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Improving the Mechanical Properties of Natural Soil Using Rice Husk Ash and Soy Bean Hull Ash in Biu – Borno State

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Abstract
This study investigated the potential of rice husk ash (RHA) and soy bean hull ash (SBHA) as sustainable stabilizers for enhancing the mechanical properties of Biu soil in Borno State, Nigeria. Given the poor geotechnical characteristics of the native soil, the research explored the viability of these agro-waste pozzolans in improving the mechanical properties of the soil. A constant 20% pozzolanic replacement level was adopted across various mix proportions using a 1:4 cement-to-aggregate ratio. Laboratory tests were conducted on both untreated and treated soil samples using standardized methods. Results showed a consistent improvement in UCS and CBR values with varying proportions of RHA and SBHA, while PI values decreased accordingly, indicating reduced soil plasticity and improved stability. The highest UCS of 1400 kPa and CBR of 135% were recorded in BSC-04, while PI reduced to 16%, signifying enhanced load-bearing capacity and suitability for construction. These findings support the use of RHA and SBHA as effective, low-cost, and environmentally friendly alternatives for soil stabilization.

Keywords: California Bearing Ratio, Mechanical properties**,** Unconfined Strength, Pozzolana, Soil, Stabilization

Introduction
Soil stabilization is a fundamental technique in engineering aimed at enhancing the physical and mechanical properties of weak soils to make them suitable for construction purposes (Fondio *et al*., 2021; Abdallah *et al*., 2020). According to Abdulla and Majeed (2021), conventional stabilizers such as cement and lime have been widely used for soil improvement; however, the environmental implications and rising costs associated with these conventional methods have prompted the search for alternative, sustainable materials. In this context, agricultural waste products such as groundnut shell ash (GSA), sugar cane baggasee ash (SCBA), rice husk ash (RHA) and soy bean hull ash (SBHA) have gained attention due to their pozzolanic properties and eco-friendly potential (Nwonu and Ikeagwuani, 2021; Parkash and Kumar, 2017)

Studies have shown that, Rice husk ash, obtained by burning rice husk, contains a high percentage of amorphous silica, making it a viable pozzolanic material (Maxwell and Job, 2016). When combined with cement, RHA reacts with calcium hydroxide in the presence of water to form cementitious compounds that enhance the strength and durability of concrete (Soji *et al.,* 2020; Maxwell *et al*., 2016). Similarly, soy bean hull ash, obtained from the combustion of soybean husks, contains silica, alumina, and iron oxides, which also contribute to pozzolanic activity and improved mechanical behaviour of concrete (Wageti *et al*., 2023). These agricultural wastes have been used previously to improve the properties of concrete with great success (Wageti *et al*., 2023; Soji *et al*., 2020). Therefore, this study assumes that when these wastes are used appropriately, they may significantly modify soil properties such as unconfined compressive strength (UCS), California Bearing Ratio (CBR), and plasticity, thereby enhancing their suitability for construction

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applications, since the wastes have improved performance in concrete studies. The use of locally available materials like RHA and SBHA may not only provide an economical solution to soil stabilization but also supports waste recycling and environmental conservation (Maxwell and Job, 2016).

With Nigeria generating vast quantities of rice husks and soybean hulls annually, their effective utilization in construction presents a sustainable approach to managing agro-waste while addressing infrastructural challenges (Wageti *et al*., 2023; Nwonu and Ikeagwuani, 2021; Maxwell and Job, 2016; Joseph, 2015). Moreover, reducing dependence on conventional stabilizers aligns with global sustainability goals and promotes green construction practices (Amiri *et al*., 2022; Fondio *et al*., 2021; Scheuermann *et al*., 2020), especially in rural and economically constrained regions like Biu, Borno State.

Existing research has shown promising results in the use of RHA and other pozzolanic materials in concrete production, yet limited studies have focused on soil stabilization. Furthermore, limited studies exist on the combined effect of RHA and SBHA on soil specifically. Hence, investigating the synergy between these two ashes can provide new understanding into optimal blending ratios and treatment procedures that yield superior mechanical performance especially for residents of Biu and environs. Such findings can inform local engineering practices and policy frameworks that encourage the adoption of sustainable construction materials.

Therefore, this study aims to investigate the mechanical properties of Biu soil stabilized with varying proportions of rice husk ash and soy bean hull ash. It seeks to assess parameters such as compaction characteristics, UCS, and CBR, to determine the most effective mix proportions and treatment conditions for enhancing the strength and durability of Biu, Borno State soil.

