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Geotechnical Characterization and Rice Husk Ash Stabilization of Vermiremediated Crude Oil–Contaminated Lateritic Soil for Highway Applications

John E. Sani, Alabi O. Gideon, George Moses
Department of Civil Engineering,
Nigerian Defence Academy, Kaduna, Nigeria

ABSTRACT

Crude oil contamination severely degrades the index, compaction, and strength properties of lateritic soils in Nigeria's oil-producing regions, limiting their suitability for road construction. This study evaluated the geotechnical response of crude oil–contaminated lateritic soil to sequential treatment by vermiremediation and rice husk ash (RHA) stabilization. Lateritic soil sourced from Shika, Zaria, Kaduna State (11°15′ N, 7°45′ E) was artificially contaminated with crude oil at 75 cl per 10 kg of soil and subsequently vermiremediated using the earthworm Eudrilus eugeniae at a rate equivalent to 300 worms per 200 kg of soil over 30 days, achieving a total petroleum hydrocarbon (TPH) reduction of approximately 27%. The vermiremediated soil was then stabilized with RHA at 0, 4, 8, 12, and 16% by dry weight and evaluated in accordance with BS 1377 (1990) and BS 1924 (1990) using index, compaction (British Standard Light [BSL], West African Standard [WAS], and British Standard Heavy [BSH] efforts), unconfined compressive strength (UCS), California bearing ratio (CBR), and durability tests. Untreated vermiremediated soil classified as A-7-6 (CL) with a plasticity index of 19.5% and unsoaked CBR values below 9% for all compactive efforts, confirming its unsuitability as a pavement material. RHA stabilization increased CBR values to a maximum of 26–32% and produced peak 28-day UCS gains of up to 227.7 kN/m² for the WAS effort at 16% RHA, although the optimum RHA content varied with compactive effort (8% for BSL, 16% for WAS and BSH). The results indicate that RHA is a viable, low-cost pozzolanic stabilizer capable of restoring vermiremediated, oil-impacted lateritic soil to a condition suitable for subgrade and light sub-base applications, although values generally remained below the 80% CBR threshold specified for base-course material by the Nigerian General Specifications for Roads and Bridges (2016).

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INTRODUCTION

Nigeria's oil-producing states — Delta, Bayelsa, Rivers, and Edo — experience frequent crude oil spillage arising from pipeline vandalism, equipment failure, and illegal refining, resulting in extensive degradation of soil quality across the Niger Delta (Adeniran, 2023). Crude oil contamination alters the physicochemical and engineering behaviour of soils by coating soil particles with hydrophobic hydrocarbon films, which reduces shear strength, permeability, and compaction efficiency while increasing plasticity (Ali & Zhang, 2023). For lateritic soils, which are the predominant subgrade and pavement material across tropical Africa, such contamination compromises their suitability for road construction, foundations, and other geotechnical applications (Adeyemi et al., 2022). Restoring the engineering

Corresponding author: John E. Sani
jesani@nda.edu.ng
Department of Civil Engineering, Nigerian Defence Academy, Kaduna, Nigeria.

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suitability of oil-impacted lateritic soils is therefore essential to sustainable infrastructure delivery in Nigeria's oil-producing regions.

Remediation of hydrocarbon-contaminated soils has traditionally relied on physical, chemical, and microbial techniques, but these methods are frequently costly, slow, or environmentally intrusive. Vermiremediation — the use of earthworms to degrade and detoxify organic contaminants — has emerged as a low-cost, environmentally friendly alternative. Earthworms such as Eudrilus eugeniae enhance soil aeration, stimulate hydrocarbon-degrading microbial populations in their gut and casts, and progressively lower total petroleum hydrocarbon (TPH) concentrations in contaminated soils (Adhikari et al., 2022, Veena et al., 2023). Recent work combining earthworm activity with bioaugmentation has reported TPH removal efficiencies of over 50% under optimized conditions, underscoring the potential of vermiremediation as a pre-treatment step ahead of engineering stabilization (Ameen & Al-Homaidan, 2024). However, vermiremediation alone rarely restores the full geotechnical competence of contaminated soil, and a complementary stabilization step is typically required.

