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Original Research Article

Sustainable Stabilization of Expansive Soil Using Rice Husk Ash, Sisal Fiber, and Lime

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Abstract

Expansive soils pose a major challenge to infrastructure stability due to their significant volumetric changes during wetting and drying cycles. Conventional stabilizers such as cement and lime are effective but carbon intensive. The use of agro-industrial residues combined with natural fibers presents a sustainable alternative, though it remains insufficiently investigated in tropical environments. This study examines the synergistic effects of rice husk ash (RHA), sisal fiber, and lime on the engineering behavior of expansive soil. Laboratory tests conducted in accordance with BS 1377 and ASTM standards included Atterberg limits, compaction, unconfined compressive strength (UCS), and California bearing ratio (CBR). XRF analysis confirmed the high silica content of RHA, indicating strong pozzolanic potential when blended with lime. The results showed that small percentages of RHA (12.5–17.5%) yielded the most significant improvements: plasticity index reduced from 32.6% to 12.7%, linear shrinkage decreased from 12.7% to 4.3%, the maximum UCS was 0.69 MPa, and soaked CBR increased to 48% compared with 3.8% in unstabilized soil. Beyond 17.5% RHA, strength and compaction performance declined due to excess fines and incomplete pozzolanic bonding. The findings from this study demonstrate that agro-industrial residues and natural fibres can provide low-carbon, locally sourced solutions for subgrade stabilization.

Keywords: Expansive soil; lime; rice husk ash; sisal fiber; sustainability

1. Introduction

Expansive soils, typically high-plasticity clays, are among the most problematic geomaterials encountered in geotechnical practice. Their inherent ability to undergo significant volumetric changes in response to variations in moisture content poses substantial challenges to the stability and serviceability of civil infrastructure (Niyomukiza et al., 2020, 2023; Zhang & Cao, 2002). Upon wetting, these soils absorb water and swell, exerting considerable uplift pressures on foundations, retaining walls, and pavements. Conversely, drying induces shrinkage, leading to differential settlement and the development of desiccation cracks that compromise both structural integrity and hydrological isolation. The economic burden associated with expansive soil behavior is formidable; annual expenditures related to distress mitigation, maintenance cycles, and premature replacement of affected infrastructure are estimated in billions of dollars worldwide. Traditional stabilization techniques have relied predominantly on the addition of ordinary Portland cement or quicklime to curtail plasticity and suppress volumetric changes (Niyomukiza, Nkugwa, et al., 2025). While these binders are effective in many geochemical contexts, their production is energy-intensive and contributes significantly to global anthropogenic carbon dioxide emissions (Alaoui et al., 2025). Consequently, geotechnical researchers are increasingly pursuing low- carbon stabilization strategies that meet both engineering performance standards and environmental sustainability goals.

The concept of sustainable soil stabilization is grounded in the principles of the circular economy and industrial ecology, where waste or underutilized by-products are valorized as supplementary cementitious or pozzolanic materials. Among the various agro-industrial residues investigated, rice husk ash (RHA) has emerged as a particularly promising candidate due to its high silica content and pozzolanic reactivity. Rice husk, the protective outer layer of rice grains, is generated in substantial quantities during post-harvest processing. Global paddy-rice production is around 750 million tonnes per year, and estimates suggest that about 150 million tonnes of rice husk are generated annually as a by-product (Ordi et al., 2024). When husk is combusted under controlled conditions, it yields ash with a high proportion of amorphous silica, typically ranging from 86% to 93% by mass (Atef, 2025; Domphoeun et al., 2025; Hossain et al., 2018). This silica-rich phase exhibits strong pozzolanic reactivity, enabling it to consume calcium hydroxide released during lime or cement hydration and to form additional calcium silicate hydrate (C-S-H) phases that densify the soil matrix. The incorporation of RHA into lime-stabilized clays has been shown to enhance strength development, reduce plasticity index, and refine pore structure, thereby mitigating swelling potential (Bhowmik, 2023; Pushpakumara & Mendis, 2022). However, the pozzolanic efficacy of RHA is highly sensitive to its production parameters, including combustion temperature, residence time, and grinding regime. Optimal reactivity is typically achieved when the husk is combusted at 600–700 °C under limited oxygen availability, promoting the formation of amorphous silica. Subsequent pulverization to particle sizes comparable to or finer than ordinary Portland cement further enhances its surface area and reactivity in cementitious systems (Kumar et al., 2022).