Materials and Methods

Cement and Aggregates

The Ashaka brand of Ordinary Portland Cement (OPC) manufactured by Lafarge Cement Company Plc located in Ashaka in Bauchi State which conforms to ASTM C 150 (1994) was used throughout the test. The fine aggregate used in this study was natural soil obtained from the premises of Nigerian Army University Biu, Borno State.

Experimental Details

Rice husk and Soybeans hull used for this research were sourced from Biu in Biu LGA of Borno State, Nigeria. The agricultural wastes were burnt under controlled conditions in the concrete laboratory at the Department of Building, Modibbo Adama University Yola, (MAU, Yola) Adamawa State, Nigeria into ashes at a temperature of 750^{o}C. The pulverized ashes were sieved using 212um sieve. A representative sample of the soil in Nigerian Army University Biu – Borno State was collected to perform the tests. The sample collected represented the general characteristics of the soil in Biu – Borno State. 15kg of the sample size of the soil was collected. The soil sample was homogeneous in nature. Samples of the Rice husk and Soybeans hull were analysed chemically in the laboratory of Umaru Yar'adua University, Katsina State through Energy Dispersion X- RAY fluorescent analysis (ED - XRF Test). The adopted replacement level was based on previous similar works by (Joseph, 2015; Maxwell and Job, 2016; Okala *et al*., 2016) which recommends between 10% - 40% as the most suitable replacement level for blended concrete. The laboratory analysis was performed at the Building Department, MAU, Yola.

The basic properties of the untreated soil were first assessed. These tests include: the Unconfined Compressive Strength (UCS), to determine the strength of the soil without any stabilization. The California

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Bearing Ratio (CBR), to assess the soil's resistance to penetration. And, the Plasticity Index (PI), to evaluate the soil's plasticity, which can help predict the behaviour when adding pozzolans. The various mixtures were prepared at a constant pozzolana level replacement of 20%. After mixing the soil with pozzolans, the same tests (UCS, CBR, PI) on the soil with each proportion of pozzolan was conducted. To ensure the accuracy and reliability of the results, multiple replicates tests were conducted for each percentage replacement of the soil. Four mixes containing the pozzolanas were produced with identities BSC10, BSC20, BSC30 and BSC40 by mass (weight) of cement. BSC10 is the control, BSC20 is made up of (100% OPC + 5%RHA + 15% SBHA), BSC30 is made up of (100% OPC + 15%RHA + 5% SBHA), while BSC40 composed of 100% OPC + 7.5%RHA +7.5% SBHA Mix ratio 1:4 and 0.5 W/C ratios were adopted for this work. Cylindrical cubes of dimension 100mm x 200mm were produced (Plate 1). A total of 12 cylindrical cubes were cast. The absolute volume method was adopted for the computation of the various quantities of materials required.

Plate 1: Sample of Cast Cylindrical Cubes

Results and Discussion

Table 1 and Figure 1 show the result of chemical composition of the Rice Husk Ash (RHA) used in this research. The combined percentage of Silicon Oxide, Aluminium Oxide and Iron Oxide (SiO_2 + Al_2O_3 + Fe_2O_3) of the RHA is 83.4%. This meets the specification for pozzolans (70% minimum requirement) as provided in ASTM C 595 (2003). The oxide with the highest percentage is SiO_2 (81.41%); this is greater than the range in OPC

(17 - 25%). While the percentage of the calcium oxide (CaO) content is far lower in RHA (3.18%), this value is less than that present in OPC (73.96%). This Calcium Oxide which is a major constituent of OPC is responsible for the high rate of hydration, this might explain the reason for the slow rate of hydration and strength gain in pozzolana cement and also the increase in the setting time of cement pastes mixed with RHA (Maxwell and Job, 2016).

