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EFFECT OF SODIUM CARBONATE ON RICE HUSK ASH TO STABILIZE LATERITIC SOIL FOR USE IN ROAD CONSTRUCTION

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Abstract

Lateritic soils commonly used in tropical road construction often exhibit high plasticity and inadequate strength, limiting their direct application in pavement layers. This study investigates the effectiveness of rice husk ash (RHA) activated with sodium carbonate (Na_2CO_3) as a sustainable stabilizing system for lateritic soil improvement. The materials were characterized for their chemical and mineralogical composition using X-ray fluorescence (XRF) and X-ray diffraction (XRD). The soil was treated with varying proportions of RHA (0–15%) and Na_2CO_3 (0–12%), and evaluated through Atterberg limits, compaction characteristics, California Bearing Ratio (CBR) under soaked and unsoaked conditions, unconfined compressive strength (UCS), and shear strength tests following relevant British Standards. A two-way ANOVA was employed to assess the statistical significance of the stabilizers' effects. Results revealed that RHA is rich in reactive silica, while the lateritic soil is predominantly kaolinitic, enabling effective alkali-activated pozzolanic reactions. Stabilization significantly reduced plasticity and enhanced strength properties, with the optimum blend of 15% RHA and 12% Na_2CO_3 yielding the highest CBR, UCS, and shear strength values. Statistical analysis confirmed the significant influence of the stabilizers on key engineering properties. The study demonstrates that sodium carbonate–activated RHA is an effective and environmentally sustainable alternative for lateritic soil stabilization in pavement applications.

Keywords
Alkaline Activation,
Lateritic Soil,
Rice Husk Ash,
Road Construction,
Sodium Carbonate,
Soil Stabilization

1. INTRODUCTION

Lateritic soil is abundantly available in many parts of Africa, particularly Nigeria, and is routinely utilized in civil engineering works due to its cost-effectiveness and accessibility [1, 2]. Despite its prevalence, most lateritic soils possess inherent engineering limitations, such as poor workability, high compressibility, and low bearing capacity, which often fall outside the acceptable limits for road pavement construction [1-3]. For instance, the Nigerian Federal Ministry of Works and Housing recommends that the percentage of soil passing the No. 200 sieve (0.075 mm) should not exceed 35%, yet many local lateritic soils significantly exceed this threshold, necessitating stabilization to improve their mechanical properties.

Soil stabilization involves treatments applied to alter soil texture, grain size, and load-bearing capacity to ensure the material can endure traffic stresses under all-weather conditions without deformation [2]. Traditionally, this has been achieved through mechanical means or the addition of binders like ordinary portland cement (OPC) and lime [4]. However, the production of OPC is a major environmental concern, estimated to contribute 5–10% of global anthropogenic CO_2 emissions, thereby exacerbating global warming [5]. Furthermore, approximately 40% of these emissions stem from the combustion of fossil fuels in the kiln process, while 50% result from the roasting of limestone [6]. Consequently, identifying alternative, environmentally friendly stabilizers has become a vital issue for sustainable construction [7-9].

Rice Husk Ash (RHA) has emerged as a viable agricultural waste byproduct for soil improvement, with approximately 108 million tons generated globally each year. RHA is characterized by a high content of amorphous silica, which facilitates significant pozzolanic reactivity when used as a soil additive [10, 11]. While recent experimental evidence demonstrates that RHA significantly enhances the geotechnical properties of subgrade soil, it often lacks the inherent binding potency of traditional stabilizers; consequently, it is frequently used in combination with secondary binders like lime or cement to ensure long-term durability [12, 13]. Most studies have used RHA only as a partial replacement for cement or lime, but the goal of completely eliminating conventional binders remains a significant challenge in the field.

Recent studies have demonstrated that geotechnical beneficiation can be significantly enhanced through composite stabilization strategies using industrial or agricultural wastes. For example, [14] revealed that the admixture of stabilizers like steel slag with traditional binders can effectively control soil plasticity and improve workability, qualifying treated lateritic soil as a subgrade material in line with Nigerian standards. Similarly, the incorporation of RHA has been shown to improve consolidation and bearing capacity, with [15] reporting that 15% RHA addition effectively improved the California Bearing Ratio (CBR) of soft soils. Beyond physical blending, the role of chemical additives is critical; research by [16] indicated that sodium compounds, including sodium carbonate (SC), increase the strength of soil-cement mixtures and reduce swelling potential. Furthermore, recent evaluations by [2, 17-19] suggest that alkali-activated agricultural wastes can transform the failure mode of soils from brittle to ductile, thereby significantly increasing shear resistance and structural integrity for sustainable ground improvement

This study proposes the use of SC (Na_2CO_3) as a chemical activator to enhance the pozzolanic reactivity of RHA. Sodium carbonate, commonly known as soda ash, is a strong alkaline salt that is safe to handle and non-corrosive. It is recognized in industrial processes for its ability to accelerate the hardening of soil-lime-fly ash and soil-cement mixtures, suggesting a synergistic potential when combined with the high silica content of RHA [20]. By creating an alkaline environment, sodium carbonate can activate the aluminosilicates in RHA, promoting the formation of cementitious compounds like calcium silicate hydrates (C-S-H) that improve soil inter-particle bonding [20, 21].

