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Sustainable Performance Optimization of Lateritic Soil Stabilized With Rice Husk Ash and Cow Bone Ash using Response Surface Methodology

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ABSTARCT: Lateritic soils, common in tropical regions and widely used in roadworks, often exhibit high plasticity, low strength, and volume instability, which restrict their direct use in load-bearing applications. The aim of this study is to optimize the sustainable performance of lateritic soil stabilized with rice husk ash (RHA) and cow bone ash (CBA) using response surface methodology (RSM). This study involved the collection and characterization of lateritic soil, RHA, and CBA, followed by evaluating the geotechnical performance of the stabilized soil. Furthermore, statistical optimization was conducted to determine optimal stabilization conditions using response surface methodology (RSM). The natural moisture content and geotechnical properties for the natural soil showed LL, PL, PI, SL, MDD OMC, CBR, UCS, and shear strength values of 47%, 25%, 22%, 5.5%, 1.65 g/cm³, 9.12%, 33.15%, 132 kN/m², and 67 kN/m², respectively. The properties of the modified soil include LL, PL, PI, and SL values ranging from 46–57%, 25–44%, 5–22%, and 5.5% respectively. The MDD and OMC values ranged from 1.32–1.65 g/cm³ and 9.12–25.19%. Furthermore, the CBR values ranged from 33.15–122.14%, UCS values from 132–264 kN/m², and shear strength values from 67–132 kN/m². The stabilization of lateritic soil with RHA and CBA significantly enhanced its strength, compaction, and load-bearing properties compared to the natural soil. Improvements in CBR, UCS, and shear strength demonstrate their effectiveness as sustainable stabilizers. It is recommended that RHA and CBA be adopted in pavement and subgrade applications, with optimal mix ratios carefully considered.

KEYWORDS: Stabilization, Rice Husk Ash, Cow Bone Ash, Response Surface Methodology, Compaction, Shear Strength, California Bearing Ratio, Sustainability.

1.0 INTRODUCTION

Lateritic soils are widely encountered across tropical and subtropical regions, including Nigeria, where they are frequently used as subgrade and fill materials in road and infrastructure projects (Hamidu *et al.*, 2022). Despite their abundance, lateritic soils often display high plasticity, low bearing capacity, and susceptibility to swelling and shrinkage, limiting their suitability for direct application in load-bearing structures (Gbadamosi, 2021). Traditional stabilization with cement or lime is effective but comes with cost and environmental drawbacks, necessitating a sustainable approach to soil improvement (Mohammed *et al.*, 2023).

Sustainable performance optimization emphasizes not only improving the geotechnical properties of soil but also achieving these enhancements in an environmentally responsible manner. The reliance on industrial by-products or agricultural waste for soil stabilization has gained significant attention due to reduced carbon emissions, cost efficiency, and waste recycling benefits (Gidebo *et al.*, 2021). Thus, incorporating sustainability in soil stabilization aligns with global efforts to promote green construction practices and reduce reliance on carbon-intensive materials.

Rice Husk Ash (RHA) is an agricultural by-product generated in large quantities from rice milling processes. Rich in silica and known for its pozzolanic activity, RHA has been extensively studied as a soil stabilizer and shown to improve strength, reduce plasticity, and enhance compaction characteristics of lateritic soils (Gautam, and Bhowmik 2023). Its utilization addresses waste management issues while simultaneously providing an eco-friendly material for geotechnical engineering applications (Roque *et al.*, 2022).

Cow Bone Ash (CBA), on the other hand, is a less common stabilizer but has been identified as a potential pozzolanic material due to its high calcium oxide content. Studies indicate that SSA Geopolymer can improve the California Bearing Ratio (CBR) and unconfined compressive strength (UCS) of treated soils, especially when blended with other supplementary stabilizers (Olugbenga *et al.*, 2022). Its application not only valorizes abattoir waste but also complements agricultural ashes like RHA, making it a promising candidate for blended soil stabilization strategies (Gautam, and Bhowmik 2023).

The integration of Design Expert software into this study provides a scientific framework for optimizing soil stabilization. Unlike trial-and-error methods, Design Expert employs statistical design of experiments and response surface methodology to determine the optimal proportions of RHA and CBA for achieving maximum geotechnical performance (Omoniyi, 2023). Although lateritic soils are abundant, their poor geotechnical performance limits their direct application in engineering projects. Conventional stabilizers like cement are costly and environmentally unsustainable, while research on alternative stabilizers often lacks rigorous optimization (Styer *et al.*, 2024). There is therefore a need for systematic evaluation and optimization of blended RHA and CBA in lateritic soil stabilization using advanced statistical tools.

Previous studies have independently investigated the effects of Rice Husk Ash or Cow Bone Ash on lateritic soil stabilization; however, limited research exists on their combined utilization, particularly with optimization frameworks. Moreover, most available works have relied on conventional laboratory experimentation without integrating advanced statistical modeling tools such as Design Expert, which can identify optimal mix proportions. This leaves a critical gap in developing sustainable, cost-effective, and performance-optimized stabilization methods for lateritic soils.

This study provides a sustainable solution to soil stabilization by valorizing agricultural and animal wastes, thereby reducing environmental pollution and dependence on conventional stabilizers. By employing Design Expert to optimize RHA–CBA blends, the research will generate practical mix proportions that improve soil strength while promoting cost-effectiveness and sustainability in geotechnical engineering.

2.0 MATERIALS AND METHOD

2.1 Collection of Materials

Lateritic soil was collected from a borrow pit in Owode area, Osun State, Nigeria, at a depth of 1.5–2.0 m using disturbed sampling, while avoiding the weathered topsoil. The sample was air-dried, thoroughly mixed, and stored for laboratory use. Cow bones obtained from Sabo market abattoir in Osogbo, Osun State, Nigeria, were cleaned, sun-dried for 21 days, calcined at 800 °C for 90 minutes in the Department of Mechanical Engineering, Afe Babalola University, Ado-Ekiti, Nigeria, and then sieved through a 150 µm (No. 100 ASTM sieve) to produce Cow Bone Ash (CBA). Similarly, rice husk sourced from a milling factory in Ode Omu, Osun State, Nigeria, was calcined at 550 °C for 60 minutes in the same facility and sieved through a 75 µm (No. 200 ASTM sieve) to obtain Rice Husk Ash (RHA).

2.2 Characterization of Materials

The natural soil sample was characterized to determine its geotechnical properties. Laboratory tests were conducted to establish the Plastic Limit (PL), Liquid Limit (LL), and Plasticity Index (PI) in accordance with ASTM D4318. The Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) were determined using the Standard Proctor Test (ASTM D698), while the California Bearing Ratio (CBR) test was performed in accordance with ASTM D1883 to evaluate the load-bearing capacity. In addition, the Unconfined Compressive Strength (UCS) of the soil was assessed using ASTM D2166 to determine its shear strength under unconfined conditions. These tests provided baseline data on the engineering behavior of the natural soil before stabilization.

The Rice Husk Ash (RHA) and Cow Bone Ash (CBA) were subjected to detailed characterization to establish their suitability as soil stabilizing agents. The chemical composition of both ashes was determined through X-ray Fluorescence (XRF) analysis, which quantified the proportions of major oxides such as SiO_2, Al_2O_3, Fe_2O_3, CaO, and MgO. These data were used to classify the pozzolanic reactivity of the RHA and the lime-rich content of the CBA.

2.3 Evaluation of the Geotechnical Performance of Stabilized Soil

The geotechnical performance of the stabilized soil was evaluated under different mix proportions of Rice Husk Ash (RHA) and Cow Bone Ash (CBA). Laboratory tests were conducted to determine the California Bearing Ratio (CBR), Unconfined Compressive Strength (UCS), shear strength, and compaction characteristics of the natural soil blended with varying percentages of the stabilizing agents. The control sample, which consisted of natural soil without any additives, was first tested to establish baseline geotechnical properties. Subsequently, soil specimens were prepared with incremental replacement levels of RHA and CBA, as outlined in the mix design.

