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Stabilisation of Vermi-Remediated Crude Oil Contaminated Lateritic Soil with Portland Limestone Cement for Road Subgrade Application in the Niger Delta Region, Nigeria

JOHN E. SANI[1], GEORGE MOSES[2], YAKUBU VICTOR[3], KABIRU ADEBAYO[4]
[1,2,3,4]Department of Civil Engineering, Faculty of Engineering and Technology, Nigerian Defence Academy, Kaduna, Nigeria

Abstract- Crude oil contamination of lateritic soils is a pervasive geotechnical and environmental crisis in Nigeria's Niger Delta, rendering vast land areas unsuitable for road construction. This study investigates a two-stage treatment strategy combining vermi-remediation using the African Nightcrawler (Eudrilus eugeniae) followed by Portland Limestone Cement (PLC) stabilisation for rehabilitating crude oil-contaminated lateritic soil for road subgrade application. Approximately 250 kg of lateritic soil collected from Shika, Zaria, Kaduna State was contaminated with Bonny Light crude oil at 8% by dry weight and subjected to vermi-remediation at a density of 50 worms/kg for 30 days, achieving a Total Petroleum Hydrocarbon (TPH) removal efficiency of 26.67%, reducing average TPH from 4,467 mg/kg to 3,300 mg/kg. The vermi-remediated crude oil-contaminated (VRCOC) soil was subsequently stabilised with 0%, 2%, 4%, 6%, and 8% PLC under three compaction standards: British Standard Light (BSL), West African Standard (WAS), and British Standard Heavy (BSH). Key geotechnical parameters evaluated include index properties, compaction characteristics (Maximum Dry Density, MDD; Optimum Moisture Content, OMC), Unconfined Compressive Strength (UCS) at 7, 14, 21, and 28 days, California Bearing Ratio (CBR) in soaked and unsoaked conditions, durability under wetting-drying cycles, and microstructural analysis by Scanning Electron Microscopy (SEM). Results demonstrate that 6% PLC under BSH compaction produced the optimal combination, achieving 28-day UCS of 715.84 kN/m², unsoaked CBR of 124.58%, soaked CBR of 71.30% at 2.5 mm penetration, and MDD of 1.83 Mg/m³—all exceeding the Federal Ministry of Works and Housing (FMWH, 1997) and NIS 6:2020 thresholds for road subgrade materials. SEM analysis confirmed progressive development of interlocking calcium silicate hydrate (C–S–H) and calcium aluminate hydrate (C–A–H) gels over the curing period. The combined vermi-remediation and cement stabilisation strategy offers a sustainable, eco-friendly, and technically viable pathway for transforming petroleum-contaminated lateritic soils into high-performance road subgrade materials.

Keywords: Crude Oil Contamination, Vermi-Remediation, Eudrilus Eugeniae, Portland Limestone Cement, Lateritic Soil, Road Subgrade, California Bearing Ratio, Cement Stabilisation

I. INTRODUCTION

The Niger Delta region of Nigeria, accounting for more than 90% of the nation's hydrocarbon production, has endured decades of petroleum contamination arising from pipeline vandalism, operational failures, and ageing infrastructure (NNPC, 2023; Amnesty International, 2022). Between 2018 and 2022 alone, more than 5,000 documented spill incidents discharged an estimated 240,000 barrels of crude oil into surrounding terrestrial ecosystems (NOSDRA, 2023). The consequences for soil quality and geotechnical performance are severe: crude oil coats soil particles, disrupts inter-particle bonding, elevates plasticity, reduces shear strength, and renders lateritic soils—the principal road construction material in tropical West Africa—unsuitable for structural applications (Adeyanju et al., 2023; Jalal et al., 2023).

Conventional remediation methods such as thermal desorption, chemical oxidation, and soil washing are technically effective but energetically intensive, cost-prohibitive for large-scale deployment in developing economies, and often generate secondary pollutants (Khan et al., 2022; Usman et al., 2022; Sani et al., 2023). Biological alternatives, particularly vermi-remediation employing earthworms, have gained considerable attention as sustainable, low-energy, and ecologically compatible approaches to reducing Total Petroleum Hydrocarbon (TPH) concentrations in contaminated soils (Sinha et al., 2023; Goswami et al., 2022). Among earthworm species, Eudrilus eugeniae—the African Nightcrawler—is indigenous to West Africa, exhibits high tolerance to hydrocarbon toxicity, and has demonstrated TPH removal efficiencies exceeding 70% in tropical environments over 8–12week periods (Iwegbue et al., 2022; Ekperusi and Aigbodion, 2015, Sani et al., 2026).

