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Strength Performance and Durability of Lateritic Soil Stabilised with Periwinkle Shell Ash and Cement Kiln Dust for Road Construction

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Abstract- Lateritic soils are widespread across Nigeria yet frequently inadequate for direct use as pavement structural layers due to low bearing capacity and moisture susceptibility. This study evaluates the strength performance and durability of lateritic soil stabilised with Periwinkle Shell Ash (PSA) and Cement Kiln Dust (CKD)—two locally available, low-cost, waste-derived pozzolanic materials—for road subbase and base course applications. A systematic 5×5 factorial design was employed, combining PSA and CKD at 0%, 2%, 4%, 6%, and 8% by dry soil weight, tested under British Standard Light (BSL), West African Standard (WAS), and British Standard Heavy (BSH) compaction energy levels. Strength was assessed by Unconfined Compressive Strength (UCS) at 7, 14, and 28 days of curing, and California Bearing Ratio (CBR) under both unsoaked and soaked conditions. Long-term performance was evaluated by a wetting–drying cycle durability test. Two-way Analysis of Variance (ANOVA) was used to confirm statistical significance at $\alpha = 0.05$. UCS increased from 840 kN/m² (natural soil) to a peak of 2,600 kN/m² (209% improvement) at 4% PSA + 6% CKD under BSH compaction at 28 days curing. Unsoaked CBR reached 85.0% under BSH at 6% PSA + 8% CKD, meeting the Nigerian ≥80% base course requirement; soaked CBR peaked at 50.2%, limiting saturated-condition use to subbase classification. Durability values of 35–66% across all compaction levels fell below the 80% base course threshold, classifying the material as suitable for subbase use. Two-way ANOVA confirmed CKD as the dominant stabilising factor ($p < 0.001$ for CBR and UCS) with a statistically significant PSA–CKD synergistic interaction ($p \leq 0.010$). This is the first study to apply a full 5×5 factorial design with two-way ANOVA to quantify the synergistic PSA–CKD interaction on lateritic soil strength and durability, providing statistically validated mix design guidance for waste-material road construction in tropical Nigeria.

Keywords: Periwinkle Shell Ash, Cement Kiln Dust, Lateritic Soil, UCS, CBR, Durability, Pozzolanic Stabilisation, Two-Way ANOVA

I. INTRODUCTION

Lateritic soils are the dominant engineering material across the tropical belt of sub-Saharan Africa, covering more than 50% of Nigeria's land area and forming the standard subgrade and pavement fill in most road construction projects (Rahaman, 1976; Afolagboye et al., 2024). Characterised by intense weathering of silicate parent rocks, they accumulate secondary iron and aluminium sesquioxides—hence the diagnostic reddish-brown colour—but concurrently develop high plasticity, low shear strength, significant compressibility, and acute sensitivity to moisture fluctuations (Kiuru et al., 2023; Kaze et al., 2022). These engineering deficiencies routinely produce premature pavement failures: rutting, longitudinal cracking, and differential settlement that impose enormous maintenance burdens on national and state highway agencies (Amadi, 2020; Bello et al., 2022).

Conventional chemical stabilisation using Portland cement or lime reliably improves lateritic soil performance, but both materials carry prohibitive unit costs in remote construction environments, are subject to supply-chain volatility, and generate significant CO_2 emissions during manufacture (Oti & Nnochiri, 2022; Liu et al., 2023). This has stimulated a sustained search for waste-derived alternatives that are low-cost, locally abundant, and environmentally beneficial through diversion from landfill (Laishram et al., 2021; Koukouzas et al., 2022).

Two such materials are Cement Kiln Dust (CKD) and Periwinkle Shell Ash (PSA). CKD is generated during clinker production at approximately 1,450°C; it contains free lime, calcium silicates, and alkali compounds conferring direct cementitious and pozzolanic activity (Giri et al., 2025; Peethamparan et al., 2008). Nigeria's cement sector produces an estimated 1.5–7.0 million tonnes of CKD annually, most of which is stockpiled or disposed of at significant environmental and economic cost (Al-Rubaiee & Hussian, 2022; Sreekrishnavilasam et al., 2007). PSA is derived by calcining the shells of Littorina littorea—the common periwinkle—at 500–700°C; the product is calcium oxide-rich and capable of ion exchange and indirect pozzolanic reactions with clay minerals (Etim et al., 2022; Jibu & Moses, 2020). Periwinkle shell waste is generated in multi-tonne quantities annually in Nigeria's coastal seafood industry and presents a recognised disposal problem (Oke et al., 2022).

Published studies have individually documented the stabilising capacity of CKD (Abdulkareem et al., 2012; Oluremi et al., 2016; Bello et al., 2022; Miller & Azad, 2000) and PSA (Segun & Adeinlewo, 2016; Jibu & Moses, 2020; Etim et al., 2022; Oke et al., 2022) on lateritic and fine-grained soils. However, no prior study has systematically investigated their combined, synergistic application using a fully factorial experimental design with rigorous statistical validation—leaving a critical knowledge gap for mix design guidance. The PSA–CKD system is theoretically attractive because CKD provides the alkaline calcium environment (pH > 12) required to catalyse the pozzolanic reactivity of PSA's silica and alumina components, while PSA simultaneously supplies additional CaO and aluminosilicate reactants (Mehta & Monteiro, 2006; Sherwood, 1993).

This paper reports the strength performance and durability of PSA–CKD stabilised lateritic soil from Shika, Zaria, presenting: (i) UCS development at 7, 14, and 28 days under three compaction energy levels; (ii) unsoaked and soaked CBR under BSL, WAS, and BSH compaction; (iii) durability under wetting–drying cycles; and (iv) two-way ANOVA statistical analysis of PSA and CKD main effects and their interaction. Index properties and compaction characteristics are reported separately and excluded from the present paper to maintain focused scope.

II. LITERATURE REVIEW

2.1 Pozzolanic Stabilisation Mechanisms

The improvement of lateritic soil through pozzolanic stabilisation involves a well-established two-stage reaction sequence. In the immediate term (hours to a few days), calcium-releasing materials produce Ca^{2+} ions that replace exchangeable monovalent cations on clay particle surfaces, compressing the diffuse double layer, inducing flocculation, and reducing plasticity—an effect dominant in lime and CKD stabilisation (Mitchell & Soga, 2005; Sherwood, 1993). Over the medium to long term (days to months), $Ca(OH)_2$ reacts with reactive silica (SiO_2) and alumina (Al_2O_3) from clay minerals and supplementary pozzolans under alkaline conditions to form calcium silicate hydrate (C–S–H) and calcium aluminate hydrate (C–A–H) gels—products that progressively bind soil particles, fill inter-particle voids, and dramatically increase stiffness and strength (Mehta & Monteiro, 2006). The pozzolanic reaction can continue for months or years, providing long-term strength gains that make it particularly valuable for permanent road construction (Anshu & Tamut, 2022).

The effectiveness of pozzolanic stabilisation depends on pH (>12 for optimal silica dissolution), temperature, available moisture, reactive silica and alumina content, and stabiliser dosage (Roshan & Rashid, 2024). CKD's high free lime content readily achieves the pH threshold; its aluminium and silica phases also contribute directly to gel formation. PSA, though lower in reactive silica (0.5–2.0% SiO_2), contributes significant CaO and acts through indirect lime-type reactions with clay-bound aluminosilicates (Etim et al., 2022). The synergy between CKD and PSA lies in CKD providing the alkaline Ca^{2+}-rich environment that unlocks PSA's reactivity, while PSA supplies supplementary silica and CaO to sustain gel development beyond the capacity of CKD alone (Segun & Adeinlewo, 2016; Oke et al., 2022).

2.2 Cement Kiln Dust in Soil Stabilisation

CKD has been studied as a soil stabiliser since the 1990s. Miller and Azad (2000) demonstrated that CKD effectively stabilises a range of fine-grained soils, with optimal treatment at 2–10% content producing measurable plasticity reduction and UCS improvements. Peethamparan et al. (2008) systematically characterised CKD from multiple plants, linking its hydration behaviour and stabilising capacity to free lime and alkali sulfate content. Oluremi et al. (2016) reported significant reductions in liquid limit and plasticity index for CKD-treated Nigerian lateritic soils at dosages of 2–8%. Bello et al. (2022) documented CBR improvements from 8% to 56% and UCS increases exceeding 600% in CKD-stabilised laterite from northern Nigeria, confirming its strong individual stabilisation potential. Abdulkareem et al. (2012) found that CKD alone consistently reduced plasticity and improved compressive strength in Nigerian clay soils. More recently, Ahmed et al. (2023) confirmed CKD's suitability as a partial cement substitute, reinforcing its cementitious properties through mineralogical analysis.