The compaction test was performed to establish the Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) of the stabilized soils in accordance with ASTM D698. The CBR test was carried out using ASTM D1883 to assess the load-bearing capacity of the soil samples, while the Unconfined Compressive Strength (UCS) test was performed in line with ASTM D2166 to evaluate the shear resistance under axial loading conditions. Additionally, the direct shear test was conducted to determine the shear strength parameters of the stabilized soils. This approach provided insight into the synergistic effects of the two additives on soil strength and durability. The combinations tested are presented in Table 1, which outlines the different mix codes and corresponding stabilizer contents.

Table 1: Mix Proportions of RHA–CBA Stabilized Soil

Mix Code	**CBA (%)**	**RHA (%)**
M01	0	0
M02	0	4
M03	0	12
M04	2	8
M05	4	4
M06	4	12
M07	6	4
M08	6	8
M09	8	4
M10	8	12

2.4 Statistical Optimization

Statistical optimization was carried out using Design-Expert software based on Response Surface Methodology (RSM) to determine the optimal blend of Rice Husk Ash (RHA) and Cow Bone Ash (CBA). The independent variables were the percentages of RHA (0–12%) and CBA (0–8%), while the responses were CBR, UCS, shear strength, MDD, and OMC. A central composite design (CCD) was employed to capture both linear and quadratic effects, as well as interaction terms. Experimental runs were randomized, and second-order polynomial models were fitted to the responses.

Model adequacy was verified using ANOVA, R^2 values, and lack-of-fit tests. Optimization was achieved using the numerical desirability function, where CBR, UCS, shear strength, and MDD were maximized, while OMC was minimized. The software suggested the most desirable mix proportion, which was validated through confirmation experiments by comparing predicted and experimental results. As part of the statistical optimization showing the ANOVA analysis, Regression equations and 3D surface plots were generated in Design-Expert to illustrate the influence of RHA and CBA on CBR, UCS, shear strength, and compaction.

3.0 RESULTS AND DISCUSSION

3.1 Characterization of Materials

The geotechnical and chemical properties of the natural soil and stabilizing materials were assessed to establish their suitability and potential influence on soil stabilization performance.

3.1.1 Geotechnical Properties of Natural Soil

The results of the geotechnical tests conducted on the natural lateritic soil are presented in Table 2. The Atterberg limits showed a liquid limit (LL) of 47% and a plastic limit (PL) of 25%, yielding a plasticity index (PI) of 22%. These values suggest that the soil is moderately plastic, indicating its susceptibility to volumetric changes when subjected to moisture variations. The shrinkage limit (SL) of 5.5% further implies that the soil is prone to shrinkage under drying conditions, which could affect its long-term stability. A similar observation was made by Oluremi *et al.*, (2019), who reported that lateritic soils in Southwestern Nigeria exhibited high plasticity, rendering them less suitable for engineering applications without stabilization.

In terms of compaction characteristics, the soil recorded a maximum dry density (MDD) of 1.65 g/cm³ and an optimum moisture content (OMC) of 9.12%. The relatively low MDD suggests the soil has a loose particle arrangement, while the moderate OMC indicates the level of water required for effective compaction. These values highlight the soil's limited load-bearing potential in its natural state. Comparable findings were reported by Ampadu and Arthur, (2022), who demonstrated that lateritic soils often require chemical stabilization to achieve higher compaction densities suitable for pavement layers.

The strength tests revealed that the California Bearing Ratio (CBR) value of the natural soil was 33.15%. While this value places the soil in the category of subgrade material that can provide moderate support, it may not be sufficient for heavy traffic loading without treatment. This aligns with the results of Azunna *et al.*, (2020), who emphasized that untreated lateritic soils generally fail to meet the strength requirements for road base and sub-base applications.

Furthermore, the unconfined compressive strength (UCS) was measured at 132 kN/m², which is relatively low when compared to the threshold for soils considered suitable for engineering works as shown in Table 2. This low UCS is indicative of weak soil structure, necessitating stabilization for structural improvement. In contrast, Ikeagwuani and Nwonu, (2023), found that stabilization with agro-based ash significantly enhanced UCS values, underscoring the need for modifying natural lateritic soils before use.

Finally, the shear strength (c) of the soil was determined to be 67 kN/m², which again reflects its moderate but insufficient resistance to shear stresses under applied loads. This limited shear strength makes the soil vulnerable to deformation under traffic or structural pressure. A similar conclusion was drawn by Fekadu, (2021), who reported that untreated lateritic soils typically lack adequate shear strength for construction purposes.

Table 2: Geotechnical Test Results for Natural Soil

Tests	Test (with Units)	Value
Atterberg Limit	Liquid Limit (LL, %)	47
	Plastic Limit (PL, %)	25
	Plasticity Index (PI)	22
	Shrinkage Limit (SL, %)	5.5
Compaction	Maximum Dry Density (MDD, g/cm³)	1.65
	Optimum Moisture Content (OMC, %)	9.12
Strength	California Bearing Ratio (CBR, %)	33.15
	Unconfined Compressive Strength (UCS, kN/m²)	132
Shear Strength	Shear Strength (c, kN/m²)	67

3.1.2 Chemical properties of Materials

The chemical composition of the lateritic soil, rice husk ash (RHA), and cow bone ash (CBA), as determined by X-ray fluorescence (XRF) analysis, is summarized in Table 3. The lateritic soil exhibited high concentrations of iron oxide (Fe_2O_3) at 52.80% and silicon oxide (SiO_2) at 23.45%, with aluminum oxide (Al_2O_3) accounting for 11.25%. These oxides are characteristic of lateritic soils, which are often described as ferrallitic due to the predominance of iron and aluminum compounds. The elevated Fe_2O_3 content explains the reddish-brown coloration of the soil and reflects its limited pozzolanic potential when compared with silica-rich materials. This observation aligns with the findings of Akintunde and Osuolale, (2023), who noted that lateritic soils in Southwestern Nigeria typically contain high levels of Fe_2O_3 but relatively lower silica, thereby reducing their reactivity unless blended with supplementary stabilizers.

In contrast, rice husk ash (RHA) was found to be dominated by silica (SiO_2) at 78.60%, which is substantially higher than that of both lateritic soil and cow bone ash. This elevated silica content demonstrates the strong pozzolanic potential of RHA, as reactive silica readily combines with calcium during stabilization to form cementitious products. The loss on ignition (LOI) of RHA, recorded at 12.92%, indicates the presence of residual carbon and volatile matter, which, if excessive, may slightly diminish its reactivity. Nonetheless, the result corresponds with the report of Amran *et al.*, (2021), who affirmed that RHA obtained under controlled burning conditions is highly enriched in amorphous silica and is therefore effective for soil and concrete stabilization.

Cow bone ash (CBA), by contrast, was characterized by exceptionally high calcium oxide (CaO) content at 50.20% and phosphorus oxide (P_2O_5) at 35.40%. This composition highlights its potential as a lime-rich stabilizer, supplying the free calcium ions necessary for cementitious reactions, particularly when combined with the silica-rich RHA. The presence of both CaO and P_2O_5 presents a dual advantage: improving strength through cementitious binding while simultaneously enriching the soil matrix with phosphates, which can influence microstructural development. However, its low silica content of 3.40% indicates that its contribution lies primarily in calcium provision rather than pozzolanic activity as presented in Table 3. A similar trend was described by Shahbaz *et al.,* (2023), who emphasized that bone ash is particularly effective when used in combination with silica-rich agro-waste materials, as it ensures a balanced calcium-to-silica ratio in stabilization processes.

A comparative evaluation of the three materials underscores the complementarity of their chemical compositions, making them highly suitable for combined application in soil stabilization. While lateritic soil is rich in iron and aluminum oxides but deficient in reactive silica and calcium, RHA provides abundant silica for pozzolanic reactions, and CBA contributes calcium and phosphorus oxides to facilitate cementitious reactions. This synergy is particularly important, as observed by Liu *et al.,* (2024), who demonstrated that the blending of calcium-rich and silica-rich materials significantly enhances stabilization through the formation of durable calcium silicate hydrates (C-S-H) and calcium aluminate hydrates (C-A-H). Furthermore, the LOI values—3.97% for lateritic soil, 6.08% for CBA, and 12.92% for RHA—reflect the degree of calcination efficiency and stability of the materials, providing additional insights into their suitability for engineering applications.

