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Locust Bean Waste Ash Treatment of Vermi-Remediated, Crude Oil-Contaminated Lateritic Soil for Road Subbase

J. E. Sani[1*], M.U. Dutsinma[2], G. Moses[1], Z. I. Ummisawa[1], I.I. Hassan[1]

[1]Department of Civil Engineering, Nigerian Defence Academy, Kaduna.

[2]Postgraduate Student, Department of Civil Engineering, Nigerian Defence Academy, Kaduna.

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ABSTRACT: This study evaluates the engineering performance of crude oil-contaminated lateritic soil reclaimed through sequential vermi-remediation and chemical stabilization using Locust Bean Waste Ash (LBWA) for road subbase development. The biological remediation phase achieved a 27% reduction in Total Petroleum Hydrocarbons (TPH), from 4500 mg/kg to 3300 mg/kg. Despite this improvement, the baseline soil remained structurally deficient, displaying high plasticity (PI = 20.71%), high fines content (72.42%), and low specific gravity (Gs = 2.0), classifying as A-7-6 (AASHTO) and CL (USCS). LBWA stabilization triggered significant particle flocculation, reducing fines content sharply to between 2.54% and 5.82%. Compaction testing revealed Maximum Dry Density (MDD) optimized at 1.89 Mg/m³ under British Standard Heavy (BSH) energy with 4% LBWA. Mechanical strength peaked at 12% LBWA with BSH compactive effort, achieving 7-day, 14-day, and 28-day Unconfined Compressive Strength (UCS) values of 701.2 kN/m², 800.6 kN/m², and 889.6 kN/m² respectively, substantially surpassing untreated baseline values. California Bearing Ratio (CBR) values peaked at 55.43% (unsoaked) and 32.56% (soaked). Durability indices confirmed that only the 12% LBWA + BSH configuration exceeded the 80% strength-retention threshold, achieving 81.5%. The findings validate that vermi-remediation mitigates environmental hazards, but subsequent stabilization with 12% LBWA under BSH compaction is technically necessary to fulfil structural and durability criteria for flexible-pavement subbase layers.

KEY WORDS: Lateritic Soil, Crude Oil Contamination Vermi-remediation, Locust Bean Waste Ash, Soil Stabilization, Road Subbase.

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1.0 INTRODUCTION

Hydrocarbon spills present a dual challenge: severe environmental toxicity and compromised structural integrity of the underlying soil. Entrained crude oil acts as an artificial lubricant within lateritic soils, separating clay grains, disrupting moisture–density mechanics, and degrading shear strength and bearing capacity. Hydrocarbon contamination alters soil–water chemistry, reduces shear-strength parameters, elevates compressibility, and produces erratic compaction curves. Consequently, contaminated soils fail to meet subgrade or subbase specifications without specialized remediation.

Vermi-remediation serves as an eco-engineered pre-treatment in which earthworms physically modify soil fabric by increasing porosity and void ratio, optimizing pore-air exchange, and accelerating aerobic microbial biodegradation of petroleum fractions. Their burrowing action breaks up hydrocarbon clusters, increases contaminant bioavailability, and homogenizes the soil matrix ahead of subsequent stabilization, a mechanism consistent with the earthworm-mediated treatment systems reported for polluted soils (James et al., 2024).

Lateritic soils are highly weathered residual profiles rich in sesquioxides of iron and aluminium, formed through chemical decomposition of parent rocks under alternating seasonal cycles. Although laterites display desiccation hardening upon exposure, their unaltered state is generally unsuitable for structural applications because of low CBR values, high plasticity indices, and pronounced shrink–swell potential. The road subbase layer, being a critical high-density pavement component designed to distribute traffic loads and facilitate drainage, requires structural modification through chemical stabilization.

Conventional stabilization employs ordinary Portland cement (OPC) to induce hydration-driven flocculation and calcium-silicate-hydrate (C-S-H) cementation. Contemporary research, however, focuses on replacing energy-intensive commercial binders with economical, locally sourced agro-industrial wastes possessing latent pozzolanic properties. Locust Bean Waste Ash (LBWA), derived from calcination of agricultural waste pods, represents a promising green alternative. In Northern Nigeria, large volumes of raw pod material are currently mismanaged through open burning, generating environmental pollution. When processed into ash, LBWA functions as a reactive pozzolan rich in amorphous silica (SiO_2) and alumina (Al_2O_3). Blended with moisture and soil, these components activate secondary pozzolanic reactions that produce cementitious matrices, reducing plasticity index, suppressing shrink–swell strain, and elevating bearing capacity — integrating waste management with cost-effective structural stabilization.

Related work on biochar amendment of highly weathered tropical soils has shown that a porous carbon matrix can significantly alter soil micro-fabric, optimize moisture retention and enhance aggregate stability against water-induced desiccation and erosion (Obiahu et al., 2020). Similarly, organic matter content has been shown to govern the compaction and strength response of tropical soils, with higher organic residues generally reducing interparticle friction and achievable density (Okorie & Uche, 2021). Together, these studies demonstrate a sustainable pathway for stabilizing fragile, clay-rich tropical soil profiles using localized biomass waste.

Bio-mediated stabilization has also been explored as an alternative to purely chemical approaches. Osinubi et al. (2024) reported that microbially induced calcite precipitation using *Bacillus pumilus* produced peak UCS values of up to 3,144 kN/m² under British Standard Heavy compactive effort at a 75% bacterial-to-25% cementation reagent mix ratio, with dense calcite crystals precipitating within the soil pore network to bind the clay–sand matrix and progressively increase strength with curing time up to 28 days.