The primary aim of this research is to assess the influence of SC as an activator on RHA-stabilized lateritic soil for highway pavement construction. This work fills a critical gap in the literature by evaluating a composite agricultural-chemical binder that avoids the environmental drawbacks of OPC. The study follows a rigorous methodology including chemical characterization via X-ray Fluorescence (XRF) and X-ray Diffraction (XRD), and mechanical evaluations using CBR and UCS tests. Finally, a two-way Analysis of Variance (ANOVA) is employed to statistically validate the effectiveness of various RHA and SC proportions on the soil's engineering performance

2. MATERIALS AND METHOD

2.1 Materials

The primary materials utilized in this research include natural lateritic soil, RHA, and SC. The lateritic soil, characterized by its reddish-brown color, was obtained from a burrow pit located in Ajinapa, Orire Local Government Area, Ogbomoso, Nigeria (8º17′ N and 4º14′ E) as shown in Figure 1a. Disturbed specimens were collected at a depth of 100 cm below the ground surface. RHA was sourced from a Hilcrest Rice Mill in Offa, Kwara State, as a product of controlled incineration as shown in Figure 1b. SC commonly referred to as soda ash, was procured from a government approved chemical store at Ojota, Lagos State in a crystalline, water-soluble form.

(a) (b)

Figure 1: Samples of (a) Lateritic Soil and (b) Rice Husk Ash

2.2 Preparation of Materials

Soil samples were air-dried, pulverized, and sieved through the British Standard sieve No. 4 (4.75 mm) in accordance with BS 1377-2 (2022) [22] to ensure a uniform texture for geotechnical testing. The RHA was similarly air-dried and pulverized, then sieved through the BS No. 200 sieve (75 μm) to remove foreign matter and increase its surface area for enhanced chemical reactivity. All prepared materials were stored in airtight containers to prevent moisture absorption prior to testing

2.3 Stabilization Protocols and Mix Design

The stabilization process involved a partial replacement method, where specific percentages of the stabilizers replaced a corresponding dry weight of the lateritic soil. RHA proportions were varied at 0, 5, 10, and 15%, while SC was applied at concentrations of 0, 4, 8, and 12% as shown in Table 1. For instance, a composite binder consisting of 5% RHA and 4% SC resulted in a 9% total reduction of the natural soil component, which was then replaced by the composite mixture

Table 1: Variation of Rice Husk Ash and Sodium Carbonate

RHA (%)	SC (%)			
	0	4	8	12
0	0,0	0,4	0,8	0,12
5	5,0	5,4	5,8	5,12
10	10,0	10,4	10,8	10,12
15	15,0	15,4	15,8	15,12

2.4. Chemical and Geotechnical Tests Procedures

2.4.1. Chemical and mineralogical analysis

The chemical characterization of RHA and lateritic soil was carried out using XRF to determine various oxides present in the ash as specified in BS EN 196-2 (2025) [23] at Larfarge Cement Plant, Ewekoro, Ogun State, Nigeria. Based on the types and percentage composition of the oxides found present, the pozzolanicity of the ash was assessed. Also the two equations below were used to determine the Hydration Modulus (HM) and the Total Reactive Oxide Content (TROC)) of the RHA to determine the reactivity of the ash as a pozzolan.

$$HM = \frac{CaO}{(SiO_2 + Al_2O_3 + Fe_2O_3)} \quad (1)$$

$$TROC = \left(CaO + MgO - LOI - (Na_2O + K_2O)\right) \quad (2)$$

Furthermore, the mineralogical phases and microstructural characteristics of the RHA and lateritic soil sample were examined using XRD Spectrometry in accordance with ASTM C1365-06 (2011) [24].