While chemical stabilization primarily enhances matrix bonding and modifies pore-fluid chemistry, the mechanical performance of stabilized expansive soils can be further improved through discrete fiber reinforcement (Gowthaman et al., 2018; Yazici & Ksekin, 2021). Sisal is particularly attractive due to its high tensile strength, low density, and abundant availability in tropical and subtropical regions. Sisal fiber is extracted from the leaves of *Agave sisalana*, a drought-tolerant species that thrives on marginal lands with minimal agrochemical inputs, thereby avoiding competition with food crops. When randomly distributed within a soil–lime–RHA matrix, sisal fibers act as micro-reinforcements that provide distributed tensile resistance, delaying crack initiation and impeding crack propagation. As a result, the composite can exhibit more ductile behaviour, with improved residual (post-peak) load capacity and enhanced energy absorption relative to chemically-stabilized soils without fibres (Kafodya & Okonta, 2018; Muntohar et al., 2013; Niyomukiza, Eisazadeh, et al., 2025). The combined use of lime and rice husk ash (RHA) in soil stabilization exhibits a synergistic effect. Lime provides the alkaline environment and calcium ions necessary for the formation of secondary calcium silicate hydrate (C–S–H) phases, while RHA contributes amorphous silica that reacts with excess calcium hydroxide, refining the pore structure and reducing the presence of brittle, leachable phases (Bhowmik, 2023; Domphoeun et al., 2025).

Despite the growing body of research on individual soil stabilizers, comprehensive investigations that integrate lime, rice husk ash (RHA), and sisal fiber within a unified stabilization framework remain scarce. Most existing studies have concentrated on binary combinations, such as lime with RHA or lime with fiber, leaving the interactions among all three constituents insufficiently examined. This study therefore aims to assess the effectiveness of a composite stabilization strategy involving RHA, a fixed proportion of sisal fiber, and lime in enhancing the engineering properties of expansive soil. A series of laboratory experiments was conducted, including material characterization, Atterberg limits, compaction, unconfined compressive strength (UCS), and California Bearing Ratio (CBR).

2. Materials and Methods

2.1 Materials

The primary materials employed in this investigation comprise expansive soil, rice husk ash (RHA), and lime, each selected for its distinct role in the stabilization process. Their visual appearance are presented in Figure 1.

(a) (b) (c) (d)

Figure 1. Materials used in the current study (a) expansive soil; (b) RHA; (c) lime; (d) sisal fiber

2.1.1 Expansive soil

Expansive soil samples (Figure 1 (a)) were obtained from Migenda, a permanent swamp located at chainages 19+088 and 19+090 along the Kisubi–Nakawuka road in Ssanda Village, Ssisa Sub-County, Nakawuka Parish, Wakiso District, Uganda. The sampling coordinates were (0°10′44.1″N, 32°28′48.8″E). Soil was extracted from two locations spaced 1.5 meters apart using a hoe and spade at a depth of 0.5 meter, where the in-situ bearing capacity ranged between 22 and 53 kPa. A total of approximately 360 kilograms of soil was collected, packaged in three airtight polythene bags of 120 kilograms each, and transported to Teclab for laboratory analysis. While the majority of geotechnical tests were conducted at Teclab, X-ray fluorescence (XRF) analysis was performed at the Government Analytical Laboratory (GAL). The particle size distribution is presented in Figure 2, and the physical properties of the tested soil are summarized in Table 1.