Table 3: Chemical Composition of Lateritic Soil, Rice Husk Ash (RHA), and Cow Bone Ash (CBA)

S/N	Basic Oxides	Formulae	Lateritic Soil (%)	Rice Husk Ash (%)	Cow Bone Ash (%)
1	Iron Oxide	Fe_2O_3	52.80	2.10	1.25
2	Silicon Oxide	SiO_2	23.45	78.60	3.40
3	Aluminum Oxide	Al_2O_3	11.25	0.95	1.10
4	Calcium Oxide	CaO	3.10	1.45	50.20
5	Magnesium Oxide	MgO	1.85	0.62	1.70
6	Potassium Oxide	K_2O	0.95	2.40	0.35

7	Sodium Oxide	Na_2O	0.40	0.55	0.28
8	Phosphorus Oxide	P_2O_5	0.32	0.12	35.40
9	Titanium Oxide	TiO_2	2.05	0.21	0.08
10	Manganese Oxide	MnO	0.65	0.07	0.04
11	Zinc Oxide	ZnO	0.05	0.03	0.01
12	Copper Oxide	CuO	0.02	0.01	0.01
13	Sulphur Oxide	SO_3	0.10	0.06	0.09
14	Chromium Oxide	Cr_2O_3	0.08	0.01	0.01
15	Tin (IV) Oxide	SnO_2	0.01	0.01	0.01
16	Loss on Ignition	LOI	3.97	12.92	6.08

3.2 Evaluation of the Geotechnical Performance of Stabilized Soil

The geotechnical performance of the stabilized soil was evaluated through Atterberg limits, compaction, shear strength, California Bearing Ratio (CBR), and Unconfined Compressive Strength (UCS) tests.

3.2.1 Atterberg Limits

The Atterberg limits of the treated and untreated lateritic soils reveal distinct trends in response to the incorporation of rice husk ash (RHA) and cow bone ash (CBA). The untreated soil (M01) recorded a liquid limit (LL) of 47%, a plastic limit (PL) of 25%, and a plasticity index (PI) of 22%. This relatively high PI reflects the soil's high clay activity and inherent plasticity, indicating a weak subgrade performance in its natural state. Similar observations were made by Wahab *et al.*, (2023), who reported that untreated lateritic soils in tropical regions often exhibit high PI values, limiting their direct application in pavement construction.

Upon the addition of RHA alone, as seen in M02 and M03, the liquid limit increased slightly to 49% and 54% respectively, while the plasticity index decreased drastically in M02 (PI = 5%) but rose to 16% in M03. The significant reduction in plasticity in M02 suggests that the fine silica particles in RHA effectively altered the soil's clay-water interactions, reducing its cohesive properties. This observation aligns with the findings of Adajar *et al.*, (2024), who noted that the pozzolanic nature of RHA contributes to reduced plasticity by encouraging the flocculation of clay particles. However, the subsequent increase in PI observed in M03 indicates that excessive RHA may lead to higher silica presence without adequate calcium for cementitious binding, thereby reducing the stabilization efficiency.

When both CBA and RHA were introduced in combination, the results revealed more balanced effects. For instance, M04 (2% CBA and 8% RHA) showed the highest LL value of 56% and a PI of 21%, while M05 (4% CBA and 4% RHA) demonstrated improved stability with a reduced PI of 15%. The interaction between calcium oxide in CBA and silica in RHA promoted the formation of cementitious products, effectively lowering the soil's plasticity compared to the untreated sample. Interestingly, M06 (4% CBA and 12% RHA) and M10 (8% CBA and 12% RHA) exhibited the lowest PI values of 10% and 11% respectively, indicating optimal stabilization performance.

The reduction in PI to near the acceptable range for subgrade materials demonstrates the effectiveness of the CBA-RHA synergy in minimizing soil plasticity. This aligns with the findings of Kumbasaroglu and Kumbasaroglu, (2024), who highlighted that durable stabilization is achieved when silica from agro-waste is adequately balanced with calcium from industrial or animal-based ashes. The low PI values in M06 and M10 therefore suggest improved soil workability and reduced susceptibility to volume changes, making these mixes particularly suitable for road construction. On the other hand, M07 and M08, which contained higher CBA proportions (6%), recorded elevated LL values of 57% and 56% respectively, with PI values of 20% and 17% as shown in Figure 1. This trend indicates that while calcium addition is beneficial, excessive proportions may contribute to higher water affinity, increasing the LL and maintaining moderate PI values.

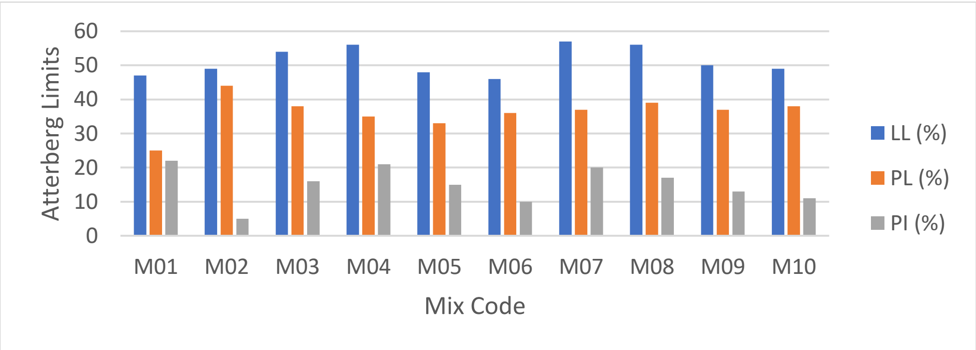

Figure 1: Atterberg Limits of Natural and Stabilized Lateritic Soil

3.2.2 Compaction Test

The compaction characteristics of the treated and untreated lateritic soil samples presented in Figure 2 illustrate significant variations in maximum dry density (MDD) and optimum moisture content (OMC) across the mixes. The natural soil (M01) recorded an MDD of 1.65 g/cm³ with an OMC of 9.12%, values consistent with untreated lateritic soils that generally display moderate densities and low water requirements. When RHA was introduced alone, as in M02 and M03, the MDD decreased to 1.56 g/cm³ and 1.39 g/cm³ respectively, while the OMC increased drastically, reaching 21.99% in M02 and 18.78% in M03 as shown in Figure 2. This reduction in density alongside an increase in OMC may be attributed to the lightweight, porous nature of RHA particles, which increase water demand during compaction.

Similar findings were reported by Mezie *et al.,* (2023), who noted that replacing soil fines with agro-waste ash reduced dry density due to the lower specific gravity of the additives. When CBA was added alongside RHA, the MDD values showed relative improvement, particularly in M04 is 1.55 g/cm³ and M10 is 1.45 g/cm³, suggesting that calcium-rich CBA partially offset the lightweight effect of RHA. However, high OMC values persisted across the combinations, with M05 and M06 recording 24.80% and 25.19% respectively, indicating that the combined stabilizers enhanced water absorption and altered compaction behavior.

