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Rice Husk Ash Stabilization and Its Influence on the Index, Compaction and Strength Properties of Three Lateritic Soils of Contrasting Mineralogy

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Abstract

The stabilization of weak lateritic soils using rice husk ash (RHA) has emerged as a sustainable alternative to conventional stabilizers; however, the influence of mineralogy on the variability of stabilization performance has received limited attention. This study investigated the effects of RHA, added at 0, 4, 8, 12, and 20% by dry soil weight, on the index, compaction, and strength properties of three lateritic soils of contrasting mineralogy from southeastern Nigeria, developed on tephrite basalt (L1), mica-schist (L2), and granodiorite (L3). The soils contained 0%, 6%, and 54% kaolinite, respectively, determined by X-ray diffraction. RHA reduced the plasticity index of all soils, with the greatest reductions observed in L1 and L2, while L3 exhibited increased water demand beyond a threshold dosage. Specific gravity and maximum dry density peaked at 8% RHA in all soils. Unconfined compressive strength (UCS) and California Bearing Ratio (CBR) also reached optimum values at 8% RHA, although the magnitude of improvement varied considerably. The kaolinite-rich L3 soil recorded the greatest improvement, with CBR increasing from 4.9% to 16.3% (233%) and UCS from 26.3 to 95.9 kN/m² (265%), despite having the lowest untreated strength. In contrast, L1 and L2 showed approximately 47% increases in CBR. Beyond 8% RHA, engineering properties declined in all soils. The findings demonstrate that mineralogical composition strongly influences RHA stabilization performance, with kaolinite-rich lateritic soils exhibiting the greatest response. RHA content of 8% is recommended as the optimum dosage for the soils investigated.

Keywords: Kaolinite, California Bearing Ratio, Unconfined Compressive Strength, Plasticity Index

1. Introduction

Lateritic soils are the dominant residual soil type across the humid tropics and are extensively relied upon as subgrade, sub-base and embankment fill material in highway and foundation engineering [1]. They form through intense in-situ chemical weathering of parent rock, a process governed principally by parent material, climate, organisms, topography and time, of which parent material has been identified as the dominant control on the resulting engineering behaviour [2]. Because lateritic soils inherit their mineral composition from the underlying lithology, soils formed on different rock types within the same climatic zone can present markedly different plasticity, swelling and strength characteristics, even where a purely index-based classification would group them together [3, 4]. Lateritic soils derived from the weathering of crystalline basement rocks,

which underlie approximately 60% of Nigeria [5], and in their natural state often exhibit low bearing capacity and reduced strength on wetting, on account of their clay-mineral content [6].

Poorly characterized or untreated problematic lateritic soils have repeatedly been implicated in pavement and structural distress across Nigeria. [7] linked poor lateritic subgrade quality to elevated road-failure rates along the Benin-Ore corridor; [8] traced cracking, failure and eventual collapse of roads, buildings and drainage structures in Awka to the same cause; [9] found the majority of residential structures in the Atani community of Anambra State badly cracked or collapsed as a result of expansive soil; [10] attributed recurrent pavement failure along the F209 highway at Ado-Ekiti to poor subgrade material; and [11] reported that approximately 42% of buildings in the Demsa area of the Benue Valley exhibited major cracking, with a further 26% having collapsed outright, owing to the expansive soil behaviour. [12] characterize such soils as a significant natural hazard for civil engineering practice in Nigeria more broadly. Internationally, [13] estimated the annual cost of expansive-soil-related damage in the United States at approximately \$9 billion. [14] reported that this figure exceeds the combined cost of damage from earthquakes, floods, hurricanes and tornadoes in a typical year.

Conventional stabilization of such soils with cement and lime remains costly and carries a substantial environmental burden, cement manufacture being a significant contributor to global CO₂ emissions [15]. This has motivated growing interest in agricultural waste ashes as low-cost, more sustainable alternative stabilizers. Rice husk ash (RHA), a by-product of rice milling generated at a rate of approximately 120 million tonnes globally per year [16], is among the most extensively studied of these materials. Once burnt under controlled or open-air conditions, RHA yields a silica-rich residue capable of reacting with calcium hydroxide, whether already present in the soil or introduced by an activator, to form cementitious calcium silicate hydrate phases [17]. According to the American Concrete Institute, this capacity to react with lime in the presence of moisture to form cementitious compounds is precisely what qualifies a material as a pozzolan [18], and ASTM C618 specifies that the combined SiO₂, Al₂O₃ and Fe₂O₃ content of a natural pozzolan must reach at least 70% [19].

A substantial body of work supports the potential of RHA as a soil stabilizer, though reported optimum dosages and magnitudes of improvement vary considerably, likely reflecting differences in soil mineralogy that are seldom characterized alongside the geotechnical testing. [20] combined RHA with coconut husk ash (CHA) on lateritic soil from Kano State and found that increasing ash content raised optimum moisture content

but lowered maximum dry density, while both plasticity and CBR increased, with a 70:30 RHA:CHA blend giving the best CBR result. [21] treated two genetically dissimilar shales with RHA and CHA and found RHA produced a greater reduction in plasticity index, higher UCS and higher maximum dry density than CHA at equivalent dosage, with 10% RHA identified as the practical optimum. [22] compared bagasse ash and RHA on soft clay and recorded CBR and UCS gains of 619.8% and 85.23% for RHA at a 10% optimum. [23] applied RHA combined with coconut shell to an expansive subgrade soil and found CBR improved appreciably at 20% RHA. [24] evaluated RHA-stabilized soil specifically for pavement structural-layer performance, and [25, 6] both confirmed the general strength enhancing potential of RHA for residual tropical soils.