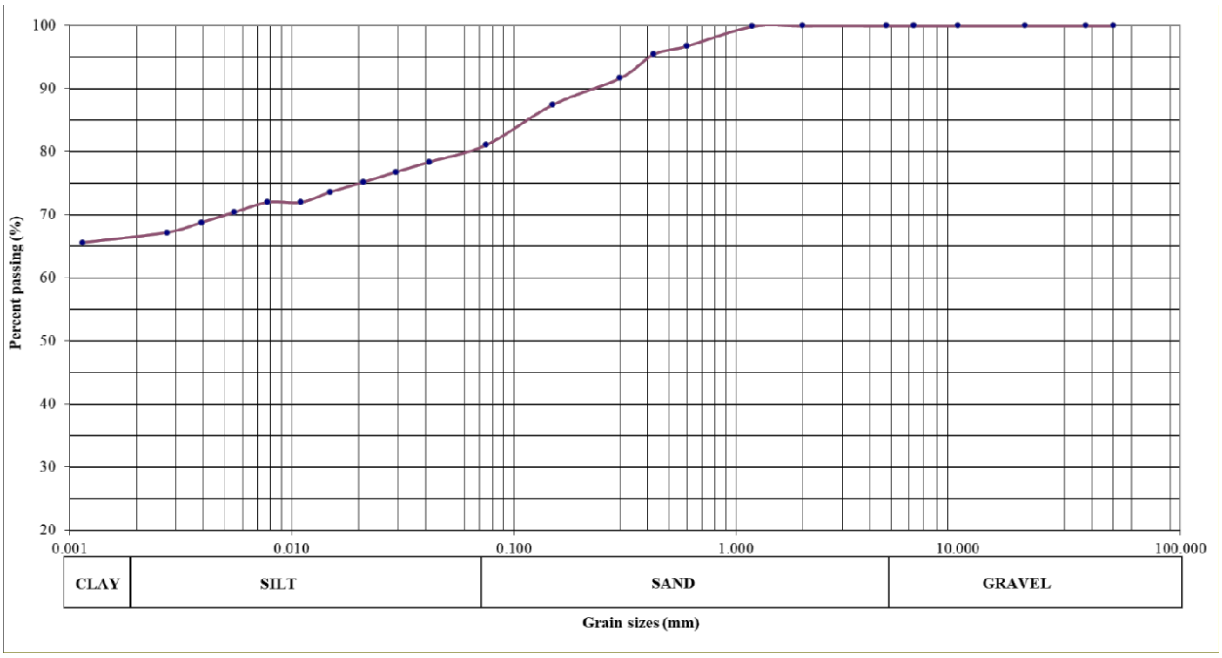

Figure 2. Particle size distribution of the tested soil

Table 1. Properties of the tested soil

Property	Value	Test Method / Standard
Specific gravity	2.65	ASTM D854-14 (2014)
Particle size distribution		BS EN ISO 17892-4 (2016)
— Gravel (%)	0	
— Sand (%)	18.9	
— Silt and clay (%)	81.1	
Plasticity characteristics		BS EN ISO 17892-12 (2018)
— Liquid limit (%)	83.6	
— Plastic limit (%)	32.6	
— Plasticity index (%)	51.1	
Linear shrinkage (%)	12.7	BS 1377-2 (1990)
Classification		
— USCS	CH	ASTM D2487 (2001)
— AASHTO	A-7-6	AASHTO M145 (2012)
Optimum moisture content (OMC) (%)	16.5	ASTM (2012)
Maximum dry density (MDD) (kg/m^3)	1275.7	
Soaked California Bearing Ratio (%)	3.8	ASTM D1883 (2016)
Unconfined compressive strength (MPa)	0.23	ASTM D2166 (2016)

2.1.2 Rice Husk Ash

The rice husk used for ash production was originally sourced from Namutumba District. A total of 120 kilograms of pre-processed rice husk ash (RHA), incinerated under controlled conditions at 700°C, was obtained from the Uganda National Roads Authority (UNRA) laboratory located in Kireka. The visual appearance of the RHA used in this study is shown in Figure 1 (b).

2.1.3 Lime

Lime (Figure 1 (c) used as a chemical stabilizing agent in this study was obtained from Seroma Hardware, located along Entebbe Road in Uganda. To determine the appropriate quantity of lime required for effective soil stabilization, the Initial Consumption of Lime (ICL) test was conducted in accordance with ASTM Standard D6276 (2006). The procedure involved adding varying proportions of lime (2%, 3%, 4%, 5%, and 6%) by dry weight of soil to a distilled water solution with an initial pH of 7.14. This test was designed to evaluate the reactivity of the soil and identify the optimal lime dosage for mix design. The results, presented in Figure 3, show that the pH of the soil–lime mixture increased progressively with each incremental lime addition, reaching a plateau at approximately pH 12.40 when 5.0% lime was added. This plateau indicates the point at which further lime addition does not result in significant pH increase, signifying completion of the lime–soil reaction. Based on these findings, the optimal lime content for initial stabilization was determined to be 5.0%.

