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Synergestic Effect of Rice Husk Ash Blended With Cement on the Stabilization of Lateritic Soil for Road Construction

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ABSTRACT

Lateritic soils are widespread in tropical regions and are often unsuitable in their natural state due to their high plasticity and low strength. Although Portland cement has been used for soil stabilization over time, its heightened environmental concerns due to carbon emissions from its production have led to the need for alternatives. This study, therefore, aimed at investigating the effects of stabilization of Lateritic soil with Rice Husk Ash (RHA) blended with cement for highway application. Oxide compositions of lateritic soil obtained from Aroje, Ogbomoso, Nigeria and RHA were determined using X-Ray Fluorescence (XRF) Spectrophotometer. Natural Moisture Content (NMC), Percentage passing sieve No. 200 (P-200) Liquid Limit (LL), Plastic Limit (PL), Plasticity Index (PI), Optimum Moisture Content (OMC), Maximum Dry Density (MDD) California Bearing Ratio (CBR), and Unconfined Compressive Strength (UCS) were determined for the lateritic soil after it had been admixed with varying proportions of Portland Lime Cement (PLC) (5, 10 and 15%) and RHA (2, 4, 6, 8 and 10%) by dry weight of soil to evaluate the best mix for the stabilization. The SiO_2, Al_2O_3 and Fe_2O_3 contents in the lateritic soil and RHA were 58.057, 18.212 and 13.620%, and 84.195, 2.819 and 0.863%, respectively. The NMC, PI and P-200 of natural soil were 10, 50 and 32.76%. The LL, PL, PI, MDD, CBR, and UCS of stabilized soil ranged 25.0 - 31.50, 25.0 – 29.3.0, 0 -3.5, 7.95 – 10.81%, 1.84 - 1.960 g/cm^3, 76 -94 and 186 - 334 kPa, respectively. There was a good improvement in the strength properties of lateritic soil using 10 as the best mix of cement and RHA and this can be used as a subbase and base material in road construction.

INTRODUCTION

Engineering properties of soil play a significant role in civil engineering construction works, particularly in road constructions, foundations, embankments, slope stability, subgrade materials and dams (Basha *et al*., 2021). In recent times, the alarming rate at which lives are being lost due to collapsed buildings and road failures calls for a solution (Onyelowe *et al*., 2022). The long-term performance of any construction project depends on the engineering competence of the underlying soils. This made it imperative to critically and deliberately carry out geotechnical tests of the engineering soil. This would determine its geotechnical stability as a construction material (Singh *et al*., 2020).

Lateritic soil is also said to be a type of soil that forms in tropical and subtropical climates under conditions of intense weathering and leaching. According to Nnochiri and Aderinlewo (2016), the term lateritic soil can be described as the soil rich in iron and aluminum oxide with high plasticity, low permeability, and stiffness; although it is commonly used in road construction, it may become unstable in wet conditions and can only provide good bearing capacity when adequately compacted. It is of great importance to then stabilize the lateritic soil by altering its properties and making it suitable for construction works. (Nnochiri and Aderinlewo, 2016). Laterite soil consists of high plastic clay; the plasticity of laterite may result in cracks and damage to building foundations, pavement, highway, or any other construction projects, thus the need for the stabilization of laterite (Budhu, 2015; Adegun and Adesina, 2023).

However, one of the most effective ways to improve soil properties is through stabilization, which implies modifying soils to enhance their strength characteristics. Soil stabilization can increase shear strength, control shrink-swell behavior, and improve load-bearing capacity and durability under adverse moisture conditions (Horpibulsuk *et al*., 2019). It also addresses issues such as high permeability, poor workability, and dust nuisance, and can withstand both static and dynamic stresses (Muntohar *et al*., 2021). Moreover, stabilization increases resistance to erosion and weathering, and reduces undesirable properties such as swelling, shrinkage, high plasticity, and difficulty in compaction (Islam *et al*., 2023). Stabilization of soils can also aid in dust control on roads and highways, particularly unpaved roads, in water erosion control and in fixation and leaching control of waste and recycled materials (Ameta and Solanki, 2020). Soil stabilization deals with physical, physico-chemical and chemical methods to make the stabilized soil serve its purpose as a construction material through the use of controlled compaction, proportioning and addition of suitable admixture (Jha and Sivapullaiah, 2021; Adedokun *et al.,* 2022).

The basic principle of soil stabilization is the evaluation of the properties of the soil, then deciding the method of supplementing the lacking property by the effective and economical method of stabilization and designing the stabilized soil mix for desired stability values, which would be considered for construction (Dash and Hussain, 2018). When selecting a stabilizing agent, the types of soil, purpose for which the stabilized layer will be used, the desired quality of the stabilized soil, required strength and durability of the stabilized layer, cost and environmental conditions are some key factors to consider (Onyelowe *et al*., 2022).

Although cement, lime and other non-conventional materials have been proposed for use (Adedokun *et al.,* 2022; Oluremi *et al.,* 2022; Adebayo *et al.,* 2023; Akinwunmi and Philip, 2023), environmental pollution is a serious threat to the sustainability of the human race, hence the use of Rice husk for the stabilization of laterite materials in this study. It was discovered that Portland cement, by the nature of its chemistry, produces large quantities of Carbon dioxide for every tonne of its final product (Oluremi *et al.,* 2020; Adedokun *et al.,* 2022).