The reactivity of RHA is further corroborated by concrete technology, where partial cement replacement with RHA consistently improves compressive strength; [26] found RHA replacement of cement improved the mechanical properties of concrete up to approximately 10% replacement; [27] found that blending RHA with sugarcane bagasse ash produced the greatest strength gain at 5% cement replacement, attributed to depletion of calcium hydroxide and its conversion to calcium silicate hydrate gel; and [28] reported similarly favourable results for RHA and related agricultural ashes in high strength self-compacting concrete. [29] combined cement kiln dust with RHA at dosages up to 25% on lateritic soil subgrade material and used an artificial neural network to predict the resulting Atterberg limits, compaction and UCS behaviour with high accuracy, confirming the strong non-linearity of RHA dosage-response relationships. [30] developed predictive models for the UCS of RHA-treated fine-grained soils, underscoring the sensitivity of strength gain to both dosage and host-soil properties. [31] combined RHA with lime and coir fibre to stabilize laterite soil for pavement sub-base application, reporting that increasing RHA content, in combination with lime, reduced maximum dry unit weight while increasing optimum moisture content, broadly consistent with the compaction trends reported for lateritic soils in earlier studies.

What remains comparatively under examined is a controlled comparison of RHA performance across lateritic soils that differ principally in bulk mineralogy, and specifically in kaolinite content, rather than in other respects such as climate or classification group. This study addresses that gap directly, using three lateritic soils from a single highway corridor that share an essentially uniform climatic setting but differ sharply in parent rock mineralogy and, consequently, in the kaolinite content of their fines.

2. Materials and Methods

2.1 Study area and sample collection

Lateritic soil samples were collected by disturbed bulk sampling at 1.5 m depth from three locations along the Calabar-Ikom Highway, Cross River State: Ikom (L1; 08°42'E, 05°56'N; underlain by columnar tephrite basalt), Akpet (L2; 8°05'E, 5°39'N; underlain by quartz-biotite-muscovite schist) and Ehom (L3; 8°08'E, 5°27'N; underlain by granodiorite). Sample locations are shown in Fig. 1. Approximately 50 kg of bulk disturbed soil was collected at each location, below the overburden and vegetation debris, and air-dried under shade for three weeks prior to laboratory testing.

Rice husk was sourced from a rice-milling facility in Adim, Biase Local Government Area, Cross River State, air-dried, and burnt to ash under open-air atmospheric conditions on a clean zinc sheet, before being sieved through a 75 μm sieve (Plate 1). The chemical composition of the resulting RHA was determined by X-ray fluorescence (XRF) analysis.

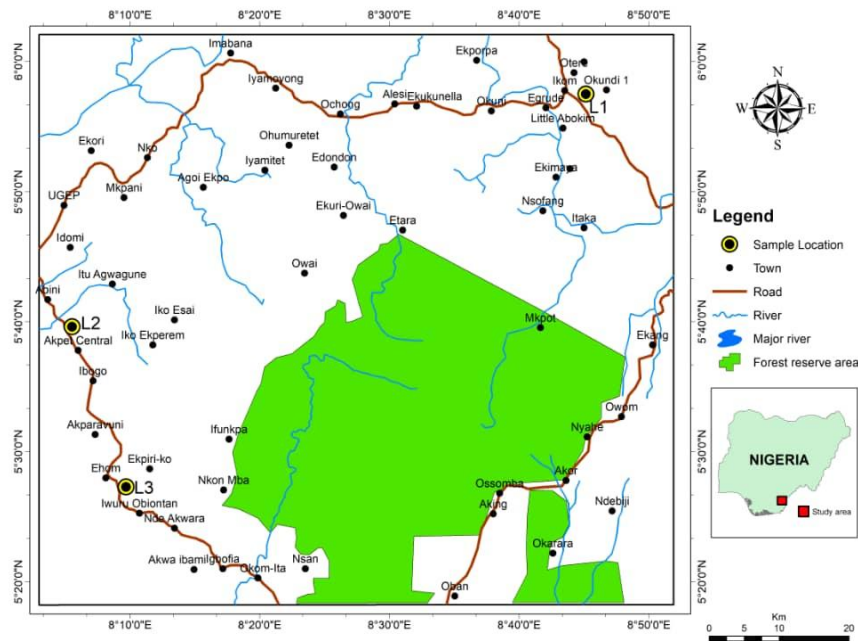


Fig. 1. Map of the study area showing the three sampling locations (Ikom, Akpet, Ehom) along the Calabar-Ikom Highway, Cross River State.



Plate 1. The prepared rice husk ash used in this study.

2.2 Treatment programme and testing

Grain-size distribution, natural moisture content, Atterberg limits, specific gravity, Modified AASHTO compaction, unconfined compressive strength (UCS) and soaked California Bearing Ratio (CBR) were determined for each untreated soil in accordance with [32]. Soils were classified using both the AASHTO [33] and Unified Soil Classification systems [34], with specific gravity testing following [35] and swelling potential evaluated using the classification of [36]. Bulk mineralogy of each soil was determined by X-ray diffraction (XRD) analysis.