Soil stabilization using agricultural and industrial waste pozzolans offers a sustainable route to improving the strength and durability of problem soils while simultaneously addressing waste disposal challenges. Rice husk ash (RHA), obtained from the controlled combustion of rice husk, is silica-rich and pozzolanically active, Nigeria alone generates an estimated 1.96–2.46 million tonnes of rice husk annually from its rice industry, making RHA a widely available and inexpensive stabilizing agent (Ogbonwa & Okoro, 2025). RHA has been shown to improve the strength, bearing capacity, and durability of lateritic and expansive soils (Alhassan & Mustapha, 2020, Almuaythir et al., 2024), and has more recently been applied specifically to crude oil–polluted lateritic soils in combination with cement, with measurable gains in CBR and UCS (Adedokun et al., 2024).

Despite this growing body of work, few studies have examined the combined, sequential effect of biological remediation (vermiremediation) followed by pozzolanic stabilization (RHA) on the same crude oil–contaminated lateritic soil across multiple compactive efforts. This study therefore investigates the index, compaction, strength, and bearing-capacity characteristics of a lateritic soil that was first contaminated with crude oil, then vermiremediated using Eudrilus eugeniae, and finally stabilized with RHA at varying admixture levels, with the aim of establishing its suitability for use as a road construction material.

MATERIALS AND METHODS

Materials

Lateritic soil was obtained from a borrow pit at Shika, Zaria, Kaduna State (11°10'25" N, 7°36'54" E) and transported to the laboratory in air-tight sacks. Crude oil was sourced from Port Harcourt, Rivers State. Rice husk was obtained from Station Roundabout Market, Kakuri, Kaduna, and incinerated for five days at the Yusuf Dan Tsoho Hospital incinerator, the resulting ash was sieved and stored in air-tight bags prior to use as the stabilizing agent. Earthworms of the species Eudrilus eugeniae were collected from the River Kaduna axis around Kabala Doki (10.499° N, 7.421° E), an area selected for its moist, organic-rich soil that supports a healthy epigeic earthworm population.

Contamination and Vermiremediation Procedure

Air-dried and pulverized soil, sieved through the BS No. 4 sieve (4.76 mm aperture) to remove the gravel fraction, was contaminated with crude oil at a rate of 75 cl of crude oil per 10 kg of soil and 1000 mL of water, then sealed and cured for one month to allow full contamination. The contaminated soil was subsequently treated with earthworms at a rate equivalent to 300 worms per 200 kg of soil (40–80 worms per 40 kg subsample) in perforated, aerated tanks for 30 days, with daily moisture replenishment. TPH concentrations of the soil before and after vermiremediation were determined gravimetrically to evaluate remediation efficiency.

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jesani@nda.edu.ng
Department of Civil Engineering, Nigerian Defence Academy, Kaduna, Nigeria.

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Rice Husk Ash Stabilization

The vermiremediated soil was stabilized with RHA at 0 (control), 4, 8, 12, and 16% by dry weight, in accordance with BS 1924 (1990).

Laboratory Testing Programme

Index properties (natural moisture content, specific gravity, particle size distribution, and Atterberg limits), compaction characteristics, unconfined compressive strength (UCS), California bearing ratio (CBR), and durability were determined in accordance with BS 1377 (1990). Compaction was carried out using three compactive efforts — British Standard Light (BSL): 3 layers × 27 blows with a 2.5 kg rammer, West African Standard (WAS): 5 layers × 10 blows with a 4.5 kg rammer, and British Standard Heavy (BSH): 5 layers × 27 blows with a 4.5 kg rammer. CBR specimens were cured for 6 days in sealed bags and soaked in water for 24 hours prior to testing, in line with the Nigerian General Specifications for Roads and Bridges (Federal Ministry of Works, 2016). UCS specimens were tested at 7, 14, and 28 days of curing to evaluate strength gain with time, and durability was assessed as the percentage resistance to loss in strength after soaking.