METHODOLOGY

Materials

Collection of materials

Lateritic soil samples were collected at the Aroje area in Ogbomoso, Oyo State, Nigeria. The lateritic soil samples were air-dried, pulverized, and sieved in accordance with BS 1377 (1990) before their use without the addition of any additive to achieve uniform texture and color. Rice Husk Ash (RHA) used was produced by collecting a considerable amount in volume of rice husk from a rice milling factory at Iresa, Ogbomoso, Oyo State, Nigeria. The collected rice husk was taken to Ladoke Akintola University of Technology, Ogbomoso, Oyo State, Nigeria, where it was sundried for 24 hours and calcinated at 600 °C. The oxide composition of Silica, Alumina and Iron oxide was determined using the X-Ray Fluorescence method.

Stabilization of the lateritic soil

Various percentages of RHA and cement, as shown in Table 1, were introduced to replace an equivalent weight of lateritic soil. The RHA and cement additive were added to the lateritic soil and thoroughly mixed to obtain a homogenous mixture. Water was added to the soil and the additive mix.

Equipment

The equipment used for this study included a set of sieves, a mechanical sieve shaker, a weighing balance, a drying oven, a flat glass plate of 10 mm thick, a Cassagrande apparatus, a grooving tool, a desiccator, a palette, knives, a wash bottle, cylindrical moulds, metal rammer, spatula, CBR, UCS, XRF and XRD.

Table 1: Variation of Cement and Rice Husk Ash

Cement (%)	RHA (%)				
	2	4	6	8	10
5	5,2	5,4	5,6	5,8	5,10
10	10,2	10,4	10,6	10,8	10,10
15	15,2	15,4	15,6	15,8	15,10

Geotechnical Investigation on Samples

The laboratory tests that were carried out on the natural lateritic soil and lateritic soil admixed with varied percentages of cement and RHA include sieve analysis, Atterberg limits, Compaction, California Bearing Ratio (CBR) for unsoaked conditions and Unconfined Compressive Strength UCS.

Particle size distribution

This test was carried out to determine the various sizes of soil particles in a given sample of soil and also the percentage of the total weight represented by various range of grain sizes. The particles were divided into groups in agreement with BS 1377 (1990): Part 2. The equipment used for this experiment is a set of sieves, a mechanical sieve shaker, a weighing balance, a mortar and rubber pestle, an evaporating dish, a drying oven and a scoop. 400g of the dry soil was wet-washed on a sieve 75 µm to cleanliness and the retained sample was oven-dried for 24 hours at a temperature of 105°C, before sieving was done. The sieves were arranged orderly from the largest sieve size (4.75 mm) to the smallest sieve size (75 µm) on a pan as a dust collector, and placed into the mechanical sieve shaker, which was operated for about 5 minutes.

The sample was placed on the topmost sieve, covered and the mechanical sieve shaker was operated. After sieving, the amount of soil sample retained in each sieve was determined and the percentage passing for each sieve was estimated. After the calculation, the graph of percentage passing was plotted against the sieve size. The same procedure was repeated for other lateritic soil samples admixed with varied percentages of cement and RHA. This was done in agreement with BS 1377 (1990) Part 2 Section 9.2.

Atterberg limits

Atterberg Limits are basic measures of the nature of fine-grained soils appearing in four states: solid, semi-solid, plastic and liquid relative to the quantity and type of clay minerals present in it. The regularity and behavior of different soils are different; thus, their engineering properties are too. The Atterberg consistency limit test was used to determine certain soil properties, including liquid limit (LL), plastic limit (PL) and plasticity index (PI). The apparatus used for this experiment is a drying oven, a flat glass plate about 10mm thick, a Cassagrande apparatus, a grooving, a desiccator, palette knives, a wash bottle, a sieve of size 425µm, and a corrosion-resistant container. These tests were done in accordance with the provisions of BS1377 (1990) Part 2 Section 5.0.

Compaction

Compaction of soil is the procedure through which the solid particles are packed more strongly together, usually by mechanical means, thereby increasing the dry density of the soil. The dry density that can be achieved depends on the degree of compaction applied and on the amount of water present in the soil. For a given compaction of a given cohesive soil, there is an optimal moisture content at which the dry density obtained reaches a maximum value.

As described in BS 1377 (1990) Part 4 Section 3.6 for WAS, the natural soil was compacted inside a 1000 cm^3 BS mould in 5 layers using 10 blows of a 4.5 kg rammer dropped from 450mm height. The soil sample was mixed with 4% of water by weight of the soil sample as assumed moisture content and then compacted in 5 layers using 10 blows of a 4.5 kg rammer dropped from 450 mm height. For each of the compacted soils, protruding soils will be carefully leveled off with a straight edge. The weight of the soil samples in the mould was determined with the corresponding moisture content. From the data obtained, the bulk density and the dry density were calculated for each compacted sample. Thereafter, the MDD and the OMC were determined from the graphical representation of the connection between dry density and the moisture content.