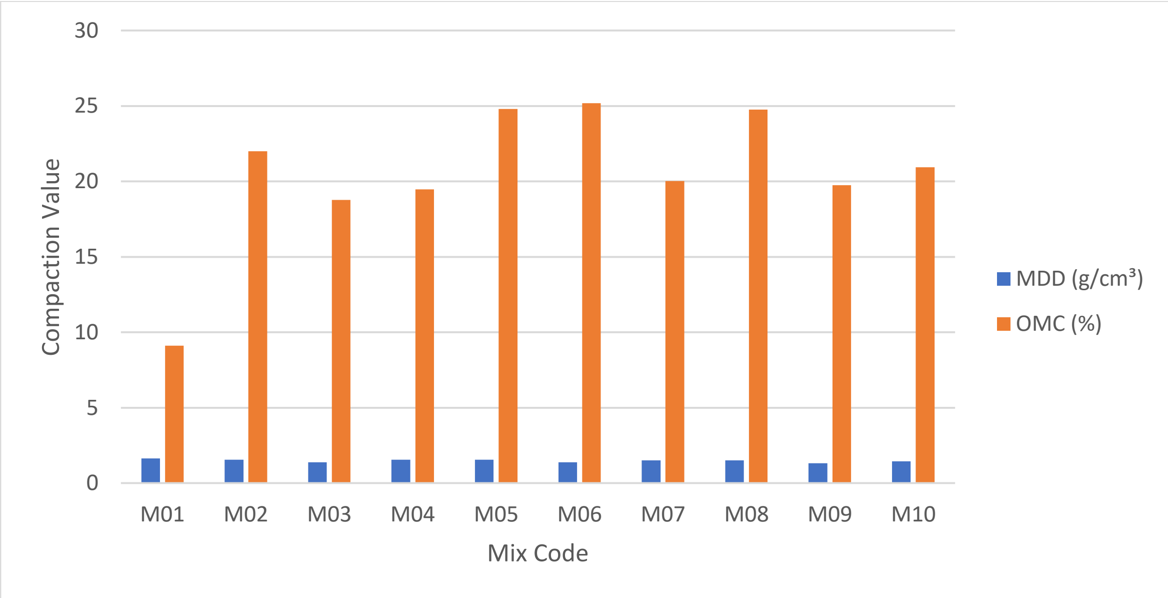

Figure 2: Compaction Characteristics of Natural and Stabilized Lateritic Soil.

3.2.3 Shear Strength (c)

The shear strength results reveal distinct improvements with the incorporation of stabilizers. The untreated soil, designated as M01, recorded the lowest cohesion value of 67 kN/m², which reflects its inherently weak binding capacity. When rice husk ash (RHA) was introduced, there was a progressive increase in shear strength, as demonstrated in M02 with 75 kN/m² and M03 with 105 kN/m², culminating in 108 kN/m² in M04. This notable enhancement can be attributed to the pozzolanic reaction between the silica content in RHA and the calcium present in the soil, which effectively strengthens interparticle bonding. The inclusion of corn cob ash (CBA) further magnified these improvements, with M06 reaching 121 kN/m², M07 at 122 kN/m², and M09 attaining the highest value of 132 kN/m² as illustrated in Figure 3.

The presence of calcium oxide in CBA released free calcium ions that reacted with the silica in RHA, leading to the formation of cementitious compounds such as calcium silicate hydrates, thereby significantly increasing cohesion. This outcome aligns with the findings of Jalal *et al.,* (2020), who observed that calcium-rich stabilizers enhance shear strength by promoting cementitious reactions that improve soil cohesion. It is also noteworthy that M10 achieved a shear strength of 122 kN/m², indicating that even at different blend proportions, the synergy between CBA and RHA consistently improved the stability of the soil. This confirms the effectiveness of balanced CBA-RHA mixtures in producing durable and stable soil structures suitable for engineering applications.

3.2.4 California Bearing Ratio (CBR) Test

The California Bearing Ratio (CBR) values further corroborate the improvements in soil performance upon stabilization. The untreated soil (M01) exhibited a low CBR value of 33.15%, which is inadequate for subgrade applications. With the inclusion of RHA alone, the CBR values rose sharply to 71.3% (M02) and 89.66% (M03), reaching a peak of 75.32% in M04. When combined with CBA, the CBR values exceeded 100%, with M05 recording 122.14%, M07 achieving 101.16%, and M10 producing 103.46% as shown Figure 4.

The remarkable improvement in CBR performance underscores the complementary role of CBA and RHA, where calcium-silica reactions yield strong cementitious products that enhance soil load-bearing capacity. These results align with the study by Yang *et al.*, (2019), who highlighted that synergistic blending of silica-rich and calcium-rich additives significantly improves CBR values beyond those of natural soils. The consistently high CBR values observed in the treated samples demonstrate the suitability of RHA-CBA combinations for subgrade stabilization.

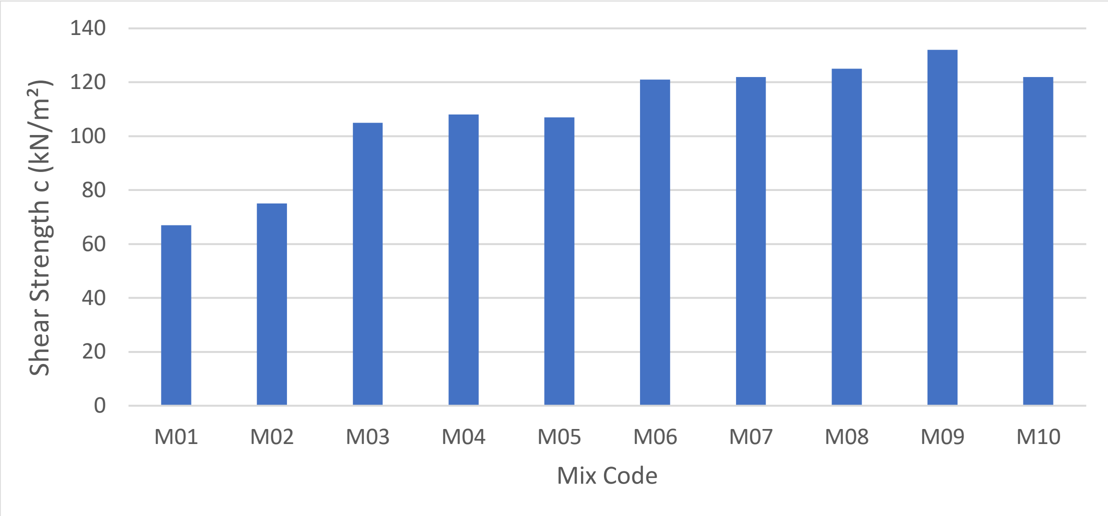

Figure 3: Shear Strength (SS) of Natural and Stabilized Lateritic Soil.

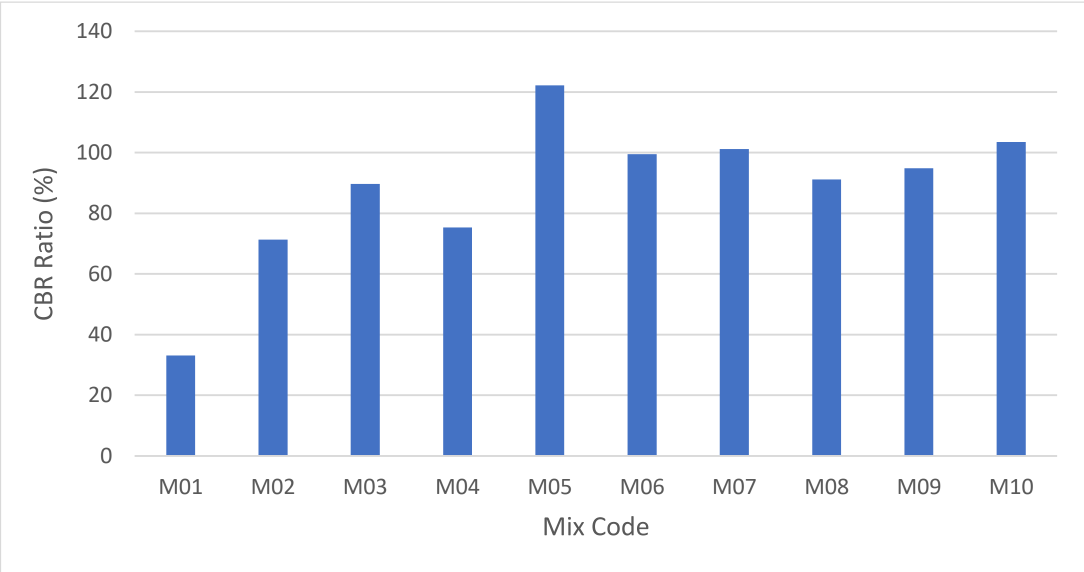

Figure 4: California Bearing Ratio (CBR) of Natural and Stabilized Lateritic Soil.