Air-dried soil was mixed thoroughly with RHA at 4, 8, 12 and 20% by dry weight, with untreated soil (0%) retained as control. Atterberg limits, specific gravity, Modified AASHTO compaction, UCS and soaked CBR were determined for each treated batch following the same procedures applied to the untreated soils.

3. Results and Discussion

3.1 Baseline properties and mineralogy of the soils

The untreated properties of the three soils are summarized in Table 1. L1 classified as A-6 (USCS: ML), a silty clay of medium plasticity ($LL = 46.0\%$, $PL = 30.4\%$, $PI = 15.6\%$), with the highest maximum dry density (1.70 Mg/m^3) and bearing capacity ($CBR = 17.3\%$) of the three soils. L2 and L3 both classified as A-7-5 under AASHTO but diverged under USCS, L2 as MH ($LL = 50.0\%$, $PI = 20.0\%$) and L3 as CL ($LL = 44.8\%$, $PI = 19.8\%$).

Despite similar plasticity, L2 and L3 diverge sharply in bearing capacity; L2 recorded a soaked CBR of 15.2% against only 4.9% for L3, the lowest of the three soils. The baseline atterberg limits of the three natural soils and their positions on the casagrande plasticity chart is shown in figures 2 and 3 respectively.

Table 1. Untreated geotechnical properties of the three soils.

Property	L1 (Ikom)	L2 (Akpet)	L3 (Ehom)
Liquid limit, LL (%)	46.0	50.0	44.8
Plastic limit, PL (%)	30.4	30.0	25.0
Plasticity index, PI (%)	15.6	20.0	19.8
Specific gravity, G _s	1.86	2.21	2.20
Maximum dry density, MDD (Mg/m ³)	1.70	1.50	1.30
Optimum moisture content, OMC (%)	19.5	13.9	25.3
UCS (kN/m ²)	32.73	33.9	26.3
Soaked CBR (%)	17.30	15.20	4.90
AASHTO classification	A-6	A-7-5	A-7-5
USCS classification	ML	MH	CL

3.2 Chemical composition of the rice husk ash

The XRF result showing the chemical composition of the RHA is presented in Table 2. The combined SiO₂, Al₂O₃ and Fe₂O₃ content of the RHA (84.75%) exceeds the 70% minimum specified by ASTM C618 for classification as a natural pozzolan, confirming its suitability for the stabilization trials that follow.

Table 2. Chemical composition of the rice husk ash used in this study (XRF).

Oxide	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	K ₂ O	P ₂ O ₅	SiO ₂ +Al ₂ O ₃ +Fe ₂ O ₃
wt. %	82.14	1.34	1.27	1.21	1.96	2.09	6.44	84.75

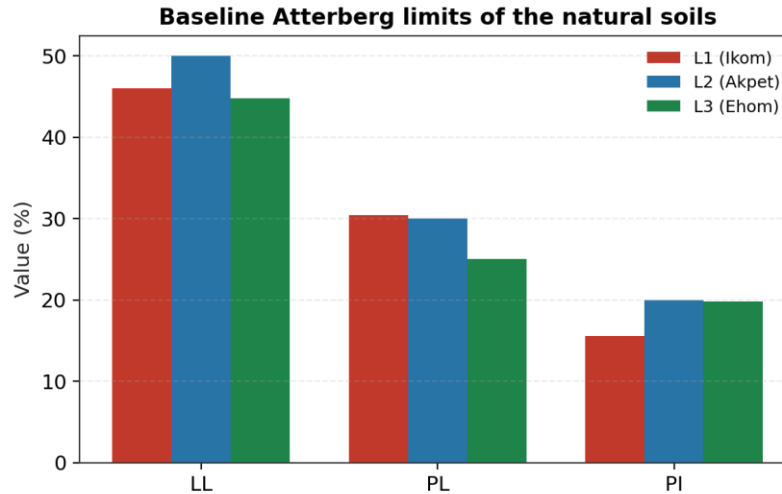


Fig. 2. Untreated Atterberg limits (LL, PL, PI) of the three soils.

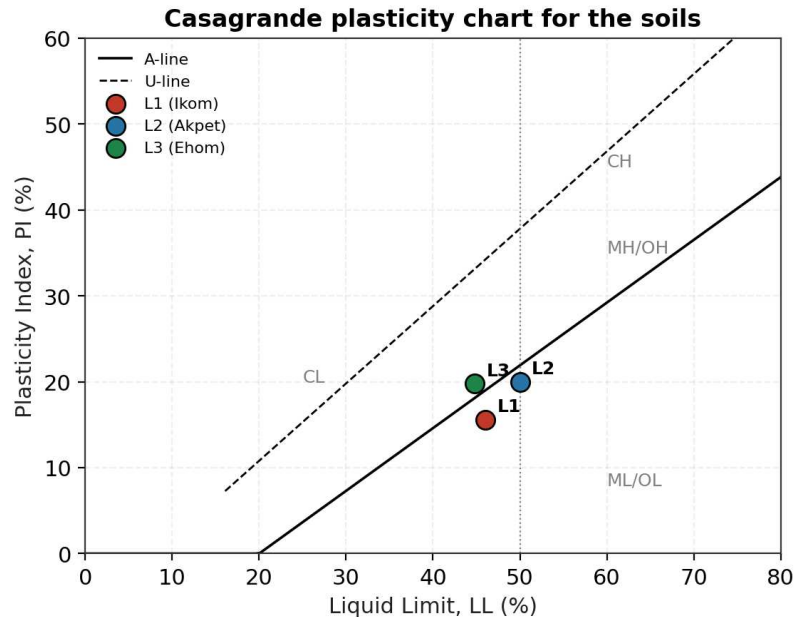


Fig. 3. Casagrande plasticity chart position of the three untreated soils.