California Bearing Ratio (CBR)

For unsoaked, the soil material was compacted at its OMC and its MDD. The sample was compacted in a CBR mould relative to the WAS compaction effort selected for this work. For WAS, compaction was done in five layers with 27 blows of a 4.5 kg rammer dropped from a height of 450 mm per layer. The compacted sample was laced on the CBR machine and incremental load was applied via piston at the top and the base of the sample, which will be read off from the load dial gauge at varying penetration depths. The graph of dial load was plotted against penetration. The dial loads at 2.5 mm and 5 mm were recorded and the corresponding CBR value will be determined. The same procedure was repeated for other lateritic soil samples admixed with varied percentages of potash and rice husk ash. This was done based on BS 1377 (1990) Part 4 Section 7.2.4.

Unconfined Compressive Strength (UCS)

Unconfined compressive strength is the load per unit area at which an unconfined cylindrical specimen of soil will fail in a simple compression test. It is suited for measuring the unconsolidated undrained shear strength of intact and saturated soil. The mass of the prepared test specimen was determined to the nearest 0.1g. Make at least three measurements of the length and of the diameter of the specimen to the nearest 0.1 mm and determine the average dimensions. The specimen was placed centrally on the pedestal of the compression machine between the upper and lower platens. The machine was adjusted so that contact is just made between the specimen, the upper platen and the force measuring device. The axial deformation gauge was adjusted to read zero or a convenient initial reading. The initial readings of the force and compression gauges were recorded.

Chemical Characterization of Rice Husk Ash and Lateritic Soil

The Chemical Characterization of lateritic soil and RHA was carried out using X-Ray Fluorescence, and X-Ray Diffraction, as specified in BS EN 196-2 (1995) at Nigerian Geological Survey, Kaduna State, Nigeria.

Statistical Analysis

Statistical analysis was conducted to evaluate the significance and reliability of the effects of cement and RHA on the geotechnical properties of lateritic soil. Two-way Analysis of Variance (ANOVA) was performed for each engineering property to assess the individual and interactive effects of cement percentage and RHA percentage on the measured responses.

RESULTS AND DISCUSSION

Chemical Characterization

The chemical characterization provided fundamental insights into the stabilization mechanisms. XRF analysis of lateritic soil and rice husk ash (Table 2) revealed predominantly the presence of siliceous compounds with SiO_2 content of 58.057 and 84.195%, confirming a synergetic relationship between the two materials and excellent pozzolanic potential of RHA. The sum of SiO_2, Al_2O_3 and Fe_2O_3 contents in RHA is 87.88% significantly exceeding the minimum requirement of 70% specified in ASTM C618 for pozzolanic materials. These percentages conform with the range specified for RHA in (Onyelowe *et al.,*2018). The lateritic soil showed a typical tropical composition with SiO_2 (58.057%), Al_2O_3 (18.212%), and Fe_2O_3 (13.620%).

Table 2. Oxide composition of lateritic soil and RHA

Oxide	Lateritic soil Concentration (%)	Rice Husk Ash Concentration (%)
SiO_2	58.057	84.195
V_2O_5	0.040	0.040
Cr_2O_3	0.000	0.003
MnO	0.127	0.339
Fe_2O_3	13.620	0.863
Co_3O_4	0.039	0.000
NiO	0.000	0.002
CuO	0.054	0.093
Nb_2O_3	0.006	0.006
P_2O_5	0.000	0.490
SO_3	0.873	0.864
CaO	1.029	4.529
MgO	2.185	0
K_2O	1.888	2.728
BaO	0.094	0
Al_2O_3	18.212	2.819
Ta_2O_5	0.003	0.005
TiO_2	1.989	0.457
ZnO	0.032	0.033
Ag_2O	0.012	0.007
Cl	1.451	2.549
ZrO_2	0.292	0.017

XRD analysis of lateritic soil presented in Figure 1 and Table 3, confirmed the presence of kaolinite as the predominant clay mineral, with a minute amount of Quartz and Muscovite, which explains its moderate plasticity characteristics. For RHA, there is the presence of Urea and graphite (Carbon), as shown in Figure 2 and Table 4, which completely masked the presence of amorphous phases as revealed in the XRF result. This may result from the incomplete combustion of rice husk, which limits its potential as an excellent pozzolanic material.

Sieve Analysis Results

Figure 5 showed that the lateritic soil exhibits a well-graded particle size distribution with 30.20% of particles passing through the 0.075 mm sieve, classifying these as fines (clay and silt particles).