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Table 1. Chemical composition of RHA

Oxides	Al_2O_3	SiO_2	SO_3	K_2O	CaO	V_2O_5
Mass (%)	0.89	81.41	**-**	1.92	3.18	-
Oxides	Fe_2O_3	TiO	ZnO	Cr_2O_3	MnO	LOI
Mass (%)	1.08	0.47	0.01	0.02	0.84	5.06

Source: Field work (2025)

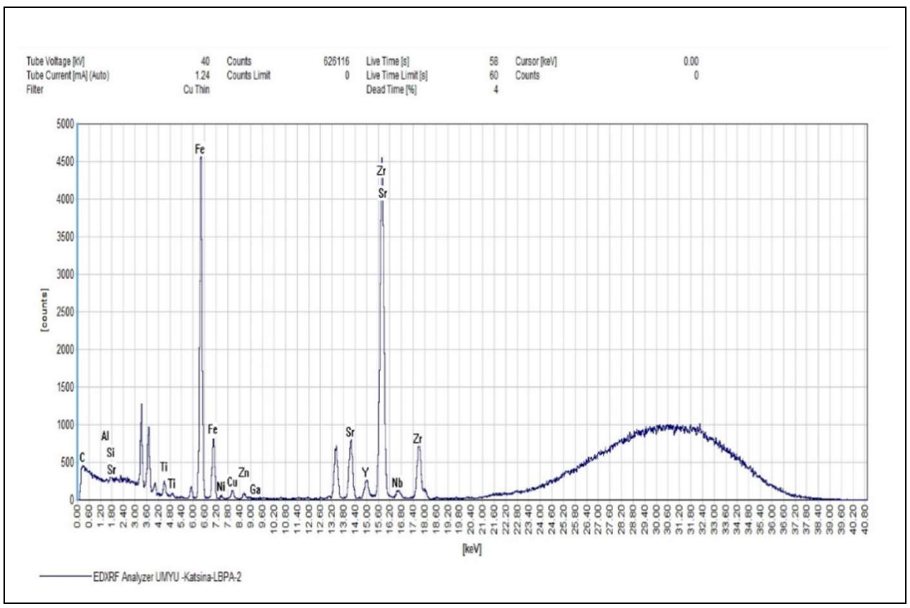

Figure 1. Characterization of Rice Husk Ash
Source: Field Work (2025)

Table 2 and Figure 2 show the result of chemical composition of the soy bean hull ash (SBHA) used in this study. The combined percentage of Silicon Oxide, Aluminium Oxide and Iron Oxide (SiO_2 + Al_2O_3 + Fe_2O_3) of the SBHA was 85.2%. The absence of SO_3 (Sulphur IV Oxide) in the soy bean hull ash indicates that there may be reduction or no likelihood of Sulphate attack on concrete reinforcements; as sulphur dioxide according Neville (2006) corrodes reinforcement. From the chemical analysis, Sodium Oxide (Na_2O) is absent in the SBHA. The SBHA has MgO (2.73%), according to Wageti *et al*. (2023), natural pozzolans with a high content of SiO_2 + Al_2O_3 (≥80%) but a low content of MgO and SO_3 generally exhibit a high pozzolanic activity. The chemical analysis confirms soy bean hull ash as a good pozzolana.

Table 2. Chemical composition of SBHA

Oxides	Al_2O_3	SiO_2	SO_3	Na_2O	CaO	V_2O_5
Mass (%)	1.73	82.20	-	-	3.67	-
Oxides	Fe_2O_3	TiO	ZnO	Cr_2O_3	MgO	LOI
Mass (%)	1.27	0.33	0.003	0.001	2.73	3.05

Source: Field work (2025)

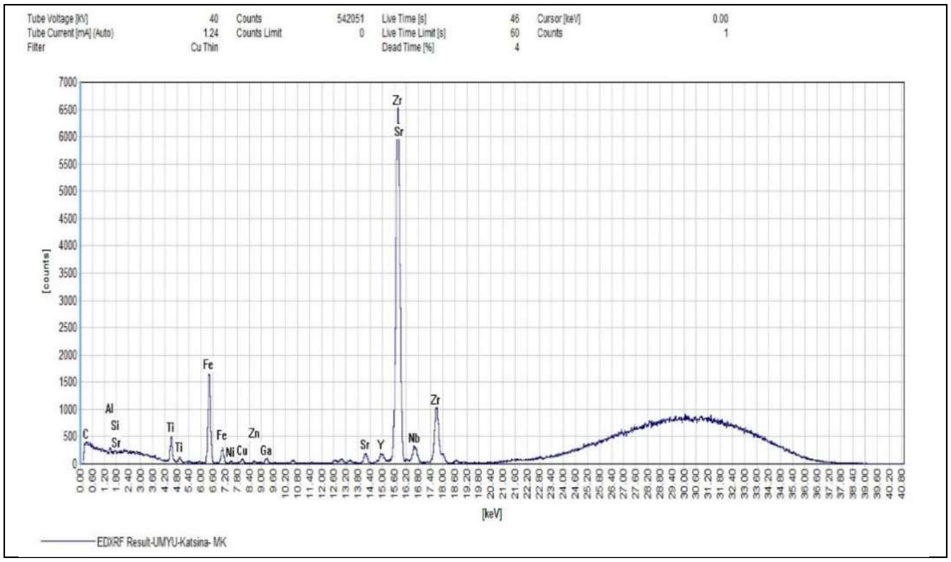

Figure 2. Characterization of Soy Bean Hull Ash
Source: Field work (2025)