Bulk mineralogy, (Table 3), shows that L1 is dominated by quartz (65%), orthoclase (23%) and muscovite (9%), with minor hematite and albite, and contains no kaolinite. L2 and L3 both carry kaolinite, but at markedly different proportions, 6% and 54% respectively, with L3 additionally depleted in quartz (42.1%) relative to L1 and L2 (65% each). This is graphically represented in a bar chart (Fig. 4) and the X-ray diffractograms of the three soils are shown in figures 5, 6, and 7 respectively.

Table 3. Bulk mineralogical composition (%) of the three untreated soils .

Mineral	L1 (Ikrom)	L2 (Akpet)	L3 (Ehom)
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Quartz	65	65	42.1
Orthoclase	23	19	2.7
Muscovite	9	10	1.2
Hematite	1.9	-	-
Albite	1.1	-	-
Kaolinite	-	6	54

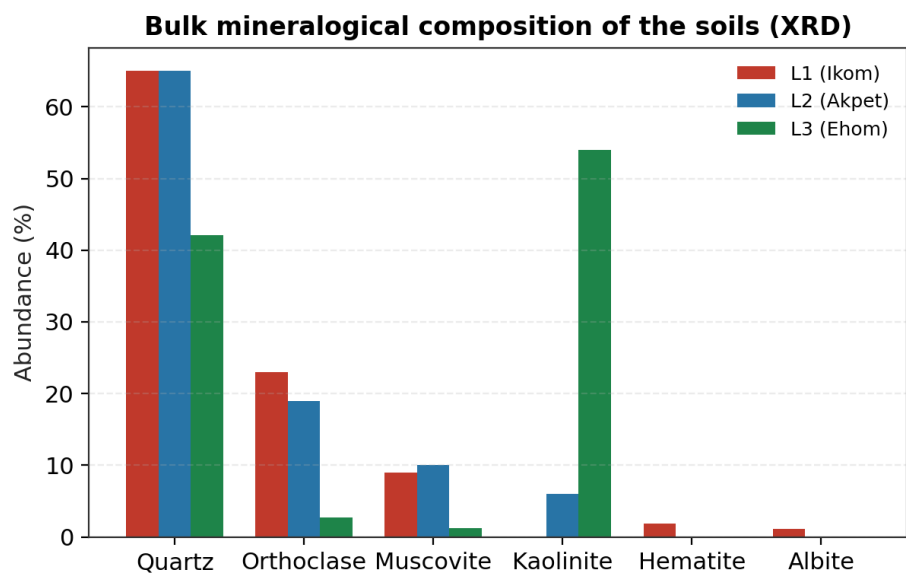


Fig. 4. Bulk mineralogical composition of the three soils (XRD).

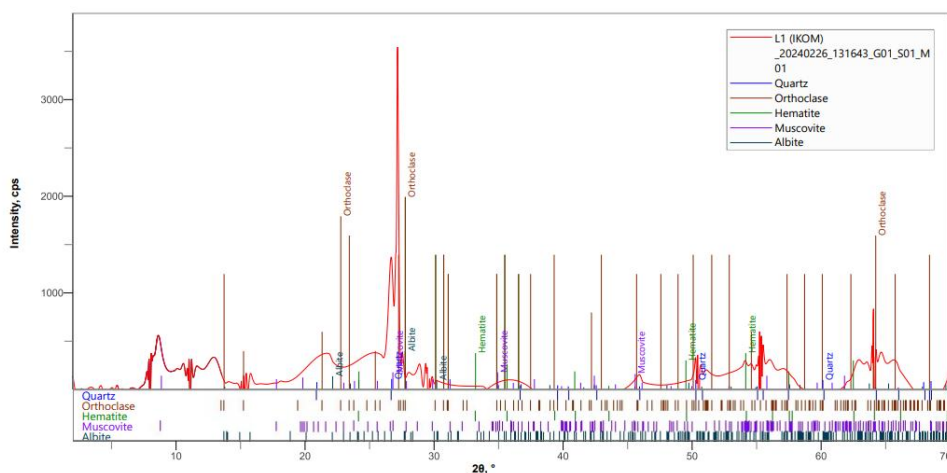


Fig. 5. X-ray diffractogram of soil L1 (Ikrom).