2.3 Periwinkle Shell Ash in Soil Stabilisation

Research on PSA in soil stabilisation accelerated in the 2010s in response to Nigeria's growing periwinkle shell waste stream. Segun and Adeinlewo (2016) demonstrated that PSA at 6–10% reduced PI by 4–8 percentage points and improved CBR by 15–25% in tropical Nigerian laterite, establishing a benchmark for PSA applications. Jibu and Moses (2020) confirmed plasticity reduction and bearing capacity improvement in coastal Nigerian fine-grained soils with PSA additions of 4–8%. Etim et al. (2022) evaluated a lime–PSA combination, finding that synergistic effects between the two calcium-releasing materials produced superior CBR and UCS compared to either material individually—an early indication of the combinatorial potential that motivates the present study. Oke et al. (2022) compared oyster shell ash and PSA for lateritic soil stabilisation, confirming PSA's effectiveness and highlighting its widespread availability as a construction material. The primary limitation of PSA relative to CKD is its lower reactive silica content, which makes standalone pozzolanic gel formation slow; however, in combination with CKD's stronger alkaline environment, this limitation is substantially overcome.

2.4 Compaction Energy and Strength Development

The relationship between compaction energy, stabiliser performance, and pavement layer suitability is well-established in the literature. Higher compaction energy produces greater particle rearrangement, reduced air voids, improved particle contact, and a denser, less permeable matrix—all of which enhance pozzolanic gel distribution and accelerate strength development (Ayodele et al., 2021; Akinwumi et al., 2023). Eberemu (2022) demonstrated that BSH compaction consistently outperformed BSL and WAS conditions for waste-stabilised Nigerian soils, producing higher MDD, lower OMC, and superior UCS and CBR values. This compaction-energy dependency has critical implications for field performance specifications: laboratory-derived optimum stabiliser contents derived under light compaction may underestimate the performance achievable under field BSH-equivalent compaction. The present study applies all three energy levels to quantify this sensitivity and provide practical guidance for field specification.

2.5 Durability of Stabilised Soils

Durability—the ability of a stabilised soil to maintain its engineering properties under repeated wetting and drying—is a critical but often under-evaluated criterion for road material classification. Ola (1974) established a Nigerian-context durability classification based on wetting–drying resistance: base course materials require ≥80% strength retention; subbase materials require 40–80%; materials below 40% are unsuitable for structural pavement layers. Afolayan et al. (2023) confirmed that waste-derived pozzolanic stabilisers frequently produce excellent strength improvements but may fall short of base course durability thresholds due to incomplete long-term gel maturation. These findings underscore the need to evaluate durability independently from strength, as the two properties do not always co-develop at the same rate—particularly at low stabiliser dosages or short curing periods.

2.6 Research Gap and Study Contribution

Despite the substantial individual literature on CKD and PSA stabilisation, no published study prior to the present work has: (i) applied a full 5×5 factorial design combining both materials at five levels each;

(ii) evaluated the combined system under three compaction energy levels simultaneously; (iii) provided two-way ANOVA statistical validation of the PSA–CKD interaction for both strength and durability outcomes; or (iv) quantified the threshold conditions under which the combined system satisfies the Nigerian ≥80% CBR base course specification. This paper fills all four gaps, providing a statistically rigorous foundation for engineering decision-making in sustainable pavement construction.

III. MATERIALS AND METHODS

3.1 Materials

3.1.1 Lateritic Soil

Disturbed soil samples were collected from Shika, Zaria (Kaduna State, Nigeria) at depths of 1.5–2.0 m, representative of the pavement subgrade horizon. The reddish-brown profile with visible iron oxide nodulation was consistent with well-developed lateritic profiles typical of the Guinea Savannah geological belt (Rahaman, 1976; Afolagboye et al., 2024). Samples were sealed in polythene sacks immediately after collection and transported to the ABU Zaria Soil Mechanics Laboratory, where they were air-dried and pulverised to pass the 4.75 mm BS sieve before testing.

3.1.2 Periwinkle Shell Ash (PSA)

Periwinkle shells (Littorina littorea) were obtained from the Apapa seafood market, Lagos. Shells were thoroughly washed to remove salt and organic residue, sun-dried for 48 hours, then calcined at 600°C for three hours in a muffle furnace. The cooled ash was pulverised and sieved through the 75 µm mesh. The calcination temperature was selected based on thermogravimetric evidence of complete $CaCO_3 \rightarrow CaO$ conversion between 580°C and 650°C, beyond which sintering reduces reactive surface area (Etim et al., 2022).

3.1.3 Cement Kiln Dust (CKD)

CKD was sourced directly from BUA Cement Industry, Kalambaina, Sokoto State—one of Nigeria's largest integrated cement production facilities. The material was collected as-generated at the kiln exhaust filtration stage, stored in sealed bags, and used without additional processing. The CKD exhibited a pale grey colour, fine particle size, and rapid exothermic reaction with water indicative of significant free lime content, consistent with characterisation data reported by Giri et al. (2025) and Peethamparan et al. (2008).

3.1.4 Water

Potable tap water from the ABU Zaria supply network was used for all mixing, compaction, and curing operations, consistent with standard practice in Nigerian geotechnical laboratories (BS 1377, 1990).

3.2 Experimental Design

A 5×5 full factorial design was employed, combining PSA at five levels (0%, 2%, 4%, 6%, 8% by dry soil weight) with CKD at five levels (0%, 2%, 4%, 6%, 8% by dry soil weight), yielding 25 unique mix proportions. For combination treatments, additive percentages are stated independently (e.g., 4% PSA + 6% CKD = 10% total additive by dry soil weight). Each mix was tested at three compaction energy levels—BSL (600 kJ/m³), WAS (1,600 kJ/m³), and BSH (2,700 kJ/m³)—giving a total of 75 experimental conditions for strength tests. The stabiliser range was selected from prior studies which indicate optimum performance in pozzolanic stabilisation typically between 4% and 10% (Segun & Adeinlewo, 2016; Bello et al., 2022; Oluremi et al., 2016).

3.3 Laboratory Testing

3.3.1 Unconfined Compressive Strength (UCS)

Cylindrical specimens (38 mm diameter × 76 mm height) were prepared at optimum moisture content (OMC) and compacted in three layers under BSL, WAS, and BSH energy in a standard 1 kg split mould. Immediately after preparation, specimens were sealed in polythene bags and cured at room temperature (25 ± 2°C) for 7, 14, or 28 days. Testing was performed at a displacement rate of 1.0 mm/min in accordance with BS 1924 (1990) and ASTM D2166. Three replicate specimens were prepared per mix–curing–energy combination; the reported value is the arithmetic mean. The minimum UCS threshold of 1710 kN/m² for base course cited by TRRL (1977) was used as the benchmark.

3.3.2 California Bearing Ratio (CBR)

CBR specimens were compacted in standard 152 mm diameter moulds at OMC under BSL (3 layers, 55 blows/layer), WAS (5 layers, 25 blows/layer), and BSH (5 layers, 55 blows/layer) compaction conditions. Unsoaked CBR tests were conducted immediately after preparation; soaked CBR specimens were immersed under a 4.5 kg annular surcharge for 96 hours before penetration testing. Penetration was applied at 1.25 mm/min; CBR was determined at 2.5 mm and 5.0 mm penetration, with the larger value reported. All CBR tests were conducted without curing to represent immediate post-compaction in-situ conditions. The Nigerian General Specifications for Roads and Bridges (Federal Ministry of Works & Housing, 2013) minimum unsoaked CBR of 80% for base course and 30% for subbase under BSH compaction were applied as classification criteria.

3.3.3 Durability

Durability was assessed following the Ola (1974). Companion UCS specimens compacted under BSL, WAS and BSH were cured for 7 days, then wax and soaked in water for another 7 days. After completion UCS was measured on the 7 days cured and 7 days-soaked. Another sample was cure for 14 days and \UCS value also determined. Durability was expressed as:

Durability (%) = [(UCS of 7 days cure + 7 days Soaked) / UCS of 14-day specimens] × 100

Results were classified per Ola (1974): ≥80% = suitable for base course; 40–80% = suitable for subbase; <40% = unsuitable for pavement structural layers.

3.4 Statistical Analysis

Two-way ANOVA was applied to all geotechnical response variables using SPSS v26, with PSA content and CKD content as fixed categorical factors. The null hypothesis (H_0) stated that PSA and CKD content had no significant effect on mean response values; H_0 was rejected where the observed p-value fell below the significance level $\alpha = 0.05$. Where significant main effects or interactions were identified, post-hoc Tukey HSD tests were conducted to determine which factor level means differed significantly. The complete ANOVA results table is reproduced in Section 4.4.