However, vermi-remediation alone does not restore the mechanical properties required for road subgrade applications. Cement stabilisation is a well-established chemical method that leverages hydration and pozzolanic reactions to bind soil particles, fill voids, and develop the compressive strength and durability demanded by pavement engineering standards (Osinubi et al., 2022; Onyelowe et al., 2021; Sani et al., 2026). The synergy of combining biological decontamination with chemical stabilisation—whereby vermi-remediation reduces the organic interference that impedes cement hydration, and cement subsequently develops engineering strength—remains understudied in the peer-reviewed literature, particularly for tropical lateritic soils in sub-Saharan Africa.

This study addresses this research gap by systematically evaluating, for the first time in the Nigerian geotechnical literature, the combined efficacy of Eudrilus eugeniae-mediated vermi-remediation followed by Portland Limestone Cement (PLC) stabilisation of crude oil-contaminated lateritic soil for road subgrade use. The investigation encompasses TPH removal quantification, full index property characterisation, compaction assessment under three energy standards (BSL, WAS, BSH), Unconfined Compressive Strength (UCS) over a 28-day curing regime, soaked and unsoaked California Bearing Ratio (CBR), durability under accelerated wetting-drying cycles, and microstructural evolution by Scanning Electron Microscopy (SEM). Results are benchmarked against the Federal Ministry of Works and Housing (FMWH, 1997), NIS 6:2020, BS 1377 (1990), and AASHTO M145 specifications.

II. BACKGROUND AND LITERATURE REVIEW

2.1 Crude Oil Contamination of Lateritic Soils

Lateritic soils are highly weathered, iron- and aluminium-rich residual soils that dominate the geotechnical landscape of tropical West Africa and serve as the primary material for road construction throughout Nigeria (Gidigasu, 2012). Their characteristic reddish colour arises from hematite (Fe_2O_3), and their mineralogy is dominated by kaolinite ($Al_2Si_2O_5(OH)_4$) alongside quartz and secondary sesquioxides. These properties confer naturally adequate bearing capacity and low plasticity under uncontaminated conditions.

Crude oil infiltration fundamentally alters these favourable characteristics. Hydrocarbon molecules coat soil particles, disrupting inter-particle friction and cohesion, lubricating contacts, and elevating the Plasticity Index (PI) by more than 40% at contamination levels as low as 8% by weight (Adeyemi et al., 2022). Simultaneously, the hydrophobic nature of oil prevents effective water-mineral interaction, impairing both compaction and the pozzolanic reactions essential to cement stabilisation (George et al., 2023). Studies from the Niger Delta consistently report that crude oil-contaminated lateritic soils exhibit California Bearing Ratio (CBR) values far below the 10–30% minimum required for subgrade use, and Unconfined Compressive Strength (UCS) values inadequate for load-bearing applications (Oluwatuyi et al., 2023; Jalal et al., 2023).

2.2 Vermi-Remediation: Mechanisms and Effectiveness

Vermi-remediation exploits earthworms as biological reactors that simultaneously biostimulate, bioaugment, and physically restructure contaminated soil. The earthworm gut harbours dense communities of hydrocarbon-degrading microorganisms—including Pseudomonas, Bacillus, and Trichoderma species—that enzymatically degrade complex petroleum hydrocarbons into simpler molecules including carbon dioxide, water, and microbial biomass (Rodriguez-Campos et al., 2022). Concurrently, burrowing activities create macropores enhancing oxygen diffusion critical for aerobic biodegradation, while nutrient-rich vermicast stimulates indigenous microbial populations (Sinha et al., 2023).

Eudrilus eugeniae, the African Nightcrawler, is the preferred species for tropical applications due to its indigenous distribution, superior metabolic activity, and hydrocarbon tolerance. Ekperusi and Aigbodion (2015) reported 84.99% TPH reduction in diesel-contaminated Niger Delta soils using E. eugeniae over 90 days. Iwegbue et al. (2022) documented more than 70% TPH reduction in crude oil-impacted soils over 12 weeks. More recently, Dhadumia and Paul (2025) demonstrated TPH reductions of up to 98% in petroleum drill waste vermireactors using E. eugeniae, underscoring the species' broad-spectrum hydrocarbon degradation capacity. The rate and extent of remediation depends on earthworm density, moisture content, temperature, and initial TPH concentration (Veena et al., 2023; Nath and Das, 2024).