3.2.5 Unconfined Compressive Strength (UCS)

The unconfined compressive strength (UCS) results present further evidence of the beneficial effects of stabilization. The natural soil (M01) exhibited a UCS of 132 kN/m², a relatively weak strength for engineering applications. The introduction of RHA alone increased the UCS to 150 kN/m² in M02 and further to 210 kN/m² in M03, peaking at 216 kN/m² in M04. The inclusion of CBA yielded even greater improvements, with M06 (242 kN/m²), M07 (244 kN/m²), and M09 (264 kN/m²) recording the highest strengths. These values clearly demonstrate the effectiveness of calcium from CBA in reacting with silica from RHA to form cementitious compounds, thereby improving soil strength. In particular, M10 recorded a UCS of 238 kN/m², confirming its effectiveness as a balanced mix suitable for stabilization as shown in Figure 5. This observation is in agreement with the findings of Fawzy *et al.*, (2023), who established that the synergy between agro-waste ashes and bone-derived calcium sources produces significant increases in compressive strength due to enhanced pozzolanic and cementitious activity.

3.3 Statistical Optimization of Geotechnical Properties

3.3.1 ANOVA for Quadratic model

The model summary statistics presented in Table 1 provide important insights into the adequacy and predictive strength of the quadratic regression model used to explain variations in the soil properties. Beginning with the liquid limit (LL), the model p-value of 0.3614 indicates that the regression was not statistically significant. The coefficient of determination (R^2) stood at 0.482, suggesting that approximately 48.2% of the variation in LL could be explained by the model. However, both the adjusted R^2 (0.112) and the negative

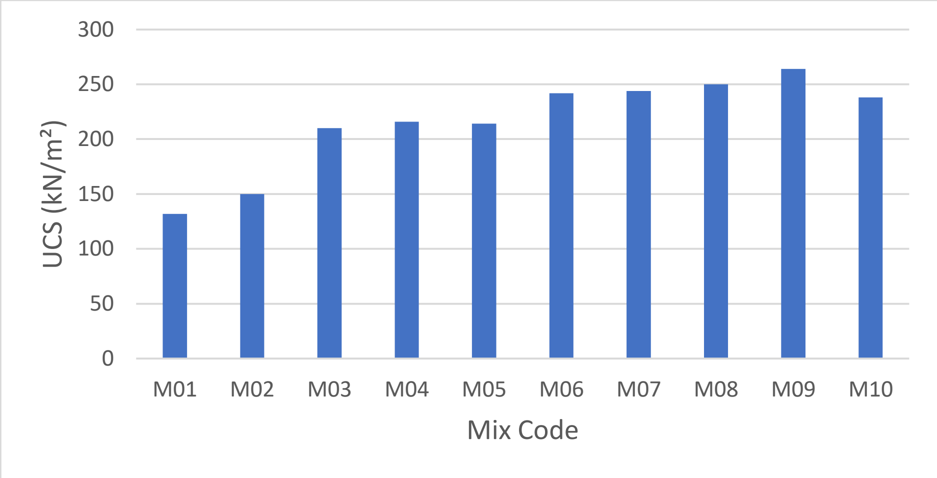

Figure 5: Unconfined Compressive Strength (UCS) of Natural and Stabilized Lateritic Soil.

predicted R^2 (-0.799) reveal a weak predictive ability, implying that the model performs poorly when applied beyond the sample data. This aligns with the observation of Raman *et al.,* (2020), who reported that soil plasticity characteristics often exhibit inconsistent relationships with additive proportions, thereby limiting the predictive power of regression models.

In the case of the plastic limit (PL), the model's explanatory power was even lower, with an R^2 value of 0.393 and a negative adjusted R^2 of -0.04. The predicted R^2 further dropped to -2.66, clearly signifying overfitting and weak external validity. The coefficient of variation (C.V. %) of 12.29 suggests considerable variability relative to the mean. Such findings suggest that the model was unable to effectively capture the underlying interactions influencing PL. Similarly, Zeini *et al.,* (2023), observed that the prediction of PL values under soil stabilization scenarios often suffers from weak statistical significance, emphasizing the complexity of clay-water-additive interactions.

The plasticity index (PI) revealed even poorer model adequacy, with an R^2 of 0.342 and both adjusted and predicted R^2 values being negative (-0.128 and -1.552, respectively). The high C.V. of 43.33% reflects substantial variability, further undermining the reliability of the regression in predicting PI. These results underscore the difficulty of statistically modeling soil plasticity indices when influenced by multiple stabilizers. In contrast, a study by Al-Swaidani *et al.,* (2024) demonstrated stronger predictive capacities for PI when lime stabilization was employed, indicating that the choice of stabilizers plays a significant role in the robustness of regression outcomes.

For maximum dry density (MDD), the regression model recorded a p-value of 0.6566 and an R^2 of 0.325, confirming the insignificance of the model in explaining variations in compaction characteristics. Both adjusted R^2 (-0.157) and predicted R^2 (-2.841) values indicated limited predictive accuracy. The coefficient of variation remained modest at 6.78%, suggesting consistency within the measured data but little statistical backing for the regression model itself. A comparable observation was made by Nawar *et al.,* (2020).who reported that compaction characteristics are often more influenced by field conditions than by laboratory-based regression predictions.

Turning to the optimum moisture content (OMC), the model performed slightly better than in previous cases, with an R^2 of 0.461 and adjusted R^2 of 0.076. However, the predicted R^2 was -2.217, again highlighting poor generalizability. The relatively high C.V. of 19.07% shows noticeable variability. This limited performance mirrors the findings of Zhang and Du, (2024). who noted that OMC responses to stabilizers are highly non-linear and often poorly captured by polynomial regression models.

Shear strength exhibited better performance compared to the Atterberg limits, with an R^2 of 0.512 and an adjusted R^2 of 0.164. Despite this, the predicted R^2 of -2.031 reduced the model's reliability for prediction beyond the data. The C.V. of 16.54% indicates moderate variability in the data. These findings contrast with the work of Zhang *et al.,* (2022), who demonstrated higher regression accuracy in shear strength prediction under cementitious stabilization, suggesting that the strength-enhancing nature of stabilizers significantly influences the reliability of predictive models.

The California Bearing Ratio (CBR) test demonstrated the strongest model fit among the soil parameters. With an R^2 of 0.601, adjusted R^2 of 0.317, and the highest adequacy precision (4.074) among the indices, the model explained about 60.1% of the variation in CBR values. Nonetheless, the predicted R^2 of -1.145 shows that predictive capacity was still below acceptable levels. The C.V. of 20.88% points to noticeable variability, yet the moderate explanatory power of the regression remains consistent with the findings of Anburuvel, (2024), who reported that CBR values often show clearer trends in response to stabilizer blends compared to Atterberg limits.

Finally, the unconfined compressive strength (UCS) showed relatively strong regression performance with an R^2 of 0.571 and an adjusted R^2 of 0.264. The adequacy precision was also the highest (5.113), highlighting reasonable model reliability. However, the predicted R^2 of -0.586 limited the model's external applicability. With a C.V. of 18.5%, the data exhibited moderate variability, but the results still reflect potential usefulness for within-sample estimations as shown in Table 4. Comparable findings were reported by Bahmed *et al.,* (2024), who showed that regression models for UCS tend to outperform those of plasticity indices because strength properties are more directly influenced by stabilization processes.

Table 4: Model Summary Statistics for Soil Properties under Quadratic Regression Analysis.