IV. RESULTS AND DISCUSSION

4.1 Unconfined Compressive Strength (UCS)

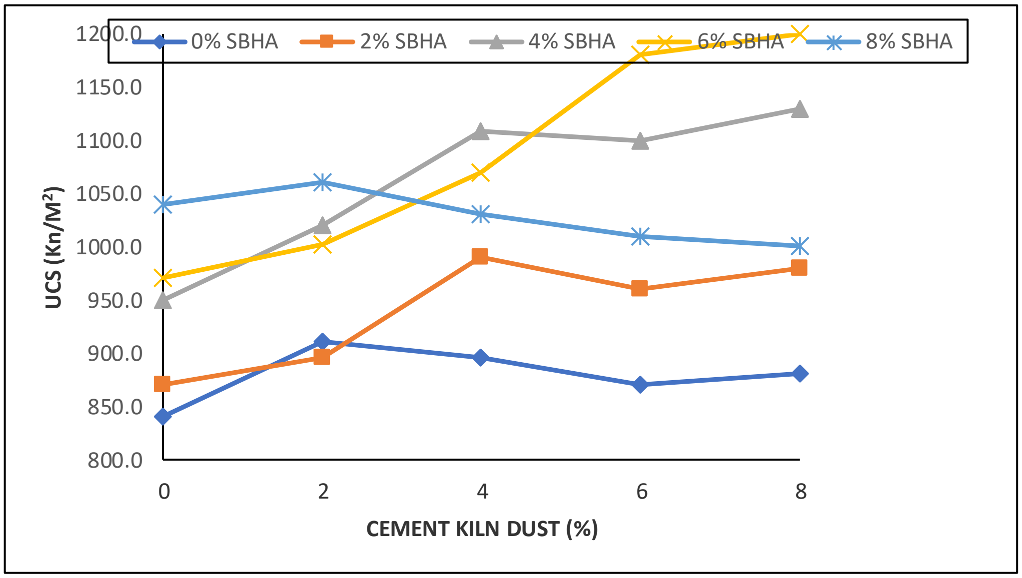
4.1.1 Effect of Curing Period on UCS Development

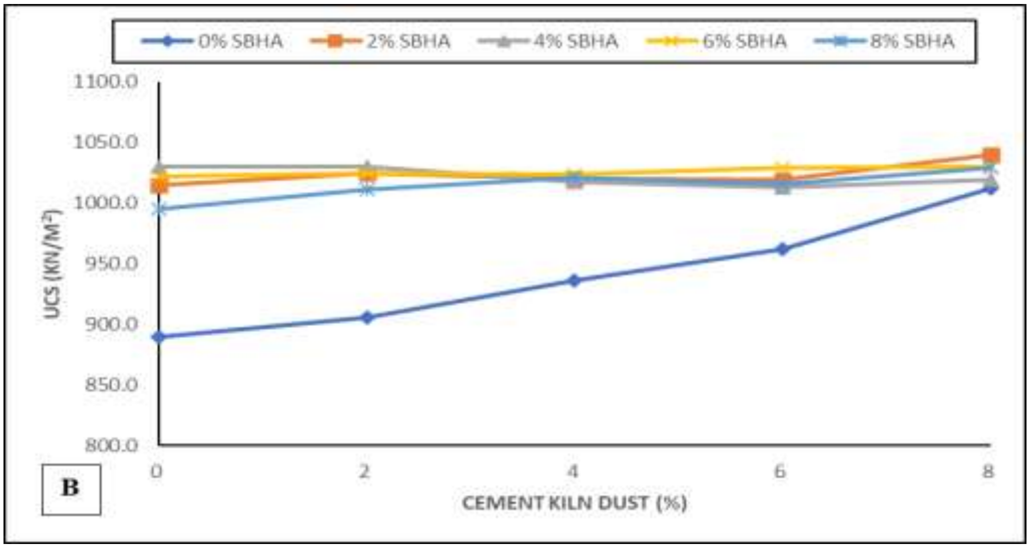
The progressive development of UCS with increasing curing age is the defining characteristic of pozzolanic stabilisation systems, reflecting the time-dependent formation and densification of C–S–H and C–A–H gel networks (Mehta & Monteiro, 2006). Figure 1 shows UCS at 7, 14, and 28 days for all PSA–CKD combinations under BSL compaction; Figures 2 and 3 present corresponding data for WAS and BSH respectively. Table 1 summarises peak UCS values at each curing age and compaction level.

Under BSL compaction at 7 days, UCS ranged from 840 kN/m² (natural, 0% PSA + 0% CKD) to 1,130 kN/m² at 4% PSA + 8% CKD—a 34.5% increase reflecting early-stage C–S–H gel formation from CKD hydration. Under WAS at 7 days, UCS reached 1,112 kN/m² (8% PSA + 6–8% CKD), driven by improved particle contact under moderate compaction energy accelerating pozzolanic reactions. Under BSH at 7 days, UCS values were notably irregular (560–990 kN/m²), with peak at 990 kN/m² at 2% PSA + 4% CKD. This irregularity at high compactive effort is attributed to early-stage hydration disruption: BSH densification compresses the inter-particle matrix before nascent C–S–H gels develop sufficient tensile strength to bridge contacts, producing localised weak zones that temporarily suppress apparent strength (Eberemu, 2022; Akinwumi et al., 2023); Sani et al., 2026a, Sani et al., 2026b, Sani et al., 2026c). By 14 days, this effect had resolved, consistent with the maturation hypothesis.

At 14 days, UCS values showed markedly more consistent trends across all compaction levels: BSL reached 1,040 kN/m² (peak), WAS achieved 1,680 kN/m² at 2% PSA + 8% CKD, and BSH peaked at 1,690 kN/m² at 2% PSA + 2% CKD. The continued strength gain from 7 to 14 days confirms ongoing $Ca(OH)_2$ release from CKD and progressive pozzolanic reaction with clay-bound silica and alumina supplied by PSA (Bello et al., 2022; Oti & Nnochiri, 2022; Sani et al., 2026a, Sani et al., 2026b, Sani et al., 2026c)). The slightly higher WAS and BSH values at 14 days over BSL reflect the dual benefit of better initial densification and more uniform binder distribution.

At 28 days—the design curing period for pavement construction specification—UCS values were highest across all conditions. Under BSL, peak UCS reached 1,700 kN/m² at 4% PSA + 6% CKD. Under WAS, peak was 1,990 kN/m² at 2% PSA + 8% CKD. Under BSH, the global maximum of 2,600 kN/m² was achieved at 4% PSA + 6% CKD, representing a 209% improvement over the natural soil. The peak at 4% PSA + 6% CKD, rather than at the maximum 8% + 8%, demonstrates that pozzolanic gel systems exhibit an optimum binder ratio: beyond this point, excess unreacted particles dilute the cementitious consistent with findings for both CKD (Bello et al., 2022) and PSA (Etim et al., 2022) individually. Across all 28-day conditions under WAS and BSH, UCS values generally exceeded the 1,710 kN/m² benchmark for stabilised base materials (TRRL, 1992), confirming structural suitability for subbase applications at 28-day curing.