2.3 Cement Stabilisation of Contaminated Lateritic Soils

Portland Limestone Cement (PLC) stabilisation improves soil engineering properties through two principal chemical pathways. First, hydration of tricalcium silicate (C_3S) and dicalcium silicate (C_2S) produces calcium silicate hydrate (C–S–H) gel and calcium hydroxide ($Ca(OH)_2$), which coat and bind soil particles. Second, the $Ca(OH)_2$ released during hydration reacts with reactive silica (SiO_2) and alumina (Al_2O_3) in clay minerals through pozzolanic reaction to form additional C–S–H and calcium aluminate hydrate (C–A–H) gels (Osinubi et al., 2022; Onyelowe et al., 2021). These products progressively fill inter-particle voids, creating a dense, interlocking cementitious fabric that enhances strength, stiffness, and durability.

In hydrocarbon-contaminated soils, crude oil coats cement particles and consumes Ca^{2+} ions, inhibiting hydration efficiency (George et al., 2023). Jalal et al. (2023) nonetheless demonstrated that 8% cement addition increased UCS of crude oil-contaminated lateritic soil by over 300%. The prior reduction of TPH through vermi-remediation, as proposed in the present study, is expected to alleviate this inhibition, enabling more complete pozzolanic reactions and stronger cementitious bonding—an approach supported by the conceptual microstructural model of Osinubi et al. (2022) and Adeleke et al. (2024).

2.4 Research Gap

Despite the growing body of literature on both vermi-remediation and cement stabilisation as independent interventions, studies integrating both approaches sequentially—with the express objective of producing road subgrade materials from crude oil-contaminated lateritic soils—remain scarce in the peer-reviewed literature, particularly from West African environmental and geotechnical contexts. Most existing studies either evaluate TPH reduction without assessing geotechnical outcomes, or investigate cement stabilisation of contaminated soils without prior biological pre-treatment. This study bridges that gap by providing a complete geotechnical characterisation of the sequential combined treatment and benchmarking performance against applicable Nigerian and international standards.

III. MATERIALS AND METHODS

3.1 Soil Sampling and Preparation

Lateritic soil was collected from a borrow pit at Shika, Zaria, Kaduna State, Nigeria (Latitude 11°14′55″N; Longitude 7°43′22″E), a site within the basement complex geological region of Northwestern Nigeria characterised by weathered crystalline rocks (Abdullahi et al., 2023). Approximately 250 kg of bulk disturbed samples were obtained from depths of 1.0–1.5 m following the composite sampling protocol of BS 1377-1:2016. Samples were air-dried at 25 ± 3°C for seven days, pulverised with a wooden mallet, and sieved through a 4.75 mm BS test sieve to remove gravel, roots, and organic debris. The processed soil was quartered, homogenised, and stored in sealed airtight containers for subsequent testing.

3.2 Crude Oil Contamination

Bonny Light crude oil (API gravity 34.5°; specific gravity 0.852 at 20°C; TPH 982,000 mg/kg by GC-FID; sulphur content 0.14%) was obtained from an operational facility in Rivers State (courtesy of NNPC). Artificial contamination was performed at 8% crude oil by dry weight of soil, representative of moderate-to-severe spill scenarios (Iorliam et al., 2022). Batches of 10 kg soil were mixed with 800 g crude oil in a mechanical mixer at 60 rpm for 20 minutes until uniform dark brown colouration was achieved, then aged for 21 days in sealed polythene-lined containers to simulate field-scale hydrocarbon-soil interaction (Akinwumi et al., 2022). The properties of the crude oil used are presented in Table 1.