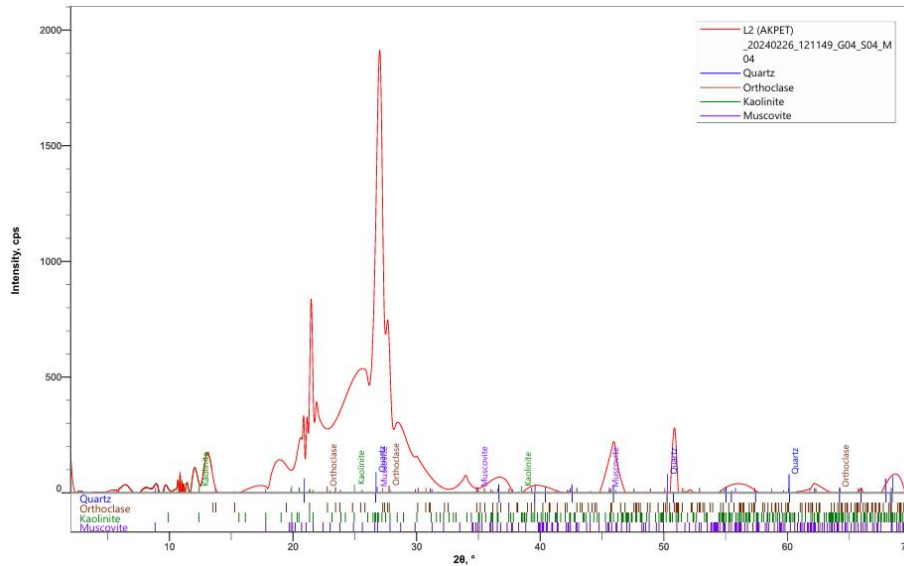


Fig. 6. X-ray diffractogram of soil L2 (Akpet).

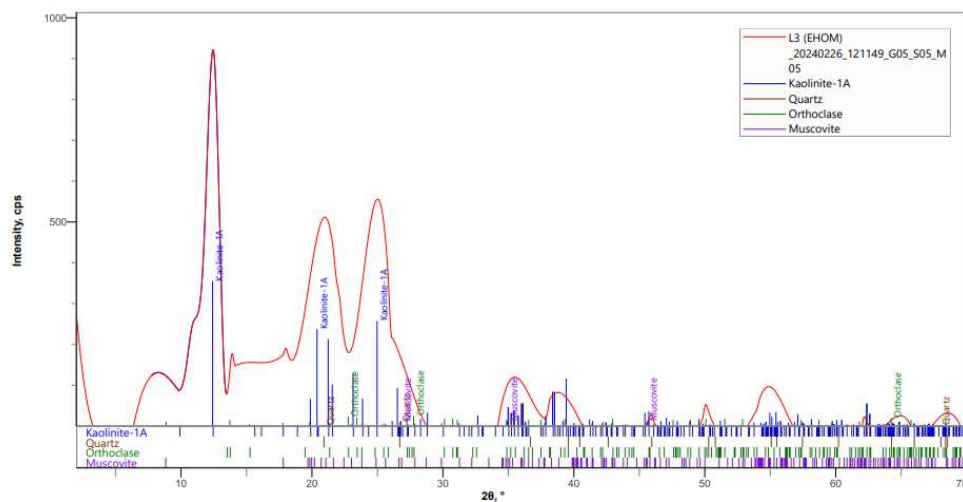


Fig. 7. X-ray diffractogram of soil L3 (Ehom).

3.3 Effect of RHA on Atterberg limits

RHA reduced plasticity index in all three soils, although the trajectory of change differed between them (Table 4; Figs. 8-9). In L1, liquid limit rose slightly at 4% RHA, from 46.0 to 49.0%, before declining to 29.0% by 20%; plasticity index fell from 15.6% to 8.0% over the same range. L2 and L3 both declined from 4% RHA onward, reaching 30.0% and 34.0% liquid limit respectively, with plasticity index falling to 7.5% (L2) and 7.7% (L3). L3 exhibits a relatively constant liquid limit between 4 and 8% RHA (38.0%), followed by an increase at 20%, consistent with a reaction threshold beyond which additional RHA behaves as an inert filler rather than as a reactant.

Table 4. Effect of RHA on Atterberg limits (LL, PL, PI, %) of soils L1, L2 and L3.

RHA (%)	L1 LL	L1 PL	L1 PI	L2 LL	L2 PL	L2 PI	L3 LL	L3 PL	L3 PI
0	46.0	30.4	15.6	50.0	30.0	20.0	44.8	25.0	19.8
4	49.0	33.0	16.0	41.7	27.3	14.4	38.0	25.5	12.5
8	39.0	27.0	12.0	44.4	32.6	11.8	38.0	28.0	10.0
12	39.0	27.5	11.5	29.0	20.0	9.0	30.0	21.5	8.5
20	29.0	21.0	8.0	30.0	22.5	7.5	34.0	26.3	7.7

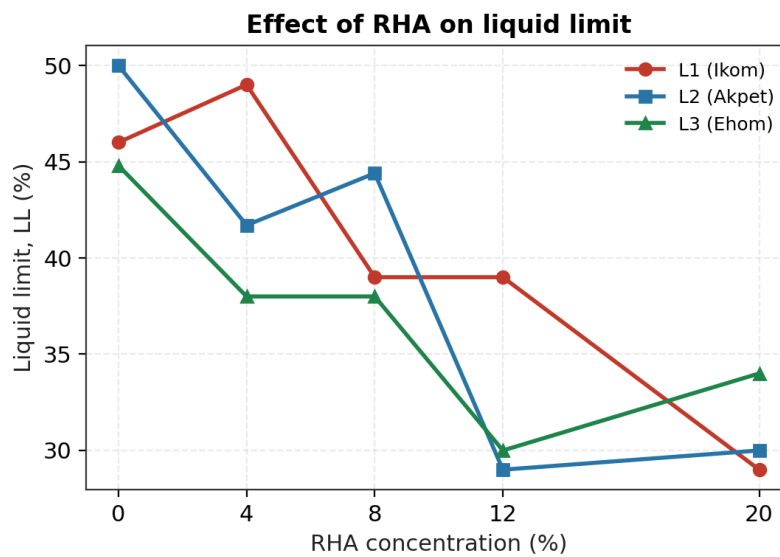


Fig. 8. Effect of RHA concentration on liquid limit.