RESULTS AND DISCUSSION

Index Properties of Vermiremediated Crude Oil–Contaminated Soil

The vermiremediated, unstabilized soil classified as A-7-6 (group index 12) under the AASHTO system (AASHTO, 1996) and CL under the Unified Soil Classification System (ASTM, 2022). Table 1 summarizes its physical and compaction properties. The soil exhibited a liquid limit of 51.8%, plasticity index of 19.5%, and specific gravity of 2.4, with 72.42% of particles passing the BS No. 200 sieve, indicating a fine-grained, plastic material of generally poor quality for direct use in pavement layers — consistent with the reported effects of hydrocarbon contamination on lateritic soil plasticity and gradation (Ali & Zhang, 2023, Adeyemi et al., 2022).

Table 1. Physical and compaction properties of vermiremediated crude oil–contaminated lateritic soil.

Property	Value
Percentage passing BS sieve No. 200 (%)	72.42
Liquid limit, LL (%)	51.8
Plastic limit, PL (%)	32.3
Plasticity index, PI (%)	19.5
Linear shrinkage (%)	11.0
Specific gravity	2.4
AASHTO classification	A-7-6 (12)
USCS classification	CL
Colour	Dark brown
Dominant clay mineral	Kaolinite
MDD – BSL / WAS / BSH (Mg/m³)	1.63 / 1.66 / 1.69
OMC – BSL / WAS / BSH (%)	18.87 / 17.18 / 15.78
Unsoaked CBR at 2.5 mm – BSL / WAS / BSH (%)	4.45 / 5.45 / 8.97
Soaked CBR at 2.5 mm – BSL / WAS / BSH (%)	4.07 / 3.53 / 8.51

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Remediation Efficiency of Vermiremediation

The mean TPH content of the crude oil–contaminated soil prior to treatment was 4,500 mg/kg. After 30 days of vermiremediation, TPH concentration reduced to 3,300 mg/kg, corresponding to a removal efficiency of approximately 27%. This is consistent with the moderate, single-species removal rates reported for Eudrilus eugeniae over comparable exposure periods (Adhikari et al., 2022), and lower than the removal rates achieved when vermiremediation is combined with bacterial bioaugmentation, which has been reported to reach TPH reductions above 50% (Ameen & Al-Homaidan, 2024). This suggests that, while earthworm activity meaningfully reduces hydrocarbon burden through enhanced aeration and microbial stimulation, vermiremediation alone was insufficient to fully restore the soil's engineering properties, reinforcing the need for the subsequent RHA stabilization step evaluated in this study.

Chemical Composition of Soil and Rice Husk Ash

Oxide analysis (Table 2) showed the vermiremediated soil to be dominated by SiO_2 (41.05%), Al_2O_3 (24.16%), and Fe_2O_3 (10.16%), typical of kaolinitic lateritic soils. The RHA (Table 3) contained 76.61% SiO_2, 4.57% Al_2O_3, and 1.25% Fe_2O_3, giving a combined SiO_2 + Al_2O_3 + Fe_2O_3 content of 82.4%, which exceeds the 70% threshold specified for a Class N natural pozzolan, confirming the strong pozzolanic potential of the RHA used for stabilization.

Table 2. Oxide composition of vermiremediated crude oil–contaminated soil.

Oxide	Soil (%)
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
Loss on ignition (LOI)	19.35

Table 3. Oxide composition of rice husk ash (RHA).

