
CALIFORNIA BEARING RATIO OF GEOPOLYMER-STABILIZED LATERITIC SOIL USING SUGARCANE BAGASSE ASH AND RICE HUSK ASH AS PRECURSORS

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ABSTRACT

Environmental concerns coupled with economic considerations have heightened interests towards sustainable pavement construction. Several studies in sustainable pavement construction had explored stabilization of weak, unstable or problematic soils using agricultural wastes. Agricultural waste materials such as sugarcane bagasse ash (SBA) and rice husk ash (RHA) are rich in reactive silica and possess considerable pozzolanic potential, making them promising geopolymer precursors for soil stabilization. However, limited studies have investigated the combined performance of alkali-activated with 1% NaOH (prepared as a 5 M solution) SBA and RHA in improving tropical lateritic soils used in road construction. This study evaluated the engineering performance of geopolymer-stabilized lateritic soil incorporating SBA and RHA activated with 1% sodium hydroxide. Lateritic soil (having silica-sesquioxide ratio of 1.30) obtained from Ahmadu Bello University Teaching Hospital (ABUTH), Shika, Nigeria, was stabilized using three SBA: RHA blends (3:1, 2:2, and 1:3), while soil stabilized with 4% Portland limestone cement served as the control. Laboratory tests included particle size distribution, specific gravity, Atterberg limits, X-ray fluorescence (XRF), compaction characteristics, and California Bearing Ratio (CBR) in accordance with BS 1377-2:2022. The natural soil was classified as A-7-5 under AASHTO and CL under the Unified Soil Classification System, indicating poor engineering quality. XRF analysis confirmed high silica contents in both ashes, particularly RHA (73.76% SiO₂), supporting their suitability for geopolymerization. Among the geopolymer mixes, the balanced 2 % SBA + 2 % RHA blend produced the largest reduction in plasticity index (from 43.36 % to 23.11 %) and the highest unsoaked CBR (81.9 %), approaching the cement control (86.6 %). Soaked CBR values for all geopolymer mixes (17.0-18.31 %) satisfied Overseas Road Note 31 requirements for improved subgrade. The results indicate that a 2:2 SBA-RHA geopolymer activated with 5 M NaOH at 4 % total stabilizer content is a practical cement-free alternative for improving tropical lateritic soils for pavement subgrade applications. Stabilized specimens exhibited slightly higher optimum moisture contents (17-18%) while maintaining comparable maximum dry densities (1.83-1.86 Mg/m³). The results showed that alkali-activated SBA-RHA geopolymer is a viable and sustainable alternative to conventional cement stabilization for enhancing tropical lateritic soils for pavement applications.

Keywords: Lateritic soil; Geopolymer stabilization; Sugarcane bagasse ash; Rice husk ash; Sustainable pavement; California Bearing Ratio

1. INTRODUCTION

Lateritic soils are common in tropical regions and are frequently used as subgrade or fill material in road construction. In their natural state many of these soils exhibit high plasticity, low bearing capacity and poor volume stability, making stabilization necessary prior to used in pavement construction. Traditional cement stabilization is effective but has a high greenhouse gas footprint (Ahmad et al., 2023; Ahmad et al., 2024). Geopolymer technology is a sustainable alternative that uses aluminosilicate-rich waste materials. Rice husk ash (RHA) has high content of reactive silica and sugarcane bagasse ash (SBA) has silica and calcium which can be used for geopolymerization (Anburuvel et al., 2023; Aurelie Tchouateu Kamwa et al., 2023; Burhan & Mohammed, 2025).

Both materials have been studied separately but little information is available on their use together for stabilization of lateritic soils (Chompoorat et al., 2025; Kamwa et al., 2023; Kuasakul et al., 2025; Mathew et al., 2026). This study evaluates the compaction characteristics and CBR performance of lateritic soil stabilized using RHA and SBA as precursors and, compares the results with untreated and cement-treated soils. The rest of the paper is structured as follows. Section 2 reports on materials, methods and methodology adopted in this study. Section 3 presents results and discusses findings. Section 4 ends the paper with conclusions and recommendations.