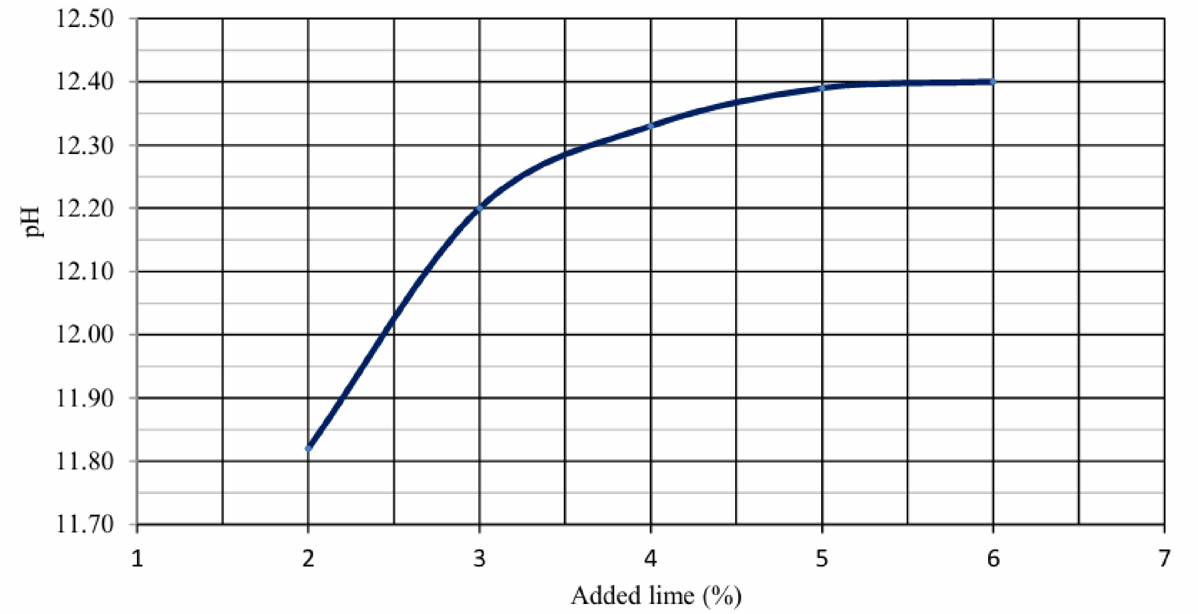

Figure 3. Results of initial consumption of lime

2.1.4 Sisal Fiber

Sisal fiber (Figure 1 (d)) derived from the *Agave sisalana* plant, was employed in this study as a reinforcing agent for expansive soil. Six bundles of pre-processed sisal fiber ropes were sourced from the central market in Kamuli District. The ropes, initially uncut, were manually processed in the laboratory by cutting them into uniform lengths of 30 mm. This preparation was guided by previous studies that utilized fiber lengths ranging from 10 to 30 mm(Kafodya & Okonta, 2018; Muntohar et al., 2013; Sani et al., 2020; Sani & Eisazadeh, 2023). The selection of sisal fiber was based on its advantageous properties, including high tensile strength, durability, local availability, cost-effectiveness, and environmental sustainability.

2.2 Experimental Program

Laboratory tests on the stabilized and unstabilized soil samples were conducted according to BS and ASTM standards. The mix proportions are shown in Table 2. First, Modified Proctor compaction tests were performed on all mix designs in accordance with ASTM International (2012) to evaluate their compaction characteristics. Prior to mixing, the expansive soil and rice husk ash were oven-dried for 24 hours to ensure consistent moisture conditions. Sisal fiber was incorporated into the mixture in small increments after the addition of water to promote uniform dispersion. To facilitate adequate moisture equilibration among all components, the prepared mixtures were covered with thin plastic sheets and left to condition for a minimum of three hours before compaction.

Table 2. Mix proportions

Mix ID code	Soil (%)	RHA (%)	Lime	Sisal fiber (%)
0.0% RHA	100.0	0.0	0.0	0.0
12.5% RHA	82.0	12.5	5.0	0.5
15.0% RHA	79.5	15.0	5.0	0.5
17.5% RHA	77.0	17.5	5.0	0.5
20.0% RHA	74.5	20.0	5.0	0.5
22.5% RHA	72.0	22.5	5.0	0.5

Specimens for the California Bearing Ratio (CBR) test were prepared in accordance with ASTM D1883–14 (2014). The unstabilized and stabilized soil mixtures were compacted at their respective optimum moisture contents using the modified Proctor effort in standard CBR molds. Following compaction, the specimens were carefully extruded and sealed in plastic bags to prevent moisture loss. To simulate saturated field conditions, the samples were submerged in a water tank and soaked for a period of four days, as prescribed by the standard. After soaking, surcharge weights were applied to the specimens, and penetration testing was conducted to determine the CBR values. The soaking setup is illustrated in Figure 4.

Figure 4. Soaking of compacted CBR specimens in a water tank

In addition to CBR testing, unconfined compressive strength (UCS) test, as shown in Figure 5 was conducted to evaluate the shear strength characteristics of the unstabilized and stabilized expansive soil. The test was conducted in accordance with British Standards Institution (1990).

Figure 5. UCS test

3. Result and Discussion

3.1 Chemical Composition of RHA and Expansive Soil

The chemical composition of expansive soil and RHA are shown in Table 3. XRF analysis revealed that the RHA used in this study contains high silica (SiO_2) content of 98.78%, while the expansive soil exhibits 67.05% silica. The high SiO_2 proportion in RHA indicates strong pozzolanic potential, as amorphous silica readily reacts with calcium from lime to form cementitious compounds such as calcium silicate hydrate (C–S–H), which enhance soil strength and reduce plasticity. In contrast, the silica-rich expansive soil primarily comprises aluminosilicate minerals responsible for its swelling behavior. The chemical disparity between RHA and the soil thus promotes beneficial lime–silica reactions, leading to improved microstructural stability and reduced volume change upon treatment (Choobbasti et al., 2010;

Pushpakumara & Mendis, 2022).