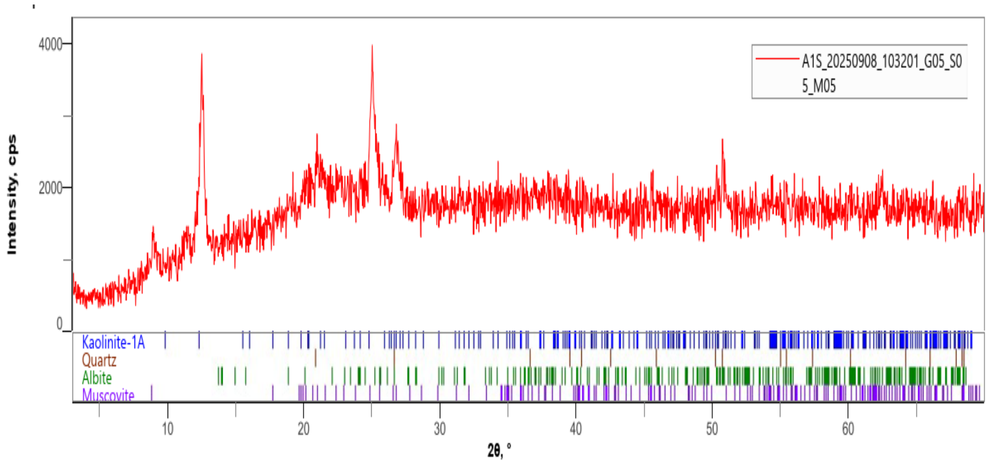

Figure 1: Analyzed the X-ray diffraction spectrum of lateritic soil

Table 3: Phase minerals in lateritic soil

Mineral Phase Name	Formula	Concentration (%)
Kaolinite-1A	$Al_2Si_2O_5(OH)$	76
Quartz	SiO_2	9
Albite	$NaAlSi_3O_8$	0.5
Muscovite	$KAl_2(Si_3Al)O_{10}(OH,F)$	15

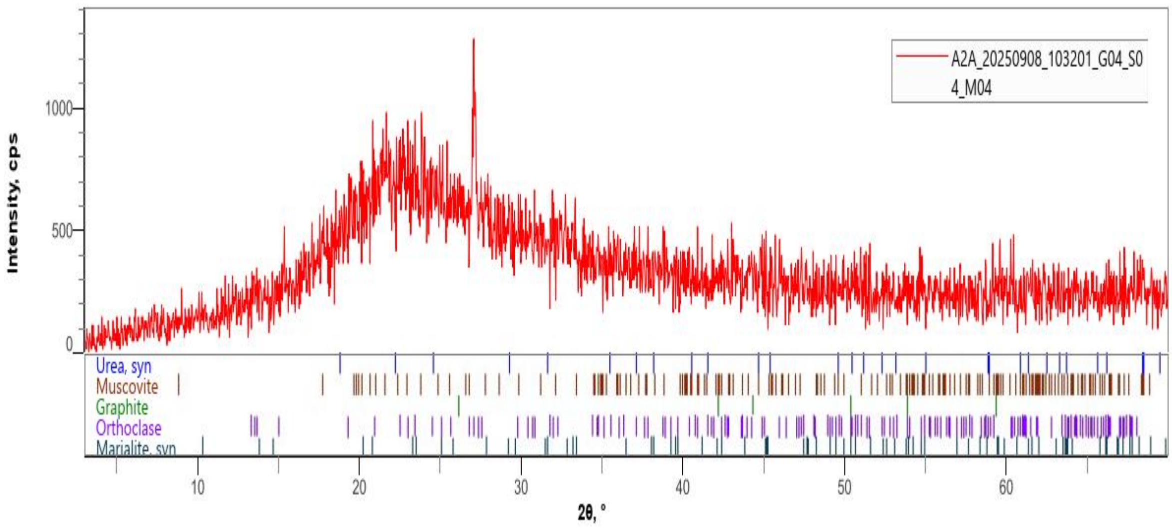

Figure 2: Analyzed the X-ray diffraction spectrum of rice husk ash

Table 4: Phase minerals in rice husk ash

Mineral Phase Name	Formula	Concentration (%)
Urea, syn	CH_4N_2O	59
Muscovite	$KAl_2(Si_3Al)O_{10}(OH,F)$	13
Graphite	C	17
Orthoclase	$K(Al,Fe)Si_2O_8$	4
Marialite, syn	$Na_4Al_3Si_9O_{24}Cl$	7

The remaining 69.80% consists of coarser particles ranging from fine sand to gravel sizes, providing the soil's skeletal structure. The largest single fraction (13.00%) was retained on the 1mm sieve, followed by 12.28% on the 4 mm sieve and 11.90% on the 2 mm sieve, indicating a relatively uniform spread of particle sizes in the medium to coarse sand range. This particle size distribution is particularly favorable for stabilization with cementitious materials, as the well-distributed particle sizes create numerous contact points for cement hydration products and pozzolanic reactions to develop. The presence of approximately 30% fines provides sufficient cohesion for binding coarser particles, while the 70% coarser fraction ensures adequate bearing capacity and reduced compressibility. The percentage finer than 75 µm is less than 35% as stipulated in the Nigerian Highway and Road Specification (1997). Recent research by Nnochiri *et al.* (2024) on lateritic soil stabilization with agricultural waste reported similar particle size distributions, with fine content ranging from 28-35% for tropical lateritic soils, supporting the suitability of such gradation for stabilization applications.