Oxide	RHA (%)
SiO_2	76.61
Al_2O_3	4.57
Fe_2O_3	1.25
CaO	2.32
MgO	2.27
SO_3	1.01
Na_2O	2.22
K_2O	2.00
TiO_2	0.09
Loss on ignition (LOI)	5.02

Particle Size Distribution

Wet sieving indicated that 72.42% of the vermiremediated soil passed the BS No. 200 sieve, confirming a fine-grained gradation dominated by silt- and clay-sized particles. RHA addition did not materially alter the overall gradation envelope of the soil, consistent with the fine, powdery nature of RHA itself, though a modest coarsening of the fines fraction was observed with increasing admixture, likely due to flocculation of clay particles by the pozzolanic reaction (George et al., 2023).

Compaction Characteristics

Figures 1 and 2 present the variation of maximum dry density (MDD) and optimum moisture content (OMC) with RHA content for the three compactive efforts. MDD generally

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jesani@nda.edu.ng
Department of Civil Engineering, Nigerian Defence Academy, Kaduna, Nigeria.

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decreased with increasing RHA content for the BSL and, to a lesser extent, WAS efforts — falling from 1.63 to 1.51 Mg/m³ for BSL and from 1.66 to 1.56 Mg/m³ for WAS between 0% and 16% RHA — consistent with the low specific gravity and bulking effect of RHA particles, which replace denser soil solids in the compacted matrix. The BSH effort showed a slight net increase in MDD, from 1.69 to 1.74 Mg/m³, reflecting the greater compactive energy available to overcome the bulking effect at this energy level. OMC values fluctuated with RHA content but showed a general upward trend at higher admixture levels across all three compactive efforts, attributable to the high water absorption capacity and porous cellular structure of RHA particles.

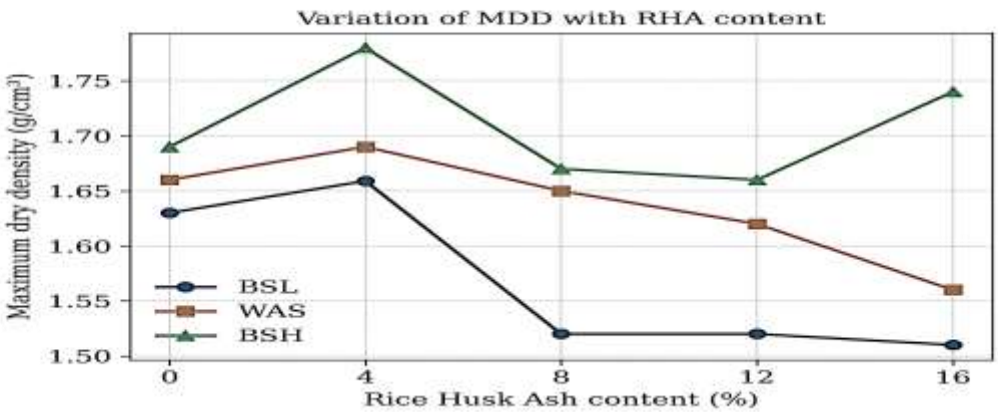

Figure 1. Variation of maximum dry density (MDD) of RHA-stabilized vermiremediated soil with RHA content.