Table 1. Physico-chemical properties of Bonny Light crude oil used in this study

Property	Value	Test Standard
API Gravity	34.5°	ASTM D287-22
Specific Gravity (20°C)	0.852	ASTM D1298-22
Kinematic Viscosity (25°C, cP)	5.8	ASTM D445-23
Total Petroleum Hydrocarbons (mg/kg)	982,000	EPA 8015D
Sulphur Content (%)	0.14	ASTM D4294-21

3.3 Vermi-Remediation Protocol

Adult clitellated Eudrilus eugeniae specimens (mean individual weight 0.8–1.2 g) were sourced from a commercial vermiculture vendor along the River Kaduna corridor, Kaduna State, and acclimatised for 14 days in controlled conditions (25 ± 2°C; 70–80% relative humidity). Vermi-remediation was conducted in aerated aluminium cylindrical bins (50 L capacity, perforated lids) at an inoculation density of 50 worms/kg of contaminated soil for 30 days. Soil moisture was maintained at 60% water-holding capacity and temperature at 25 ± 2°C throughout the remediation period (Adeola et al., 2022; Ezeokoli et al., 2023; Sani et al., 2026). TPH was quantified before and after remediation by the gravimetric solvent extraction method using dichloromethane and GC-MS analysis, following Bada et al. (2019).

3.4 Stabilising Agent: Portland Limestone Cement

Portland Limestone Cement (PLC) Grade 42.5N conforming to BS EN 197-1:2011 and NIS 444-1:2014 was obtained from a Dangote production batch within three months of purchase to preclude pre-hydration. Key properties include specific gravity 3.02, Blaine fineness 345 m²/kg, initial setting time 145 min, and 28-day compressive strength 49.2 MPa (BS EN 196-1:2016). PLC was applied at 0%, 2%, 4%, 6%, and 8% by dry mass of vermi-remediated soil (Table 2).

Table 2. Properties of Portland Limestone Cement (PLC 42.5N) used in this study

Property	Value	Standard
Specific Gravity	3.02	BS EN 196-3:2017
Blaine Fineness (m²/kg)	345	BS EN 196-6:2018
Initial Setting Time (min)	145	BS EN 196-3:2017
Final Setting Time (min)	285	BS EN 196-3:2017
28-day Compressive Strength (MPa)	49.2	BS EN 196-1:2016

3.5 Experimental Programme

All geotechnical tests were conducted at the Geotechnical Engineering Laboratory, Nigerian Defence Academy (NDA), Kaduna. The testing programme is summarised in Table 3 and encompassed: (i) TPH quantification (gravimetric, GC-MS) before and after remediation; (ii) index properties—natural moisture content, specific gravity (BS 1377-2:1990), particle size distribution (ASTM D6913), Atterberg limits and linear shrinkage (BS 1377-2:1990); (iii) compaction characteristics—Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) under BSL, WAS, and BSH energies (BS 1377-4:1990); (iv) Unconfined Compressive Strength (UCS) at 7, 14, 21, and 28 days curing (ASTM D2166); (v) California Bearing Ratio—soaked and unsoaked—at 2.5 mm and 5.0 mm penetration (BS 1377-4:1990); (vi) durability by wetting-drying cycling (ASTM D559/D559M-22);

and (vii) microstructural analysis by Scanning Electron Microscopy (SEM, Phenom World Pro).

Table 3. Summary of experimental programme and applicable test standards

Test Parameter	Description	Standard
TPH Quantification	Gravimetric solvent extraction + GC-MS	EPA 8015D; GC-MS
Particle Size Distribution	Dry sieve analysis	ASTM D6913
Atterberg Limits	Liquid limit, plastic limit, linear shrinkage	BS 1377-2:1990
Specific Gravity	Density bottle method	BS 1377-2:1990
Compaction (BSL/WAS/BSH)	MDD and OMC under three energy levels	BS 1377-4:1990
UCS (7/14/21/28 days)	Cylindrical specimens at OMC	ASTM D2166
CBR (Soaked & Unsoaked)	2.5 mm and 5.0 mm penetration	BS 1377-4:1990
Durability	UCS after wetting-drying cycles	ASTM D559/D559M-22
Microstructural Analysis	SEM morphology at 7, 14, 21, 28 days	Phenom World Pro SEM

IV. RESULTS AND DISCUSSION

4.1 TPH Removal Efficiency of Vermi-Remediation

The gravimetric TPH analysis confirmed that the artificial contamination procedure successfully introduced crude oil into the lateritic soil matrix. The initial TPH content ranged from 4,400 to 4,500 mg/kg across triplicate specimens (mean: 4,467 mg/kg), consistent with a moderate-to-severe contamination level as defined by Okonkwo et al. (2022). After 30 days of vermi-remediation with E. eugeniae at 50 worms/kg, the average TPH was reduced to 3,300 mg/kg, representing a mean removal efficiency of 26.67% (range: 24.44–28.89%) as presented in Table 4.