2.4.2 Consistency and compaction limits

The Atterberg limits were determined to assess the consistency and plasticity characteristics of the lateritic soil and its stabilized mixtures. These limits define the moisture contents at which the soil transitions between different states and provide insight into its engineering behaviour. The Liquid Limit (LL), Plastic Limit (PL), Plasticity Index (PI), and Shrinkage Limit (SL) were determined in accordance with BS 1377-2 (2022) [22]. The LL was obtained using the Casagrande apparatus by preparing soil paste passing the 425 µm sieve, allowing moisture equilibrium for 24 hours, and determining the moisture content corresponding to 25 blows from the flow curve. The PL was determined by rolling remolded soil into threads of approximately 3 mm diameter until crumbling occurred. The PI was computed as the difference between the LL and the PL as given in Equation 3, and the SL was obtained by measuring the volume of a soil pat at its plastic state and after oven-drying. The same procedures were applied to all soil samples stabilized with varying proportions of RHA and SC.

$$PI = LL - PL \quad (3)$$

Compaction tests were conducted to determine the Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) of the lateritic soil and its stabilized mixtures. Samples were subjected to West African Standard (WAS) energy levels (compacting in 5 layers with 10 blows of a 4.5 kg rammer dropped from 450 mm). This standard was specifically adopted to assess the material's suitability for road sub-base applications.

2.4.3. Strength evaluations

The CBR test was conducted in accordance with BS 1377-2 (2022) [22] to evaluate the strength and bearing capacity of the lateritic soil and its stabilized mixtures for pavement applications. All specimens were compacted at their respective OMC and MDD using a 4.5 kg rammer falling through 450 mm in five layers with 27 blows per layer.

For the unsoaked CBR, compacted specimens were cured for 7 days and then tested using a CBR machine by applying load through a penetration piston at a uniform rate. Load readings were recorded at penetration depths of 2.5 mm and 5.0 mm, from which the CBR values were determined. For the soaked CBR, specimens were similarly cured for 7 days, soaked in water for 72 hours, allowed to drain for 15 minutes, and then tested following the same procedure. The tests were repeated for soil samples stabilized with varying proportions of RHA and SC.

The UCS test was employed as a primary index to evaluate the compressive resistance of the stabilized soil without lateral confinement, thereby reflecting the inherent bonding and cementation developed within the soil matrix. In this study, UCS was used to assess the effectiveness of SC as an alkali activator in enhancing the pozzolanic reactivity of RHA and improving inter-particle bonding within the lateritic soil. An increase in UCS values indicates improved soil stiffness, load-bearing capacity, and structural integrity resulting from the formation of cementitious compounds within the RHA–soil system.

In addition, shear strength tests were conducted to evaluate the soil's resistance to failure under applied shear stresses, which is critical for pavement and geotechnical stability. When considered alongside UCS results, the shear strength characteristics offer a comprehensive assessment of the mechanical performance of the stabilized soil, confirming its suitability for subgrade or subbase applications under traffic loading.

2.5. Statistical Evaluation

A two-way ANOVA without replication was conducted at a 95% confidence level ($\alpha = 0.05$) to statistically evaluate the effects of RHA and SC on the stabilization of lateritic soil. The analysis assessed the significance of variations in RHA and SC proportions on key geotechnical properties, including PI, MDD, OMC and CBR under soaked and unsoaked conditions. This statistical approach enabled the differentiation between random experimental variability and the actual influence of the stabilizing agents. Where p-values were less than 0.05, the null hypothesis was rejected, indicating a statistically significant effect of RHA and SC on the corresponding soil property.

3. RESULTS AND DISCUSSION

3.1. Chemical and Mineralogical Characterization

The oxide compositions of the RHA and lateritic soil determined by XRF are presented in Table 2. The lateritic soil is dominated by SiO_2 (42.48%), Al_2O_3 (22.61%), and Fe_2O_3 (26.48%), reflecting a quartz-rich and highly weathered lateritic profile. While the soil exhibits limited inherent cementitious activity, the high alumina and iron contents suggest favourable interaction with reactive silica under alkaline conditions. Minor oxides including TiO_2, K_2O, MgO, and CaO occur in low concentrations and may contribute marginally to particle bonding during stabilization.

RHA is predominantly composed of SiO_2 (80.26%), confirming its classification as a siliceous pozzolan. Previous studies report silica contents ranging from 70 to 95% in well-burnt RHA depending on combustion conditions and rice variety [25, 26], and the value obtained in this study falls within this documented range, aligning with its suitability for pozzolanic activation with sodium carbonate. The high silica content is essential for pozzolanic reactivity, particularly under alkaline activation with sodium carbonate. Moderate amounts of Al_2O_3 (4.56%), CaO (4.03%), and K_2O (4.08%) further enhance its reactivity by supporting the formation of cementitious and aluminosilicate phases. Minor oxides such as SO_3 (1.097%) and P_2O_5 (1.103%) occur at concentrations typical of biomass ashes and are well within the acceptable thresholds stipulated by ASTM C618 ($SO_3 \leq 5\%$; $P_2O_5 \leq 5\%$), and are therefore not expected to adversely affect stabilization performance [27, 28]. To establish the pozzolanicity of RHA, the sum of the three principal reactive oxides ($SiO_2 + Al_2O_3 + Fe_2O_3$) was evaluated in accordance with ASTM C618 (2019) [28]. The combined oxide content of 87.01% (SiO_2: 80.26%, Al_2O_3: 4.56%, Fe_2O_3: 2.19%) exceeds the minimum threshold of 70% stipulated for Class N pozzolans, confirming that the RHA used in this study qualifies as a pozzolanic material.