Broader reviews of tropical lateritic soil behaviour map the transition from conventional chemical stabilizers (cement and lime) to eco-friendly, locally sourced alternatives such as agricultural ashes, industrial tailings, and bio-cementation techniques, evaluating their efficiency in optimizing plasticity index, maximum dry density, and California Bearing Ratio (Osinubi et al., 2021). The durability criterion applied in the present study — a minimum of 80% strength retention after conditioning — follows the classical framework established for stabilized tropical soils (Ola, 1974).

Etim et al. (2023) examined the coupled effect of cementation-solution concentration (0.25–1.00 M), curing time (up to 28 days), moulding water content, and compactive effort on the strength of bio-treated lateritic soil, finding that UCS increased steadily to a peak at a 0.5 M cementation concentration, safely exceeding the regulatory strength threshold of 200 kN/m² specified for waste-containment applications.

Yusuf et al. (2024) investigated periwinkle shell ash (PSA) stabilization of lateritic soil at 0–10% ash content (2% intervals) under standard Proctor compaction and reported a reduction in liquid limit from 36% to 32% and an increase in plastic limit from 16% to 25%, sharply lowering the plasticity index and volumetric-swelling risk. Maximum dry density increased from 1.72 to 1.82 Mg/m³, optimum moisture content fell from 15.34% to 11.55%, and unsoaked CBR rose from 26% to a peak of 40% at 8% PSA. Baseline UCS rose from 44 to 133 kN/m² on treatment, reaching a cured peak of 215 kN/m² attributable to calcium-silicate/calcite formation confirmed by SEM/FTIR analysis.

Blended agro-waste ash systems have similarly been shown to lower maximum dry density relative to cement or lime — owing to the comparatively low specific gravity of the ash — while still preserving favourable strength development at optimal hybrid blending ratios (Mezie et al., 2023).

Despite this growing body of work on stabilization of uncontaminated lateritic soils, limited attention has been paid to soils that have first undergone hydrocarbon contamination and biological remediation before chemical stabilization is applied. This study therefore investigates the sequential treatment pathway — vermi-remediation followed by LBWA stabilization — of crude oil-contaminated lateritic soil, and evaluates its suitability as a flexible-pavement road subbase material.

2.0 MATERIALS AND METHODS

2.1 Materials

2.1.1 Laterite Soil: Disturbed sample obtained from Shika, Zaria, Kaduna State (Latitude 11°15'N, Longitude 7°45'E) at depths of 1.5–2.0 m.

2.1.2 Crude Oil: Obtained from Port Harcourt, Rivers State, Nigeria.

2.1.3 LBWA: Locust bean pod waste purchased from Rigachukun and Tudun Biri, Kaduna, and incinerated at Yusuf Dantsoho Memorial Hospital, opposite Kaduna Polytechnic, Kaduna (Latitude 10.676377°N, Longitude 7.303105°E).

2.1.4 Earthworms (*Eudrilus eugeniae*): Obtained from the River Kaduna axis around Kabala Doki.

2.2 Methods

2.2.1 Mixing Scheme: Soil was air-dried, sorted, and contaminated at 75 cl crude oil per 10 kg soil with 1000 ml water, then covered for one month. Contaminated soil was remediated with earthworms at densities of 40, 50, 60, 70, and 80 worms per 40 kg (300 worms per 200 kg soil total) in perforated tanks for one month with daily watering.

2.2.2 Total Petroleum Hydrocarbons (TPH) Test

TPH content was determined by the gravimetric (toluene cold-extraction) method in accordance with USEPA Method 9071B. Soil samples (5,000 g) were air-dried for 72 hours; 2,500 g of each sample was extracted using 10 ml toluene, stirred for 30 minutes, allowed to stand for 2 hours, filtered through Whatman No. 42 filter paper, and oven-dried at 50°C. TPH was computed as:

$$\text{TPH (mg/kg)} = (W_0 - W_1) / (W_0 \times 10^6) \qquad (1)$$

where W_0 = initial sample weight and W_1 = weight after extraction.

2.2.3 Natural Moisture Content

Determined per BS 1377 (1990), Part 2, using oven drying at 105–110°C for 24 hours:

$$w = [(M_2 - M_3) / (M_3 - M_1)] \times 100 \qquad (2)$$

where w = moisture content (%), M_1 = weight of empty container (g), M_2 = weight of container + moist soil (g), and M_3 = weight of container + dry soil (g).