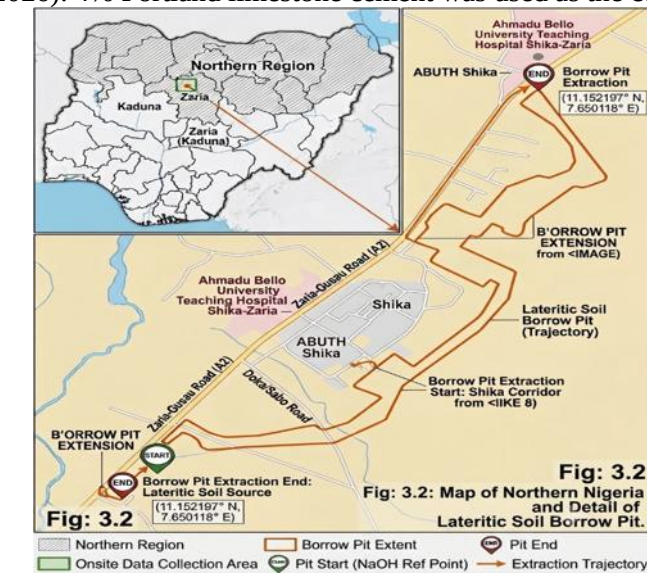
2. MATERIALS AND METHODS

2.1 Study Design

An experimental laboratory programme was conducted to compare untreated lateritic soil, cement-stabilized soil and geopolymer-stabilized soil. The investigation focused on material characterization, compaction behaviour and California Bearing Ratio performance.

2.2 Materials

The Lateritic soil used in this study was obtained from ABUTH, Shika, Zaria (Figure 1(a)). SBA and RHA were sourced locally, washed, air dried and calcined at 700°C for 3 hours, then cooled to room temperature, ground and sieved through BS sieve 200 before use (Figures 1 (b-d)). A 5 M sodium hydroxide solution was prepared and dosed at 1 % by dry weight of soil (i.e., 1 % NaOH solids). These conditions yield the optimum geopolymerization for agricultural wastes ashes (Kumar & Reddy, 2023; Mathew et al., 2026). 4% Portland limestone cement was used as the control stabilizer.



(a) Location of borrow pit for lateritic soil sample collection



(b) Cement



(c) RHA



(d) SBA



(e) NaOH

Figure 1: Location for lateritic soil sample collection and geopolymer stabilization materials.

The constituent materials were tested for chemical composition, and the soil was further tested for water absorption, specific gravity, bulk density and Atterberg limits.

2.3 Geopolymer Mix Design

Three geopolymer mixtures were prepared using a total stabilizer content equivalent to 4% of dry soil weight: 3S1R1N, 2S2R1N and 1S3R1N (Table 1). A cement-treated sample (4C) and untreated soil served as controls for cement stabilised and natural samples respectively. Specimens were mixed at the optimum moisture content determined for each blend, sealed in plastic bags and cured at ambient laboratory temperature (25-28 °C) for 7 days before compaction and CBR testing. Modified Proctor compaction and both soaked (4 day immersion under surcharge) and unsoaked CBR tests were performed in accordance with BS 1377-2:2022. The choice of this proportioning strategy drew inspiration from Anburuvel et al. (2023). At least three replicate specimens were tested for each mix; mean values are reported.

Table 1: Proportion of mixes used in evaluating performance of the geopolymer stabilization.

Mix ID	Soil (%)	SBA (%)	RHA (%)	NaOH (%)	Cement (%)
S	100	-	-	-	-
4C	100	-	-	-	4
3S1R1N	100	3	1	1	-
2S2R1N	100	2	2	1	-
1S3R1N	100	1	3	1	-

Modified Proctor compaction tests were conducted to determine Maximum Dry Density (MDD) and Optimum Moisture Content (OMC). Both soaked and unsoaked CBR tests were performed according to BS 1377 (2022).

3. RESULTS AND DISCUSSION

3.1 Characterization of Constituent Materials

3.1.1 Chemical composition and physical characteristics of constituent materials

The natural moisture content of the lateritic soil averaged 10.47%. The soil contained 59.25% fines, 39.80% sand and 0.95% gravel, confirming its fine-grained nature and susceptibility to moisture-related performance problems (Phummiphan et al., 2018, 2021; Phummiphan et al., 2016). The soil was classified as A-7-5 under AASHTO and CL under USCS, indicating fair-to-poor subgrade quality (Rangan et al., 2020). XRF analysis showed that RHA contained 73.76% SiO₂, SBA contained 31.28% SiO₂ and 13.53% CaO, while the soil contained substantial silica and alumina. These compositions confirmed their suitability for geopolymer stabilization (Sahoo & Gupta, 2026). The degree to which the tested soil qualifies as a true laterite is checked quantitatively using the silica-sesquioxide ratio (SSR). SSR is defined as the ratio of the free silica remaining in a weathered profile to the combined sesquioxide (alumina and iron oxide) content that has accumulated through laterization. The control sample has an SSR value of 1.41, which qualifies it as a lateritic soil (Burhan & Mohammed, 2025).

Table 2: Oxide composition and physical properties of constituent materials.