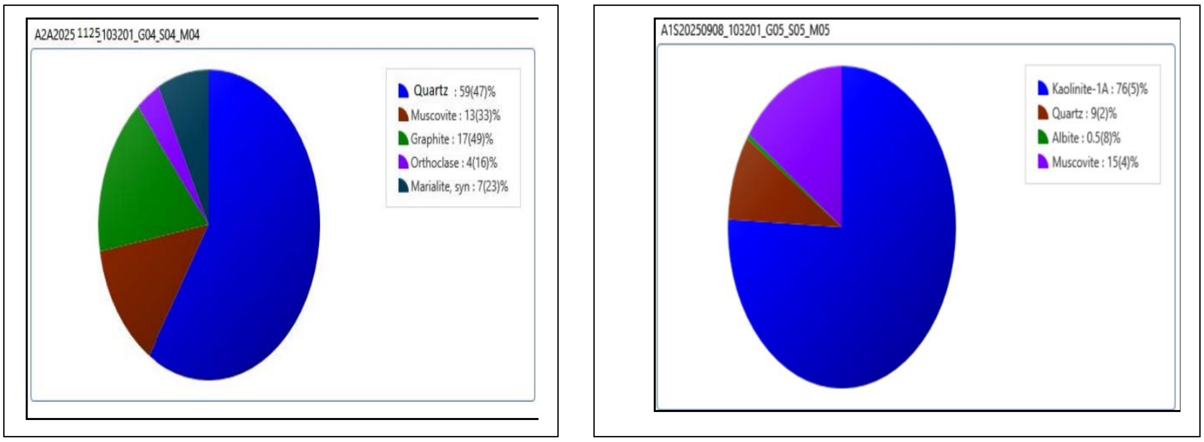
XRD analysis revealed that RHA is dominated by quartz, reflecting silica concentration after combustion and confirming its suitability as a silica-rich stabilizing material, with minor aluminosilicate and alkali-bearing phases that support cementitious bonding upon chemical activation. The lateritic soil is primarily kaolinitic as revealed by XRD, indicating advanced tropical weathering, with muscovite and quartz as secondary phases and trace albite, characteristic of mature lateritic soils with low swelling potential and moderate plasticity suitable for road subgrade applications (Figure 2).

3.2. Consistency and Compaction Limits of the Natural and Stabilized Soil

The consistency characteristics of the natural lateritic soil and soils stabilized with varying proportions of RHA and SC were evaluated using Atterberg limit tests. The variations in LL, PL, PI and SL with increasing stabilizer content are illustrated in Figure 3. The natural lateritic soil exhibits an LL of 46%, PL of 33%, PI of 13%, and SL of 11.02%, indicating intermediate plasticity. Upon stabilization with RHA and SC, the liquid limit generally decreased, with values ranging from 25% to 38.5%.

Table 2: Chemical Composition of the Rice Husk Ash (RHA)

Components	Concentration (%)	
	Lateritic Soil	**Rice Husk Ash**
SiO_2	42.476	80.264
V_2O_5	0.088	0.001
Cr_2O_3	-	0.008
MnO	0.110	0.382
Fe_2O_3	26.483	2.186
NiO	-	0.002
Co_3O_4	0.113	-
CuO	0.052	0.117
Nb_2O_3	0.018	0.020
WO_3	0.002	0.002
P_2O_5	-	1.103
SO_3	0.851	1.097
CaO	0.702	4.030
MgO	1.072	-
K_2O	2.165	4.077
Al_2O_3	22.611	4.561
Ta_2O_5	0.018	0.032
TiO_2	1.934	0.579
ZnO	0.031	0.043
Ag_2O	0.033	0.027
Cl	0.626	1.434
ZrO_2	0.438	0.034



(a) (b)

Figure 2: Quantitative mineral composition of (a) Rice Husk Ash and (b) Lateritic Soil

This reduction reflects decreased soil affinity for water and improved workability, making the stabilized mixtures less sensitive to moisture variations. Similar reductions in liquid limit have been reported in comparable studies: [15] observed progressive LL reduction with increasing RHA content in soft soil stabilization, while [8, 17] reported analogous decreases in LL for alkali-activated and wood ash–stabilized lateritic soils respectively, confirming that the pozzolanic and cation exchange mechanisms driving plasticity reduction are consistent across RHA-based stabilization systems. Based on the plasticity classification system of BS 5930 (2015) [29], the stabilized soils predominantly fall within low to intermediate plasticity ranges, confirming improved engineering behaviour suitable for pavement applications.