2.2.4 Linear Shrinkage

Conducted per BS 1377 (1990), Test 5, using soil passing the BS No. 40 sieve, mixed to liquid-limit consistency, placed in a shrinkage mould, dried at 60°C and then 105–110°C, with length measured after cooling:

$$\text{Linear Shrinkage (\%)} = [(\text{Initial length} - \text{Oven-dried length}) / \text{Initial length}] \times 100 \qquad (3)$$

2.2.5 Compaction Characteristics

Compaction was performed per BS 1377 (1990), Part 4, using British Standard Light (BSL), West African Standard (WAS), and British Standard Heavy (BSH) energies. Approximately 3 kg of soil mixture was blended with 8% water and compacted in 1000 cm³ moulds: BSL — 27 blows of a 2.5 kg rammer in 3 layers; WAS — 10 blows of a 4.5 kg rammer in 5 layers; BSH — 27 blows of a 4.5 kg rammer in 5 layers. Bulk and dry densities were calculated, and MDD and OMC were obtained from the resulting compaction curves:

$$\rho = (M_2 - M_1) / 1000 \qquad (4)$$

$$\rho d = 100\rho / (100 + w) \qquad (5)$$

2.2.6 Unconfined Compressive Strength (UCS)

Performed per BS 1377 (1990), Part 7, at BSL, WAS, and BSH energy levels. Stabilized samples were compacted at OMC in 1000 cm³ moulds, extruded, and trimmed into 38.1 mm diameter × 76.2 mm length cylinders for testing at 7, 14, and 28 days of curing.

3.0 RESULTS AND DISCUSSION

3.1 Properties of Materials

3.1.1 Physical Properties of Vermi-Remediated Crude Oil-Contaminated Soil

Table 1: Physical properties of the vermi-remediated crude oil-contaminated soil

Property	Quantity
Percentage passing BS No. 200 sieve (%)	72.42
Liquid Limit (%)	53.01
Plastic Limit (%)	32.30
Plasticity Index (%)	20.71
Specific Gravity	2.0
AASHTO Classification	A-7-6
USCS Classification	CL
Maximum Dry Density (Mg/m³)	
— British Standard Light	1.68
— West African Standard	1.69
— British Standard Heavy	1.71
Optimum Moisture Content (%)	
— British Standard Light	20.38
— West African Standard	17.18
— British Standard Heavy	15.78
Unconfined Compressive Strength, 7-day curing (kN/m²)	
— British Standard Light	182.7

Property	Quantity
— West African Standard	201.5
— British Standard Heavy	545.6
California Bearing Ratio — Unsoaked (%)	
— British Standard Light	7.11
— West African Standard	10.65
— British Standard Heavy	12.01
California Bearing Ratio — Soaked (%)	
— British Standard Light	4.03
— West African Standard	4.40
— British Standard Heavy	8.58
Colour	Light brown
Dominant clay mineral	Kaolinite

Table 1 shows that, despite vermi-remediation, the soil remains structurally deficient — with unacceptable plasticity, poor compaction characteristics, negligible strength, and inadequate bearing capacity — making it unsuitable for subbase construction without further chemical stabilization.

Table 2: Chemical composition of vermi-remediated crude oil-contaminated soil

Elemental Oxide	Composition (%)
SiO_2	41.05
Al_2O_3	24.16
Fe_2O_3	10.16
CaO	0.23
MgO	0.21
SO_3	1.04
Na_2O	1.37
K_2O	0.34
TiO_2	0.39
P_2O_5	1.31
Mn_2O_5	0.02
Rb_2O_5	0.27
PbO	0.010
Cr_2O_3	0.02
MnO	ND
Loss on Ignition (LOI)	19.35

The chemical composition in Table 2 reveals a soil with adequate silica and alumina for pozzolanic reaction but severely deficient in calcium (0.23%), the key reactant for cementitious bond formation. This confirms that an external calcium source — such as LBWA, with 13.32% CaO (Table 3) — is necessary for effective stabilization. The high LOI (19.35%) also indicates residual organic/hydrocarbon interference that continues to affect engineering behaviour until stabilization is applied.

Table 3: Chemical composition of Locust Bean Waste Ash (LBWA)

Elemental Oxide	Composition (%)
SiO_2	43.21
Al_2O_3	15.57
Fe_2O_3	9.27
CaO	13.32
MgO	2.27
SO_3	0.08
Na_2O	1.62
K_2O	8.02
TiO_2	0.09
P_2O_5	1.20
Mn_2O_5	0.01

Elemental Oxide	Composition (%)
Rb_2O_5	0.01
Cr_2O_3	0.01
LOI	5.70

Table 3 confirms LBWA as an effective pozzolanic stabilizer, offering: (i) abundant reactive silica and alumina for cementitious compound formation, (ii) a comparatively high calcium content (13.32%) to drive pozzolanic reaction, (iii) alkaline compounds that accelerate reaction rates, and (iv) a low organic content (LOI = 5.70%), which limits the risk of introducing further contamination. This composition explains the strength, CBR, and durability improvements observed with increasing LBWA content, particularly around the 12% optimum, where sufficient reactive material is available to maximize cementitious bond formation.

Table 4: Total Petroleum Hydrocarbon (TPH) of crude oil-contaminated soil before vermi-remediation

S/No	Soil Sample	Weight Before Extraction (mg)	Weight After Extraction (mg)	CYCLE (C)	TPH (mg/kg)	Average TPH (mg/kg)
1	COCS1	10,000.00	9,560.00	4	4,400.00	4,500.00
2	COCS2	10,000.00	9,550.00	4	4,500.00	4,500.00
3	COCS3	10,000.00	9,550.00	4	4,500.00	4,500.00

Table 5: Total Petroleum Hydrocarbon (TPH) of crude oil-contaminated soil after vermi-remediation

S/No	Soil Sample	Weight Before Extraction (mg)	Weight After Extraction (mg)	CYCLE (C)	TPH (mg/kg)	Average TPH (mg/kg)	TPH Removal Efficiency (%)
1	COCS1	10,000.00	9,680.00	4	3,200.00	3,300.00	27.00
2	COCS2	10,000.00	9,670.00	4	3,300.00	3,300.00	27.00
3	COCS3	10,000.00	9,660.00	4	3,400.00	3,300.00	24.00

3.2 Contaminant Removal Efficiency

TPH analysis (Tables 4 and 5) shows a reduction from 4,500 mg/kg to 3,300 mg/kg, an average removal efficiency of 27%. This moderate improvement indicates that vermi-remediation effectively reduced hydrocarbon content, but residual contamination continued to influence the soil's engineering behaviour, necessitating subsequent chemical stabilization.