Response	Model p-value	R^2	Adjusted R^2	Predicted R^2	Std. Dev.	Mean	C.V. %	Adeq Precision
LL (%)	0.3614	0.482	0.112	-0.799	3.43	51.08	6.71	3.978
PL (%)	0.5257	0.393	-0.04	-2.66	4.44	36.15	12.29	3.301
PI (%)	0.6246	0.342	-0.128	-1.552	6.77	15.62	43.33	2.496
MDD (g/cm³)	0.6566	0.325	-0.157	-2.841	0.101	1.49	6.78	2.978
OMC (%)	0.3984	0.461	0.076	-2.217	3.94	20.65	19.07	3.764
Shear Strength (kN/m²)	0.3096	0.512	0.164	-2.031	18.16	109.85	16.54	4.222
CBR Ratio (%)	0.1786	0.601	0.317	-1.145	19.1	91.47	20.88	4.074
UCS (kN/m²)	0.2199	0.571	0.264	-0.586	37.86	204.69	18.5	5.113

3.3.2 Regression Equations

The regression equations derived for the different soil properties provide valuable insights into how the independent variables, denoted as A and B, along with their interaction and quadratic terms, influence the responses under investigation. For the liquid limit (LL), the model shows a negative contribution from both A (-0.856694) and B (-0.438981), while the interaction term AB (0.166667) exerts a slight positive effect as shown in Equation 1. The negative quadratic terms further highlight diminishing effects of both variables with higher levels. This result implies that the liquid limit generally decreases with an increase in either stabilizer content.

Similarly, the plastic limit (PL) model demonstrates a stronger negative effect from A (-1.25581), while B (0.0622039) exerts a minor positive contribution. The presence of positive quadratic terms suggests that increases in stabilizer levels may eventually offset the initial reduction in PL as illustrated in Equation 2. Such a pattern reflects the complex interaction between stabilizers and soil fines, which influence moisture absorption and workability. The plasticity index (PI) equation indicates that A (1.02947) increases PI, while B (-0.301481) reduces it, with their quadratic effects being predominantly negative. This relationship highlights the contrasting influence of the two variables, where one contributes to enhanced plasticity while the other suppresses it as shown in Equation 3. For maximum dry density (MDD), the regression shows that A (0.0291561) contributes positively, suggesting increased compaction efficiency with higher dosages, whereas B (-0.0102557) reduces density. The quadratic terms indicate diminishing returns at higher application levels, pointing to an optimal range rather than a linear progression as illustrated in Equation 4.

The optimum moisture content (OMC) equation reveals significant negative contributions from both A (-0.926337) and B (-0.41666), implying that stabilizer addition reduces the water required to achieve compaction. This reduction is consistent with the binding effect of stabilizers, which reduces pore spaces and hence lowers water demand. However, the positive interaction (0.136667AB) and quadratic terms reflect that, at certain levels, combined applications may slightly elevate OMC as shown in Equation 5. The shear strength (SS) model highlights strong negative contributions from both A (-7.73794) and B (-1.91787), although the interaction term (0.947917AB) contributes positively. This suggests that while individual increases in stabilizer content may reduce shear strength, their combined application provides some improvement. The quadratic terms illustrate further nonlinear behavior as illustrated in Equation 6.

The California Bearing Ratio (CBR) equation shows positive contributions from both A (1.91447) and B (1.30095), indicating that both stabilizers enhance CBR performance. The positive interaction term (0.645521AB) further reinforces the synergistic effect, although the negative quadratic terms suggest eventual reduction beyond optimal levels as illustrated in Equation 7. Finally, the unconfined compressive strength (UCS) model demonstrates negative coefficients for both A (-16.9521) and B (-2.46529), pointing to reductions in strength with increased stabilizer levels when considered individually. However, the positive interaction term (1.91667AB) suggests that combined dosages offer some recovery in UCS, albeit with diminishing quadratic effects as shown in Equation 8.

$$LL\ (\%) = 55.561 - 0.857\,A - 0.439\,B + 0.167\,AB - 0.031\,A^2 - 0.028\,B^2 \quad (1)$$

$$PL\ (\%) = 38.625 - 1.256A + 0.062B + 0.052AB + 0.034A^2 + 0.001B^2 \quad (2)$$

$$\mathrm{PI}\ (\%) = 17.341 + 1.029A - 0.301B + 0.115B - 0.155A^2 - 0.048B^2 \quad (3)$$

$$\mathrm{MDD}\ (\mathrm{g/cm^3}) = 1.465 + 0.029A - 0.010B - 0.0015AB - 0.002A^2 + 0.001B^2 \quad (4)$$

$$\mathrm{OMC}\ (\%) = 23.99 - 0.926A - 0.417B + 0.137AB - 0.042A^2 + 0.011B^2 \quad (5)$$

$$\mathrm{SS}\ (\mathrm{kN/m^2}) = 134.159 - 7.737A - 1.917B + 0.947AB + 0.153A^2 - 0.147B^2 \quad (6)$$

$$\mathrm{CBR\ Ratio}\ (\%) = 103.022 + 1.915A + 1.301B + 0.646AB - 0.993A^2 - 0.289B^2 \quad (7)$$

$$\mathrm{UCS}\left(\frac{\mathrm{kN}}{\mathrm{m^2}}\right) = 255.75 - 16.952A - 2.465B + 1.917AB + 0.064A^2 - 0.277B^2 \quad (8)$$

3.3.3 Response Surface Plot

The variation of liquid limit (LL), plastic limit (PL), and plasticity index (PI) with combined incorporation of corn cob ash (CBA) and rice husk ash (RHA) is illustrated in the three-dimensional surface plots presented above. The first surface plot demonstrates how LL (%) responds to changes in CBA and RHA contents. It can be observed that the liquid limit increases with higher CBA content, particularly when RHA levels are relatively low. Conversely, at higher RHA percentages, LL tends to reduce, producing a downward slope across the RHA axis. This suggests that while CBA enhances the water affinity of the soil, RHA introduces a counteractive influence that reduces its plastic water demand. A similar observation was reported by Becerra-Duitama and Rojas-Avellaneda, (2022), who noted that pozzolanic materials with finer particle sizes tend to fill voids and reduce the soil's capacity to hold water, thereby lowering the liquid limit.

In contrast, the response surface plot illustrating the plastic limit presents a different pattern compared to the liquid limit as shown in Figure 4.6. The PL values increase steadily with increasing RHA content, whereas the effect of CBA appears less pronounced. This implies that RHA contributes significantly to the stiffening of the soil matrix, thus enhancing its resistance to deformation at lower water contents. Moreover, this trend is consistent with the findings of Mugambi *et al.*, (2023), who observed that ash-based stabilizers improve soil workability by promoting particle bonding, thereby increasing the plastic limit. However, at higher CBA levels, a slight reduction in the plastic limit is evident, suggesting that excessive CBA may compromise soil cohesion by introducing larger amounts of unreacted silica.

Furthermore, the plasticity index (PI), shows a non-linear trend in response to the stabilizers. Intermediate levels of both CBA and RHA produce higher PI values, while extreme proportions of either additive result in lower PI as illustrated in Figure 4.7. This dome-like relationship points to the existence of an optimum blending range in which the soil exhibits enhanced plastic behavior. Conversely, when either stabilizer dominates, the soil tends to lose its plasticity, becoming more brittle. This behavior agrees with the findings of Ali and Atemimi (2024), who emphasized that the synergistic effect of combining different pozzolanic ashes can initially increase plasticity through particle reorientation, though excessive inclusion reduces plasticity due to cementitious reactions that stiffen the soil matrix.

Also, the maximum dry density, the 3D surface plot demonstrates that MDD decreases with increasing RHA content, while CBA appears to enhance density at higher replacement levels as illustrated in Figure 4.8. This suggests that RHA, being more porous and lightweight, reduces compaction efficiency, whereas CBA counterbalances this limitation due to its higher specific gravity and filler properties. Thus, the interaction effect of CBA and RHA highlights that balanced proportions of both materials yield moderate improvements in density, confirming their synergistic stabilizing action. Similar findings were reported by Obianyo (2020), who noted that agro-waste ashes enhance density when used at optimal levels, though excessive application dilutes the soil fines and weakens compaction.

Moreover, the optimum moisture content, the surface plot reveals a steady increase with higher RHA percentages, while CBA exerts a more stabilizing effect at lower replacement levels as shownin Figure 4.7. The rise in OMC can be explained by the highly absorptive nature of RHA, which demands more water during compaction, whereas the denser particles of CBA slightly reduce this requirement. This behavior corroborates the findings of Ratsimbazafy *et al.*, (2021), who reported that pozzolanic materials with porous microstructures increase OMC because of their water absorption and particle-coating effects. Nevertheless, contrasting evidence exists, such as the work of Jalal *et al.*, (2021), which suggested that ashes rich in lime content reduce OMC by promoting flocculation and particle agglomeration, thereby limiting water-holding capacity.