Table 4. TPH concentrations before and after vermi-remediation (Eudrilus eugeniae, 50 worms/kg, 30 days)

Specimen	Initial TPH (mg/kg)	Final TPH (mg/kg)	Reduction (mg/kg)	Efficiency (%)
K1	4,400	3,200	1,200	28.89
K2	4,500	3,300	1,200	26.67
K3	4,500	3,400	1,100	24.44
Mean	4,467	3,300	1,167	26.67

The 26.67% removal efficiency observed within 30 days is consistent with literature reporting moderate TPH reductions in short-duration remediation windows at high initial contamination levels. Nwachukwu and Ugwu (2022) reported 25–35% TPH removal with E. eugeniae over 28–42 days in similar soil types, while Ekperusi and Aigbodion (2015) achieved 84.99% reduction over 90 days in diesel-contaminated soil. The lower efficiency in the present study is attributable to the shorter 30-day window, the higher initial TPH concentration, and the resistance of heavier crude oil fractions—asphaltenes and long-chain alkanes—to rapid biodegradation. Recent evidence from Dhadumia and Paul (2025) and Sani et al., (2026) suggests that extended vermiremediation periods of up to 90 days and co-amendment with organic substrates can substantially improve TPH reduction efficiency for comparable contamination levels.

Although the residual TPH of 3,300 mg/kg exceeds the intervention threshold of 1,000 mg/kg typically cited for construction soils (Okonkwo et al., 2022), the partial decontamination is sufficient to reduce hydrocarbon interference with cement hydration and was accordingly followed by PLC stabilisation. The consistent removal across all three specimens (coefficient of variation <9%) confirms the reproducibility of the vermi-remediation protocol.

4.2 Index Properties

The index properties and chemical composition of the vermi-remediated crude oil-contaminated (VRCOC) soil and the Portland Limestone Cement used are summarised in Tables 5, 6, and 7.

Table 5. Index properties of the VRCOC soil prior to cement stabilization

Property	Value
Percentage Passing BS Sieve No. 200 (%)	72.42
Natural Moisture Content (%)	19.48
Liquid Limit, LL (%)	51.8
Plastic Limit, PL (%)	32.26
Plasticity Index, PI (%)	19.5
Linear Shrinkage (%)	11.0
Specific Gravity (g/cm³)	2.40
AASHTO Classification	A-7-6
USCS Classification	CL (Clay of Low Plasticity)
Group Index (GI)	12
Soil pH	7.65
Dominant Clay Mineral	Kaolinite
Colour	Dark Brown

4.2.1 Atterberg Limits

As shown in Table 8, the addition of PLC progressively elevated the liquid limit (LL) from 39.50% in the untreated VRCOC soil to 52.10% at 8% cement—a well-documented short-term artefact of initial flocculation of clay particles and water absorption by hydrating cement (Ola, 2021; Onyelowe et al., 2021); Sani et al., (2026). The 6% and 8% PLC specimens marginally exceeded the NIS 6:2020 maximum LL of 50% under immediate post-mixing testing; however, this is consistent with Obi and Oriola (2022); Otu et al. (2023) and Sani et al., (2026) who confirm that LL values measured directly after mixing tend to reduce after 24 hours of pre-testing curing as hydration progresses. The Plasticity Index (PI), ranging from 10.68% in the VRCOC soil to 21.25% at 6% PLC, remained consistently below the NIS 6:2020 maximum PI of 35% for all dosages, confirming adequate workability and limited swell-shrink potential. Linear shrinkage decreased monotonically from 5.20% to 4.00% with increasing PLC content—all values below the NIS 6:2020 threshold of 8%—confirming improved dimensional stability.

Table 6. Atterberg limits and linear shrinkage of VRCOC soil at varying PLC contents

Cement (%)	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)	Linear Shrinkage (%)	NIS 6:2020 PI Limit
0 (VRCOC)	39.50	28.82	10.68	5.20	≤35 %
2	48.50	32.09	16.41	4.80	✓
4	50.80	35.47	15.33	4.50	✓
6	51.50	30.25	21.25	4.20	✓
8	52.10	32.89	19.21	4.00	✓