3.3 Compaction Characteristics

3.3.1 Maximum Dry Density

The untreated soil (see Fig. 1) recorded MDD values of 1.68 Mg/m^3 (BSL), 1.69 Mg/m^3 (WAS), and 1.71 Mg/m^3 (BSH), indicating a loosely packed structure in which residual organic matter reduces interparticle friction (Oba et al., 2020; Okorie & Uche, 2021). At 4% LBWA, MDD peaked at 1.89 Mg/m^3 (BSH), attributable to pozzolanic reactions that promote particle aggregation and stronger interparticle bonds, thereby reducing the void ratio (Obiahu et al., 2022; Akinola et al., 2021). At higher LBWA contents (12–16%), MDD decreased to 1.78–1.81 Mg/m^3 (BSH), suggesting that excess ash particles act as inert fillers rather than contributing further to cementitious bonding.

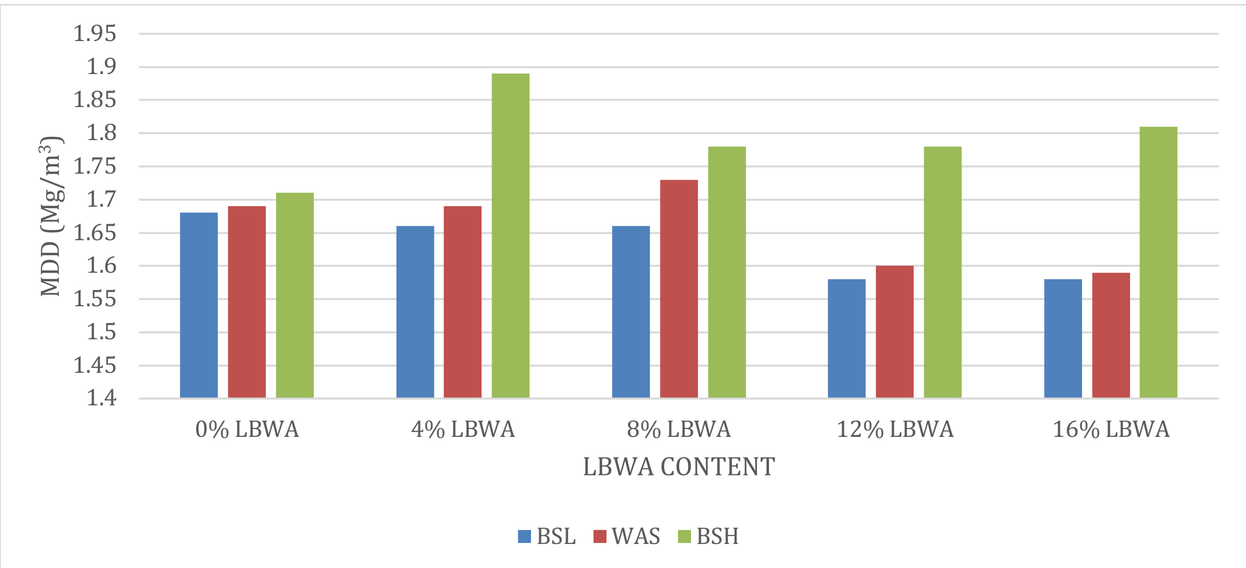

Fig.1: Variation of compaction-test MDD for vermi-remediated laterite soil with LBWA content (BSL, WAS, and BSH)

3.3.2 Optimum Moisture Content

Untreated-soil OMC values (see Fig. 2) were 20.38% (BSL), 17.18% (WAS), and 15.78% (BSH). The higher OMC observed under light compaction reflects the loosely packed structure and the additional water demand of residual hydrocarbons (Oba et al., 2020; Eze et al., 2022). With LBWA addition, OMC remained relatively stable (17.06–19.25%), indicating a consistent water demand for compaction as ash content increased, resulting from the balance between filler and pozzolanic effects.