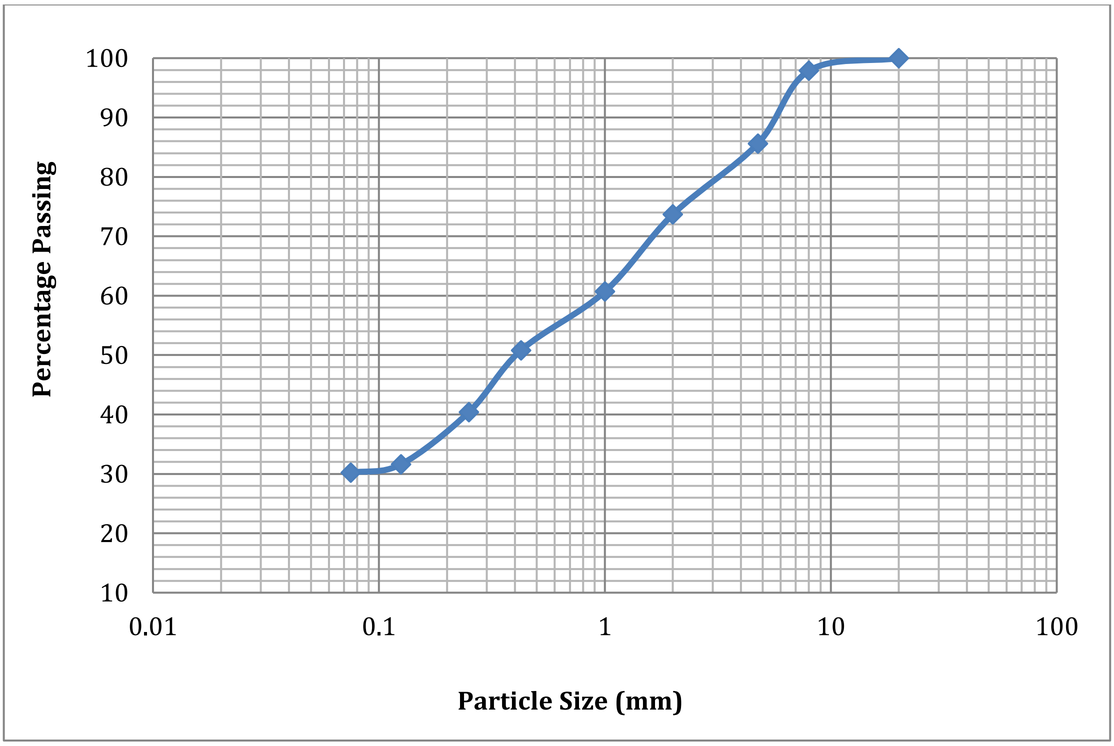

Figure 5: Sieve Analysis Result

Atterberg Limit Results

The Atterberg limits assessment in Table 5 revealed systematic variations in plasticity behavior across different stabilization scenarios. The liquid limit results show a consistent decreasing trend with increasing stabilizer content across all tested combinations. At 5% cement content, the liquid limit decreases progressively from 31.5% at 2% RHA to 27% at 10% RHA, representing a 14.3% reduction. This reduction becomes more pronounced at higher cement contents, with the 10% cement series showing liquid limits ranging from 31% to 25.8%, and the 15% cement series displaying values from 31% to 25%. The plastic limit values exhibit similar declining trends, with convergence of plastic limit and liquid limit values at higher stabilizer contents, indicating approaching non-plastic behavior.

The plasticity index provides the most significant indication of stabilization effectiveness, with values decreasing from initial values of 3.5, 2.4, and 1.8 for 5%, 10%, and 15% cement at 2% RHA, respectively, to zero at 10% RHA for all cement percentages. This achievement of zero plasticity index represents the complete elimination of plastic behavior, transforming the soil from a plastic material to a non-plastic one with minimal volume changes under moisture variation

Table 5: Atterberg Limits at Various Cement and RHA Percentages

Cement (%)	RHA (%)	Liquid limit	Plastic limit	Plasticity index
5	2	31.5	28	3.5
	4	30	29	1
	6	30	29.3	0.7
	8	29.2	28.8	0.4
	10	27	27	0
10	2	31	28.6	2.4
	4	29.6	28	1.6
	6	28.8	28	0.8
	8	29.2	28.6	0.6
	10	25.8	25.8	0
15	2	31	29.2	1.8
	4	29.5	28	1.5
	6	28	27.6	0.4
	8	28.8	28.6	0.2
	10	25	25	0

The systematic reduction in plasticity with increasing RHA content indicates the significant contribution of rice husk ash to the stabilization process through pozzolanic reactions, physical filling effects, and chemical interaction with clay minerals. Studies by Kumar *et al*. (2022) confirmed that RHA content above 8% consistently achieved non-plastic behavior in combination with cement, supporting the current findings.

Compaction Results

The compaction test results reveal complex interactions between cement content, RHA percentage, maximum dry density (MDD), and optimum moisture content (OMC). Figure 6 showed that Maximum dry density values range from 1.84 g/cm³ to 1.96 g/cm³, with the highest MDD achieved with 5% cement and 8% RHA. The 5% cement series shows MDD values increasing from 1.92 g/cm³ at 2% RHA to 1.96 g/cm³ at 8% RHA, then decreasing to 1.87 g/cm³ at 10% RHA, suggesting that 8% RHA represents the optimal proportion for maximum density with 5% cement.