The Unconfined Compressive Strength (UCS)

The Unconfined Compressive Strength (UCS) test results in the table reveal a progressive increase in strength values across the tested Biu

Soil Cement (BSC) samples, with UCS values ranging from 850 kPa to 1400 kPa (Table 3 and Figure 3)

Table 3. Unconfined Compressive Strength (UCS) Test Results

Sample ID	Diameter (mm)	Length (mm)	Failure Load (N)	Area (cm^2)	UCS (kPa)
BSC-01	100	200	65755	785.4	850
BSC-02	100	200	86395	785.4	1100
BSC-03	100	200	98175	785.4	1250
BSC-04	100	200	109955	785.4	1400

Note: UCS = Failure Load / Cross-sectional Area
Source: Field work (2025)

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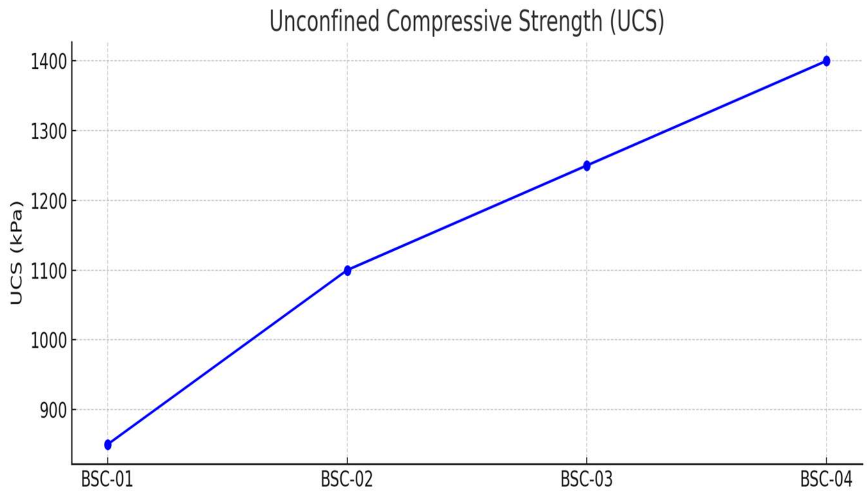

Figure 3. UCS values for different BSC samples.

According to ASTM D2166/D2166M-16 standards, UCS values above 1034 kPa (150 psi) generally indicate that the soil-cement material has sufficient strength for use in light to moderate structural applications, including pavement subgrades and stabilized base layers. In this context, samples BSC-02 (1100 kPa), BSC-03 (1250 kPa), and BSC-04 (1400 kPa) exceed the minimum recommended strength, suggesting adequate soil stabilization and successful cement modification. However, BSC-01, with a UCS of 850 kPa, falls below this benchmark, which may be due to inconsistencies in cement content, compaction effort, or curing conditions (Abdullah *et al*., 2020; Okagbue and Onyeobi, 1999). This variation points to the need for quality control during soil stabilization to ensure consistent performance across samples (Bose, 2012).

The increasing UCS values across the samples also reflect the positive effect of cement stabilization, consistent with findings by Yadav and Tiwari (2019), who emphasized that the strength gain in cement-treated lateritic soils is closely linked to cement dosage and curing time. The results imply that the Biu soil has a favourable response to cement treatment, aligning with the findings of Zada *et al*. (2021), who reported similar UCS improvements in tropical residual soils treated with Portland cement. The variation observed suggests that while the soil has good potential for stabilization, site-specific mix designs and thorough material characterization are essential. Therefore, these results validate the technical viability of using cement-stabilized Biu soil in constructions.

California Bearing Ratio (CBR) Test Results

The California Bearing Ratio (CBR) values obtained from the soil samples (BSC-01 to BSC-04) are presented in Table 4 and Figure 4 graphically.