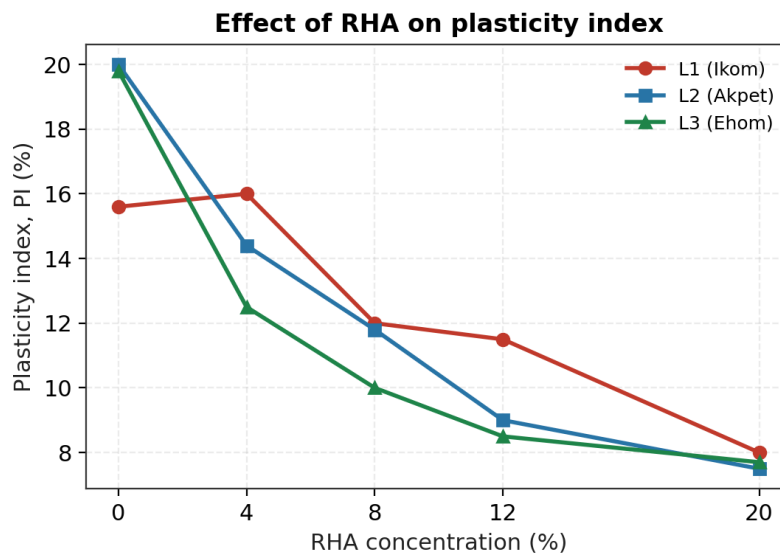


Fig. 9. Effect of RHA concentration on plasticity index.

3.4 Effect of RHA on specific gravity and compaction

The results of the effects of RHA treatment on the specific gravity and compaction characteristics of the soils are presented in Table 5. Specific gravity declined overall with increasing RHA content, consistent with the low specific gravity of RHA relative to the host soils, although each soil exhibited a local peak at intermediate dosage; 8% for L1 (2.15) and L2 (2.06), and 12% for L3 (2.14) (Fig. 10). Maximum dry density increased with RHA up to 8% in all three soils, from 1.70 to 2.05 Mg/m³ in L1, 1.5 to 1.8 Mg/m³ in L2, and 1.3 to 1.8 Mg/m³ in L3, before declining at higher dosages (Fig. 11). Optimum moisture content followed a less consistent trend as L1 fell sharply at 4% RHA before rising gradually, L3 declined steadily to 14.8% by 8%, and L2 showed no clear pattern across the dosage range (Fig. 12).

Table 5. Effect of RHA on specific gravity, maximum dry density and optimum moisture content of soils L1, L2 and L3.

RHA (%)	L1 Gs	L2 Gs	L3 Gs	L1 MDD	L2 MDD	L3 MDD	L1 OMC	L2 OMC	L3 OMC
0	1.86	2.21	2.20	1.70	1.50	1.30	19.5	13.9	25.3
4	1.50	1.85	1.36	1.80	1.60	1.52	6.0	16.8	15.0
8	2.15	2.06	1.90	2.05	1.80	1.80	7.0	11.2	14.8
12	1.51	1.76	2.14	1.90	1.44	1.58	10.8	13.0	23.0
20	1.50	1.27	2.12	1.80	1.40	1.42	11.2	18.5	13.0

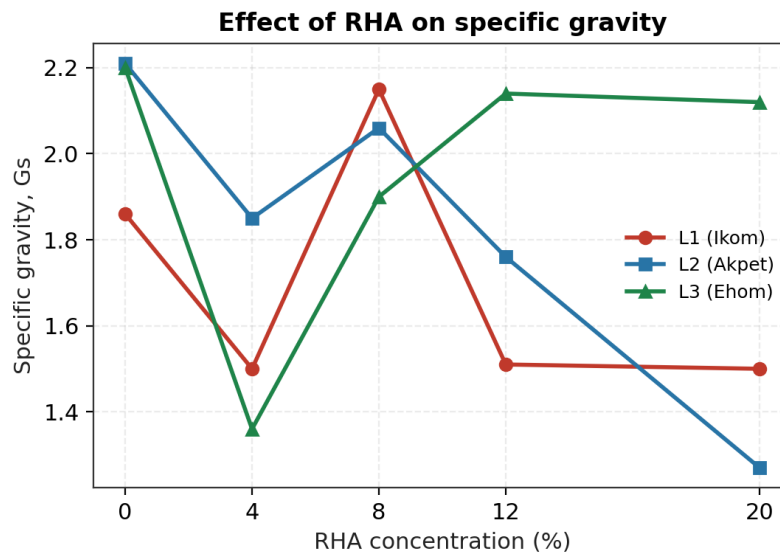


Fig. 10. Effect of RHA concentration on specific gravity.