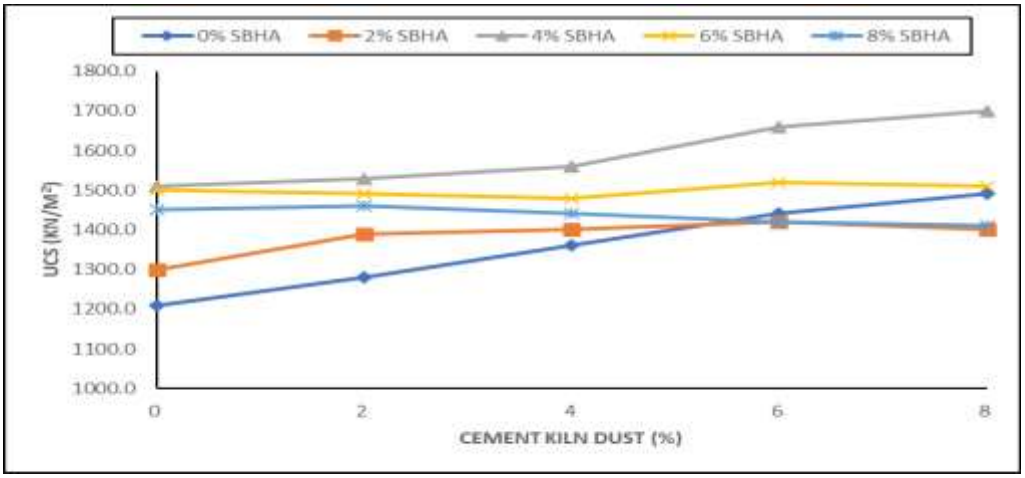
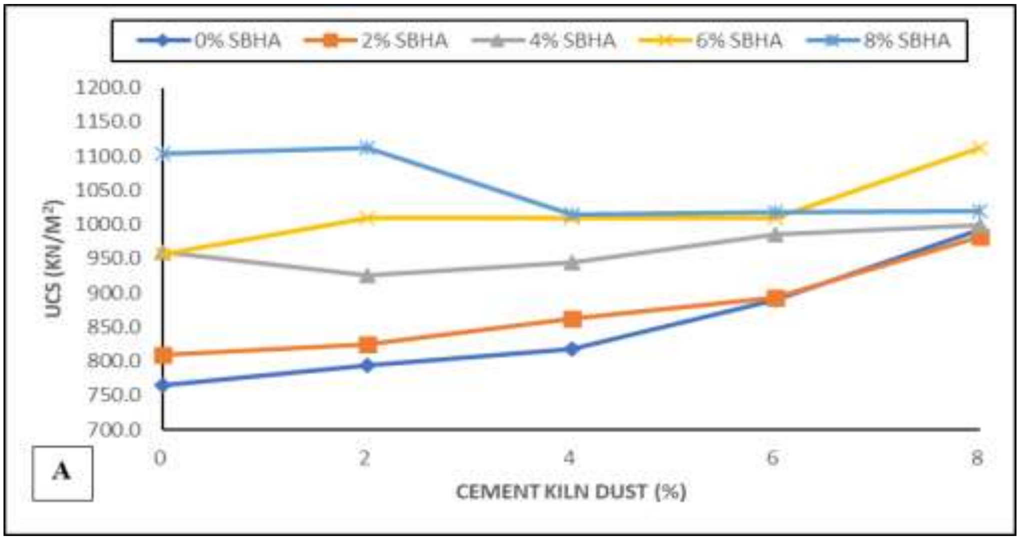
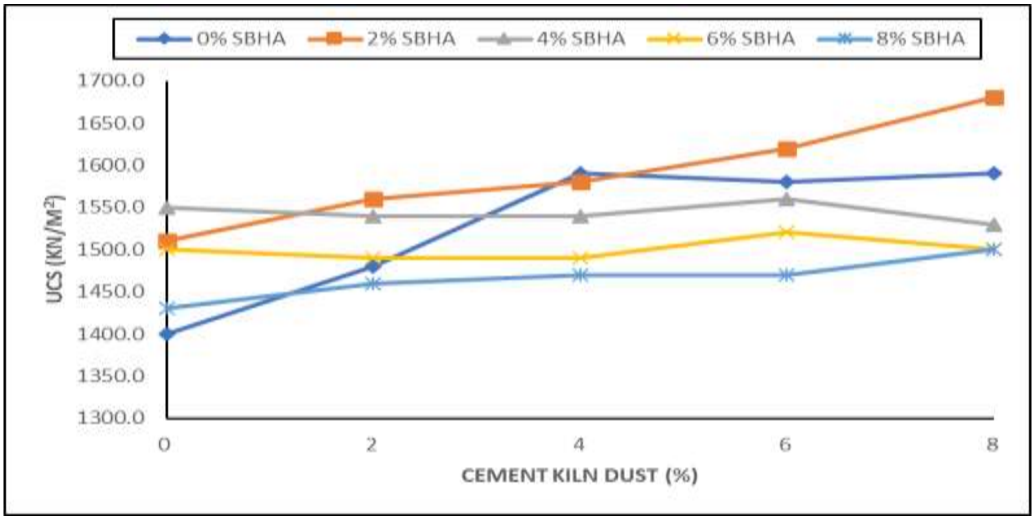


Figure 1: UCS vs. PSA and CKD content at 7, 14, and 28 days — BSL Compaction





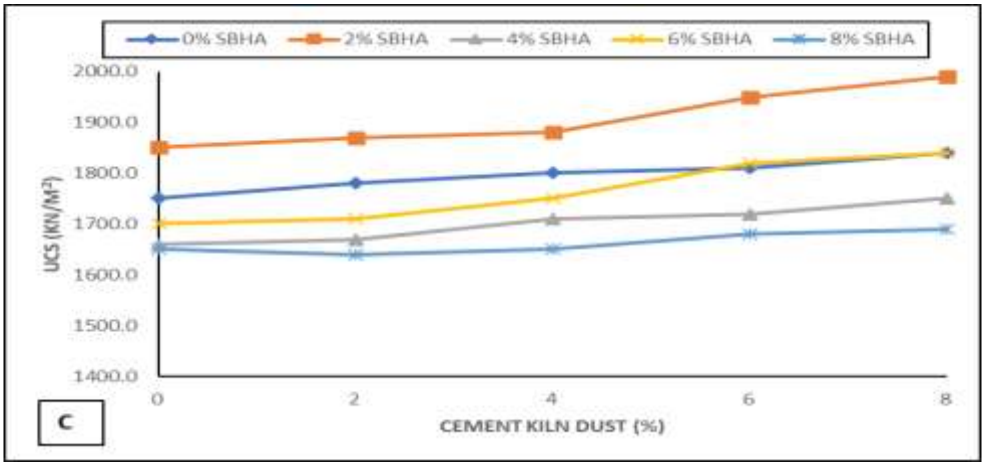
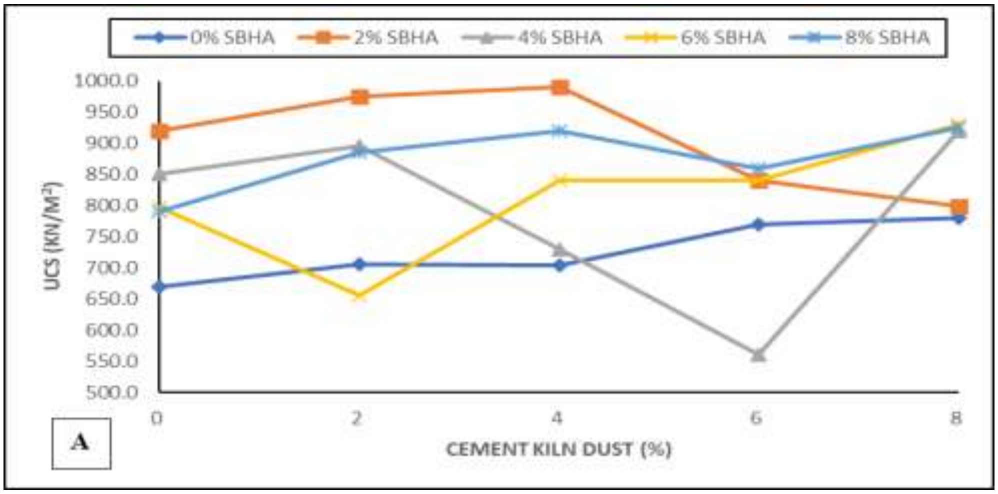
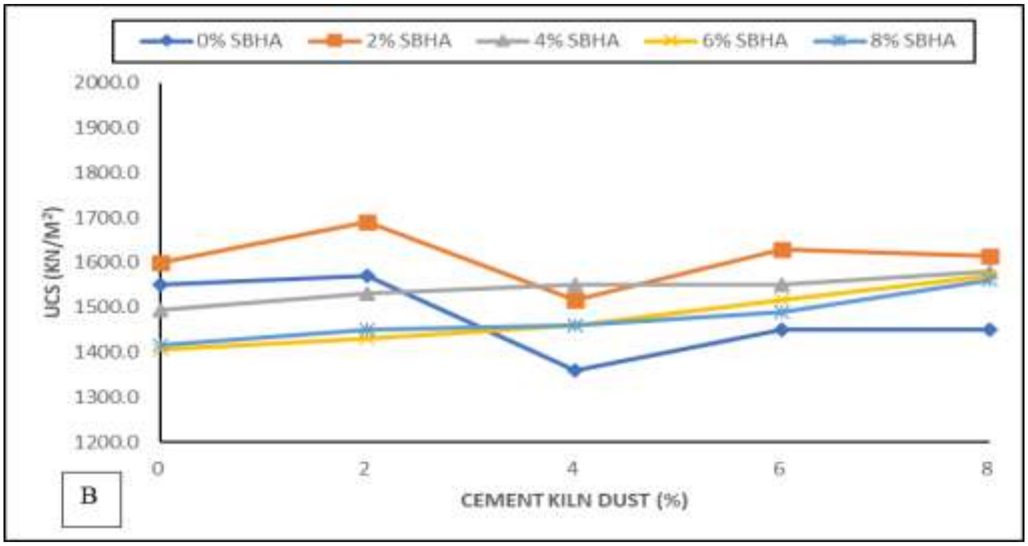


