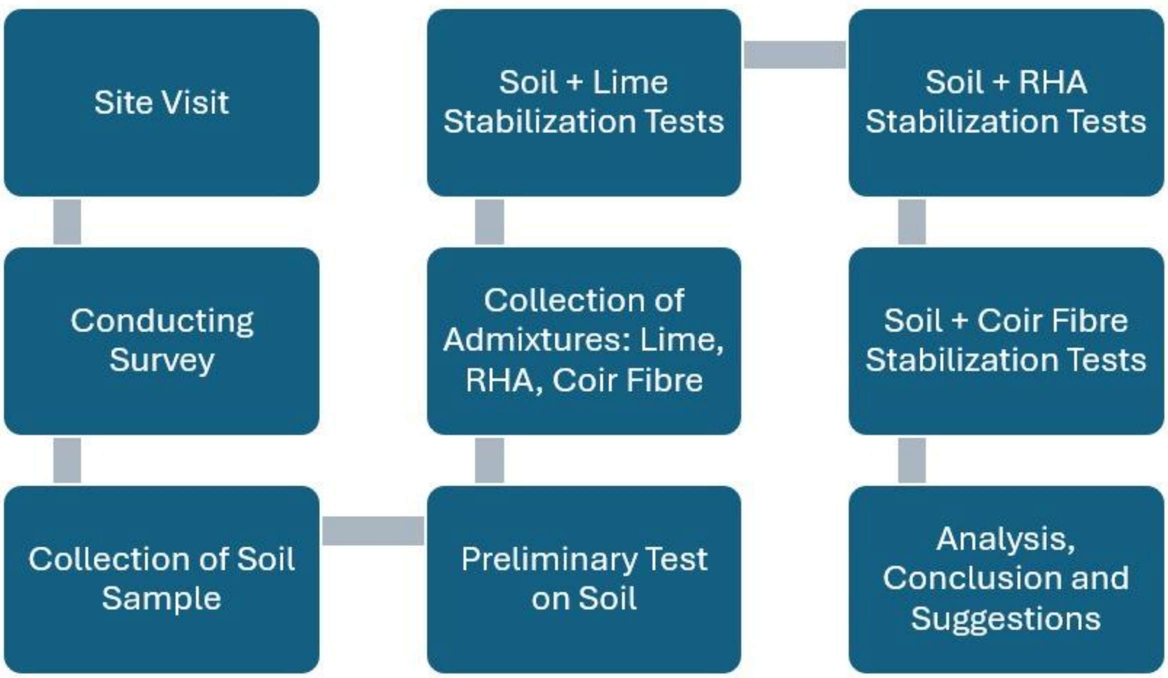


Figure 3. Graphical representation of methodology

3.2. Methods

The methodological framework of the study is developed in a way that the efficiency of coir fibre, lime, and rice husk ash (RHA) in stabilizing black cotton soil is systematically studied. The process began with a preliminary site visit aimed at determining the location of the study, understanding the type of soil, and collecting relevant field data. To assess the problems caused by expansive soils and gather information on existing methods of treatments used in the area, a survey of local engineers, contractors, and residents was conducted.

After that, the selected location is excavated for soil samples to have taken to a lab for analysis. To determine the untreated black cotton soil characteristics, several preliminary index and engineering property tests, such as the Atterberg limits, grain size distribution, compaction, and strength tests, were conducted on the collected soil. Following that, appropriate amounts of stabilizing admixtures containing coir fibre, lime, and RHA were purchased.

The laboratory experimental phase consisted of three stages. In the first stage, black cotton soil is treated with various percentages of lime to establish its influence on soil properties. In the second step, RHA was incorporated into black cotton soil in carefully measured amounts to study its pozzolanic effect. In the third stage, coir fibre was incorporated into the soil to investigate its impact on the reduction in cracks and enhancement in tensile resistance. The CBR, UCS, compaction, and plasticity properties were studied for each of the stabilized mixes. Finally, the results were analysed, and based on the relative performance of different mix combinations, conclusions and recommendations were drawn. Figure 3 shows the methodology pictorially.

3.3. Experimental Investigation

The experimental programme has been carried out to study the geotechnical, compaction, and strength behaviour of black cotton soil amended with lime, RHA and coir fibre. The entire investigation was carried out in three stages, namely material characterization, index and compaction studies and mechanical strength studies to establish whether the stabilizers chosen were suitable to improve the performance of expansive soils.

The collected black cotton soil sample, after air-drying, was pulverised and passed through a 4.75 mm IS sieve to obtain a uniform soil matrix for testing. Various treatments, including hydrated lime (5%, 10%, and 15%), rice husk ash (RHA) (5%, 10%, and 15%), and coir fibre (0.25%, 0.5%, and 1%), were added based on the dry weight of the soil. Water was added in steps to each mix, prepared in accordance with a controlled dry-mixing plan, to ensure uniform mixing. The prepared specimens were sealed and cured in accordance with accepted laboratory procedures before the strength tests were performed.