Table 3. Chemical composition for RHA and natural expansive soil

Chemical Composition (%)	RHA	Expansive Soil
SiO_2	98.78	67.05
K_2O	0.70	1.73
MnO	0.25	0.26
CaO	0.17	0.76
Fe_2O_3	0.09	5.94
Others	0.07	23.64

3.2 Atterberg Limits

The Atterberg limits for both unstabilized (0.0% RHA) and stabilized soil samples stabilized with 0.5% sisal fibre, 5% lime, and varying RHA content (12.5% to 22.5%) are presented in Figure 6. The liquid limit (LL) of the unstabilized soil was 51.1%. Upon stabilization, LL decreased to 50.3% at 12.5% RHA and further to 48.3% at 17.5% RHA, before slightly increasing to 50.8% at 22.5% RHA. Concurrently, the plastic limit (PL) increased from 18.5% to 38.1%, resulting in a reduction of the plasticity index (PI) from 32.6% to 12.7%. Linear shrinkage also declined from 12.7% to 4.3%, indicating enhanced dimensional stability. These results suggest that the lime–RHA–fibre treatment effectively reduced soil plasticity and shrinkage. Similar trends were reported in earlier studies: for example, Pushpakumara & Mendis (2022) observed that incorporating RHA and lime into soil mixtures led to a notable decline in PI, with the most significant reductions occurring at 5% RHA and 10% lime immediately after mixing (PI = 16.6, a 49.7% decrease), and at 10% RHA and 20% lime after 28 days (PI = 14.3, a 56.67% decrease). These improvements were attributed to the pozzolanic activity and the micro-filler effect of RHA, which collectively reduced the active clay content and modified the soil fabric. Niyomukiza, et al. (2025) further demonstrated that Probase SH-85 and TX-85 treatments to lateritic soils led to marked improvements in index properties, including a reduction in plasticity and shrinkage limits, thereby enhancing dimensional stability and workability. The mechanism for these changes likely involves the pozzolanic reaction between the calcium hydroxide from lime, reactive silica from RHA, and the soil clay minerals. These reactions produce cementitious gels (e.g., calcium-silicate-hydrate) that bind and aggregate clay particles, reducing the free surface area and the ability of the soil to absorb water and undergo volume changes. The inclusion of sisal fibre (0.5%) further helps restrain shrinkage by providing a reinforcing network that limits crack propagation and improves dimensional stability. However, the rebound of LL at the highest RHA dosage (22.5%) indicates that beyond a certain proportion, the ash may begin to dominate the behaviour, possibly due to increased fine content, higher water demand of ash surfaces, or incomplete pozzolanic reaction if lime is insufficient to activate all ash. However, the LL rebound at 22.5% RHA suggests that excessive ash may increase fine content or water demand, especially if lime is insufficient to activate all reactive silica. This observation highlights the importance of optimizing binder and ash proportions rather than assuming that higher dosages will always yield better results.