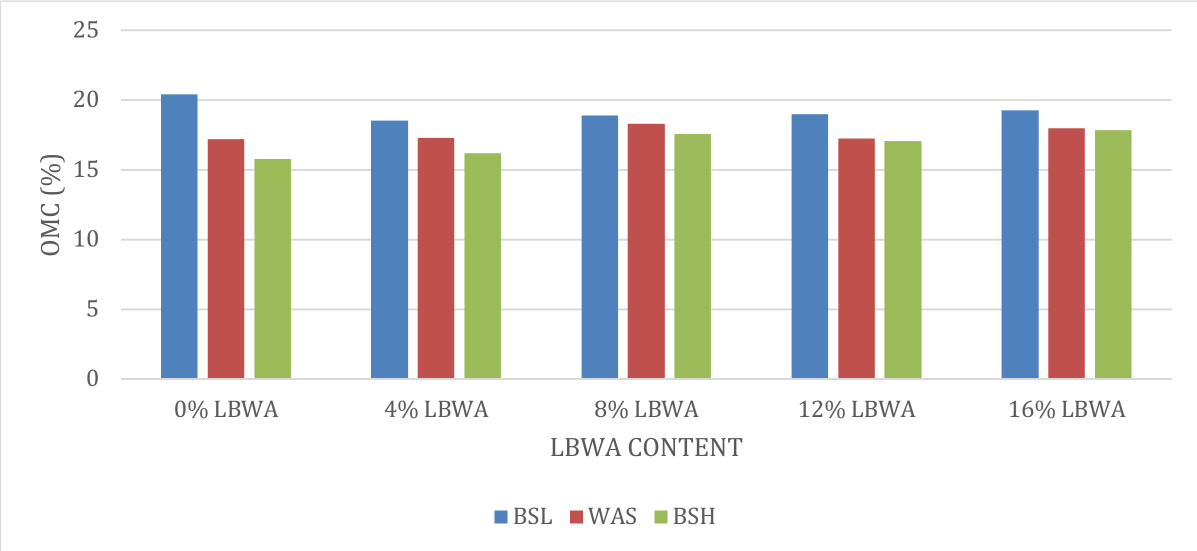

Fig. 2: Variation of compaction-test OMC for vermi-remediated laterite soil with LBWA content (BSL, WAS, and BSH)

3.4 Strength Characteristics

3.4.1 7-Day UCS

Untreated soil (see Fig. 3a) recorded UCS values of 182.7 kN/m² (BSL), 201.5 kN/m² (WAS), and 545.6 kN/m² (BSH); residual hydrocarbons interfered with particle bonding and suppressed strength development (Osinubi et al., 2021). At 4% LBWA: 243.5, 356.4, and 580.6 kN/m² (BSL, WAS, BSH), marking the onset of pozzolanic reaction. At 8% LBWA: 266.4, 361.5, and 692.5 kN/m². Peak values occurred at 12% LBWA: 269.9, 371.2, and 701.2 kN/m², reflecting the optimum stabilizer content for maximizing cementitious compound formation (Yusuf et al., 2024). At 16% LBWA, strength declined to 255.1, 364.5, and 509.5 kN/m², consistent with excess unreacted ash acting as a weak inclusion within the matrix (Mezie et al., 2023). Ingles and Metcalf (1972) recommend a 7-day UCS of 687–1,373 kN/m² for subbase materials; only the 8% and 12% LBWA mixes under BSH compaction (692.5 and 701.2 kN/m²) met this criterion.

Fig. 3a: Variation of UCS of LBWA-stabilized vermi-remediated crude oil-contaminated lateritic soil at 7 days (BSL, WAS, BSH)

3.4.2 14-Day UCS

The untreated soil (Fig. 3b) recorded UCS values of 323.2, 356.5, and 622.6 kN/m² under BSL, WAS, and BSH compactive efforts, respectively. The higher UCS under BSH reflects the effect of increased compactive effort, which enhanced particle interlock and reduced voids. Stabilization with LBWA improved UCS across all compactive efforts, reaching 451.2, 503.6, and 721.9 kN/m² at 4% LBWA, indicating the onset of pozzolanic reactions. Further increases to 485.6, 516.2, and 786.6 kN/m² at 8% LBWA and peak values of 596.2, 585.9, and 800.6 kN/m² at 12% LBWA confirm that 12% LBWA is the optimum stabilizer content, owing to maximum formation of cementitious products (C–S–H and C–A–H) that enhanced particle bonding and matrix densification (Yusuf et al., 2024). Beyond the optimum, UCS decreased to 500.1, 545.8, and 785.5 kN/m² at 16% LBWA, likely due to excess unreacted ash acting as weak inclusions within the soil matrix (Mezie et al., 2023). According to Ingles and Metcalf (1972), a 7-day UCS of 687–1,373 kN/m² is required for subbase materials; therefore, only the BSH-compacted specimens containing 4–16% LBWA (721.9–800.6 kN/m²) satisfied this requirement, highlighting the combined importance of optimum LBWA content and high compactive effort in achieving subbase-quality stabilized soil.

Fig. 3b: Variation of UCS of LBWA-stabilized vermi-remediated crude oil-contaminated lateritic soil at 14 days (BSL, WAS, BSH)

3.4.3 28-Day UCS

The untreated soil (Fig. 3c) recorded UCS values of 555.3, 642.7, and 661.6 kN/m² under BSL, WAS, and BSH compactive efforts, respectively. UCS increased consistently with LBWA content, reaching 609.3, 688.0, and 823.3 kN/m² at 4% LBWA and 641.5, 715.9, and 845.5 kN/m² at 8% LBWA, reflecting progressive pozzolanic reactions and improved interparticle bonding. Peak UCS values of 685.1, 734.2, and 889.6 kN/m² were obtained at 12% LBWA, indicating the optimum stabilizer content for maximum cementitious product formation and matrix densification (Yusuf et al., 2024). A slight reduction to 635.8, 683.1, and 829.6 kN/m² at 16% LBWA suggests that excess unreacted ash reduced strength by acting as weak inclusions within the stabilized matrix (Mezie et al., 2023). The consistently higher UCS values under BSH compared with WAS and BSL further demonstrate the beneficial effect of increased compactive effort on strength development. Moreover, the overall increase in UCS with curing time across all mixes confirms sustained pozzolanic activity and continuous development of cementitious bonds, resulting in progressive strength gain (Etim et al., 2023; Yusuf et al., 2024).