Specific Gravity tests by pycnometer were conducted to investigate changes in relative density caused by the stabilizers. The Fineness Modulus, or FM, representing variations in the particle size distribution, was determined through sieve analysis. Similarly, determination of Atterberg Limits, Liquid Limit, Plastic Limit, and Plasticity Index was used to investigate changes in soil plasticity and, hence, workability. OMC and MDD were derived from the Standard Proctor Test, which was used to investigate the compaction behaviour.

The CBR tests were conducted on soaked and unsoaked specimens in order to quantify the increase in load-bearing capacity of subgrade. Tests for UCS on 38 mm × 76 mm cylindrical specimens were carried out to determine the short-term gains in compressive strength. In addition, direct shear tests were conducted to study the shear strength parameters, such as cohesion and angle of internal friction, reflecting the resistance to shear failure. A schematic diagram showing the experimental methodology followed in the investigation is given in Figure 4.

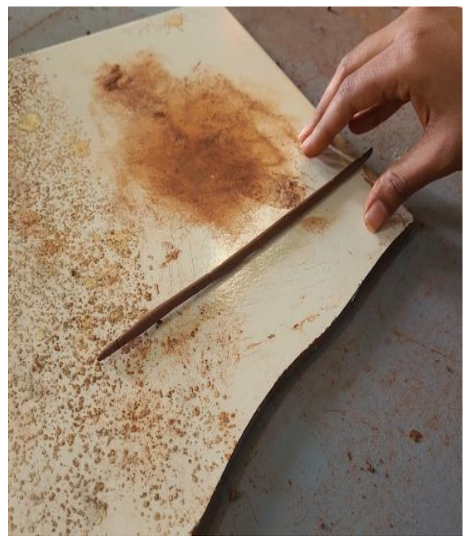
Moisture Content

California Bearing Ratio

Unconfined Compressive Strength

Sieve analysis

Standard Proctor test



Plastic limit test

Liquid limit test

Specific gravity test

Figure 4. Experimental works

4. RESULTS AND DISCUSSION

4.1. Test for Relative Density

The variation in relative density for different stabilizers provides valuable information regarding the possible influence of lime, RHA, and coir fibre on the physical characteristics of the black cotton soil. The specific gravity values for the untreated soil are generally in the range of expansive clayey soil, which is about 2.63. The addition of lime resulted in an increase in relative density values from 2.65 for 5% lime to 2.70 for 15% lime. This is because lime has high specific gravity values relative to soil and also induces pozzolanic reactions. These pozzolanic reactions tend to promote flocculation and aggregation of soil particles. The increased packing of the particles due to flocculation and aggregation enhances the interlocking between particles and ultimately leads to an overall mass densification of the particulate system. Greater density means increased development of a better fabric, leading to an improvement in load-carrying capacity.

While RHA addition led to a gradual reduction in relative density, from 2.62 at 5% to 2.58 at 15%, this can be explained by the specific gravity of RHA being lower than that of the natural soil minerals and its microstructure being more porous. Although RHA contributes to the improvement in strength upon reaction with lime, its independent addition caused a marginal reduction in density. It might therefore be said that RHA is more effective as an additive supplementary to lime, where its pozzolanic contribution may be sought without any compromise to density.

Coir fibre caused a slight decrease in the relative density, which decreased from 2.63 at 0.25% to 2.60 at 1%. This results from the fact that coir fibres are of low density and organic in nature. Although coir does not participate in providing densification, its primary role is in soil matrix reinforcement through enhancement of tensile resistance, crack control, and ductility (Abhishek et al., 2025). Overall, lime improves densification and bonding; RHA slightly reduces density but increases pozzolanic reactivity, while coir fibre adds ductility and resilience. Therefore, an optimum mix is necessary for a proper balance of improvement in density and stability along with mechanical performance. Figure 5 shows developing of relative density for each of the mix compositions.