The 10% cement combinations exhibit a different pattern, with the highest density (1.95 g/cm³) occurring at 10% RHA, while the 15% cement series shows relatively consistent values ranging from 1.84 g/cm³ to 1.91 g/cm³. Figure 7 revealed that the optimum moisture content values demonstrate an inverse relationship with MDD, ranging from 7.95% to 10.81%. The lowest OMC corresponds to the highest MDD achieved with 5% cement and 8% RHA, while higher cement contents generally require higher moisture contents for optimal compaction due to cement hydration water demands.

Comparative studies by Rahman *et al.* (2024) reported OMC values between 8.5% and 12.4% for rice husk ash stabilized clayey soils, generally higher than the current study's results, suggesting that lateritic soil's particle size distribution creates more favorable conditions for efficient compaction with reduced water requirements.

California Bearing Ratio (CBR) Results

As presented in Figure 8, the California Bearing Ratio test results demonstrate substantial improvements in bearing capacity across all stabilizer combinations, with CBR values ranging from 76% to 94%. These exceptional values represent dramatic improvements compared to typical unstabilized lateritic soils, which commonly exhibit CBR values between 5% and 15%. The 5% cement series shows CBR values increasing from 78% at 2% RHA to 87% at 8% RHA, then slightly decreasing to 82% at 10% RHA.