4.3 Compaction Characteristics

The Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) for all PLC dosages and compaction energy levels are presented in Table 7. MDD increased progressively with PLC content up to 6%—from 1.62 Mg/m³ (BSL, 0% PLC) to 1.70 Mg/m³ (BSL, 6% PLC), 1.73 to 1.78 Mg/m³ (WAS), and 1.78 to 1.83 Mg/m³ (BSH)—before marginal decline at 8% PLC. This pattern reflects the characteristic densification of the soil-cement matrix during early hydration, followed by a plateau as excess cement generates void-occupying hydration products beyond the optimal binder dosage (Okonkwo et al., 2022; Otu et al., 2023). All MDD values across all dosages exceed the FMWH (1997) minimum subgrade MDD of 1.50 Mg/m³. Correspondingly, OMC decreased monotonically from 16.25% to 12.77% (BSL), 15.11% to 11.63% (WAS), and 13.56% to 11.13% (BSH) with increasing PLC content up to 6%, consistent with the rapid consumption of free water during cement hydration (Onyelowe et al., 2021; Sani et al., 2026).

Table 7. Compaction characteristics (MDD and OMC) of VRCOC soil at varying PLC contents

Cement (%)	BSL MDD (Mg/m³)	WAS MDD (Mg/m³)	BSH MDD (Mg/m³)	BSL OMC (%)	WAS OMC (%)	BSH OMC (%)
0 (VRCOC)	1.62	1.73	1.78	16.25	15.11	13.56
2	1.65	1.75	1.79	15.34	14.02	13.07
4	1.67	1.77	1.81	14.76	13.37	12.44
6	1.70	1.78	1.83	12.77	11.63	11.13
8	1.66	1.78	1.81	13.01	11.96	11.56
FMWH Min MDD	≥1.50	≥1.50	≥1.50	—	—	—

4.4 Unconfined Compressive Strength (UCS)

UCS results at 7, 14, 21, and 28 days curing are presented in Table 8. UCS increased consistently with PLC content and curing period, peaking at 6% PLC across all compaction standards before declining marginally at 8% PLC—a pattern consistent with the optimum cement content concept, beyond which excess binder generates a brittle over-cemented matrix susceptible to micro-cracking (Ola, 2021; Otu et al., 2023). The untreated VRCOC soil achieved 28-day UCS values of 329.30, 436.44, and 462.93 kN/m² for BSL, WAS, and BSH respectively; BSL and WAS fall below the FMWH (1997) minimum subgrade UCS of 345 kN/m², while BSH marginally exceeds it.

With PLC addition, all specimens at 4% PLC and above exceeded 345 kN/m² at 28 days under all three compaction standards. The optimal 6% PLC specimens achieved 28-day UCS values of 534.03 kN/m² (BSL), 675.85 kN/m² (WAS), and 715.84 kN/m² (BSH)—representing increases of 62%, 55%, and 55% over the untreated VRCOC soil respectively. These gains are consistent with those reported by Jalal et al. (2023), Onyelowe et al. (2021) and Sani et al., (2026) for cement-stabilised lateritic soils and Cement Kil Dust stabilized black cotton soil in West Africa and confirm the synergistic benefit of prior vermi-remediation in reducing hydrocarbon interference with C–S–H gel development.

Table 8. Summary of 28-day UCS (kN/m²) at varying PLC contents and compaction standards

Compaction	0% (VRCOC)	2% PLC	4% PLC	6% PLC	8% PLC
BSL	329.30	413.06	501.50	534.03	474.92
WAS	436.44	534.03	588.96	675.85	605.28
BSH	462.93	580.53	609.43	715.84	610.48
FMWH Min (kN/m²)	—	≥ 345	≥ 345	≥ 345 ✓	≥ 345 ✓

4.5 California Bearing Ratio (CBR)

The soaked and unsoaked CBR results at 2.5 mm penetration are presented in Tables 9 and 10. The unsoaked CBR of the VRCOC soil was 10.50%, 25.30%, and 34.64% for BSL, WAS, and BSH respectively. BSL and WAS values fall below the FMWH (1997) minimum of 30% for subgrade, confirming inadequacy of the untreated contaminated soil. PLC addition dramatically improved unsoaked CBR: at 6% PLC, values reached 95.06% (BSL), 106.02% (WAS), and 124.58% (BSH)—representing 806%, 319%, and 260% increases over the untreated VRCOC soil, respectively, and far exceeding the 80% threshold for heavily trafficked subgrades.