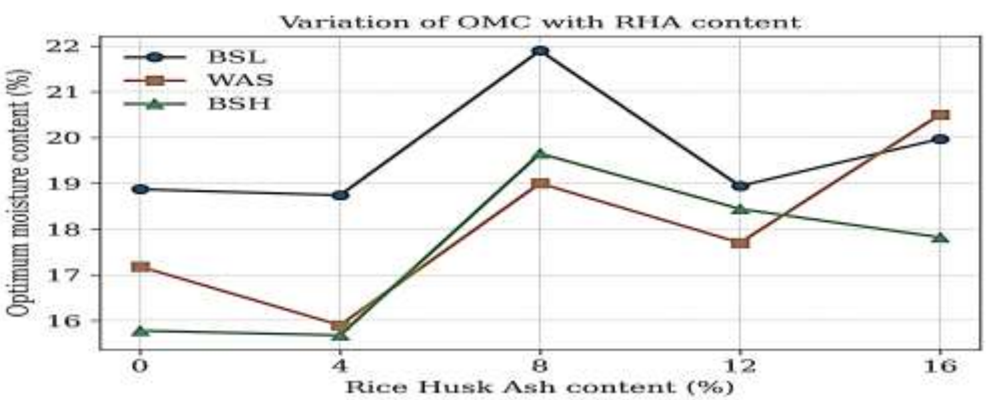

Figure 2. Variation of optimum moisture content (OMC) of RHA-stabilized vermiremediated soil with RHA content.

Strength Characteristics

Table 4 summarizes the 28-day unconfined compressive strength (UCS) and unsoaked CBR results across RHA content and compactive effort, the corresponding UCS trend is illustrated in Figure 3. Strength generally declined sharply from the unstabilized vermiremediated baseline (555.3, 567.7 and 472.6 kN/m² for BSL, WAS and BSH, respectively) upon initial RHA addition, before recovering with increasing admixture — a pattern consistent with early dilution of the more strongly bonded native clay fraction by RHA, followed by pozzolanic strength gain as curing progressed.

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jesani@nda.edu.ng
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The optimum RHA content for 28-day UCS was not uniform across compactive efforts: peak stabilized strength occurred at 8% RHA for the BSL effort (188.5 kN/m²) but continued to increase up to 16% RHA for the WAS (227.7 kN/m²) and BSH (163.5 kN/m²) efforts. This effort-dependence suggests that higher compactive energy delays the onset of the optimum pozzolanic dosage, an observation that merits confirmation with additional replicate testing.

Table 4. Summary of compaction and strength characteristics of RHA-stabilized vermiremediated crude oil–contaminated soil across British Standard Light (BSL), West African Standard (WAS), and British Standard Heavy (BSH) compactive efforts.

RHA (%)	Effort	MDD (Mg/m³)	OMC (%)	UCS 7-d (kN/m²)	UCS 14-d (kN/m²)	UCS 28-d (kN/m²)	CBR unsoaked (%)
0	BSL	1.63	18.87	182.7	323.2	555.3	4.45*
4	BSL	1.66	18.74	121.9	166.9	122.9	13.04
8	BSL	1.52	21.90	134.4	155.1	188.5	13.04
12	BSL	1.52	18.94	101.8	131.1	126.2	22.23
16	BSL	1.51	19.97	90.7	141.7	182.1	26.07– 27.21†
0	WAS	1.66	17.18	158.1	702.1	567.7	5.45*
4	WAS	1.69	15.90	119.6	195.6	107.9	—‡
8	WAS	1.65	19.00	160.2	177.9	190.6	—‡
12	WAS	1.62	17.70	106.7	131.7	213.4	29.9 (peak)
16	WAS	1.56	20.50	100.6	152.5	227.7	—‡
0	BSH	1.69	15.78	112.1*	217.3	472.6	8.97*
4	BSH	1.78	15.68	108.3	130.3	86.75	—‡
8	BSH	1.67	19.65	107.3	113.0	156.8	—‡
12	BSH	1.66	18.44	106.2	117.74	144.4	—‡
16	BSH	1.74	17.82	81.98	112.2	163.5	31.8 (peak)

* 0% RHA = vermiremediated, unstabilized baseline. † The source dataset reports two slightly different values (26.07% and 27.21%) for BSL at 16% RHA, this should be reconciled against the original laboratory sheets before submission. ‡ Intermediate CBR values for WAS and BSH at 4–12% RHA were not fully tabulated in the reviewed source material and should be supplied by the author for a complete dataset.