	Unit	Cement	SBA	RHA	Lateritic soil
Oxide composition					
SiO ₂	%	10.21	31.28	73.76	53.66
Al ₂ O ₃	%	5.95	5.37	3.27	22.24
Fe ₂ O ₃	%	3.79	10.19	1.58	15.61
CaO	%	74.35	13.53	2.91	0.45
K ₂ O	%	0.56	24.76	5.25	0.87
SO ₃	%	3.10	2.98	1.47	0.28
P ₂ O ₅	%	0.00	6.57	9.67	0.06
TiO ₂	%	0.25	0.78	0.25	1.78
Physical properties					
Specific gravity	-	3.15	1.95	1.83	2.88
Bulk density	kg/m ³	1355	325	241	1678
Fineness modulus	-	-	-	-	2.01
Water absorption	%	-	-	-	4.72

3.1.2 Atterberg limits

The Atterberg limit results indicated that the consistency characteristics of the lateritic soil were significantly altered by both cement and geopolymer stabilization. The untreated lateritic soil had a liquid limit (LL) of 54.16%, a plastic limit (PL) of 10.80%, and a plasticity index (PI) of 43.36%, indicating a highly plastic soil with a high sensitivity to moisture-induced swelling, shrinkage, and loss of strength. Such a high PI confirms the need for stabilization before the soil can be considered suitable for pavement applications (Sinkhonde et al., 2025; Swamy et al., 2021). The highest reduction in plasticity was achieved with cement stabilization, which reduced the PI to 21.15%, or about 51% less than the untreated soil. This improvement is due to the effectiveness of the cement hydration products in inducing flocculation and cementation of clay particles, which decreases the affinity for water and enhances dimensional stability of the soil (Tabyang et al., 2024).

Table 3: Atterberg limits of stabilized and control lateritic soil samples

Mix ID	LL (%)	PL (%)	PI (%)
Natural Soil (S)	54.16	10.80	43.36
4C (Cement)	44.83	23.68	21.15
3S1R1N	44.56	20.26	24.40
3R1S1N	34.11	6.67	27.44
2S2R1N	50.08	26.97	23.11

The geopolymer mixtures with the lowest PI were 2S2R1N (23.11%) and 3S1R1N (24.40%). The reductions suggest successful geopolymerization, as alkali activation of SBA and RHA produced cementitious aluminosilicate gels that bound clay particles and decreased plastic behaviour. The balanced 2S2R1N mixture performed better than the SBA-dominant mixture, indicating that the SBA-RHA ratio of 2:2:1 was more favourable for the chemical interaction that reduced the plasticity. The 3R1S1N mixture, on the other hand, had the lowest liquid limit (34.11%), which means that it has a significantly lower water holding capacity, but its plastic limit was also significantly reduced to 6.67%, and thus a relatively high PI (27.44%). This indicates that the moisture threshold for plastic behaviour decreased with increasing RHA content, but not proportionately to the increase in RHA content, which did not increase the resistance to plastic deformation of the soil (Teerawattanasuk & Voottipruex, 2019).

3.2 Compaction Characteristics of Geopolymer-Stabilized Lateritic Soil

The compaction results showed that the stabilization process generally led to a decrease in the Maximum Dry Density (MDD) and an increase in the Optimum Moisture Content (OMC). The highest MDD of 1.88 Mg/m³ was obtained at OMC of 15% for the natural soil. After stabilization, the MDD was reduced to 1.80 - 1.86 Mg/m³ and the OMC was raised to 16 - 18%. This means that the cement and geopolymer materials changed the structure of the soil and made it more water demanding when compacted. The 4C mixture had the lowest MDD (1.80 Mg/m³) and an OMC of 16%. This decrease in density could be related to the substitution of some relatively dense soil particles with stabilizing material and the change in the arrangement of the particles during mixing (Tesanasin et al., 2022). The rise in OMC was, however, comparatively small indicating that there was not a lot of extra water demand as compared to the geopolymer mixtures.

Table 4: Compaction characteristics of stabilised and control lateritic soil samples.