The PI shows a pronounced reduction with the incorporation of RHA and SC, decreasing from 13% in the natural soil to values as low as 1.75% at higher stabilizer contents. A reduction in PI is widely recognized as an indicator of soil improvement, signifying reduced plastic behaviour and lower susceptibility to deformation and volumetric changes [30]. This trend is consistent with findings from [15], who reported progressive PI reduction in RHA-stabilized soft soils, and [17], who observed similar plasticity improvements in alkali-activated RHA-treated soils, confirming the effectiveness of the RHA–SC combination in this study. The LS also decreased significantly, indicating a reduced tendency for volume change upon drying, which is widely considered desirable for pavement subgrade and subbase materials as it minimises seasonal volume fluctuations and associated surface distress [14, 31].

The observed reductions in LL, PI, and LS are attributed to cation exchange, flocculation, and the formation of cementitious bonds resulting from the interaction between the lateritic soil, silica-rich RHA, and alkaline SC [31]. These findings are consistent with those of [8], who reported comparable reductions in consistency limits for lateritic soil stabilized with high-silica wood ash activated with sodium tetraoxosulphate VI, and [2], who similarly noted significant plasticity reductions in high-plasticity lateritic soil treated with composite binders. Importantly, the stabilized soil mixtures satisfy the FMWH (1997) requirements for road construction materials, with LL values below 50% and PI values well below the maximum allowable limit of 20%, confirming their suitability for use as subgrade, subbase, and base materials [32].

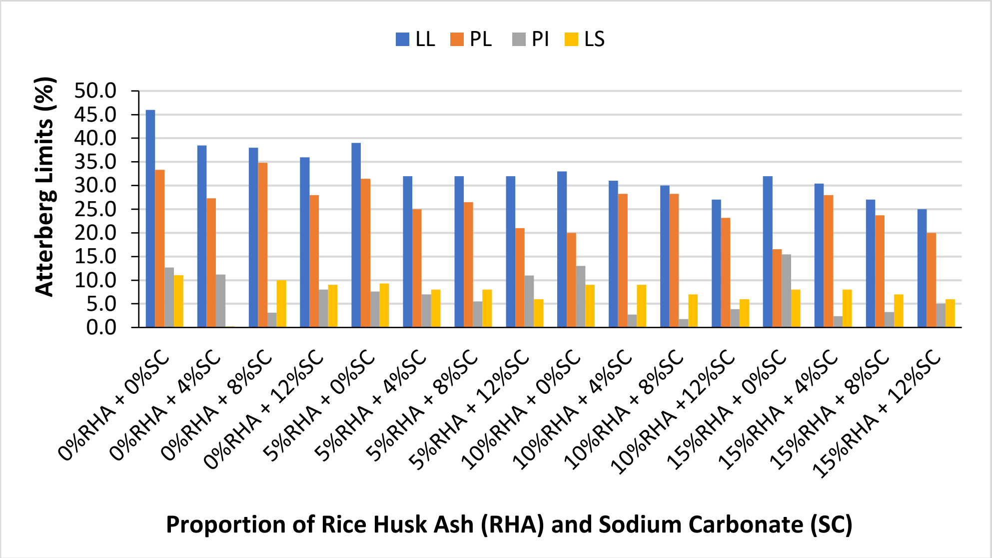
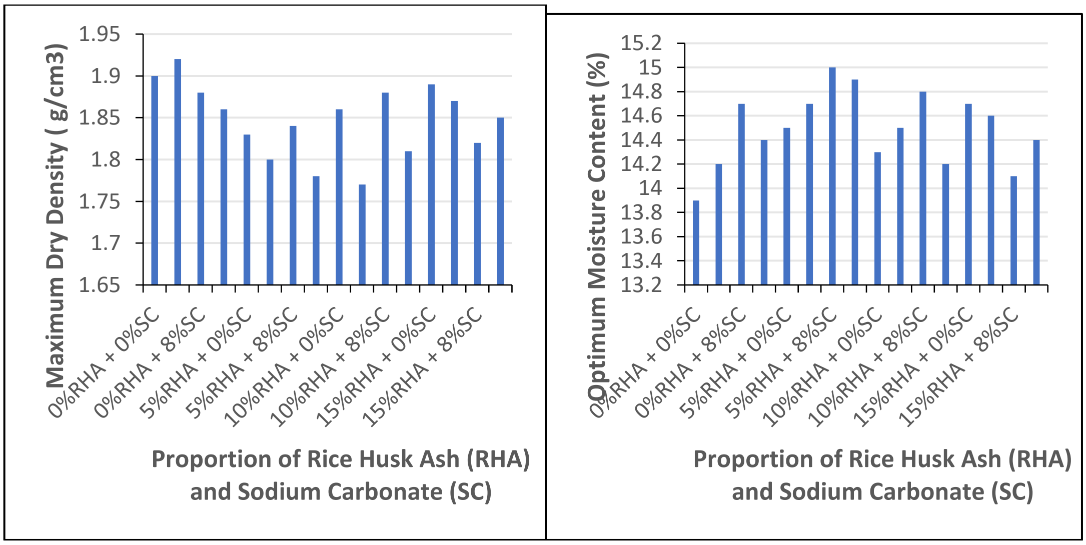