Figure 2: UCS vs. PSA and CKD content at 7, 14, and 28 days — WAS Compaction





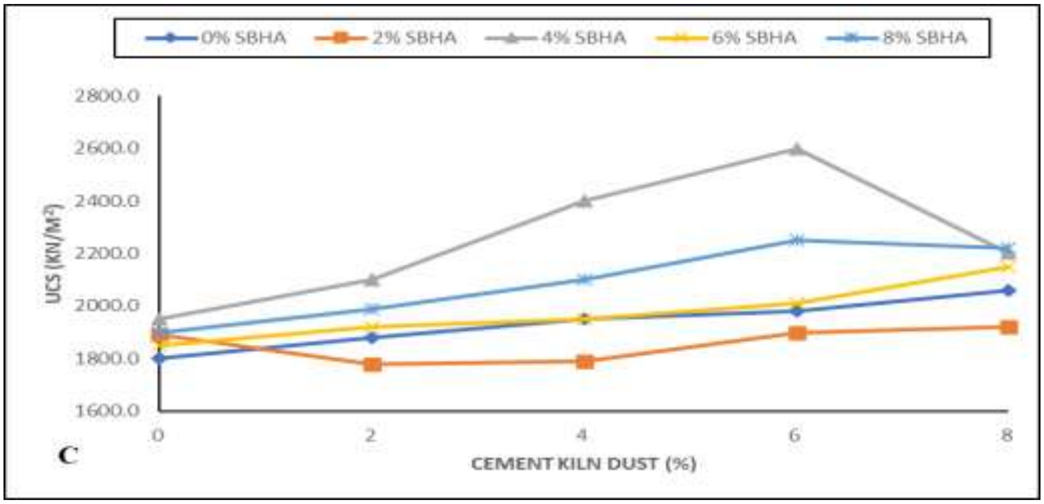


Figure 3: UCS vs. PSA and CKD content at 7, 14, and 28 days — BSH Compaction

Table 1. Summary of peak UCS (kN/m²) at 7, 14, and 28 days curing under BSL, WAS, and BSH compaction

Mix Proportion (PSA + CKD)	BSL 7d	WAS 7d	BSH 7d	BSL 28d	WAS 28d	BSH 28d
0% + 0% (Natural soil)	840	840	840	—	—	—
4% + 8% (BSL 7d peak)	1,130	—	—	—	—	—
8% + 6–8% (WAS 7d peak)	—	1,112	—	—	—	—
2% + 4% (BSH 7d peak)	—	—	990	—	—	—
2% + 8% (WAS 14d peak)	—	1,680	—	—	1,990	—
2% + 2% (BSH 14d peak)	—	—	1,690	—	—	—
4% + 6% (BSL/BSH 28d peak)	—	—	—	1,700	—	2,600*
2% + 8% (WAS 28d peak)	—	—	—	—	1,990	—

* Global peak UCS: 2,600 kN/m² at 4% PSA + 6% CKD, 28 days, BSH. Subbase benchmark: ≥1,500 kN/m² (Ingles & Metcalf, 1972).

4.2 California Bearing Ratio (CBR)

4.2.1 Unsoaked CBR

Unsoaked CBR results for all 25 mix proportions under BSL, WAS, and BSH compaction are presented in Figures 4–6 and summarised in Table 2. Under BSL compaction, unsoaked CBR increased progressively from 30.5% (natural soil, 0% PSA + 0% CKD) to a peak of 44.2% at higher stabiliser contents (8% PSA and CKD). While representing a meaningful 45% improvement, BSL values consistently fell below the ≥80% base course threshold (Federal Ministry of Works & Housing, 2013), though most exceeded the ≥30% subbase requirement at moderate and high stabiliser contents. The limited compaction energy under BSL restricts void ratio reduction and particle contact—conditions essential for both binder gel distribution and high bearing resistance (Ayodele et al., 2021; Akinwumi et al., 2023).

Under WAS compaction, unsoaked CBR improved more substantially, reaching 61.4% at 8% PSA + 8% CKD. The moderate compaction energy facilitates better particle rearrangement and more uniform distribution of C–S–H gel networks, reflected in the less erratic CBR trends compared to BSL. All WAS values at ≥4% CKD exceeded the 30% subbase threshold, confirming reliable subbase suitability. However, none reached 80%, indicating that WAS compaction is insufficient for base course CBR specification regardless of PSA–CKD dosage within the tested range.

Under BSH compaction, the most remarkable improvement was observed: unsoaked CBR rose from 15.88% (natural soil under BSH mould protocol) to 85.0% at 6% PSA + 8% CKD—satisfying the Nigerian ≥80% base course requirement (Federal Ministry of Works & Housing, 2013). The notably lower natural soil CBR under BSH (15.88%) compared to BSL (30.5%) reflects the BSH CBR test protocol: the larger compaction mould and higher surcharge used for BSH CBR effectively suppresses the apparent strength of unstabilised fine-grained soil by increasing confinement stress before penetration (Segun & Adeinlewo, 2016). As stabiliser content increases, this protocol advantage reverses: BSH's superior densification produces the highest CBR among all three energy levels at the same stabiliser content.

The mechanism for CBR improvement mirrors that of UCS: CKD-derived free lime raises soil pH above 12, initiating Ca^{2+} exchange on clay surfaces, while progressive pozzolanic reactions generate C–S–H and C–A–H gels that reduce void ratio, stiffen inter-particle contacts, and increase shear resistance (Mehta & Monteiro, 2006; Ogunribido et al., 2021). The non-monotonic CBR response with increasing CKD beyond 6% (e.g., the drop at CKD=8% vs. CKD=6% at fixed PSA=6–8%) reflects gel dilution by excess unreacted CKD particles occupying voids without contributing additional bonding—a phenomenon documented in CKD-lime systems by Miller and Azad (2000) and in Nigerian laterite by Bello et al. (2022).

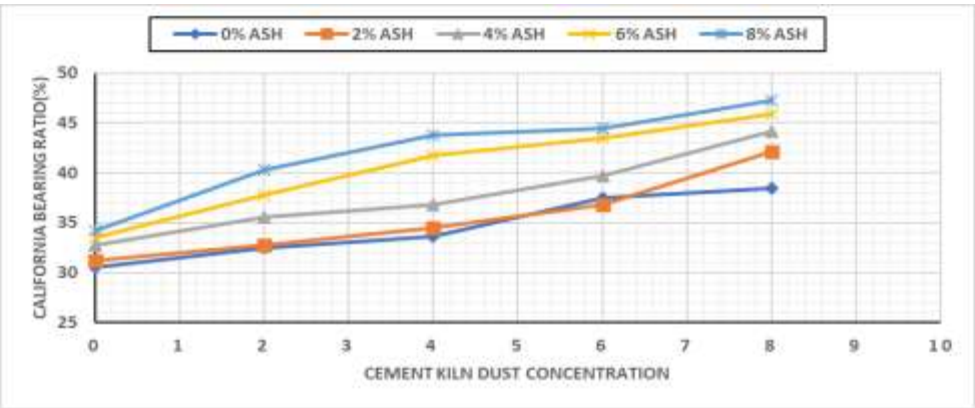


Figure 4: Unsoaked CBR vs. PSA and CKD content — BSL Compaction

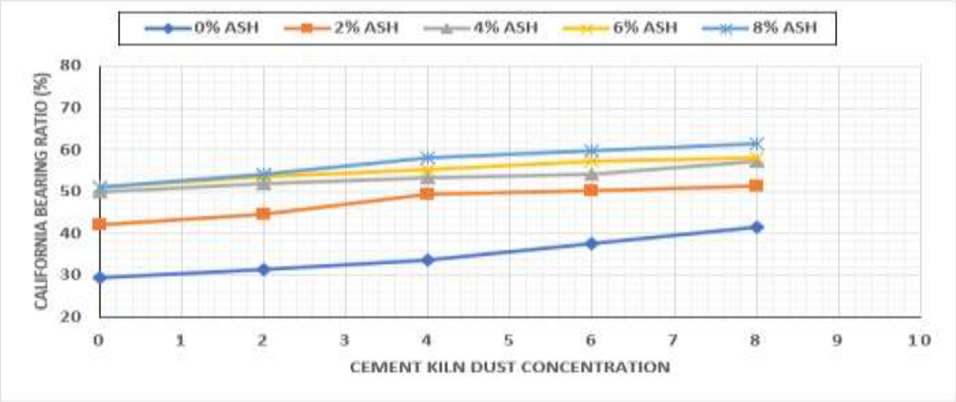


Figure 5: Unsoaked CBR vs. PSA and CKD content — WAS Compaction

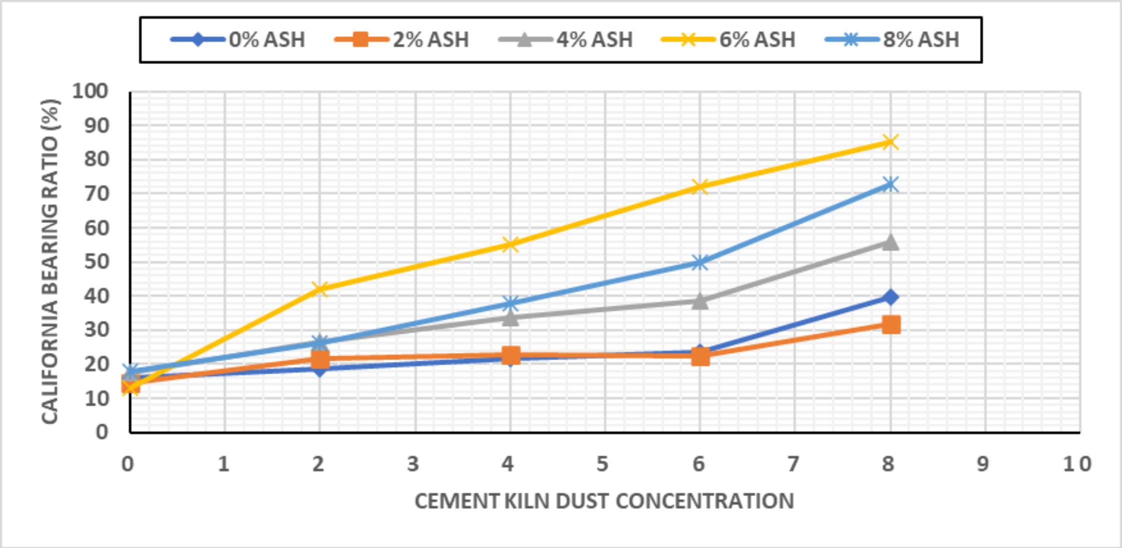


Figure 6: Unsoaked CBR vs. PSA and CKD content — BSH Compaction (base course threshold = 80%)