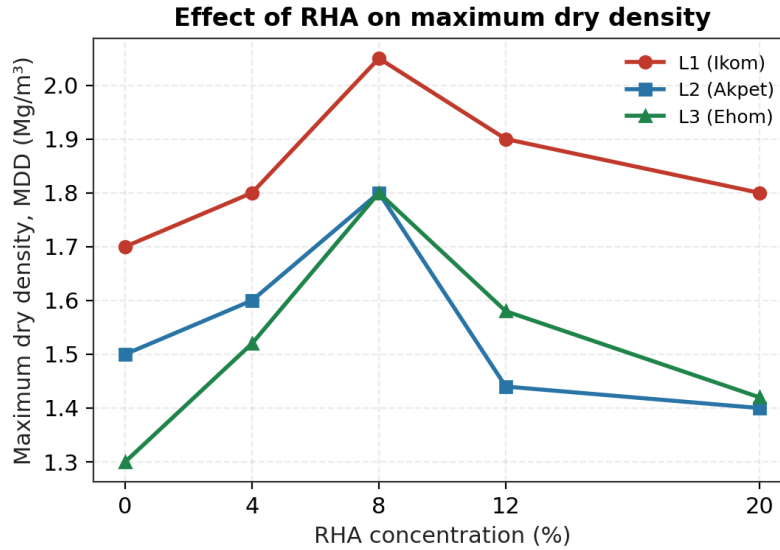


Fig. 11. Effect of RHA concentration on maximum dry density.

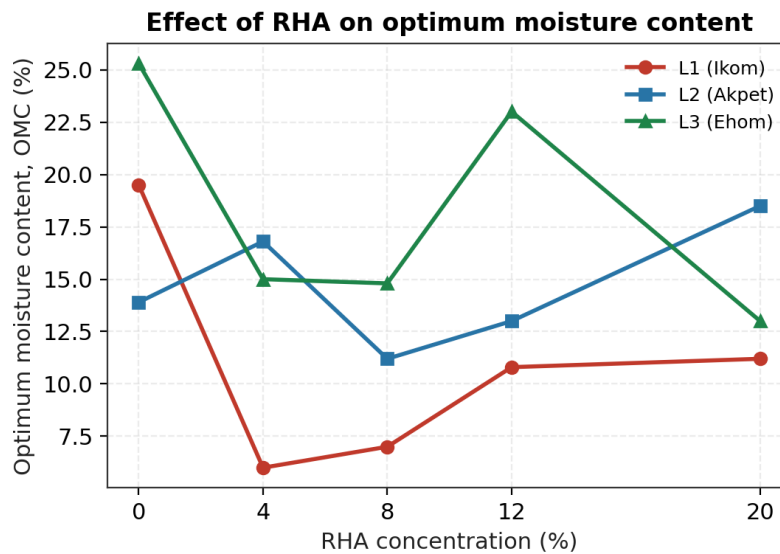


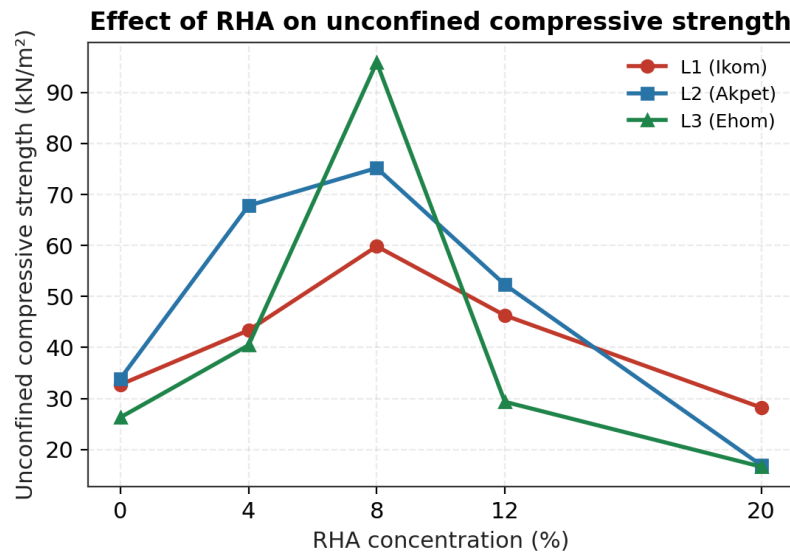
Fig. 12. Effect of RHA concentration on optimum moisture content.

3.5 Effect of RHA on unconfined compressive strength

Unconfined compressive strength increased with RHA content up to 8% in every soil before declining thereafter (Table 6; Fig. 13). L1 increased from 32.73 to 59.85 kN/m² (an 83% gain) and L2 from 33.9 to 75.2 kN/m² (122%). The largest gain occurred in L3, from 26.3 to 95.9 kN/m², a 265% increase, which resulted in L3 attaining the highest UCS of the three soils despite possessing the weakest untreated strength. Beyond 8%, strength declined in all three soils, most markedly in L3 (falling to 29.35 kN/m² at 12%).

Table 6. Effect of RHA on unconfined compressive strength (kN/m²).

RHA (%)	L1	L2	L3
0	32.73	33.9	26.3
4	43.38	67.83	40.46
8	59.85	75.2	95.9
12	46.3	52.33	29.35
20	28.23	16.93	16.63

**Fig. 13. Effect of RHA concentration on unconfined compressive strength.**

3.6 Effect of RHA on California Bearing Ratio

CBR follows the same trend as UCS, again peaking at 8% RHA across all three soils (Table 7; Fig. 14). L1 increased from 17.3% to 25.45% (47%), L2 from 15.2% to 22.4% (also approximately 47%), and L3 from 4.9% to 16.3%, a 233% gain, the largest relative improvement of the three soils. Against the minimum soaked CBR values of 6% and 30% specified for subgrade and sub-base material, respectively, by the [37] general specification for roads and bridges, all three soils satisfy the subgrade requirement at 8% RHA; L1 and L2 approach, but do not reach, the sub-base threshold.