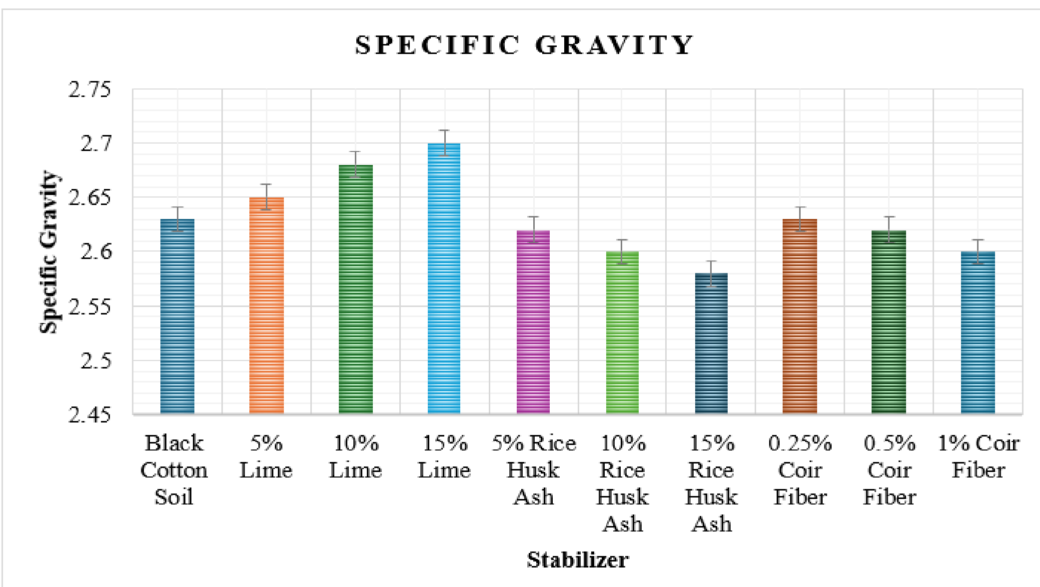


Figure 5. Relative density of soil under various mixes

4.2. Test for Fineness Modulus (FM)

FM test results reflect the impact of lime, RHA, and coir fibre on the particle size distribution of black cotton soil. The untreated soil had an FM of 2.05, which further confirms the predominance of fine clay particles with high plasticity and swelling characteristics. In the case of lime treatment, FM increased gradually from 2.10 at 5% to 2.20 at 15%, which indicates a coarsening effect due to the flocculation and agglomeration caused by the lime–clay reactions that diminish the diffuse double layer, thereby promoting larger-sized granular aggregates. Such a texture enhances workability, reduces plasticity, and makes the soil more suitable for engineering applications such as subgrade and foundation layers.

Conversely, with the gradual addition of RHA, the values of the fineness modulus (FM) decreased progressively from 2.03 at 5% addition of RHA to 2.00 at 10%, then 1.98 at 15%. This can be attributed to the fine or ash-like properties of RHA. Although the addition of fine matrix material results in the efficient packing of particles, the optimal performance can only be achieved through the composite addition of RHA and lime. This reduction in the values of FM shows that there is an increase in the fine fraction due to the ultrafine size of the RHA particles. Additionally, the addition of RHA alone mainly accounts for the increase in the fine matrix of soil due to the high pozzolanic action of RHA with lime. As a result, it may increase water demand and surface area, and thus excessive RHA may be detrimental to compaction behavior unless balanced by lime.

Coir fibre addition caused a marginal reduction in FM, from 2.04 at 0.25% to 2.01 at 1%. Since coir fibres act like reinforcing filaments on the soil particles without affecting the gradation of particles, the marginal reduction could be due to the dispersion of the fibres among the soil particles. Overall, lime causes an improvement in texture by making the soil coarser, RHA does so by making the soil finer, and coir fibre imparts reinforcement without much alteration in gradation (Tamassoki et al., 2022). The optimum combination of these can result in a mix for achieving the desired modification in texture for better geotechnical performance. Figure 6 shows the fineness modulus of soil with different mixes.

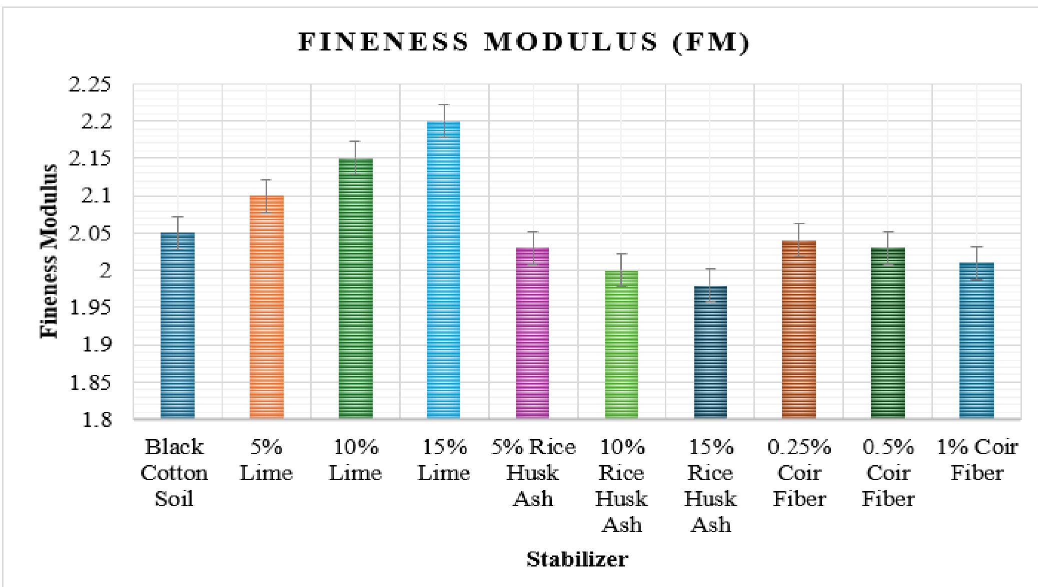


Figure 6. Fineness modulus of soil under various mixes

4.3. Atterberg's limit test

The impact of lime, RHA, and coir fibre on the consistency characteristics and moisture–compaction behaviour of black cotton soil is studied in terms of the Atterberg limits and optimum moisture content. The liquid limit, plastic limit, and plasticity index were found to be 27.5%, 20.54%, and 7%, respectively, for the untreated soil, indicating that the soil has a moderate degree of plasticity and is prone to volume instability.