Figure 3: Variation of consistency indices with RHA and SC contents



(a) (b)

Figure 4: Variation of (a) Maximum Dry Density and (b) Optimum Moisture Content with RHA and SC content

The inclusion of RHA and SC resulted in a general reduction in MDD and a corresponding increase in OMC, particularly under WAS compaction for subbase materials. As illustrated in Figure 4a, MDD values decreased with increasing stabilizer content, while Figure 4b shows a progressive increase in OMC.The observed increase in OMC indicates higher moisture requirements to achieve effective compaction, while the reduction in MDD reflects structural modification of the soil matrix due to particle replacement and flocculation. According to established geotechnical principles, a reduction in MDD accompanied by improved strength characteristics is indicative of effective soil stabilization [33, 34]. This compaction behaviour aligns with findings from [15], who reported decreasing MDD and increasing OMC in RHA-stabilized soft soils, attributing the trend to the lower specific gravity of RHA and increased water demand associated with pozzolanic hydration, mechanisms consistent with those observed in the present study. Overall, the compaction response demonstrates that RHA–SC stabilization modifies the packing arrangement and moisture sensitivity of the lateritic soil, producing a material with improved compaction behavior suitable for pavement subgrade and subbase applications.

3.3. Strength Characteristics of the Natural and Stabilized Soil

The lateritic soil showed initial CBR values of 26% (unsoaked) and 5% (soaked). Addition of SC alone (4–12%) moderately increased the unsoaked CBR to 29.5–33% and soaked CBR to 6.7–7.8%. When combined with RHA (5 – 15%), a synergistic improvement was observed, with the highest values recorded at 15% RHA and 12% SC: 54.5% unsoaked and 50.9% soaked (Figures 5a and 5b). The progressive enhancement is attributed to pozzolanic reactions between the silica in RHA and the alkaline environment created by SC, which dissolves the aluminosilicate minerals in the kaolinitic lateritic soil and triggers the formation of cementitious compounds such as C-S-H and sodium aluminosilicates [17, 31]. The improvements in soaked and unsoaked CBR with increasing RHA and SC content reflect the progressive densification of the soil matrix through pozzolanic reaction products that reduce permeability and enhance load-bearing capacity under both wet and dry conditions [35, 36]. The stabilized soils meet the FMWH (1997) minimum soaked CBR requirement of 30% for sub-base materials; the optimum blend of 15% RHA and 12% SC achieved a soaked CBR of 50.9% and an unsoaked CBR of 54.5%, both substantially exceeding this threshold and confirming their suitability for road construction [32]. These results are consistent with previous studies where optimal RHA content significantly improved CBR in soft and lateritic soils [15, 33-34].