4.2.2 Soaked CBR

Soaked CBR results under BSL, WAS, and BSH compaction are presented in Figures 7–9 and Table 2. Under BSL, soaked CBR ranged from 19.8% to 40.8%, representing a consistent 30–50% reduction from unsoaked values at the same mix proportions. The reduction is caused by water infiltration generating pore water pressure, softening clay aggregates, and partially hydrolysing nascent C–S–H gel bonds (Sani et al., 2022; Oti & Nnochiri, 2022; Sani et al., 2026a, Sani et al., 2026b, Sani et al., 2026c).

Under WAS compaction, soaked CBR values ranged from 21.8% to 54.3%, with higher stabiliser contents demonstrating greater moisture resistance. The better particle packing achieved under WAS reduces permeability and limits the rate of water ingress during soaking, while the more developed C–S–H gel network at higher CKD content provides greater resistance to hydrolysis. Despite this improvement, WAS soaked CBR values did not approach the 80% base course threshold, confirming that soaked CBR performance is the binding constraint for base course classification under WAS compaction.

Under BSH compaction, soaked CBR peaked at 50.2% at 8% PSA + 8% CKD—a substantial improvement over the natural soil (9.89% soaked CBR under BSH protocol) but well below the ≥80% base course requirement. The soaked/unsoaked CBR ratio at 8% PSA + 8% CKD under BSH was approximately 59% (50.2/85.0 × 100), indicating that approximately 41% of bearing resistance is lost upon full saturation. This moisture susceptibility reflects the partial solubility of early-age C–S–H gels and the residual swelling potential of incompletely modified clay minerals (Eberemu, 2022; Bello et al., 2022). Ugbe (2011) documented that untreated Nigerian lateritic soils in the Niger Delta show soaked CBR of 3–43%, a range that the PSA–CKD system substantially exceeds at ≥4% CKD, confirming suitability for subbase use under saturated conditions.

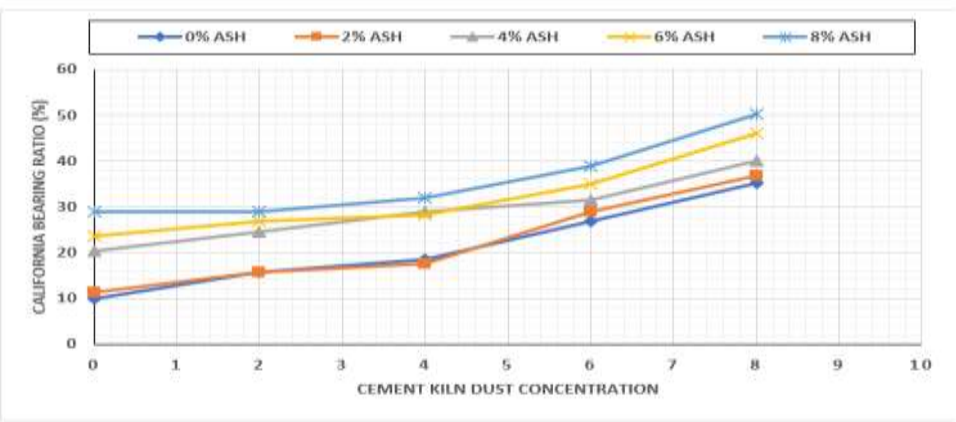


Figure 7: Soaked CBR vs. PSA and CKD content — BSL Compaction

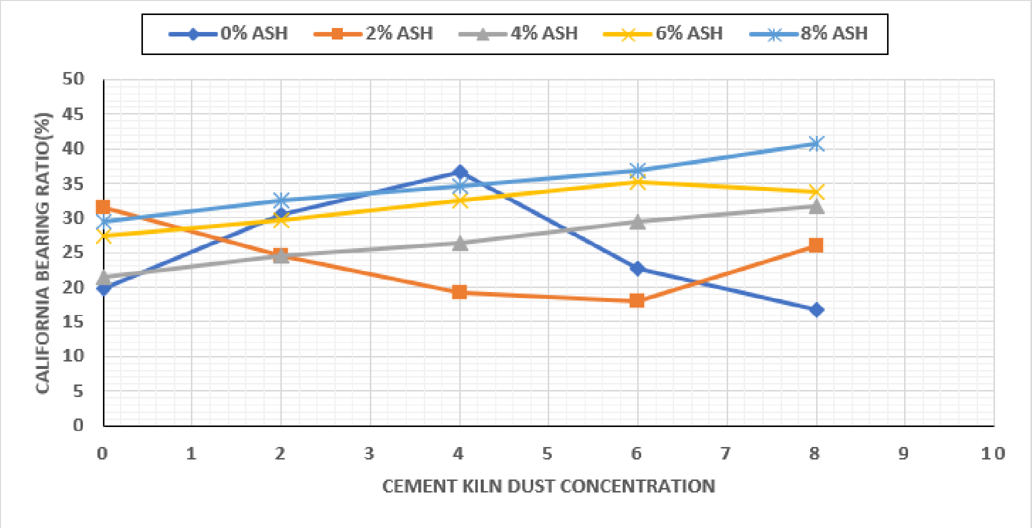


Figure 8: Soaked CBR vs. PSA and CKD content — WAS Compaction

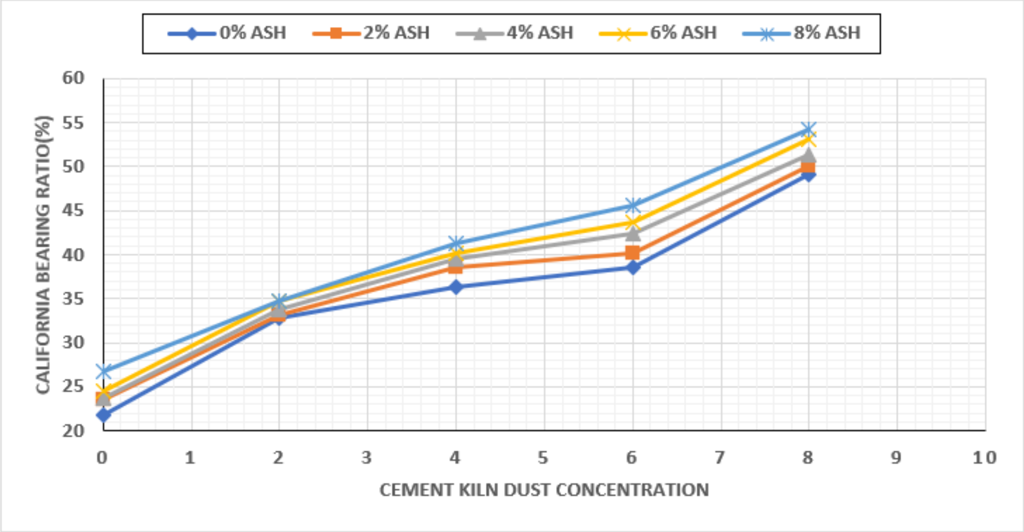


Figure 9: Soaked CBR vs. PSA and CKD content — BSH Compaction (subbase threshold = 30%)

Table 2. Unsoaked and soaked CBR (%) under BSH compaction at selected PSA–CKD combinations

CKD / PSA (%)	PSA=0	PSA=2	PSA=4	PSA=6	PSA=8	ANOVA (p)
Unsoaked CBR (BSH, %)						
CKD=0	15.88	18.60	21.50	23.50	39.70	< 0.001***
CKD=4	17.56	26.50	33.50	38.40	56.00	
CKD=6	13.00	42.00	55.00	72.00	85.00†	
CKD=8	18.00	26.00	38.00	49.88	72.60	
Soaked CBR (BSH, %)						
CKD=8	29.00	29.00	32.00	39.00	50.20	< 0.001***
Interaction effect (PSA × CKD)						
Unsoaked CBR						p = 0.002**
Soaked CBR						p = 0.001***

†Peak unsoaked CBR = 85.0% at 6% PSA + 8% CKD under BSH, meeting Nigerian base course threshold ≥80% (Federal Ministry of Works & Housing, 2013). *** p<0.001; ** p<0.01.