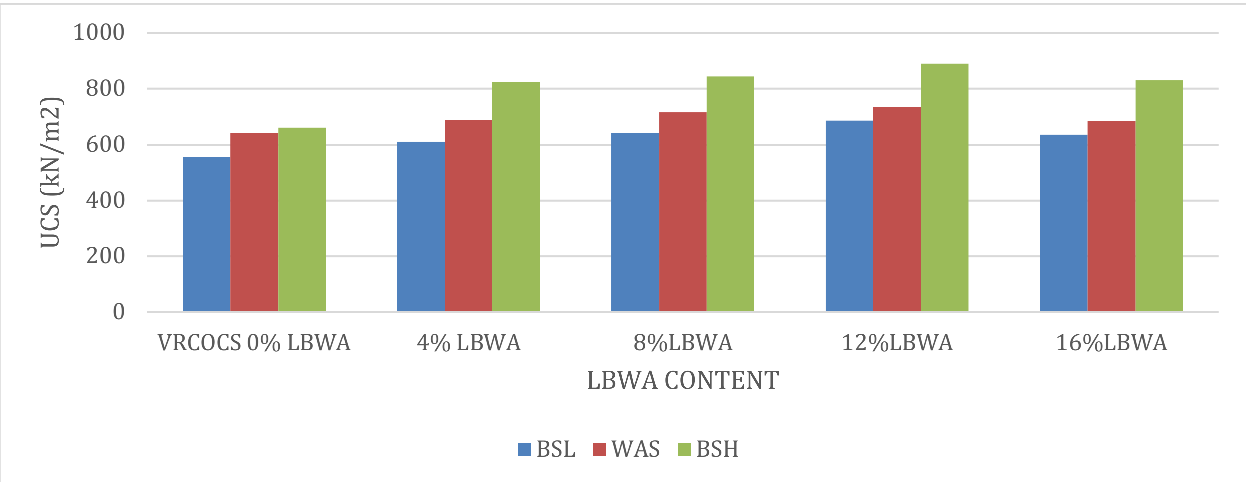

Fig. 3c: Variation of UCS of LBWA-stabilized vermi-remediated crude oil-contaminated lateritic soil at 28 days (BSL, WAS, BSH)

3.5 California Bearing Ratio

3.5.1 Unsoaked CBR

The untreated soil (see Fig. 4) recorded CBR values of 7.11%, 10.65%, and 12.01% under BSL, WAS, and BSH compactive efforts, respectively, indicating poor bearing capacity due to the adverse effects of residual hydrocarbons on soil particle bonding (Osinubi et al., 2021). Incorporation of LBWA significantly improved the CBR, increasing to 9.81%, 17.33%, and 36.89% at 4% LBWA, which marks the onset of effective stabilization through pozzolanic reactions. Further increases to 10.97%, 30.98%, and 48.19% at 8% LBWA and peak values of 11.70%, 40.15%, and 55.43% at 12% LBWA demonstrate enhanced formation of cementitious compounds that improved particle interlock, reduced voids, and increased the soil's load-bearing capacity (Yusuf et al., 2024). Beyond the optimum content, the CBR decreased slightly to 10.72%, 29.77%, and 51.33% at 16% LBWA, suggesting that excess ash remained unreacted and acted as weak inclusions, thereby reducing stabilization efficiency (Mezie et al., 2023). The consistently higher CBR values obtained under BSH compaction further highlight the importance of higher compactive effort in maximizing the effectiveness of LBWA stabilization. Based on the Nigerian General Specification for Roads and Bridges (Federal Ministry of Works, 1997; revised 2013), the 12% LBWA specimen compacted with BSH (55.43%) satisfies the minimum CBR requirement for subbase materials (≥50%), while the WAS-compacted specimen (40.15%) is suitable for subgrade improvement but falls short of the subbase requirement.

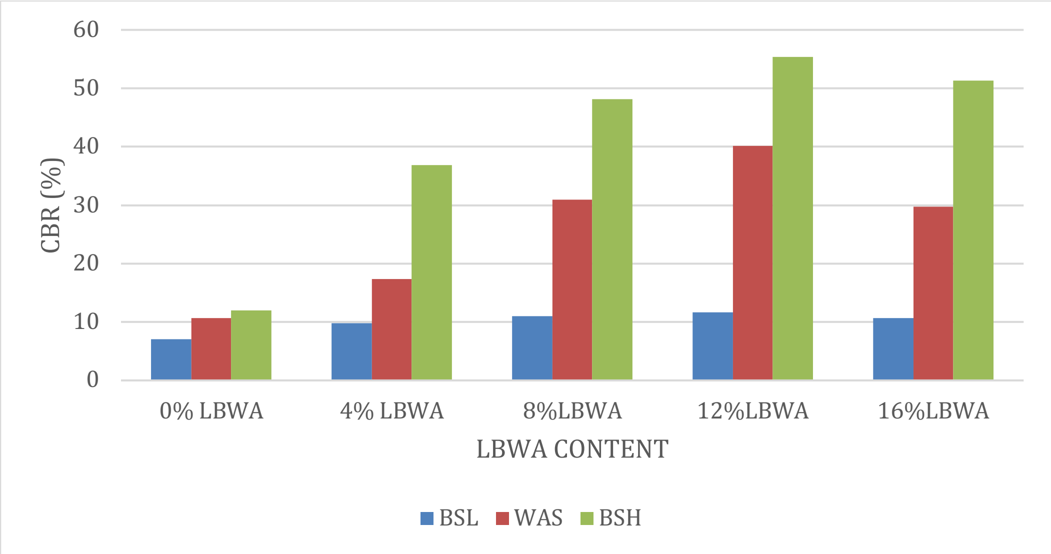

Fig. 4: Variation of unsoaked CBR of vermi-remediated laterite soil with LBWA content (BSL, WAS, BSH)