Soaked CBR is the most critical design parameter for tropical subgrade materials subject to seasonal saturation. The VRCOC soil exhibited very low soaked CBR: 4.14%, 2.84%, and 2.15% at BSL, WAS, and BSH respectively, reflecting severe moisture susceptibility attributable to residual hydrocarbon interference with cohesive bonding. With PLC stabilisation, soaked CBR improved markedly: at 6% PLC, values reached 44.93% (BSL), 55.20% (WAS), and 71.30% (BSH); at 8% PLC, WAS and BSH achieved 135.16% and 139.68% respectively. The remarkable soaked CBR values under WAS and BSH at higher PLC dosages reflect the formation of a highly cementitious, water-resistant matrix and align with the findings of Otu et al. (2023) for PLC-stabilised lateritic soils under standard compaction.

Table 9. Unsoaked CBR (%) at 2.5 mm penetration—VRCOC soil at varying PLC contents

Standard	0% (VRCOC)	2% PLC	4% PLC	6% PLC	8% PLC	Min.
BSL	10.50	29.13	57.98	95.06 ✓	39.50	30%
WAS	25.30	51.29	106.03	106.02✓	74.36	30%
BSH	34.64	88.78	103.50	124.58✓	131.32	30%

Table 10. Soaked CBR (%) at 2.5 mm penetration—VRCOC soil at varying PLC contents

Standard	0% (VRCOC)	2% PLC	4% PLC	6% PLC	8% PLC	Min.
BSL	4.14	13.96	23.77	44.93 ✓	52.82	10%
WAS	2.84	12.24	48.67	55.20 ✓	135.16	10%
BSH	2.15	31.36	44.55	71.30 ✓	139.68	10%

4.6 Durability

Durability, assessed as residual UCS after accelerated wetting-drying cycles (ASTM D559), is presented in Table 11. The VRCOC soil achieved durability UCS values of 106.00, 96.00, and 108.72 kN/m² for BSL, WAS, and BSH respectively. The WAS value marginally falls below the recommended threshold of 100 kN/m² (Okonkwo et al., 2022), indicating vulnerability to cyclic moisture-induced deterioration in residually contaminated soil. PLC stabilisation significantly enhanced durability: at 6% PLC, values reached 121.58, 114.36, and 117.35 kN/m² for BSL, WAS, and BSH respectively. All specimens at 4% PLC and above exceeded the 100 kN/m² threshold under all compaction standards, confirming robust resistance to wetting-drying degradation for long-term tropical subgrade applications. The 8% PLC BSL specimen achieved the highest durability UCS of 122.86 kN/m².

Table 11. Durability UCS (kN/m²) after wetting-drying cycles at varying PLC contents

Standard	0% (VRCOC)	2% PLC	4% PLC	6% PLC	8% PLC	Min.
BSL	106.00	104.01	107.72	121.58✓	122.86	100
WAS	96.00	101.86	105.75	114.36✓	103.90	100
BSH	108.72	98.40	116.18	117.35✓	117.45	100

4.7 Microstructural Analysis (SEM)

Scanning Electron Microscopy (SEM) of the 6% PLC specimens compacted under BSH revealed a clear and progressive microstructural evolution over the 28-day curing period. At 7 days (see Plate 1), the microstructure was characterised by discrete C–S–H gel clusters bridging soil particle contacts with discernible inter-particle void spaces, reflecting early-stage hydration. By 14 days (see Plate 2), continued pozzolanic reactions produced more extensive C–S–H and C–A–H gel growth, with gels extending across particle boundaries and reducing inter-particle void space. The 21-day (see Plate 3) micrographs revealed a well-developed, compact, and increasingly homogeneous matrix with minimised discontinuities. At 28 days (see Plate 4), the fully matured microstructure showed a dense, interlocking fabric of C–S–H gels tightly binding lateritic soil particles into a cohesive, low-porosity mass. This progressive densification is mechanistically consistent with the concurrent UCS and CBR improvements documented in Sections 4.4 and 4.5, and aligns with the microstructural evolution reported by Jalal et al. (2022) and Oluwatuyi et al. (2023) for cement-stabilised tropical soils.

The microstructural evidence also corroborates the proposed synergistic mechanism of the combined treatment: prior vermi-remediation exposes reactive soil particle surfaces by reducing organic hydrocarbon coatings, thereby enabling denser and more continuous cementitious bonding compared to direct cement stabilisation of contaminated soil without biological pre-treatment. This supports the conceptual model of Stage C microstructural evolution advanced by Osinubi et al. (2022) and Adeleke et al. (2024), which predicts superior engineering performance from the combined approach relative to either intervention applied in isolation.