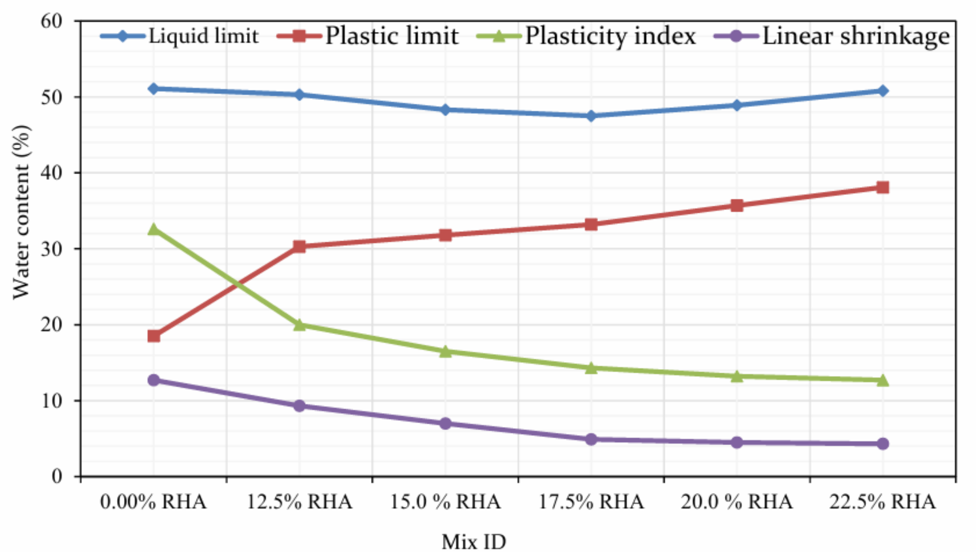

Figure 6. Atterberg limit test results

3.3 Compaction Characteristics

The compaction characteristics of both unstabilized and stabilized soil mixtures are presented in Figure 7. The unstabilized soil (0.0% RHA) achieved the highest maximum dry density (MDD) of 1655 kg/m^3 at an optimum moisture content (OMC) of 11.5%. As the RHA content increased from 0% to 22.5%, while maintaining constant lime (5%) and sisal fibre (0.5%) dosages, the MDD progressively decreased and the OMC shifted toward higher moisture levels. For example, at 22.5% RHA, the peak dry density was notably lower, and the moisture content required for optimal compaction was higher than that of the unstabilized soil. This trend is consistent with previous findings, which attribute the reduction in MDD to the lower specific gravity of RHA and the increase in OMC to the higher water absorption capacity of fibrous additives and porous ash particles. Domphoeun et al. (2025) reported similar behavior in lateritic soils stabilized with lime, RHA, and coir fibre, noting that the compaction curve shifted rightward with increasing ash content due to changes in soil texture and water demand. Pushpakumara & Mendis (2022) also observed that RHA–lime blends altered the compaction response by increasing the void ratio and reducing the bulk density of the mix. Kannan et al. (2019) further confirmed that the addition of RHA and lime to clayey soils resulted in reduced MDD and elevated OMC, emphasizing the need for tailored compaction protocols for stabilized soils.

From an engineering perspective, these results suggest that the incorporation of RHA modifies the soil matrix, reducing its compactability under standard energy levels unless moisture and compactive effort are recalibrated. It is therefore important to determine new compaction parameters for each RHA– lime–fibre blend rather than relying on baseline values from unstabilized soils. At higher RHA dosages, the balance between improved mechanical stability through pozzolanic bonding and fibre reinforcement, and reduced compaction efficiency, must be carefully considered in pavement subgrade design and construction quality control.