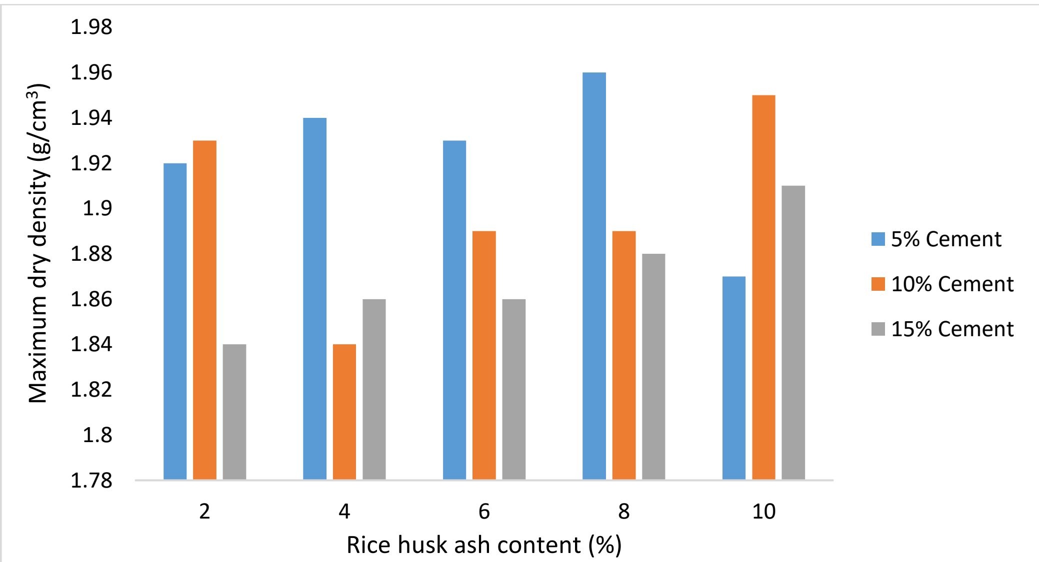

Figure 6: Maximum Dry Density with percentage Cement and RHA

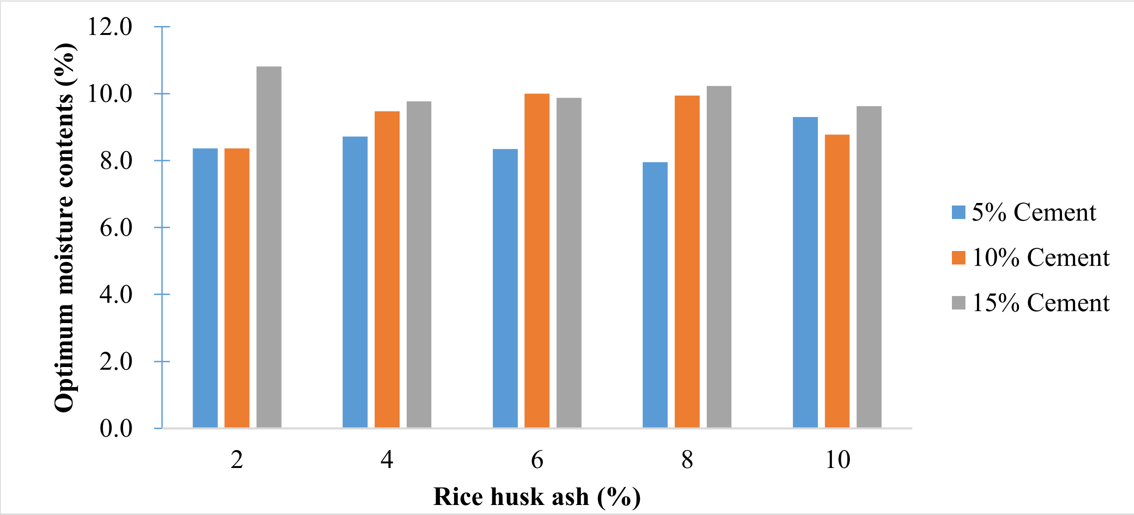

Figure 7: Optimum Moisture Content with percentage Cement and RHA

Comparative analysis with recent research by Osinubi *et al*. (2024) on cement-stabilized lateritic soils achieved CBR values ranging from 45% to 78%, significantly lower than the current study's results, highlighting the superior effectiveness of rice husk ash as a supplementary cementitious material. The consistent achievement of CBR values above 75% provides excellent suitability for various pavement applications, with values exceeding 90% suitable for heavy-duty applications, including airport runways.

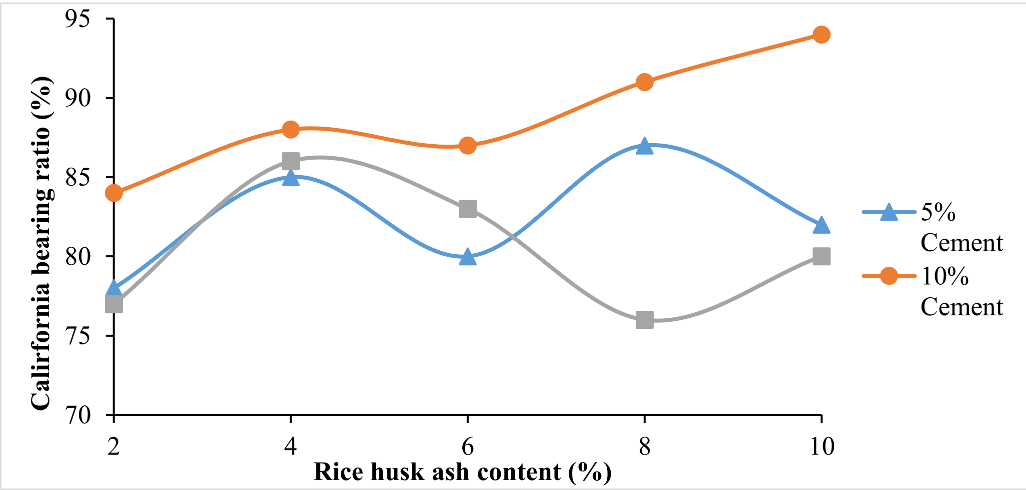

Figure 8: CBR with percentage Cement and RHA

Unconfined Compressive Strength Results

Figure 9 showed that the Unconfined Compressive Strength results demonstrate substantial strength improvements across all stabilizer combinations, with UCS values ranging from 186 kN/m² to 334 kN/m². The 5% cement series shows progressive strength development from 186 kN/m² at 2% RHA to 252 kN/m² at 10% RHA, representing a 35.5% increase. The 10% cement combinations exhibit more pronounced improvements, with UCS values ranging from 208 kN/m² to 286 kN/m², while the 15% cement series achieved the highest absolute strength values, ranging from 238 kN/m² to 334 kN/m². The strength enhancement achieved represents approximately four-fold to seven-fold increases over typical unstabilized lateritic soils, which commonly exhibit UCS values below 50 kN/m². The primary strengthening mechanism involves cement hydration, producing calcium silicate hydrate gel and calcium hydroxide, while secondary mechanisms involve pozzolanic reactions between RHA silica and calcium hydroxide, creating additional binding agents that enhance the soil matrix.