The LL progressively decreased from 26.2% at 5% lime to 23.5% at 15%, while the PL increased from 21.5% to 23%. Thus, the PI showed a significant reduction from 4.7% to 0.5%. This may be attributed to the cation exchange and flocculation processes initiated by lime, which decrease the affinity of the clay for water, besides transforming the soil into a more granular and less plastic structure. The OMC was marginally increased with lime addition from 16.2% at 5% to 17.8% at 15%, due to increased water demand for the pozzolanic reaction and hydration impact. Therefore, this is regarded as a marked reduction in PI and indicative of improved dimensional stability and decreased swelling-shrinkage potential.

RHA addition had moderate decreases in LL and PI. The LL decreased to 26%, while PI decreased to 4.4% at 15% RHA. The reduction can be attributed to the pozzolanic action of silica-rich RHA, which bonds partially with clay minerals, hence improving the consistency. The optimum moisture content (OMC) showed a slight increase with the increase in the amount of RHA due to the increase in the surface area of the ash particles. The effect of coir fiber addition caused a slight change in the Atterberg limits, which showed that it is a non-reactive and fibrous substance. A slight decrease in plasticity index value, from 6.8% at 0.25% to 6.2% at 1% coir fiber, was noted, which showed a slight improvement in soil consistency (Gokul et al., 2024). The fibre inclusion marginally raises OMC, indicating that more water is required to coat and disperse fibres uniformly. Overall, among the three types of additives, lime was found to most effectively reduce plasticity and enhance the stability of the soil, followed by RHA, whereas coir fibre reinforced with a marginal impact on the consistency characteristics. Figure 7 shows the Atterberg's limit test on soil.

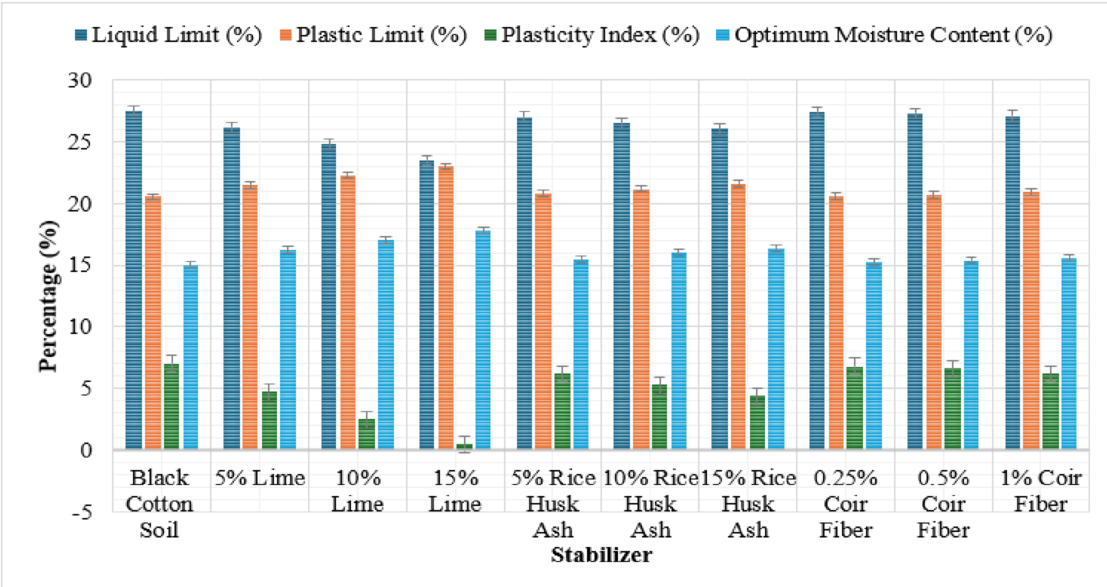


Figure 7. Atterberg's limit test on soil under various mixes

4.4. Standard proctor test

The effect of lime, RHA, and coir fibre on the compaction characteristics of black cotton soil was evaluated by determining MDD and OMC. The natural soil had an MDD of 1.92 g/cc and OMC of 15%, which agrees with the behavior of fine-grained expansive soils that require an optimum moisture content in the medium range for compaction.