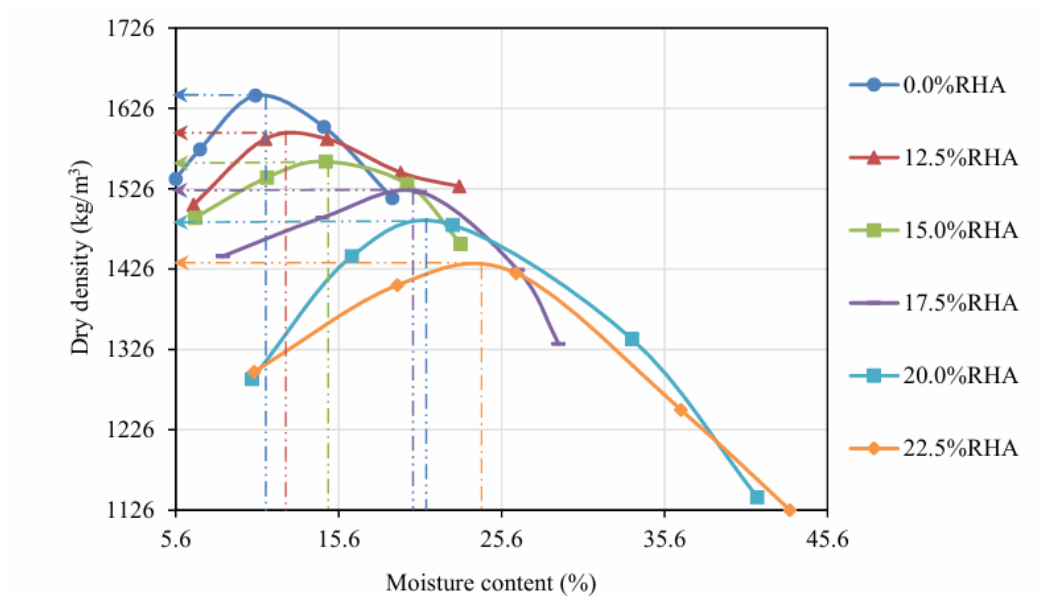

Figure 7. Compaction curves for unstabilized and stabilized soil samples

3.4 Effect of Stabilizers on the Unconfined Compressive Strength

Figure 8 presents the unconfined compressive strength (UCS) results for both soaked and unsoaked specimens across varying rice husk ash (RHA) contents. The data indicate that UCS increases progressively with RHA addition up to 17.5%, followed by a decline at 20% and 22.5%. Throughout the tested range, unsoaked specimens consistently exhibit higher strength than soaked ones, suggesting that early-age binder performance is adversely affected by moisture exposure. The peak strength observed at 17.5% RHA reflects an optimal balance among pozzolanic activity, binder activation, and structural integrity within the soil–lime–RHA–fibre matrix. This trend is consistent with previous studies involving various stabilizers (Faluyi et al., 2025; Niyomukiza et al., 2023; Pushpakumara & Mendis, 2022; Sani & Eisazadeh, 2023). Pushpakumara & Mendis (2022) reported that clayey soil stabilized with 10% RHA and 20% lime achieved a UCS increase of approximately 54% after 28 days of curing, relative to unstabilized soil. However, further increases in RHA content led to diminished strength gains, which were attributed to excess fines and incomplete pozzolanic bonding. Similarly, Niyomukiza et al. (2023) found that expansive clay soil stabilized with waste glass powder reached maximum UCS at approximately 7% additive content, with strength declining at higher dosages due to compromised matrix cohesion and unreacted particles. Manaviparast et al. (2025) in a comprehensive review on RHA and lime sludge stabilization, noted that strength improvement tends to plateau or reverse when pozzolanic additive content exceeds the binder capacity under given curing conditions.

The inclusion of natural fibres such as sisal at 0.5% may further enhance the mechanical performance of the stabilized soil by providing tensile reinforcement and bridging microcracks, thereby improving post-peak behavior and residual strength (Nguyen & Indraratna, 2023). The reduction in UCS at higher RHA dosages can be attributed to an increased fine fraction and expanded ash surface area, which elevate the demand for water and lime beyond the available supply. This imbalance may inhibit complete pozzolanic reaction and increase porosity. The lower UCS values observed in soaked specimens reflect the vulnerability of early-stage cementitious gels to moisture ingress, highlighting the importance of controlled curing and adequate binder dosage to ensure long-term durability.

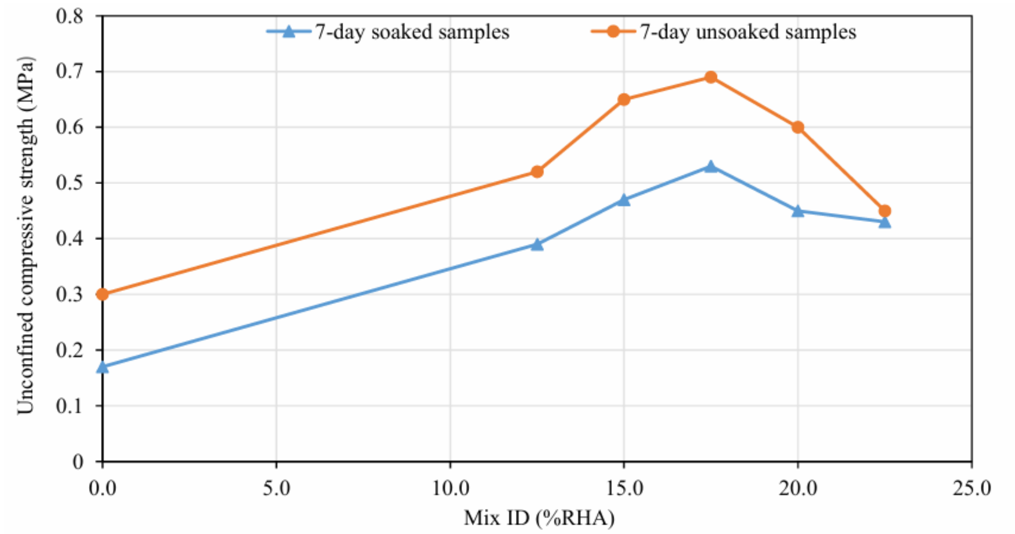

Figure 8. Variation of the UCS of the unstabilized and stabilized soil samples

3.5 Effect of Stabilizers on the California Bearing Ratio

The soaked California Bearing Ratio (CBR) results obtained at 90%, 95%, and 101% compaction levels reveal a consistent trend, as shown in Figure 9. Unstabilized soil (0% RHA) exhibits very low CBR values, typically between 1–3%, across all compaction levels. With the addition of stabilizers (RHA, sisal fibre, and lime), the CBR increases markedly, reaching a maximum of 48% at 12.5% RHA under 101% compaction. At 95% compaction, the CBR rises from 2.4% in unstabilized soil to 34% at 12.5% RHA, but then falls to 25% at 22.5% RHA. At 101% compaction the improvement is even more pronounced, with values approaching 48% at 12.5% RHA, followed by a reduction to 33% at 22.5% RHA. These results indicate that RHA–lime–sisal fibre stabilization enhances the bearing strength of expansive soil up to an optimum dosage, beyond which excessive RHA content introduces fines, increases porosity, or limits binder activation, thereby reducing CBR performance. Comparable behaviour has been reported in earlier studies, such as Choobbasti et al. (2010) who reported that the CBR values increased with 5% RHA and 6% lime additions but declined at higher RHA contents. Similarly, Niyomukiza & Yasir (2023), in a study on sawdust ash (SDA) utilization in expansive soil stabilization, noted that CBR improved with moderate SDA addition but declined beyond 6%. The observed increase in CBR at moderate RHA and SDA levels can be attributed to enhanced particle aggregation, the formation of secondary cementitious gels through pozzolanic reactions between silica in RHA and calcium from lime, and improvements in soil microstructure such as reduced void ratio and stronger inter-particle bonding. At higher RHA contents, the reduction in CBR is likely due to three factors: (i) an excessive proportion of ash relative to lime, which reduces binder effectiveness; (ii) increased water demand to saturate ash particles, which impairs compaction quality; and (iii) higher porosity or the presence of weak ash-rich zones acting as inclusions.