Mix ID	Maximum Dry Density (Mg/m ³)	Optimum Moisture Content (%)
S (Natural Soil)	1.88	15
4C	1.80	16
3S1R1N	1.86	17
3R1S1N	1.83	18
2S2R1N	1.84	17

The geopolymer mixtures gave the highest MDD (1.86 Mg/m³) which was slightly less than the natural soil (1.88 Mg/m³), and the highest OMC (17%) for 3S1R1N. This means that the mixture with SBA was relatively good in terms of compactability even with the addition of ash. The 2S2R1N mixture exhibited similar characteristics with an MDD of 1.84 Mg/m³ and OMC of 17%. The 3R1S1N geopolymer mixture, on the other hand, had the lowest MDD (1.83 Mg/m³) and highest OMC (18%) among the geopolymer mixtures. This increased moisture requirement could be attributed to the higher RHA content and porous structure that can absorb more water (Thanasisathit et al., 2026). Overall, the results indicate that geopolymer stabilization does not significantly affect the compactability of the mixture, but that higher field moisture contents would be needed, especially for the RHA-rich mixture. The 3S1R1N treatment combination showed the best balance of density and moisture requirement of the geopolymer treatments.

3.3 California Bearing Ratio (CBR) of Geopolymer-Stabilized Lateritic Soil

The unsoaked CBR of the natural soil was 60.0%, while the 3S1R1N and 3R1S1N soils were 66.5% and 61.1% respectively. The relatively small improvements indicate that the individual precursor-dominant mixtures did not provide much extra cementitious bonding, perhaps because the amount of reactive silica and alumina available was not enough to create a significant amount of geopolymeric gel formation. The unsoaked CBR of 2S2R1N was 81.9%, which is significantly better than the natural soil and is close to the CBR of the cement-stabilized mixture (86.6%). This suggests that a more balanced SBA - RHA ratio might yield a more desirable chemical composition and particle interaction for geopolymerization (Van Bui & Ho, 2026). This is especially important because it shows that agricultural waste-derived precursors can provide significant strength enhancement without the use of traditional cement stabilization.

Table 5: CBR of stabilised and control lateritic soil samples.

Mix ID	Unsoaked CBR (%)	Soaked CBR (%)	Strength retention ratio (%)
Natural Soil (S)	60.0	15.1	25
4C (Cement)	86.6	25.3	29
3S1R1N	66.5	17.6	26
3R1S1N	61.1	17.0	28
2S2R1N	81.9	18.31	22

After the 4 day soaking, the soaked CBR results, however, show a significant drawback. All of the stabilized mixtures had higher soaked CBR than the natural soil (15.1%), but the improvements were much less than under unsoaked conditions. The 2S2R1N mixture, although having a high unsoaked CBR, had only 18.31% after soaking, which gave the lowest strength retention ratio (22%). On the other hand, the geopolymer mixture with 3R1S1N exhibited the highest retention (28%) among the geopolymer mixtures, indicating comparatively high resistance to moisture-induced strength loss, although it had the lowest initial strength.

4. CONCLUSIONS

This paper investigated the compaction characteristics and CBR of geopolymer stabilised lateritic soil. The geopolymer is made up of rice husk ash and sugarcane bagasse ash as precursors and sodium hydroxide as activator. Three mixes of the geopolymer blends were investigated against conventional cement stabilized lateritic soil and untreated/natural soil to evaluate the performance of the geopolymer. From the experimental outcomes, the following conclusions can be drawn.

- The complementary oxide compositions of SBA and RHA are a promising precursor system for alkali-activated lateritic soil stabilization.
- Geopolymer stabilization caused only minor changes in the compaction characteristics of the lateritic soil. The maximum dry density of the untreated soil was found to be 1.88 Mg/m³, whereas for the stabilized mixtures it was 1.83 - 1.86 Mg/m³, which is a slight increase. The optimum moisture content of the untreated soil was 15%, whereas for the stabilized mixtures it was 17 - 18%, which is a slight increase. The changes were attributed to the lower specific gravity and porous nature of the ashes and higher water demand during geopolymerization.
- The load-bearing capacity of the lateritic soil was enhanced by geopolymer stabilization, with the 2S121N mixture showing the best performance, with unsoaked and soaked CBR values of 81.9% and 18.31% respectively, compared to 60.0% and 15.1% for the untreated soil. The improvement was attributed to the formation of geopolymeric gel which increased interparticle bonding and decreased pore connectivity. Soaking decreased CBR values, but stabilized soils exhibited greater resistance to moisture-induced strength loss.
- The optimum SBA-RHA geopolymer formulation investigated is the 2S2R1N mixture. It raised the soaked CBR from 15.1% to 18.31% and the unsoaked CBR from 60.0% to 81.9% and thus it was the most balanced formulation in terms of bearing performance. The stabilized soil can be recommended as a subgrade improvement material, not as a road-base material (based on ORN 31 benchmark). The CBR values obtained, especially under soaked conditions, are not adequate to recommend the material for higher pavement layers based on CBR alone.

DECLARATION OF COMPETING INTEREST

The authors declare that there is no conflict of interest among them regarding the publication of this article.

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