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Table 4. California Bearing Ratio (CBR) Test Results

Sample ID	Penetration (mm)	Load (N)	Standard Load (N)	CBR (%)
BSC-01	2.5	1800	2360	76
BSC-02	5.0	2200	1830	120
BSC-03	2.5	2700	2080	130
BSC-04	5.0	3400	2520	135

Note: California Bearing Ratio, BCR (%) = (Measured Load / Standard Load) × 100
Source: Field work (2025)

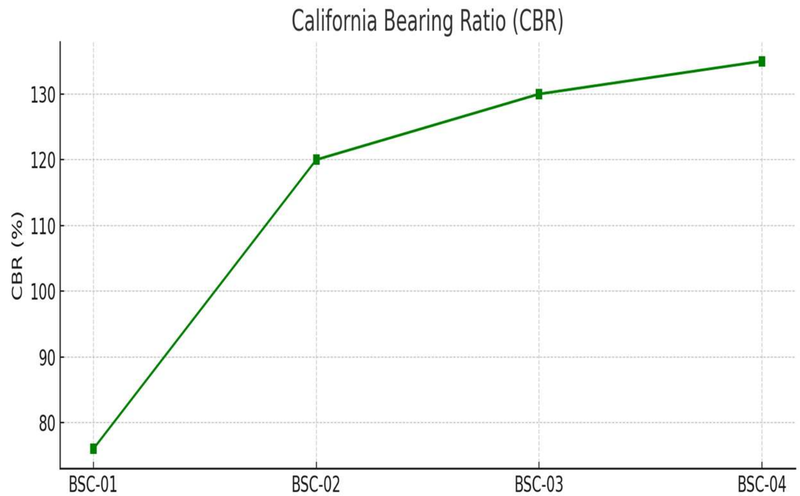

Figure 4. CBR values for different BSC samples.

The results indicate CBR values ranging from 76% to 135% for both 2.5 mm and 5.0 mm penetrations. Specifically, sample BSC-01 recorded a CBR of 76% at 2.5 mm penetration, while sample BSC-02 showed a CBR of 120% at 5.0 mm penetration. Samples BSC-03 and BSC-04 yielded CBR values of 130% and 135% respectively at both penetration depths. According to ASTM D1883-16 and relevant pavement design standards, a CBR value exceeding 20% is generally indicative of a good-quality subgrade soil (Parkash and Kumar, 2017). Moreover, values above 80% are typically suitable for use as base or sub-base materials in flexible pavement systems (Nwonu and Ikeagwuani, 2021). Therefore, the measured values suggest that the tested Biu soil samples BSC-02 to BSC-04 exhibits good load-bearing capacity and mechanical strength, warranting its application for engineering purposes. This was achieved due to the mechanical stabilization. The CBR values, particularly at the 5.0 mm penetration depth which is more representative of long-term field performance imply that the soil has a reduced tendency for deformation under repeated loading. While the CBR test results affirm the suitability of the soil for base and sub-base applications with exception of sample BSC-01, it is recommended that further evaluations be conducted on related geotechnical parameters such as permeability, and moisture-density relationships to comprehensively validate its field applicability.

Plasticity Index (Atterberg Limits Test)

The results of the Atterberg Limits test presented in Table 5 and Figure 5, provide results into the plasticity characteristics of the soil samples, which directly influence their suitability for construction purposes.

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Table 5. Plasticity Test (Atterberg Limits) Results

Sample ID	Liquid Limit (LL) (%)	Plastic Limit (PL) (%)	Plasticity Index (PI) (%)	Soil Classification
BSC-01	70	30	40	CH (High Plastic soil)
BSC-02	70	40	30	CH (High Plastic Clay)
BSC-03	45	25	20	CL (Low Plastic Clay)
BSC-04	45	29	16	CL

Note: PI = LL - PL. Classification based on Unified Soil Classification System (USCS).
Source: Field work (2025).

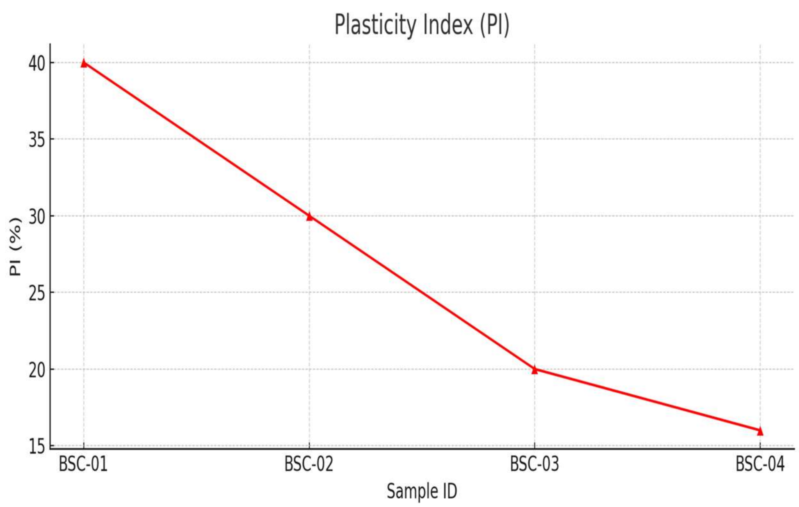

Figure 5. PI values for different BSC samples.