4.3 Durability under Wetting–Drying Cycles

Durability results—expressed as percentage strength retention after eight wetting–drying cycles—are presented in Figures 10–12 and Table 3. Under BSL compaction, durability values ranged from approximately 35% (0% PSA + 0% CKD) to 66% (8% PSA + 8% CKD). Under WAS compaction, values ranged from approximately 46% to 63%. Under BSH, values ranged from 41% to 57%. All values fell below the Ola (1974) ≥80% threshold for base course classification. All values above 40% (observed at ≥4% PSA + CKD combinations) fall within Ola's (1974) 40–80% range indicating suitability for subbase applications.

The progressive improvement in durability with increasing stabiliser content reflects the cumulative development of C–S–H and C–A–H gel matrices through pozzolanic reactions between CKD-derived $Ca(OH)_2$ and silica and alumina from PSA and clay minerals (Akinwumi et al., 2023; Eberemu, 2022). At low stabiliser contents (0–2%), insufficient calcium and silica are mobilised to initiate meaningful gel formation, leaving the soil matrix largely dependent on its natural clay structure—inherently susceptible to moisture-induced swelling and disaggregation (Sani et al., 2022). At moderate to high contents (4–8%), greater gel volumes bind particles, reduce macropore connectivity, and slow moisture ingress during wetting cycles.

The counterintuitive reduction in durability from WAS to BSH (63% vs. 57% at 8% PSA + 8% CKD) reflects the brittleness effect of high-energy compaction: BSH produces a denser, less porous matrix with lower capacity to redistribute internal swelling stress during the wetting phase. When water infiltrates during the wetting cycle, the constrained expansion of residual clay aggregates generates higher localised tensile stresses that promote microcracking—reducing apparent post-cycle UCS relative to less densely compacted specimens (Mitchell & Soga, 2005; Afolayan et al., 2023; Sani et al., 2026a, Sani et al., 2026b, Sani et al., 2026c). This behaviour also explains why durability testing under WAS compaction is the recommended standard in Ola (1974): it avoids both the low absolute strength of BSL and the brittleness effect of BSH.

The failure of all conditions to reach 80% durability is attributed to: (i) incomplete long-term pozzolanic gel maturation at 28 days—PSA's low reactive silica content (0.5–2.0% SiO_2) means full gel development may require 60–90 days or longer (Etim et al., 2022); (ii) residual swelling clay fraction that re-activates under water pressure despite treatment; and (iii) possible partial dissolution of early-stage C–S–H gel under repeated wetting cycles that exceeds re-cementation rates during drying (Eberemu, 2022; Bello et al., 2022). Two-way ANOVA for durability was not statistically significant for either PSA ($p = 0.816$) or CKD ($p = 0.071$), indicating that within the 0–8% range tested, factor-level variation does not dominate durability variation—consistent with the interpretation that gel immaturity, rather than stabiliser dosage, is the primary durability constraint.

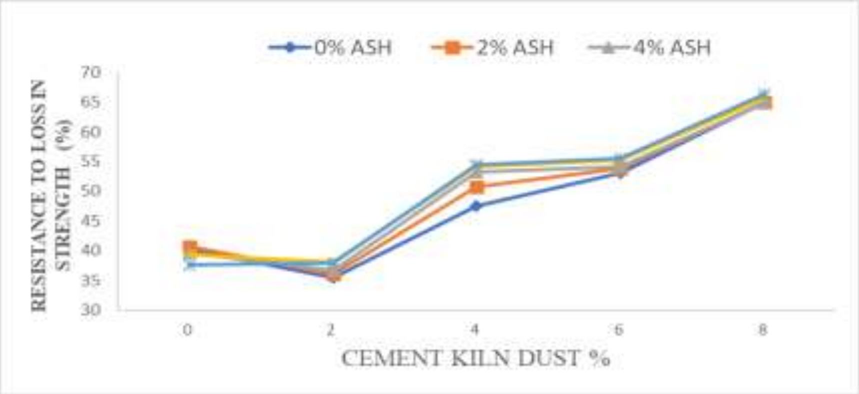


Figure 10: Durability (resistance to loss in strength) vs. PSA content — BSL Compaction

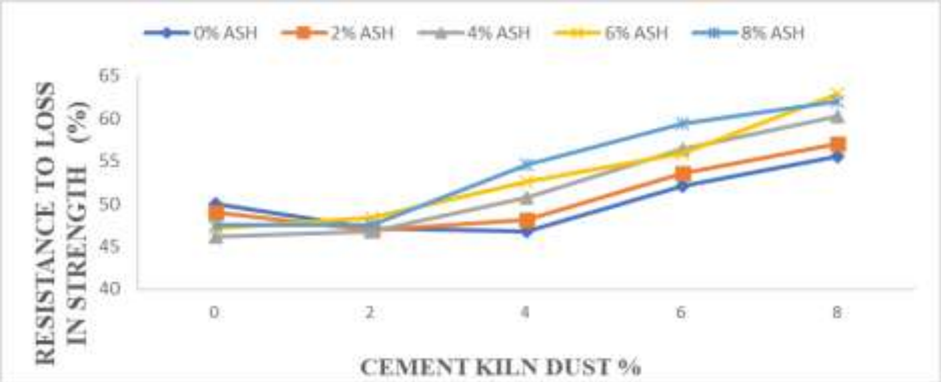


Figure 11: Durability vs. PSA content — WAS Compaction

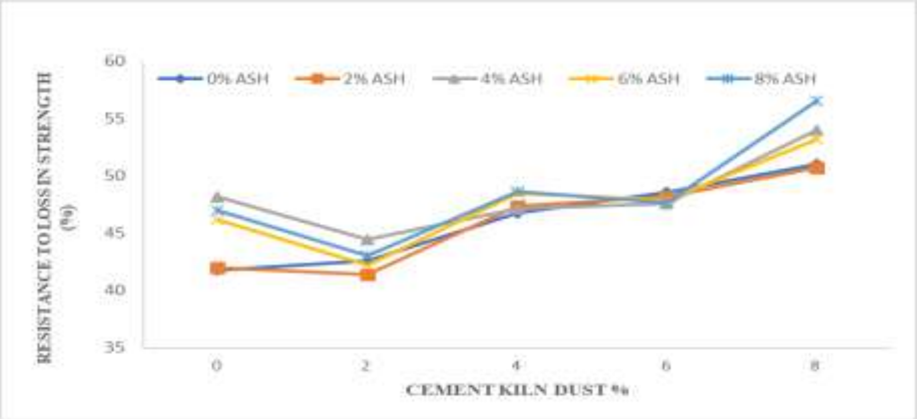


Figure 12: Durability vs. PSA content — BSH Compaction

Table 3. Durability values (%) under BSL, WAS, and BSH compaction at selected PSA–CKD contents with classification

PSA + CKD (%)	BSL (%)	WAS (%)	BSH (%)	Ola (1974) Classification
0% + 0%	~35	~46	~41	Poor — unsuitable (<40%)
2% + 2%	~42	~51	~45	Moderate — subbase (40–80%)
4% + 6%	~54	~57	~52	Moderate — subbase (40–80%)
6% + 6%	~60	~61	~55	Moderate — subbase (40–80%)
8% + 8%	~66	~63	~57	Moderate — subbase (40–80%)
Base course threshold	≥80	≥80	≥80	High — base course (≥80%)

4.4 Two-Way ANOVA Statistical Analysis

4.4.1 Strength Parameters

Two-way ANOVA results for all geotechnical properties are presented in Table 4. For unsoaked CBR under BSH compaction, both PSA ($p < 0.001$) and CKD ($p < 0.001$) were individually highly significant, and—critically—the PSA × CKD interaction was also significant ($p = 0.002$). This interaction effect provides statistical confirmation that the CBR improvement under BSH is not the independent sum of PSA and CKD contributions but a multiplicative synergistic effect: the impact of PSA on bearing capacity depends on the quantity of CKD present (and vice versa). This synergy arises because CKD provides the alkaline $Ca(OH)_2$ environment essential to activate PSA's indirect pozzolanic reactivity—without sufficient CKD, additional PSA contributes disproportionately less to gel formation. The soaked CBR analysis produced comparable results: PSA ($p < 0.001$), CKD ($p < 0.001$), and interaction ($p = 0.001$) were all highly significant, confirming that the synergistic effect persists under saturated conditions.

For UCS at 28 days under BSH, ANOVA confirmed significant effects of PSA ($p = 0.027$), CKD ($p < 0.001$), and their interaction ($p = 0.010$). The lower PSA significance ($p = 0.027$ vs. CKD $p < 0.001$) indicates that CKD is the dominant driver of long-term strength development, while PSA's contribution is primarily realised through its interaction with CKD rather than as a standalone factor. This asymmetry is consistent with PSA's lower reactive silica content and the alkalinity dependence of its pozzolanic mechanism (Etim et al., 2022; Mehta & Monteiro, 2006).