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jesani@nda.edu.ng
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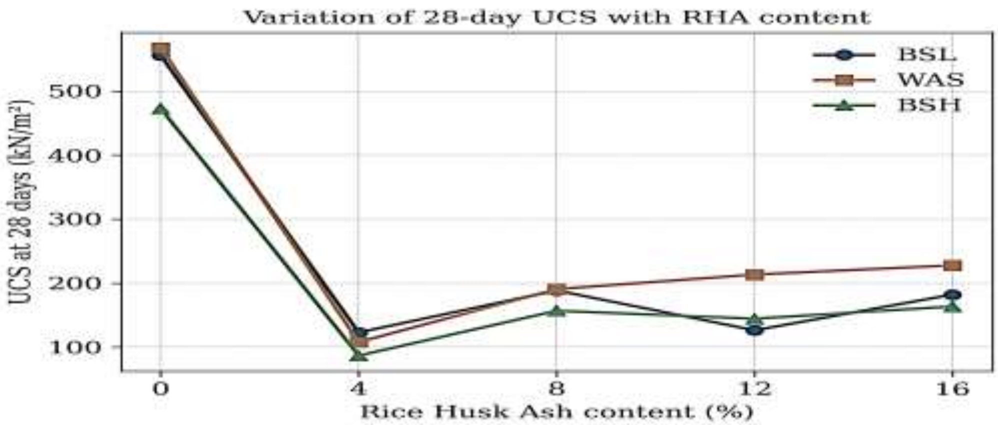

Figure 3. Variation of 28-day unconfined compressive strength (UCS) of RHA-stabilized vermiremediated soil with RHA content.

California Bearing Ratio and Durability

CBR values increased consistently with RHA content across all three compactive efforts, rising from single-digit values in the unstabilized vermiremediated soil (4.45–8.97%) to a maximum of 26–32% at higher admixture levels — an increase of roughly six-fold. The highest CBR values obtained were 26–27% (BSL, 16% RHA), 29.9% (WAS, 12% RHA), and 31.8% (BSH, 16% RHA). All values remained below the 80% minimum specified for base-course material by the Nigerian General Specifications for Roads and Bridges (Federal Ministry of Works, 2016, Clause 6201), but comfortably exceed the 10–30% range typically required for subgrade and light sub-base applications, indicating that RHA-stabilized, vermiremediated soil is best suited to these lower pavement layers rather than as a base-course material. Durability testing (resistance to strength loss after soaking) showed the highest retained-strength values of 68.4% (BSL, 16% RHA), 60.2% (WAS, 12% RHA), and 56.9% (BSH, 16% RHA), broadly following the same trend as CBR and UCS improvement with RHA content.

CONCLUSION

Crude oil contamination substantially degraded the geotechnical properties of the lateritic soil studied, producing a plastic, poorly bearing A-7-6 (CL) material unsuitable for direct use in road construction. Vermiremediation using Eudrilus eugeniae over 30 days achieved a moderate TPH reduction of approximately 27%, demonstrating the viability of earthworm-based bioremediation as a low-cost pre-treatment but confirming that biological remediation alone does not restore engineering suitability. Subsequent stabilization with rice husk ash markedly improved the strength and bearing capacity of the vermiremediated soil, increasing CBR values roughly six-fold and producing 28-day UCS gains of up to 227.7 kN/m², with the optimum RHA content ranging from 8% to 16% depending on compactive effort.

The stabilized material meets typical requirements for subgrade and light sub-base applications but falls short of the CBR threshold required for base-course use under Nigerian specifications. These findings support the combined use of vermiremediation and RHA stabilization as a sustainable, low-cost strategy for rehabilitating crude oil–impacted lateritic soils for rural and low-volume road construction in Nigeria's oil-producing regions. Further work should extend the curing regime to 21 and 90 days, complete the CBR dataset across all compactive efforts, and evaluate long-term durability under cyclic wetting–drying and field trial conditions.

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jesani@nda.edu.ng
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Corresponding author: John E. Sani
jesani@nda.edu.ng
Department of Civil Engineering, Nigerian Defence Academy, Kaduna, Nigeria.