3.5.2 Soaked CBR

The untreated soil (see Fig. 5) recorded soaked CBR values of 4.03%, 4.40%, and 8.58% under BSL, WAS, and BSH compactive efforts, respectively, indicating poor bearing capacity under soaked conditions due to hydrocarbon contamination, which weakened interparticle bonding and reduced soil strength (Osinubi et al., 2021). The addition of LBWA improved the soaked CBR to 6.56%, 8.65%, and 13.59% at 4% LBWA, reflecting the onset of pozzolanic reactions and the formation of cementitious compounds. Further increases to 8.66%, 15.50%, and 25.77% at 8% LBWA and peak values of 10.50%, 19.63%, and 32.56% at 12% LBWA demonstrate progressive enhancement in soil strength due to improved particle bonding, matrix densification, and reduced moisture susceptibility (Yusuf et al., 2024). Increasing the LBWA content to 16% resulted in lower soaked CBR values of 9.63%, 15.45%, and 16.90%, suggesting that excess unreacted ash reduced stabilization efficiency by acting as weak inclusions within the soil matrix (Mezie et al., 2023). The consistently higher soaked CBR values obtained under BSH compaction confirm the significant influence of compactive effort on bearing capacity through increased dry density and improved particle interlocking. According to the Nigerian General Specification for Roads and Bridges (Federal Ministry of Works, 1997; revised 2013), only the 12% LBWA specimen compacted at BSH (32.56%) satisfied the minimum soaked CBR requirement of 30% for subbase materials, identifying it as the optimum mixture for pavement applications under soaked conditions.

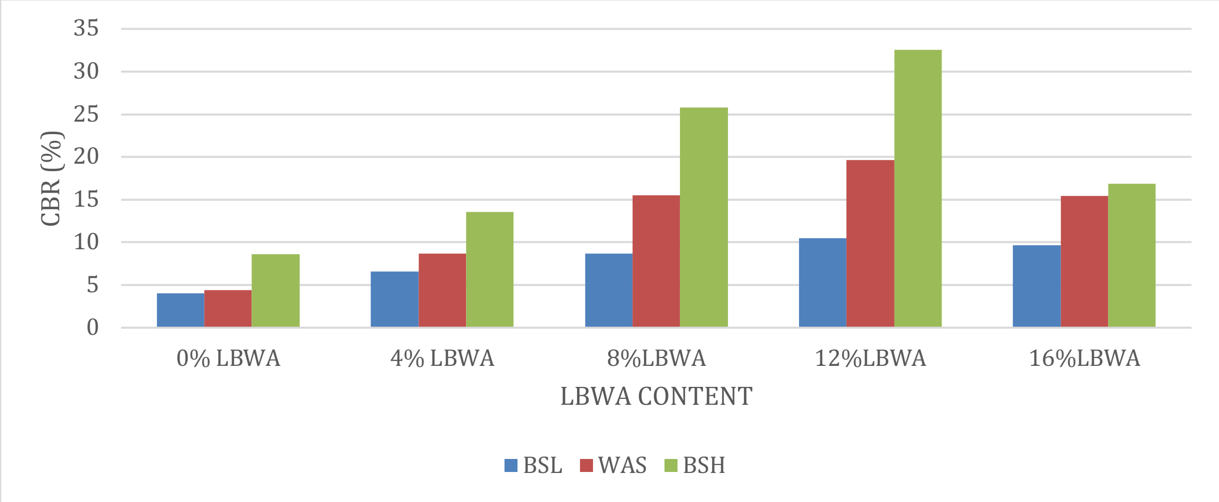

Fig. 5: Variation of soaked CBR of vermi-remediated laterite soil with LBWA content (BSL, WAS, BSH)

3.6 Durability

The durability assessment (see Fig. 6) showed that the untreated soil retained only 27.9%, 33.2%, and 36.5% of its original UCS under BSL, WAS, and BSH compactive efforts, respectively, indicating poor resistance to environmental conditioning due to weak interparticle bonding and the detrimental effects of hydrocarbon contamination (Osinubi et al., 2021). The addition of LBWA improved durability, with strength retention increasing to 28.5%, 34.5%, and 66.8% at 4% LBWA and 40.3%, 46.6%, and 73.8% at 8% LBWA, reflecting progressive development of cementitious products through pozzolanic reactions. Maximum durability was achieved at 12% LBWA, with strength retention values of 48.9%, 55.8%, and 81.5% under BSL, WAS, and BSH compactive efforts, respectively. This improvement is attributed to optimum formation of calcium silicate hydrate (C–S–H) and calcium aluminate hydrate (C–A–H) gels, which enhanced particle bonding, reduced pore connectivity, and produced a denser, more durable soil matrix (Yusuf et al., 2024; Mezie et al., 2023). Increasing the LBWA content to 16% reduced durability to 45.1%, 52.2%, and 60.9%, suggesting that excess unreacted ash weakened the stabilized matrix and reduced resistance to conditioning. According to Ola (1974), stabilized soils should retain at least 80% of their original strength after conditioning; therefore, only the 12% LBWA specimen compacted under BSH (81.5%) satisfied the durability criterion, demonstrating that optimum LBWA content combined with high compactive effort is essential for producing durable stabilized pavement materials.