4.4.2 Durability

Durability showed no statistically significant main effects for PSA ($p = 0.816$) or CKD ($p = 0.071$). This result is significant not because PSA and CKD fail to improve durability—the data clearly show progressive improvement from 35% to 66% across the tested range—but because the improvement within the 0–8% range is not statistically distinguishable from sampling variation. The most parsimonious interpretation is that at 0–8% stabiliser dosage, all conditions produce insufficiently mature gel networks to stabilise durability responses; the primary control on durability within this range is curing duration and gel maturation kinetics rather than stabiliser dosage. This finding implies that higher dosages (>8%), longer curing periods (>28 days), or supplementary stabilisers (lime, cement) would be required to achieve statistically significant and practically meaningful durability improvements beyond the subbase range.

CKD was identified as the dominant factor across the test matrix: it significantly influenced LL ($p = 0.001$), PI ($p = 0.048$), linear shrinkage ($p < 0.001$), specific gravity ($p = 0.02$), OMC ($p = 0.002$), and all strength parameters. PSA showed significant main effects for linear shrinkage ($p = 0.008$), OMC ($p = 0.017$), and sieve analysis ($p = 0.040$), while contributing through significant interaction effects in CBR and UCS. The compaction energy moderates statistical significance: MDD under BSL showed no significant PSA ($p = 0.981$) or CKD ($p = 0.773$) effect, indicating that within the tested range, compaction energy—not stabiliser dosage—is the primary determinant of density under light compaction, while strength responses consistently showed high significance under BSH.

Table 4. Two-way ANOVA results summary: p-values for PSA, CKD, and PSA×CKD interaction

Test Parameter	PSA p-value	CKD p-value	Interaction (PSA×CKD)	α	Significant Factor(s)
Liquid Limit (LL)	0.412 (ns)	0.001 (**)	0.088 (ns)	0.05	CKD
Plastic Limit (PL)	0.674 (ns)	0.193 (ns)	0.056 (ns)	0.05	None
Plasticity Index (PI)	0.218 (ns)	0.048 (*)	0.103 (ns)	0.05	CKD
Linear Shrinkage (LS)	0.008 (**)	<0.001 (***)	0.054 (ns)	0.05	PSA & CKD
Max. Dry Density—BSL	0.981 (ns)	0.773 (ns)	0.855 (ns)	0.05	None
OMC—BSL	0.017 (*)	0.002 (**)	0.150 (ns)	0.05	PSA & CKD
Sieve Analysis	0.040 (*)	0.003 (**)	0.060 (ns)	0.05	PSA & CKD
Specific Gravity	0.145 (ns)	0.020 (*)	0.091 (ns)	0.05	CKD
Unsoaked CBR—BSH	<0.001 (***)	<0.001 (***)	0.002 (**)	0.05	All Factors
Soaked CBR—BSH	<0.001 (***)	<0.001 (***)	0.001 (***)	0.05	All Factors
UCS—BSH (28 days)	0.027 (*)	<0.001 (***)	0.010 (**)	0.05	All Factors
Durability—WAS	0.816 (ns)	0.071 (ns)	—	0.05	None
Natural Moisture Content	0.062 (ns)	0.008 (**)	0.081 (ns)	0.05	CKD

ns = not significant; * $p<0.05$; ** $p<0.01$; *** $p<0.001$. Bold entries indicate statistically significant results ($p<0.05$).

4.5 Pavement Layer Suitability Synthesis

Table 5 synthesises the strength and durability outcomes against Nigerian and international pavement material classification criteria. The stabilised lateritic soil consistently meets subbase requirements under all tested conditions at ≥4% PSA + ≥4% CKD: unsoaked CBR exceeds 30% under BSL, WAS, and BSH; soaked CBR exceeds 30% under WAS and BSH at higher stabiliser contents; UCS at 28 days under WAS and BSH exceeds 1,710 kN/m^2; and durability falls within the 40–80% subbase-acceptable range. Base course qualification requires further investigation: unsoaked CBR ≥80% is achievable under BSH (85.0% at 6% PSA + 8% CKD), but soaked CBR (50.2%) and durability (57% maximum) remain below the corresponding 80% thresholds.

Table 5. Suitability assessment of PSA–CKD stabilised lateritic soil against pavement layer criteria

Parameter	Study Range	Subbase Criteria	Base Course Criteria	Assessment
UCS, 28d BSH (kN/m^2)	840–2,600	≥687*	≥1,710*	✓ Subbase (at ≥4%+4%)
Unsoaked CBR—BSH (%)	15.88–85.0	≥30	≥80	✓ Base course (unsoaked, 6%+8% only)

Soaked CBR—BSH (%)	9.89–50.2	≥30	≥80	✓ Subbase (at ≥6%+8%)
Durability (%)	35–66	40–80	≥80	✓ Subbase only
Overall verdict	—	Reliable at ≥4%+4% (BSH)	Conditional (unsoaked only)	Recommended for subbase

* TRRL (1977), CBR thresholds from Federal Ministry of Works & Housing (2013).

V. CONCLUSION

This study systematically evaluated the strength performance and durability of lateritic soil from Shika, Zaria stabilised with PSA and CKD through a 5×5 factorial design under three compaction energy levels, with two-way ANOVA statistical validation. The following conclusions are drawn:

1. UCS increased consistently with curing age and stabiliser content, reaching a global peak of 2,600 kN/m^2 (209% improvement over natural soil) at 4% PSA + 6% CKD under BSH compaction at 28 days, driven by maturation of C–S–H and C–A–H gel networks. All WAS and BSH 28-day values at optimum mix proportions exceeded the 1,500 kN/m^2 subbase benchmark, confirming structural suitability for subbase construction at minimum 28-day curing.
2. Unsoaked CBR under BSH compaction reached 85.0% at 6% PSA + 8% CKD, meeting the Nigerian ≥80% base course requirement under dry conditions. Under BSL and WAS, peak values were 44.2% and 61.4% respectively—adequate for subbase but insufficient for base course. The compaction energy was the decisive variable: BSH is essential for base course CBR performance.
3. Soaked CBR peaked at 50.2% (8% PSA + 8% CKD, BSH)—well above the natural soil's 9.89% but below the 80% base course threshold—confirming moisture susceptibility as the primary constraint on base course classification under saturated conditions. Subbase soaked CBR requirements (≥30%) were reliably met at ≥4% CKD content under WAS and BSH.
4. Durability under eight wetting–drying cycles ranged from 35% to 66% across all conditions—below the Ola (1974) ≥80% base course threshold but within the 40–80% subbase range at ≥2% PSA + CKD. Gel immaturity and residual clay swelling, rather than stabiliser dosage, were identified as primary durability constraints; ANOVA confirmed no statistically significant dosage effect on durability within the 0–8% range tested.
5. Two-way ANOVA confirmed CKD as the dominant stabilising agent, significantly influencing LL ($p = 0.001$), PI ($p = 0.048$), UCS ($p < 0.001$), and CBR ($p < 0.001$). PSA contributed principally through statistically significant synergistic interaction effects with CKD for unsoaked CBR ($p = 0.002$), soaked CBR ($p = 0.001$), and UCS ($p = 0.010$), providing rigorous statistical confirmation that the combined PSA–CKD system is not merely additive but genuinely synergistic.
6. The optimal mix for subbase construction is 4–6% PSA combined with 6–8% CKD under BSH compaction with a minimum 28-day curing period. Conditional dry-condition base course use (unsoaked CBR) is achievable at 6% PSA + 8% CKD under BSH compaction; however, this is not recommended without additional measures to improve soaked CBR and durability performance.

5.1 Practical Recommendations

1. Adopt 4–6% PSA combined with 6–8% CKD for subbase construction in Nigerian laterite road projects. Ensure BSH-equivalent field compaction (minimum roller specification to be validated by site trial) and a minimum 28-day curing period before pavement loading.
2. For base course classification: unsoaked CBR of ≥80% can be achieved at 6% PSA + 8% CKD under BSH compaction; however, this specification requires companion durability

testing with extended curing (≥60 days) to verify long-term stability before routine adoption.
3. Investigate blending with tertiary stabilisers—lime, Portland cement, or fly ash at 2–4%—to improve durability from the current 35–66% toward the ≥80% base course threshold without substantially increasing cost.
4. Conduct instrumented field pilot sections on representative Nigerian trunk roads to validate laboratory CBR and UCS predictions under actual traffic loading and seasonal moisture cycling.
5. Apply SEM, XRD, and thermogravimetric analysis (TGA) to characterise the microstructural evolution of C–S–H and C–A–H gels with curing age and PSA–CKD ratio, providing mechanistic validation of the observed strength and durability trends.

VI. DECLARATIONS

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Conflicts of interest: The authors declare no conflicts of interest.
Data availability: Research data supporting the findings of this study are available from the corresponding author upon reasonable request.

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