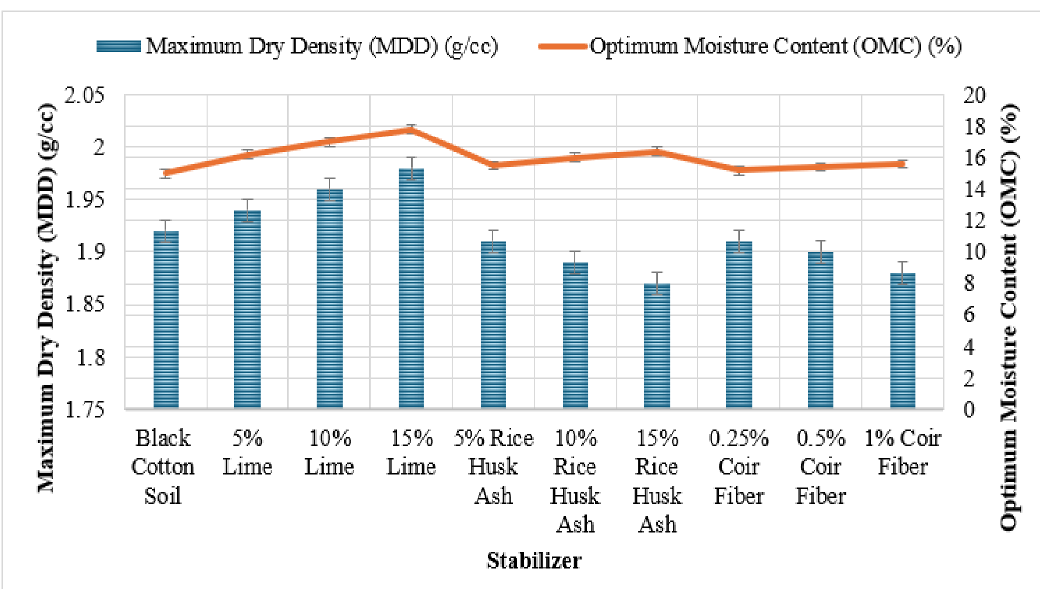


Figure 8. Standard proctor test results on soil

With lime stabilization, the MDD has gradually increased from 1.94 g/cc at 5% lime to 1.98 g/cc at 15%. Similarly, the OMC has shown an increasing trend with an increase from 16.2% to 17.8%. Improvement in MDD is explained through flocculation-agglomeration, and subsequent pozzolanic reaction between lime and clay particles would lead to the formation of denser and compact soil aggregates. Also, a higher OMC suggests that more water is required to lubricate and assist the occurrence of chemical reactions to achieve an adequate degree of compaction. Two distinct advantages of increased density and moisture requirement include structural stability and suitability for subgrade and foundation applications. On the other hand, when RHA was added, the MDD decreased from 1.91 g/cc at 5% to 1.87 g/cc at 15%. The major reason for this reduction is lightweight and porous nature of RHA, reducing the overall density of the mix. OMC slightly increased with RHA content and reached up to 16.4% at 15% ash, as imcreased in the ash particles, having a larger surface area, requires more water content for lubrication and compaction. Even though RHA exhibited decreased density, it provides strength benefits due to pozzolanic reactions upon mixing with lime.

The addition of coir fibre resulted in a slight decline in MDD values from 1.91 g/cc at 0.25% to 1.88 g/cc at 1%. This is due to the coir fibres being fibrous and of low density. OMC marginally increased owing to additional water required for mixing the fibres. Coir does not improve density but has the beneficial effect of providing an increase in tensile resistance and a reduction in cracking behaviour (Thangavel et al., 2024). In conclusion, lime significantly improves compaction efficiency, RHA reduces the density while improving performance with lime, and coir fibre acts to reinforce the structure while having minimal influence on the compaction characteristics. Standard proctor test results on soil are presented in Figure 8.

4.5. California Bearing Ratio Test

The CBR values recorded for lime-treated black cotton soil, RHA, and coir fibre provide ample evidence of the achieved improvement in load-carrying capacity through stabilization. Indeed, the CBR value of untreated black cotton soil stood at about 5.12%, much less than required for subgrade and pavement purposes. This again approves the necessity of stabilization interventions.

CBR values were remarkably improved due to lime additions, which ranged from 6.8% at 5% lime addition to 10.2% at 15% lime addition. This increase in CBR values occurred due to the pozzolanic reaction between lime and clay minerals, which improved strength by forming cementing materials. The lime-treated soils are more appropriate for flexible pavement subgrades and foundation works owing to the significant improvement in California Bearing Ratio (CBR), indicating higher load-carrying capacity. The optimal lime content of 15%, at which the maximum improvement was attained, indicates effective stabilization; however, an intermediate content may be more appropriate for optimal performance and economic viability. In respect to RHA, the CBR value moderately increased from 5.6% at a concentration of 5% RHA to 6.7% at a concentration of 15% RHA. This is because the amorphous silica present in RHA promotes secondary pozzolanic reactions. Although there was a marked improvement, it was not as significant as in lime since RHA on its own does not have adequate binding properties. RHA is more effective when mixed with lime since it has the ability to strengthen and modify the soil structure.