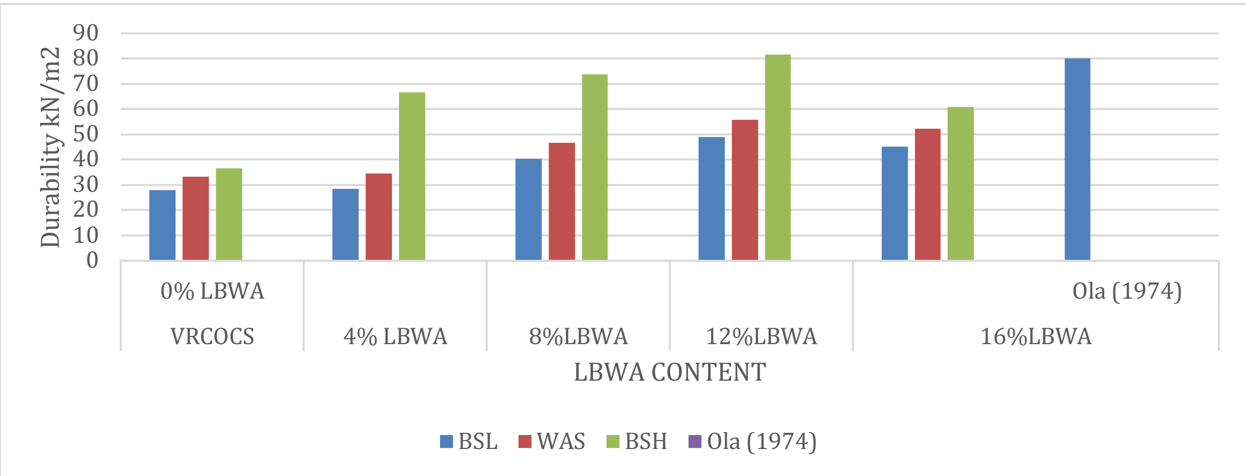

Fig. 6: Durability of vermi-remediated soil with LBWA content (BSL, WAS, BSH)

4.0 CONCLUSION

The study evaluated vermi-remediated, crude oil-contaminated lateritic soil stabilized with LBWA for road-subbase application. The following conclusions are drawn:

1. Vermi-remediation achieved a 27% TPH reduction (4,500 to 3,300 mg/kg), indicating moderate environmental improvement.
2. The untreated soil classified as A-7-6 (AASHTO) and CL (USCS), with high fines content (72.42%), high plasticity index (20.71%), and low specific gravity (Gs = 2.0). LBWA stabilization drastically reduced fines content to 2.54–5.82%, indicating improved gradation.

3. MDD improved from 1.68 Mg/m³ (untreated) to a peak of 1.89 Mg/m³ (4% LBWA, BSH). OMC varied within 15.78–20.38%.
4. 12% LBWA under BSH compaction produced peak UCS values of 701.2 kN/m² (7-day), 800.6 kN/m² (14-day), and 889.6 kN/m² (28-day), meeting subbase strength requirements.
5. Unsoaked CBR peaked at 55.43%; soaked CBR reached 32.56% at 12% LBWA under BSH compaction, meeting the Nigerian General Specification minimum of 30%.
6. Durability: Only the 12% LBWA + BSH configuration exceeded the 80% strength-retention threshold (81.5%), indicating adequate long-term performance.

Overall, while vermi-remediation mitigates the environmental hazard posed by hydrocarbon contamination, subsequent stabilization with 12% LBWA under BSH compaction is technically necessary to satisfy the combined structural and durability criteria for flexible-pavement subbase layers.

4.1 RECOMMENDATIONS

1. Adopt 12% LBWA as the optimum stabilizer content, on the basis of peak 28-day UCS (889.6 kN/m²), soaked CBR (32.56%), and durability (81.5%).
2. Use British Standard Heavy compactive effort in field compaction, as it consistently produced superior engineering properties across all mixes.
3. Avoid using untreated vermi-remediated soil directly in pavement construction, given its very low soaked CBR values (4.03–8.58%).
4. Control stabilizer content within the optimum range (≈12% LBWA), since exceeding this (16% LBWA) reduced UCS from 701.2 to 509.5 kN/m² (7-day, BSH) and soaked CBR from 32.56% to 16.90%.
5. Allow a minimum 28-day curing period in field applications, as strength increased progressively with curing time.
6. Maintain moisture control near OMC during construction, noting that OMC ranged from 15.78% to 20.38% depending on compactive effort.
7. Target high in-situ dry density during field compaction, consistent with the MDD improvement from 1.68 to 1.89 Mg/m³ observed at 4% LBWA (BSH).
8. Promote LBWA as an eco-friendly alternative stabilizer that both valorises agricultural waste and improves the geotechnical performance of contaminated lateritic soils.

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