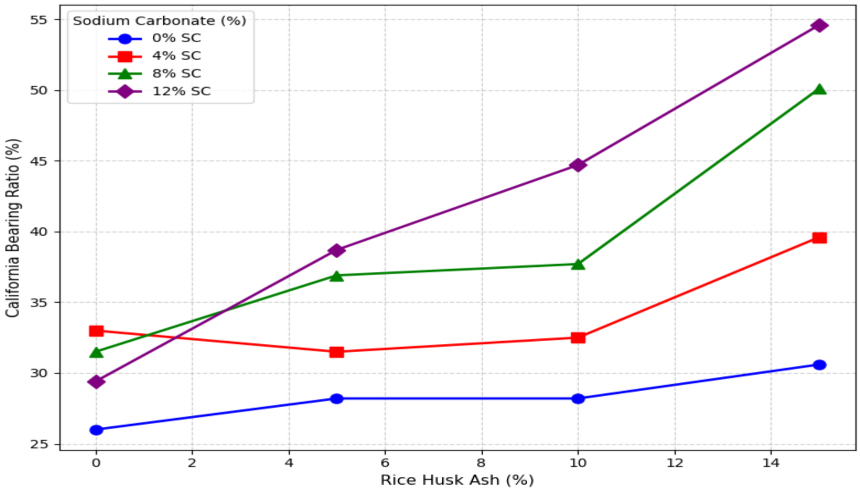


Figure 5a: Variation of unsoaked CBR with RHA and SC content

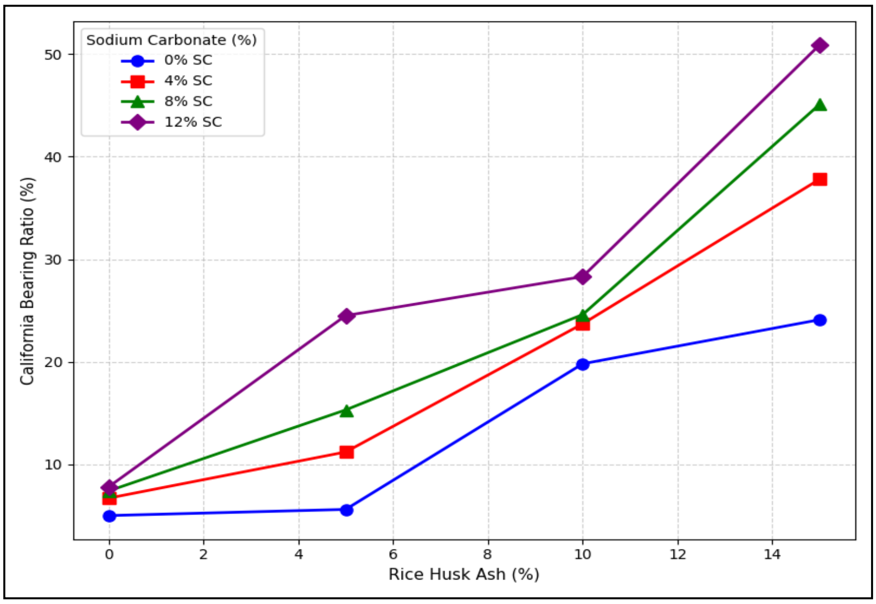


Figure 5b: Variation of soaked CBR with RHA and SC content

The UCS of the natural soil was 222 kN/m^2, increasing progressively with the addition of RHA and SC. The maximum UCS of 330 kN/m^2 was achieved at 15% RHA and 12% SC (Figure 6), classifying the stabilized soil as very stiff to hard according to BS 5930 (2015) [29]. Shear strength followed a similar trend, rising from 111 kN/m^2 in the control sample to 165 kN/m^2 at the same stabilization level.

The improvements in UCS and shear strength reflect enhanced interparticle bonding and increased internal friction due to cementitious compounds generated by pozzolanic reactions between the reactive silica in RHA and the soil aluminosilicates under the alkaline conditions created by SC [19, 31, 37]. These enhancements align with findings from [17, 19, 37], confirming the effectiveness of RHA–SC mixtures in stabilizing lateritic soils for sub-base and base course applications.

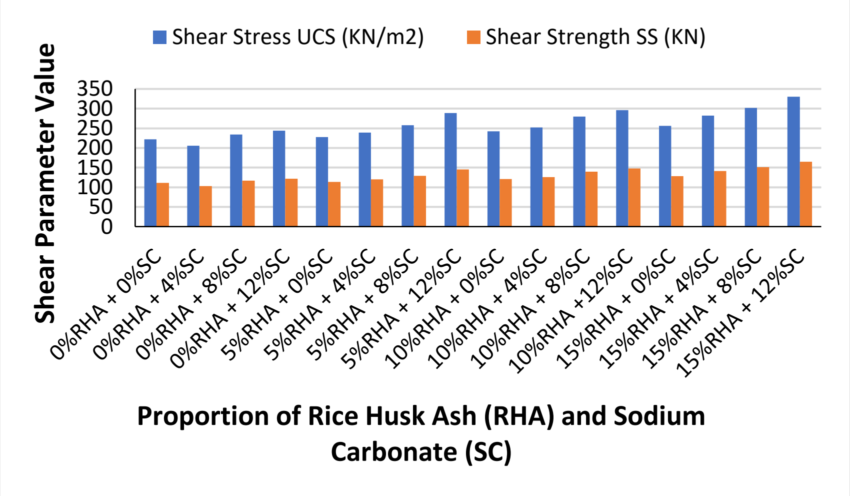


Figure 6: Variation of UCS and shear strength with RHA and SC content

3.4. ANOVA-Based Statistical Assessment

The results (Figure 7) show that both RHA and SC had statistically significant effects on LL, PI, unsoaked and soaked CBR, and UCS, with F-values exceeding the critical threshold (F = 3.86). In contrast, their influence on PL, OMC and MDD was minimal, with F-values below the critical limit.