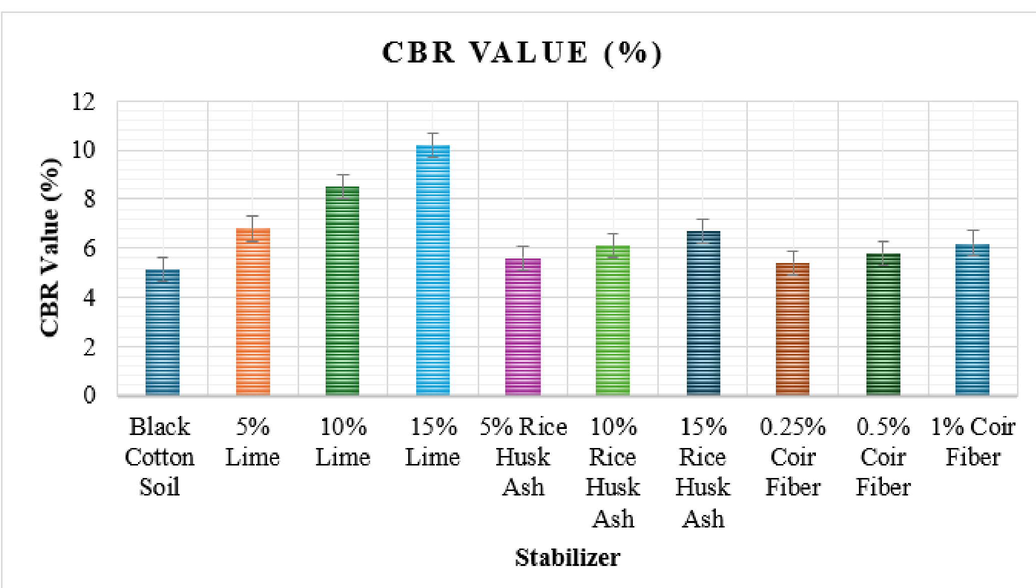


Figure 9. California bearing ratio test results on soil

The addition of coir fibre also resulted in a gradual improvement; CBR values increased from 5.4% at 0.25% fibre to 6.2% at 1% fibre. The reasons for this improvement are the bridging and reinforcing effects of fibres, which resist the effects of applied load and hence resist deformation. Though marginal, the use of coir fibre is significant in improving toughening and fatigue resistance properties; hence, the effects of surface cracking are minimal. Among the stabilizers used in this test, lime has shown the most significant improvement in CBR results, followed by RHA and coir fibre. The combination of these stabilizers may offer improved properties in terms of strength, ductility, and longer durability. Figure 9 shows the California bearing ratio test results on soil (Arya et al., 2023).

4.6. Unconfined Compressive Strength (UCC)

Results of the UCS and Shear Strength: These are among the most critical parameters describing the improvement in the mechanical performance characteristics of the black cotton soil stabilized with the use of lime, RHA, and coir fiber. Unconfined compressive strength and shear strength values of the original soil sample were 1.8 g/cm² and 0.91 g/cm², respectively. This is indicative of the poor strength or resistance to shearing of the soil sample since the black cotton soil is an expansive clay.

The lime stabilization treatment showed a significant increase in both UCS and shear strength. The UCS was improved from 2.4 g/cm² at 5% lime concentration to 3.9 g/cm² at a 15% lime concentration. The shear strength was also improved from 1.2 to 2 g/cm². The formation of pozzolanic materials CSH and CAH due to the reaction of lime with clay materials is the reason behind the significant improvement. These do, in fact, improve particle bonding and decrease plasticity, creating a stable and stiff soil matrix that can withstand greater shear and compressive stresses. Lime improves the mechanics and stability of expansive soil significantly, as shown by the data. The moderate increase in strength values was aided by RHA as well, as indicated by the increase in shear and UCS values to 1.4 g/cm² and 2.6 g/cm², respectively, for 15% RHA. The increase in strength was attributed to the high silica content in RHA, which contributed to the secondary pozzolanic reaction, thereby partially improving bonding and density. However, compared with lime, the improvement is lower, indicating that RHA alone is less effective but beneficial when used synergistically with lime.

Incremental enhancement of strengths occurred because of the addition of coir fibres, where an increase of UCS from 1.9g/cm² at 0.25% to 2.3g/cm² at 1% of fibres enhanced the value of shear strengths from 0.95g/cm² to 1.15g/cm². The main function of the presence of coir fibres in soils is reinforcement, improving ductility, cracking resistance, and tensile strengths. Overall, the highest strength improvement was achieved by lime, followed by RHA and coir fibre. The performance of black cotton soil would be better if a combination of these stabilizers were added to the soil in order to improve its compressive strength, shear resistance, and long-term performance (Anbarasu et al., 2024). Figure 10 shows the unconfined compressive strength test results on soil.