Table 7. Effect of RHA on soaked California Bearing Ratio (%).

RHA (%)	L1	L2	L3
0	17.30	15.20	4.90
4	24.62	18.0	7.16
8	25.45	22.4	16.3
12	19.66	8.53	13.46
20	17.90	7.16	4.43

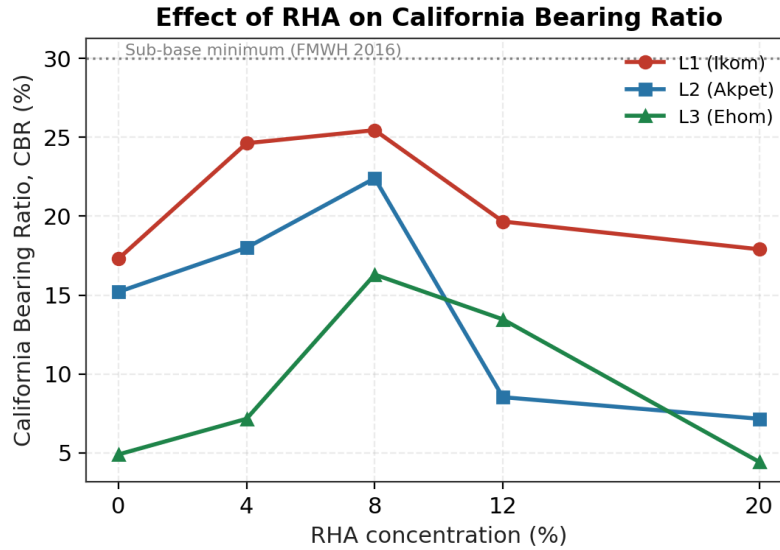


Fig. 14. Effect of RHA concentration on California Bearing Ratio.

3.7 Discussion

The reduction in plasticity index observed across all three soils is consistent with the established pozzolanic mechanism, whereby silica supplied by RHA reacts with available calcium to form cementitious products that occupy reactive clay surface area, thereby reducing the soil's capacity to hold water. This is in agreement with the findings of [21] for RHA-treated shale and [20] for RHA and CHA-treated lateritic soil, and with the compaction trends reported by [31] for RHA and lime-treated laterite. The slight interruption in the liquid limit decline of L3 between 4% and 8% RHA addition, maybe attributed to its high kaolinite content, which appears to reach its reaction threshold rapidly, beyond which additional RHA functions predominantly as filler material rather than as a reactant, whereas L1 and L2, with lower and more evenly distributed clay content, continue to respond progressively across the dosage range examined.

The strength results support the same interpretation. All three soils attain peak UCS and CBR at 8% RHA, yet the magnitude of the gain is substantially greater in the kaolinite-rich L3 than in the quartz-dominated L1 and L2. Kaolinite presents considerably more reactive surface area than quartz or orthoclase, providing more sites for calcium silicate hydrate formation provided sufficient calcium is available [38]. The 265% UCS gain recorded in L3 exceeds the gains reported for RHA-treated shale by [21] and for RHA-treated soft clay by [22], and is largely consistent with the strongly non linear, soil-dependent UCS response reported for RHA-treated fine grained soils by [30] and for RHA and cement-kiln-dust-treated lateritic subgrade by [29], both of which found host-soil properties to be a dominant factor governing the magnitude of strength gain. This suggests that kaolinite-rich lateritic soils may respond particularly favourably to RHA

treatment where an adequate calcium source, whether from the soil itself or elsewhere, is present, consistent with the general relationship between clay-mineral abundance and consistency-limit behaviour established by [39] and [40] and with the flocculation mechanism proposed for treated fine-grained soils by [41].

The decline in all properties beyond 8% RHA may be attributed to the point at which RHA ceases to react further and instead dilutes the soil-ash mixture, introducing additional porosity and low-density filler without contributing to particle bonding, a pattern also reported by [42] and [43] for other chemically stabilized Nigerian residual soils.

4. Conclusions

1. Rice husk ash reduces the plasticity index of all three soils examined, with the most progressive reduction observed in the kaolinite-poor L1 and L2, and a threshold-type response in the kaolinite-dominant L3.
2. Specific gravity and maximum dry density both attain a peak at 8% RHA, extending to 12% for specific gravity in L3; optimum moisture content shows a less consistent trend across the three soils.
3. Unconfined compressive strength and soaked CBR both peak at 8% RHA in all three soils, with the magnitude of improvement scaling with kaolinite content and reaching its largest value in L3 (265% for UCS, 233% for CBR), notwithstanding L3 possessing the weakest untreated properties of the three soils.
4. At 8% RHA, all three soils satisfy the minimum soaked CBR of 6% specified for subgrade material by the Federal Ministry of Works and Housing (2016) general specification for roads and bridges, supporting the use of RHA as a viable and sustainable stabilizer for subgrade application on soils of this type.
5. A RHA dosage of 8% by dry soil weight is recommended as the general treatment level for the lateritic soils examined, with the greatest relative benefit expected on kaolinite-rich material.

Policy Statements and Declarations

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Competing interests policy

The authors declare that they have no known competing financial or non-financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The datasets generated and analysed during the current study are available from the corresponding author on reasonable request.

Ethics, Consent to Participate, and Consent to Publish declarations

Not applicable.

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