In addition, the third response surface plot, which highlights the behavior of the plasticity index (PI), revealed a non-linear relationship. Intermediate proportions of both CBA and RHA produced higher PI values, while extreme proportions of either additive led to reductions as illustrated in Figure 4.8. This dome-shaped pattern indicates the existence of an optimum blending range that enhances soil plastic behavior, whereas the dominance of one stabilizer reduces plasticity and induces brittleness. Similarly, Ali and Atemimi (2024) observed that the combined use of different pozzolanic ashes can initially increase soil plasticity through particle reorientation; nevertheless, they emphasized that excessive incorporation results in cementitious reactions which stiffen the soil matrix and reduce plasticity.

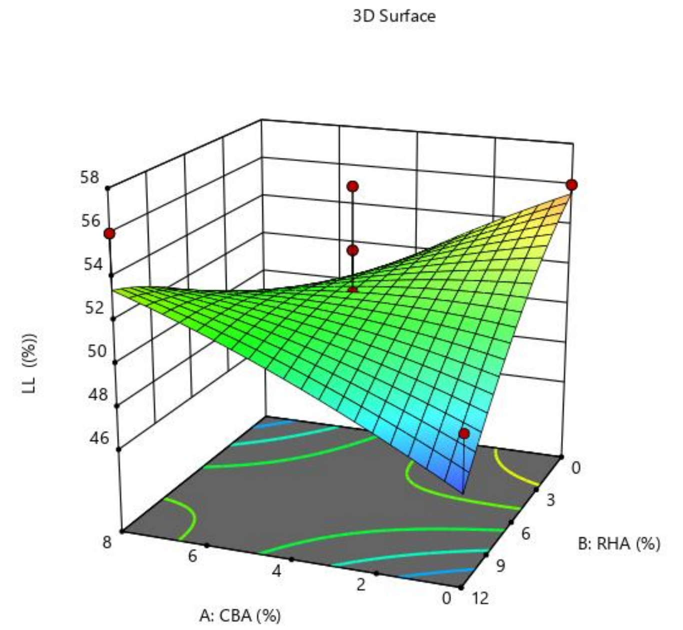

Figure 6: Response Surface Plot of LL

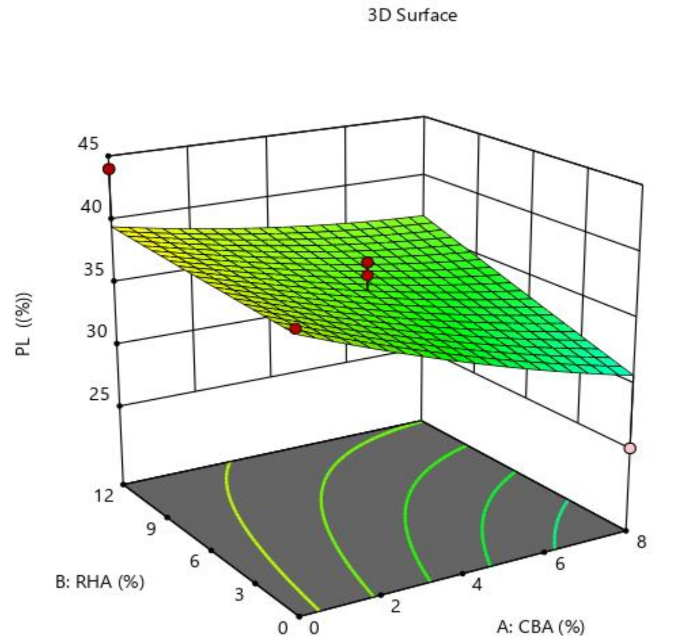

Figure 7: Response Surface Plot of PL

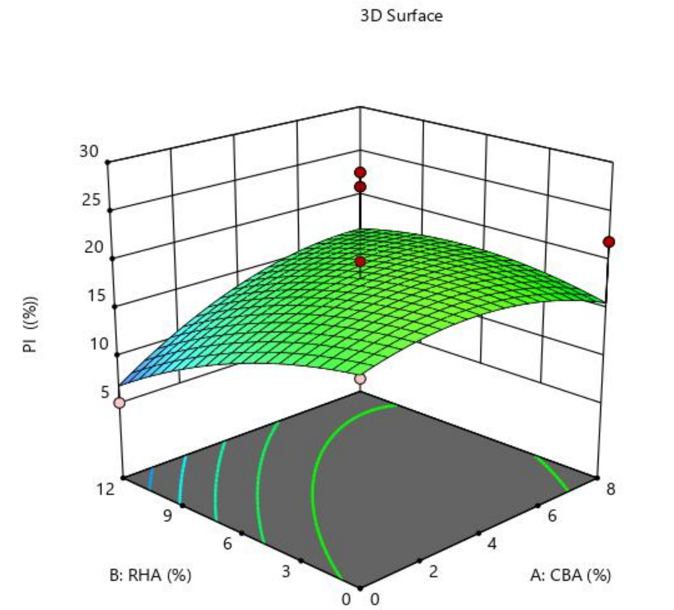

Figure 8: Response Surface Plot of PI

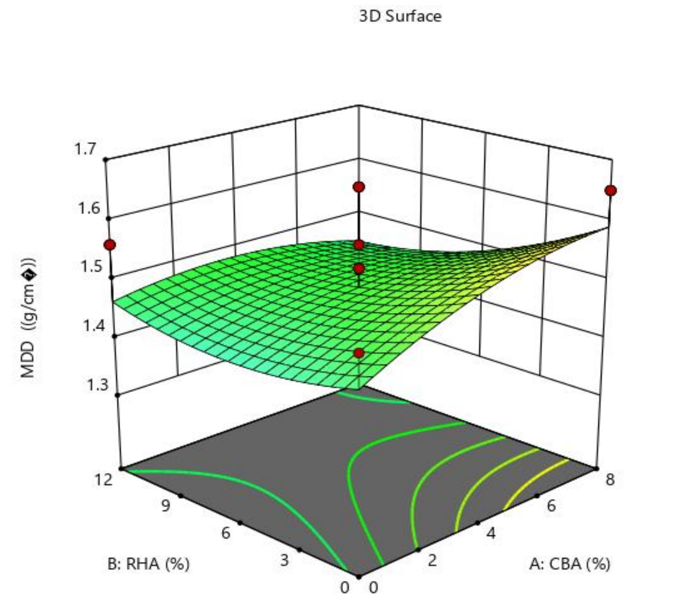

Figure 9: Response Surface Plot of MDD

Moreover, respect to the optimum moisture content, the response surface plot indicated a steady increase with higher RHA content, while CBA exhibited a stabilizing effect at lower replacement percentages. The increase in OMC may be attributed to the absorptive capacity of RHA, which demands greater water during compaction, whereas the denser nature of CBA slightly reduces this requirement as illustrated in Figure 4.10. This observation corroborates the findings of Siletani *et al.*, (2024), who emphasized that pozzolanic materials with porous microstructures increase OMC through water absorption and coating of soil particles during mixing. On the other hand, Okeke (2020) provided contrasting evidence, noting that ashes with significant lime content reduce OMC due to flocculation and agglomeration processes that limit water retention. Therefore, these contrasting results underscore the fact that the chemical composition and physical properties of each ash type play a decisive role in dictating their effect on soil moisture requirements.

The shear strength behavior, as illustrated in Figure 11, shows a remarkable improvement with increasing levels of both RHA and CBA. The plot reveals a synergistic effect, with the highest shear strength achieved at intermediate to high replacement levels of the two additives. This suggests that while RHA enhances binding through pozzolanic reactivity, CBA provides additional calcium oxide, which accelerates the formation of cementitious products that improve interparticle bonding and resistance to shear stresses. This finding aligns with the report by Iliyas *et al.*, (2024), who confirmed that the combined application of agricultural ashes in soil stabilization significantly improves strength characteristics due to complementary pozzolanic and filler effects.