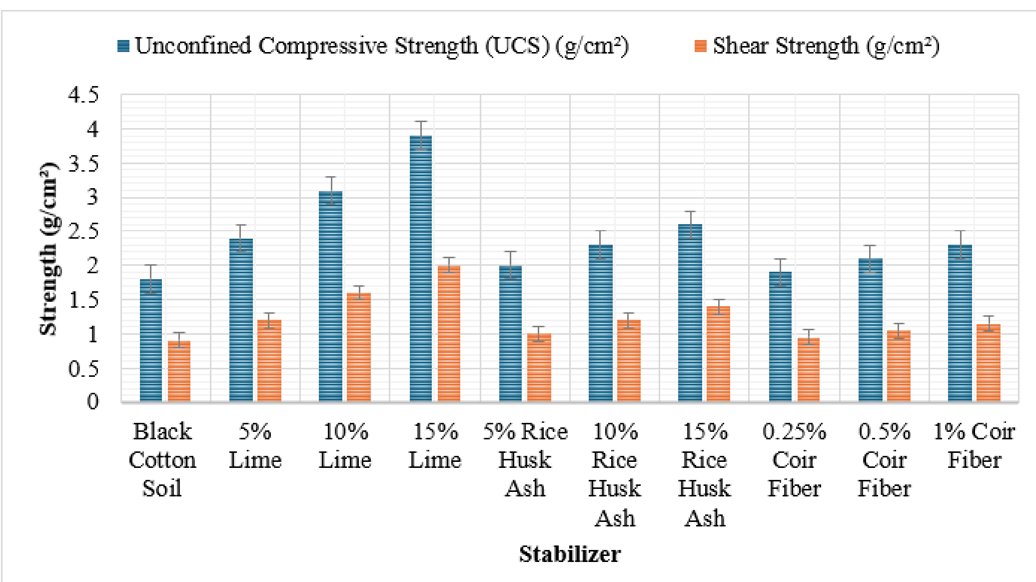


Figure 10. Unconfined compressive strength test results on soil

5. CONCLUSION

This comprehensive study has adopted an integrated approach in the investigation of the effect of lime, rice husk ash, and coir fibre on the geotechnical, compaction, and strength behavior of black cotton soil. The results of this investigation demonstrated that the untreated soil was unsuitable as a subgrade material for construction due to its high plasticity, moderate dry density, low CBR, and poor strength characteristics. Although each material showed unique mechanisms for improvement, the engineering properties were greatly enhanced by the addition of different stabilizers.

The addition of lime showed the most significant improvement among all the parameters that were tested. The relative density rise from 2.63 to 2.70 as the fineness modulus progressively increased, indicating better gradation and altered soil structure. Lime significantly decreased the plasticity index from 7% to 0.5% by accelerating cation exchange and pozzolanic reactions, which produced a more stable soil matrix. The ideal moisture content increased, and the maximum dry density increased to 1.98 g/cc as a result of better compaction and densification. Better load-bearing and structural integrity were confirmed by the mechanical performance, which doubled, the CBR increased to 10.2%, the UCS value increased to 3.9 g/cm², and the shear strength increased to 3.9 g.

In case of RHA, there was a medium level improvement due to its pozzolanic effect, that is, there was a reduction in plasticity, and there was an enhancement in strength parameters like UCS and CBR. Due to reduction in Gs, there was a slight decrease in MDD. The coir fiber has negligible effect on indices and compaction properties. In case of coir fiber, with a fiber content of 1%, there was an enhancement in UCS to 2.3 g/cm², and CBR to 6.2%.

Overall, lime was identified as the most effective stabilizer, followed by RHA and coir fibre. The results indicate that these stabilizers individually and/or in combination have the potential to improve the engineering performance of expansive soils. Further studies on hybrid stabilisation and long-term durability are recommended to aid in developing sustainable infrastructure construction on problem soils.

Acknowledgement

I would like to express my sincere gratitude to all those who supported me throughout the course of this research.

Author Contributions

Authors 1 and 2 wrote the paper and authors 3 and 4 have corrected and proofread the manuscript.

Ethical issues

Not applicable. This study does not involve any experiments on humans or animals. Hence, ethical approval was not required.

Informed consent

Not applicable.

Funding

Not applicable. This research did not receive any external funding like specific grant from funding agencies in the public, commercial, or nonprofit sectors.

Conflict of Interest

The authors declare that they have no conflicts of interest, competing financial interests or personal relationships that could have influenced the work reported in this paper.

Data and materials availability

Data that support the findings of this study are embedded within the manuscript.

REFERENCES

1. Abhishek A, Guha Ray A, Hata T, Abuel-Naga H. Microstructural characterization of expansive soil stabilized with coconut husk ash: A multi-technique investigation into mineralogy, pore architecture, and surface interactions. Minerals 2025;15(5):516.