These findings confirm that the inclusion of RHA and SC effectively enhances soil consistency and strength, particularly improving bearing capacity, compressive resistance, and moisture stability, while compaction properties remain largely unaffected by stabilizer dosage. The statistically significant F-values obtained for LL, PI, CBR, and UCS are consistent with ANOVA findings reported by [38], who confirmed statistically significant effects of pozzolanic stabilizers on strength and plasticity parameters at the 5% significance level in fine-grained soil stabilization, and by [39], who reported significant enhancements in UCS and Atterberg limits in cement kiln dust-RHA stabilized lateritic soils, affirming that RHA-based pozzolanic systems consistently produce statistically meaningful improvements in consistency and strength. The non-significant influence on PL, OMC, and MDD aligns with observations by [39], where compaction-related parameters showed comparatively muted responses to agro-industrial waste addition, a behaviour attributed to the lower specific gravity of the pozzolanic additive relative to the host soil, which increases void ratio without substantially altering the moisture-density equilibrium. The ANOVA results thus validate the observed trends from the laboratory experiments, highlighting the effectiveness of the RHA–SC stabilization system for engineering applications in subgrade and sub-base layers.

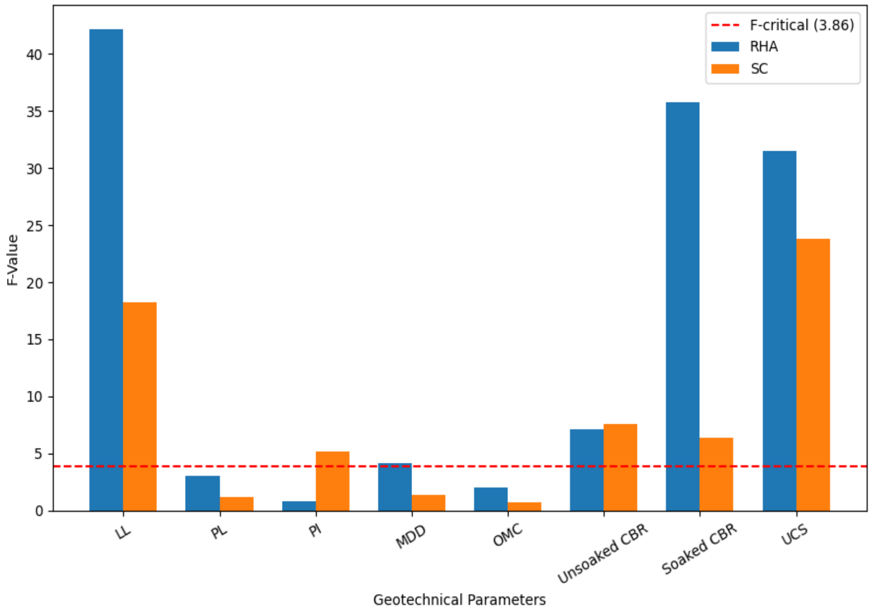


Figure 7: ANOVA F-values for geotechnical properties of lateritic soil stabilized with RHA and SC

4. CONCLUSION

From the experimental investigation and statistical evaluation carried out in this study, the following conclusions are drawn:

i. Mineralogical and chemical analyses confirmed that RHA is rich in silica, while the lateritic soil is dominated by kaolinite with associated silica and iron-bearing minerals. This mineralogical composition provides a suitable basis for effective pozzolanic stabilization when combined with an alkaline activator.

ii. The natural lateritic soil exhibited moderate plasticity and relatively low strength characteristics, with soaked CBR, UCS, and shear strength values falling below recommended requirements for pavement sub-base and base applications, indicating the need for stabilization.

iii. Stabilization with RHA and SC resulted in notable improvements in engineering properties, including reduced plasticity, enhanced bearing capacity, and increased compressive and shear strengths. The combination of 15% RHA and 12% SC produced the highest overall performance, demonstrating a strong synergistic effect between the silica-rich ash and the alkaline activator.

iv. Statistical evaluation using two-way ANOVA confirmed that RHA and SC had a significant influence on key performance indicators such as liquid limit, soaked and unsoaked CBR, and unconfined compressive strength. Although parameters such as plastic limit, plasticity index, and optimum moisture content showed statistically insignificant variations, the overall results validate the effectiveness of RHA–SC stabilization in improving lateritic soil for engineering applications.

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