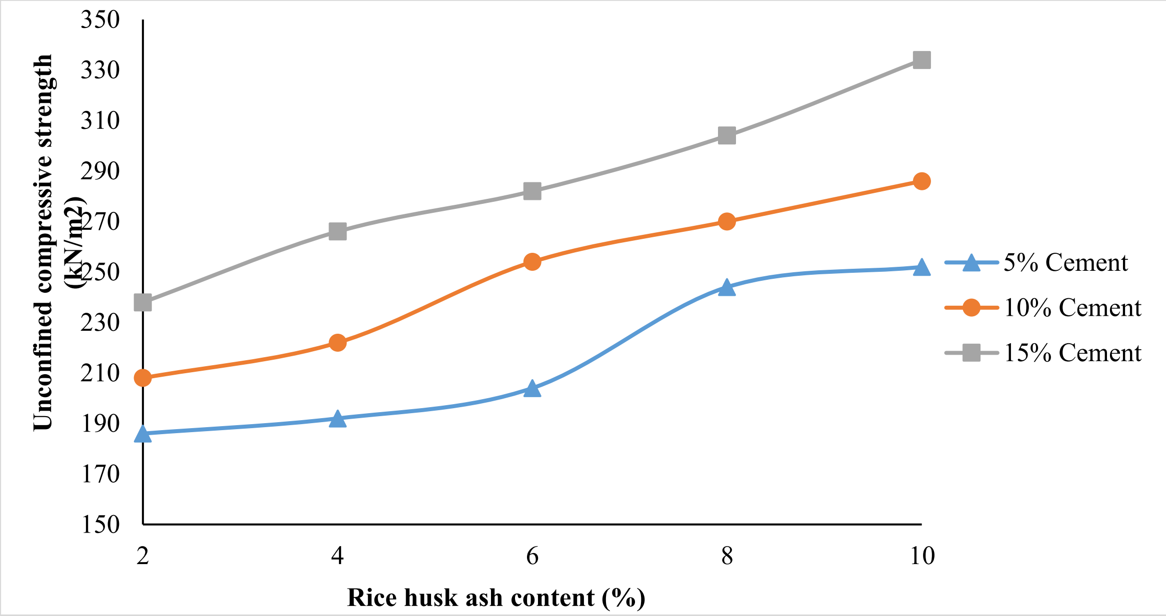

Figure 9: UCS with percentage Cement and RHA

Studies by Ogundipe *et al*. (2023) on cement-stabilized lateritic soils reported UCS values ranging from 150 to 280 kN/m², generally lower than the current study's achievements, demonstrating the superior performance of the cement-RHA combination. The systematic increase in strength with both cement and RHA content validates the effectiveness of the dual stabilization approach for achieving exceptional compressive strength suitable for structural applications.

Optimal Mix Determination

The optimal mix ratio determination employed a comprehensive multi-criteria analysis considering all engineering properties with weighted scoring based on relevance to highway pavement construction. The weighting factors were established as CBR (30%), UCS (25%), Plasticity Index reduction (20%), Maximum Dry Density (15%), and Optimum Moisture Content (10%). Based on this analysis, the optimal mix ratio was determined to be 10% cement + 10% RHA, achieving zero plasticity index, high MDD (1.95 g/cm³), reasonable OMC (8.71%), highest CBR value (94%), excellent UCS (286 kN/m²), and superior cost-effectiveness. This combination demonstrates balanced performance across all critical engineering properties while maintaining economic viability. The 15% cement with 10% RHA achieved higher absolute strength (334 kN/m²), but the marginal strength gain relative to material cost increase made the 10% cement combination more cost-effective for most pavement applications.

Statistical Analysis Results

The statistical analysis presented in Table 3 provides insights that the Liquid Limit (LL) and Optimum Moisture Content (OMC) exhibit highly significant changes with p-values of 0.0003 and 0.00007, respectively, indicating that stabilization had a profound impact on the soil's moisture-related properties. The Plastic Limit (PL) and Maximum Dry Density (MDD) also show statistically significant variations ($p < 0.05$), suggesting improved compaction characteristics and a reduction in moisture sensitivity. On the other hand, the California Bearing Ratio (CBR), a critical strength indicator for pavement subgrades, shows a high mean value of 83.5 but is not statistically significant ($p = 0.554$). In contrast, the Unconfined Compressive Strength (UCS) demonstrates both a wide range (186 - 334 kN/m²) and a highly significant p-value (0.00002), underscoring the strong influence of stabilization on structural strength.

Table 6: Statistical Analysis Results

Parameter	Mean	Standard Deviation	Range	F-Statistic	p-Value	Statistical Significance
Liquid Limit	28.5	2.8	25.0 – 31.5	12.45	0.0003	Highly significant ($p < 0.01$)
Plastic Limit	27.2	1.9	25.0 – 29.2	8.92	0.0015	Significant ($p < 0.05$)
Plasticity Index (PI)	1.3	1.5	0.0 – 3.5	2.15	0.133	Not statistically significant ($p > 0.05$)
Maximum Dry Density (MDD)	1.90	0.04	1.84 – 1.96	7.50	0.0024	Significant ($p < 0.05$)
Optimum Moisture Content (OMC)	9.2	0.9	7.95 – 10.81	14.76	0.00007	Highly significant ($p < 0.01$)
California Bearing Ratio (CBR)	83.5	5.8	76.0 – 94.0	0.72	0.554	Not statistically significant ($p > 0.05$)
Unconfined Compressive Strength	251.0	48.2	186.0 – 334.0	18.25	0.00002	Highly significant ($p < 0.01$)

CONCLUSION

The study concludes that the combined use of cement and rice husk ash (RHA) significantly enhances the geotechnical properties of lateritic soil. The optimal stabilization mix, consisting of 10% cement and 10% RHA, achieved a four-fold increase in California Bearing Ratio from 24% to 94% and an improvement in unconfined compressive strength from <50 kN/m² to 286 kN/m². Microstructural analysis, including XRF, XRD, and SEM, confirmed the compatibility and chemical stability of the materials, ensuring long-term durability. It is recommended that thorough geotechnical testing be conducted before applying this chemical stabilization technique to establish soil baseline properties. A 10% cement and 10% RHA mix should be prioritized for its superior performance, cost-effectiveness, and environmental benefits. Future projects should leverage the synergistic effect of combined stabilizers rather than relying on individual agents. Moreover, microstructural evaluations should become a standard component of soil stabilization research and quality control to ensure chemical compatibility and explore the potential of other pozzolanic materials for sustainable infrastructure development.

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