From an engineering perspective, the results suggest that mixes containing 12.5% RHA, together with 5% lime and 0.5% sisal fibre, provide substantial improvement in CBR, making them suitable for pavement subgrade or base applications. The decline in strength at higher RHA contents highlights the importance of dosage optimization rather than assuming that greater additive content will yield better performance. Furthermore, the significant improvement in CBR at higher compaction levels (101%) highlights the critical role of achieving adequate field compaction to fully realize the benefits of stabilization.

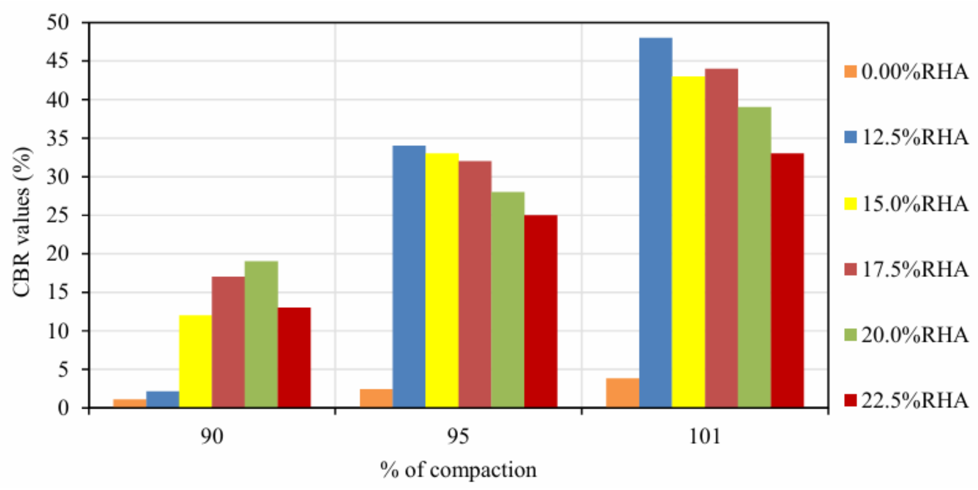

Figure 9. Variation of the soaked CBR of the unstabilized and stabilized soil samples

4. Conclusions

This study investigated the effects of rice husk ash (RHA), sisal fiber, and lime on the geotechnical performance of expansive clay soil. XRF analysis confirmed that the RHA used contained very high silica (98.78%), providing strong pozzolanic potential when combined with lime and promoting the formation of cementitious compounds (C–S–H) that enhance soil strength and reduce plasticity. Stabilization with RHA, lime, and sisal fibre reduced the liquid limit and plasticity index while increasing the plastic limit, with linear shrinkage decreasing from 12.7% to 4.3%, thereby improving workability and reducing swelling potential. Increasing RHA content led to a progressive reduction in maximum dry density and a shift of optimum moisture content to higher values, reflecting the lower specific gravity and higher water absorption capacity of RHA, which necessitates tailored compaction protocols. Unconfined compressive strength (UCS) increased with RHA addition up to 17.5%, achieving peak strength before declining at higher dosages, while unsoaked specimens consistently exhibited higher strength than soaked ones, highlighting the sensitivity of early-age cementitious gels to moisture. California bearing ratio (CBR) values improved substantially with stabilization, reaching a maximum of 48% at 12.5% RHA under 101% compaction, but declined beyond this dosage due to excess ash and incomplete pozzolanic bonding. Overall, the results confirm that mixes containing 12.5% RHA, 5% lime, and 0.5% sisal fibre are optimal for pavement subgrade and base applications.

The study showed that small percentages of RHA (12.5–17.5%) yielded the best performance results. However, the following recommendations are made for future studies: detailed microstructural analysis of the stabilized soil matrix to better understand the formation of cementitious gels and fibre–soil interactions; long-term durability tests under varying environmental conditions to assess performance over time; and the integration of other agro-industrial by-products to further advance sustainable soil stabilization practices.

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