2. Anbarasu NA, Keshav L, Raja KCP, Sivakumar V. Unraveling the flexural behavior of concrete and compare with innovative FEA investigations. Matéria (Rio de Janeiro) 2024;29(4):e20240656.
3. Annamalai K, Anbarasu NA, Govindarajan BP, Sivarethinamohan S. Sustainable concrete: Integrating environmentally friendly materials for environmentally friendly construction. Matéria (Rio de Janeiro) 2025a;30:e20250239.
4. Annamalai K, Sampathkumar S, Kachancheeri MS, Padmanaban M, Ayyanar O, Anbarasu NA. Exploring the role of recycled aggregates in modern concrete technology. Matéria (Rio de Janeiro) 2025b;30:e20250033.
5. Arathi KU, Athulya KM, Vinaya V, Pooja PV, Athira VV. Stabilization of black cotton soil using coconut fibre. Sustainability Agri Food Environ Res 2022;10:1–6.
6. Arya P, Patel SB, Bharti G, Shukla BK, Hurukadli P. Impact of using a blend of bagasse ash and polyester fibre in black cotton soil for improvement of mechanical and geotechnical properties of soil. Mater Today Proc 2023;78:738–743.
7. Behera R. An experimental study on evaluation of fibre reinforced fly ash stabilized black cotton soil as a sustainable subgrade material. Mater Today Proc 2022;62:6182–6188.
8. Bharti G, Tripathi A, Hurukadli P, Bharath B, Sharma PK, Shukla BK. Experimental analysis of fly ash and bagasse ash integration as sustainable stabilisers for improving the engineering properties of black cotton soil. In: Intelligent Infrastructure and Smart Materials. Springer Nature Switzerland 2025;341–358.
9. Bhowmik P, Hoque MR, Samonta S. Stabilization of expansive soil by using fly ash and coir fibre. J Adv Geotech Eng 2023;7(3):25-55.
10. Chethan BA, Ravi Shankar AU. Areca fibre reinforced alkali-activated black cotton soil using class F fly ash and limestone powder for pavements. In: Proc 12th Int Conf Road and Airfield Pavement Technology. Springer International Publishing; 2022;331–346.
11. Domphoeun R, Eisazadeh Otaghsaraei A, Nishimura S. Geotechnical properties of rice husk ash and coconut fibre stabilized soil and its performance evaluation as subbase material. PhD thesis. Thammasat University; 2023.
12. Gokul S, Ramakrishnan T, Manickaraj K, Devadharshan P, Mathew MK, Prabhu TV. Analyzing challenges and prospects for sustainable development with green energy: A comprehensive review. In: AIP Conference Proceedings 2024;3221:020043.
13. Goutham DR, Krishnaiah AJ. Synergistic stabilization of expansive soil using bagasse ash, lime, and coir fibre: A microstructural and mineralogical perspective. Prog Eng Sci 2025;100163.
14. Jayakrishnan R, Johnpaul V, Balasundaram N, Senthilkumar S. Augmenting the properties of black cotton soil in Chittur region, Palakkad, Kerala. Int J Environ Sci 2025. doi: 10.64252/2sbe8e86.
15. Jayakrishnan R, Sukumaran A, Aswini M, Saji A, Faiz M, Sivadas SK. Stabilization of black cotton soil using lime, coir fibre and rice husk. Int J Eng Manag Res 2022;12(2):93–96.
16. Khalak AA, Juremalani J. Enhancing subgrade stability in black cotton soil using coir fibre and micro-shredded waste plastic: An eco-friendly approach. JRTDD 2022;5(2):275–282.
17. Konai S, Ansari MS, Dutta S, Kumar V. Eco-friendly soil stabilization using rice husk ash and coconut coir. In: Indian Geotechnical Conference. Springer Nature Singapore; 2024;419–427.
18. Mai-Bade UY, Chinade AU, Batari A, Saeed SM. Stabilization of black cotton soil using various admixtures: A review. Composite Materials 2021;5(2):37–45.
19. Manaviparast HR, Cristelo N, Pereira E, Miranda T. A comprehensive review on clay soil stabilization using rice husk ash and lime sludge. Appl Sci 2025;15(5).
20. Nair KP. Technological advancements in coconut, arecanut and cocoa research: A century of service to the global farming community by the Central Plantation Crops Research Institute, Kasaragod, Kerala State, India. In: Tree Crops: Harvesting Cash from the World's Important Cash Crops. Springer International Publishing; 2020;377–536.
21. Pande PB, Raut JM, Khandeshwar SR, Mankar KC, Rangari AK, Suryawanshi VR. Improve stabilisation of black soil by bagasse ash, coir fibre, and plastic strips. In: Recent Advances in Material, Manufacturing, and Machine Learning. CRC Press 2023;1403–1413.
22. Ramesh HN, Manjunatha BVM. Morphology validation on strength properties of black cotton soil stabilized with rice husk ash and carbide lime in the presence of sulphate. Arab J Geosci 2023;16(11):596.
23. Sajeev PS, Rajagopal VSG, Arasu N. Investigation of concrete durability enhancement using supplementary cementitious materials. MethodsX 2025;103527.
24. Singh NK, Kalita A. Use of bagasse ash and coconut fibre in stabilization of black cotton soil. In: Advances in Sustainable Construction Materials. Springer Singapore; 2021;351–360.
25. Syed M, GuhaRay A, Garg A. Performance evaluation of lime, cement and alkali-activated binder in fibre-reinforced expansive subgrade soil: A comparative study. J Test Eval 2022;50(6):3054–3077.

26. Tamassoki S, Nik Daud NN, Jakarni FM, Kusin FM, Rashid ASA, Roshan MJ. Performance evaluation of lateritic subgrade soil treated with lime and coir fibre-activated carbon. Appl Sci 2022;12(16):8279.
27. Thangavel N, Shanmugavel NK, Karuppusamy M, Thirumalaisamy R. Friction and wear behavior of premixed reinforcement hybrid composite materials. Matéria (Rio de Janeiro) 2024;29(4):e20240552.