The response surface plot for the California Bearing Ratio (CBR) clearly illustrates as shown in Figure 12 which shows the interaction between CBA and RHA influenced soil strength development. The curvature of the surface shows that an increase in both additives produced a significant improvement in CBR values, with the maximum strength observed when CBA was maintained around mid-range levels (about 4–6%) and RHA at slightly higher levels (6–9%). Beyond this range, the surface tends to flatten, indicating diminishing returns with further increments of either additive. This demonstrates that the pozzolanic reaction of CBA and RHA enhanced the soil's load-bearing capacity by binding particles together and filling voids, thereby improving stiffness. Similar findings were reported by Marathe *et al.*, (2024), who observed that combining agro-industrial byproducts in optimal ratios produced synergistic effects that improved subgrade strength, while excessive amounts created weak zones due to unreacted materials.

In contrast, the response surface plot of the unconfined compressive strength (UCS) revealed a slightly different trend as shown in Figure 13. The UCS values increased consistently with higher CBA content, reaching a peak when combined with moderate amounts of RHA. However, the surface displayed some non-linear behavior, as very high percentages of RHA, particularly above 9%, resulted in a gradual decline in UCS even when CBA was kept high. This suggests that while RHA provides reactive silica for pozzolanic bonding, excess amounts can introduce unreacted residues, which weaken the soil matrix. A similar observation was made by Vieira *et al.*, (2021), who noted that high substitution levels of rice husk ash in soil stabilization could reduce density and compromise compressive strength due to poor particle packing. On the other hand, Ahmed and Musa (2020) emphasized that moderate blending of ashes produced stable mixes with sufficient cementitious products to enhance compressive resistance, which supports the results of the present study.

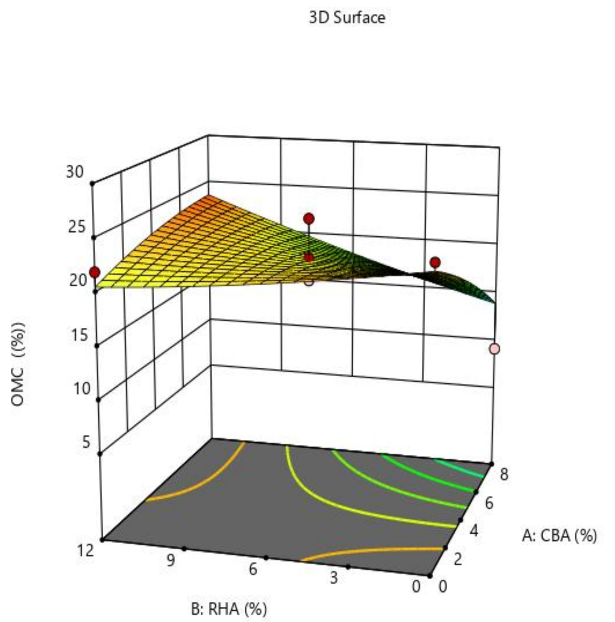

Figure 10: Response Surface Plot of OMC

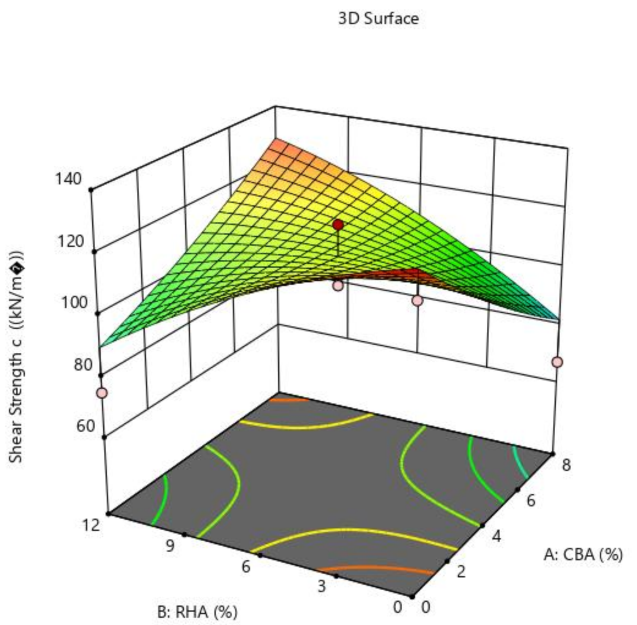

Figure 11: Response Surface Plot of SS

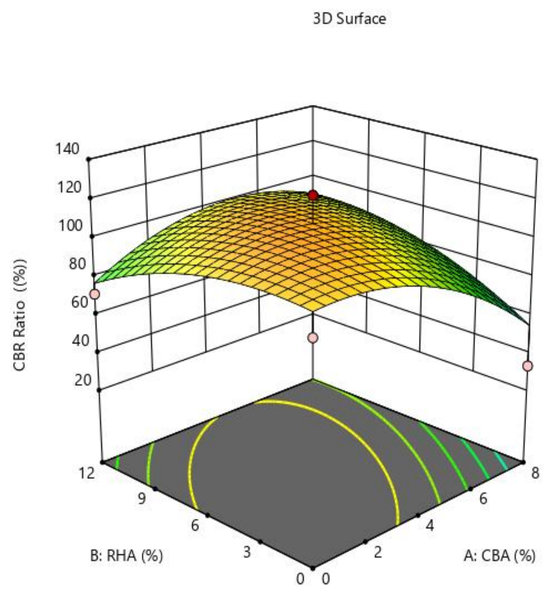

Figure 12: Response Surface Plot of CBR

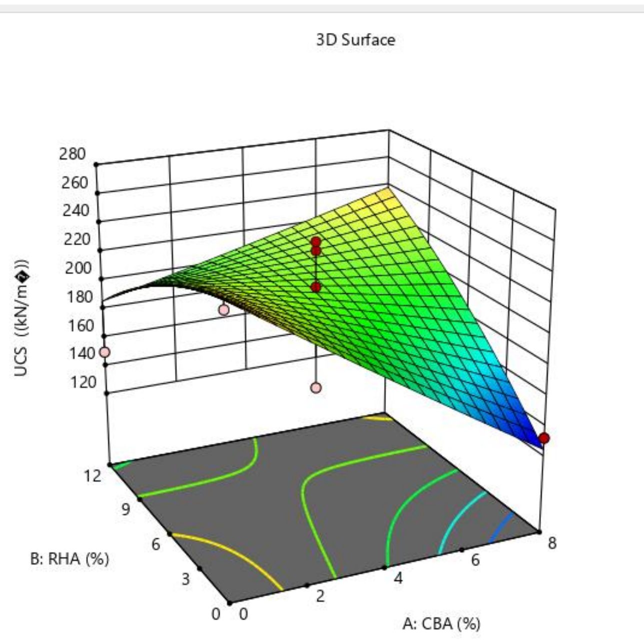

Figure 13: Response Surface Plot of UCS

4. CONCLUSION

The incorporation of rice husk ash (RHA) and cow bone ash (CBA) improved the engineering properties of lateritic soil, with reductions in plasticity index, enhanced compaction characteristics, and significant increases in shear strength, California Bearing Ratio (CBR), and unconfined compressive strength (UCS). RHA contributed to improved plasticity and strength through pozzolanic reactions, though it's lightweight and porous structure reduced density and increased moisture demand. The calcium-rich composition of CBA balanced these effects by supplying free calcium ions that reacted with RHA silica to form cementitious compounds, thereby enhancing soil stability and load-bearing capacity. Optimal blends, notably M06, M09, and M10, consistently exhibited superior performance, underscoring the effectiveness of the RHA–CBA synergy in producing durable and workable subgrade materials for road construction. However, the quadratic regression model employed showed limited predictive reliability across most soil parameters, with negative predicted R^2 values undermining external validity. Atterberg limits and compaction properties were poorly represented, reflecting the complexity of soil–stabilizer interactions. Although shear strength, CBR, and UCS displayed relatively stronger fits, their predictive power remained weak. Overall, experimental and surface response analyses affirm that balanced RHA–CBA combinations optimize soil plasticity, compaction, and strength, providing a sustainable approach to geotechnical stabilization.

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