According to the ASTM D2487 (2000), soil with a Plasticity Index (PI) less than 17 is typically categorized as low plastic clay (CL), while a PI greater than 17 is considered high plastic clay (CH). In the table, BSC-01 and BSC-02 have PIs of 40 and 30 respectively, classifying the samples as CH. This suggests that soils samples BSC-01 and BSC-02 may pose a higher risk of expansion and contraction, which can lead to structural instability in foundations if not properly managed (Zada *et al*., 2021). However, samples BSC-03 and BSC-04 with PIs of 20 and 16 respectively, also fall under CL. The increasing PI values for CH soils indicate higher clay content and greater potential for volumetric changes with moisture fluctuations (Fondio *et al*., 2021).

From an engineering perspective, the classification and corresponding plasticity behaviour have implications for construction design and ground improvement strategies. The high plasticity in samples BSC-01 and BSC-02 indicates a need for more stabilization before they can be reliably used as subgrade materials. Moreover, these findings align with standards such as ASTM D4318, which provides thresholds for evaluating soil plasticity and its effect on structural performance. According to Suresh and Murugaiyan (2021), soils with high LL and PI tend to retain moisture and swell, making them less desirable for construction unless appropriately treated.

The results demonstrate a clear enhancement in the mechanical behaviour of Biu soil upon stabilization with blended rice husk and soy bean hull ashes. The unconfined compressive strength (UCS) increased progressively across all mixes, with BSC-01 having the lowest value at 850 kPa and BSC-04 peaking at 1400 kPa. These values exceed the minimum UCS benchmark of 1034 kPa required for sub-base materials, confirming the efficacy of the pozzolanic treatment. The rise in UCS is attributed to the formation of cementitious compounds from the pozzolanic reaction between silica-rich ashes and calcium hydroxide as reported in works of (Amiri *et al*., 2022; Scheuermann *et al*., 2020). Similarly, CBR values followed a similar trend, ranging from 76% in BSC-01 to 135% in BSC-04, far surpassing the typical threshold of 20% for good subgrade soils. These CBR values suggest exceptional load-bearing capacity and reduced susceptibility to deformation which is in agreement with the work of Fondio *et al*. (2021). In contrast, the Plasticity Index showed a downward trend, from 40% in the untreated sample to 16% in the most stabilized sample, indicating improved soil workability and diminished swelling potential. The inverse relationship between PI and CBR confirms established geotechnical theory that lower plasticity enhances soil strength. Chemical analysis of the ashes revealed high silica content (> 80%), affirming their pozzolanic reactivity and suitability for soil improvement as found in related works by Zada *et al*. (2021) and Soji *et al*. (2020). Furthermore, Atterberg Limit results classified the treated soils predominantly within the low plastic clay category (CL), marking their transition from expansive and unstable conditions to more construction-friendly materials. The cumulative effect of these improvements reflects the synergistic action of RHA and SBHA, validating their role as effective stabilizers and promoting sustainable infrastructure development in resource-constrained environments.

Conclusion

Based on the findings in this study, it is concluded that:

i. The increase in unconfined compressive strength and California Bearing Ratio, coupled with a decrease in the Plasticity Index, affirms the potential of these agro-wastes as viable and sustainable stabilizers.
ii. The findings reveal that an optimized blend of these ashes can transform weak and plastic soils into structurally competent materials suitable for engineering applications. This not only addresses the geotechnical limitations of Biu soil but also promotes environmentally responsible construction practices by valorising agricultural waste.
iii. Consequently, the use of RHA and SBHA can serve as a cost-effective and eco-friendly alternative to conventional stabilizers, particularly in rural and developing regions.
iv. It is recommended that further studies explore long-term performance, field-scale validation, and the economic analysis of large-scale implementation to reinforce the applicability of this approach in sustainable construction.

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