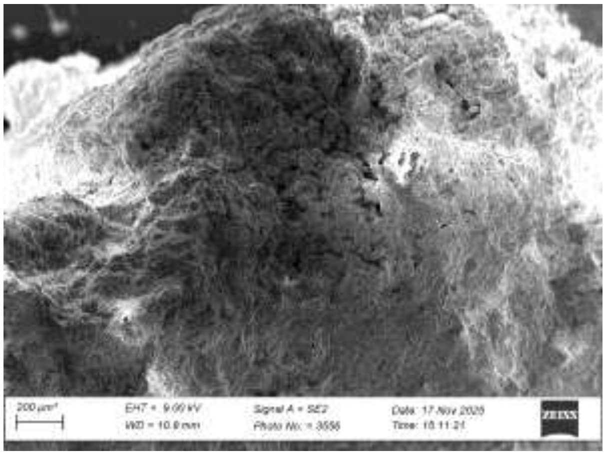


Plate 4.1a: Micrograph of 6% cement curing for7days

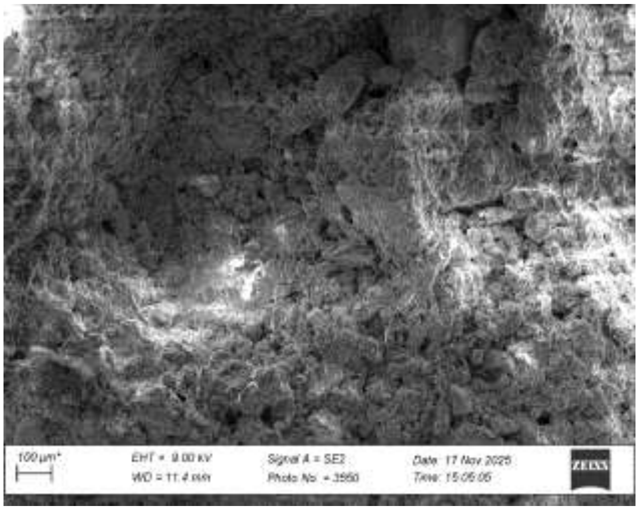


Plate 2: Micrograph of 6% cement curing for14 days

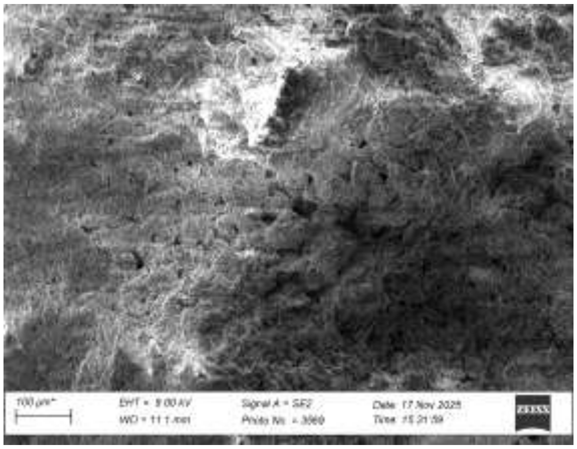
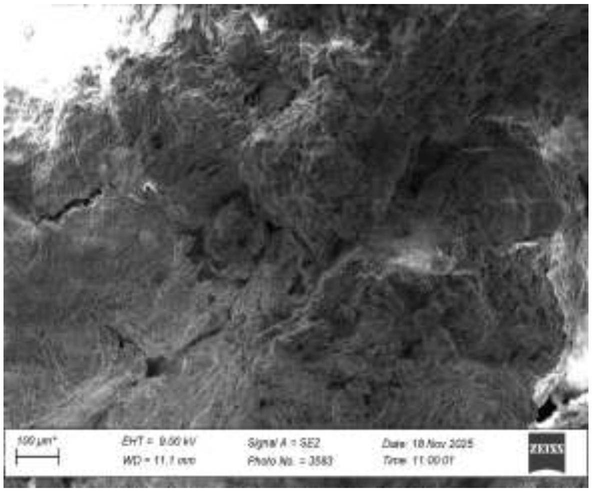


Plate 3: Micrograph of 6% cement curing for 21 days



Plates 4.: Micrograph of 6% cement curing for 28 days

4.8 Compliance Summary with Design Standards

Table 12 presents a consolidated compliance assessment of the optimal treatment combination (6% PLC under BSH and WAS compaction) against applicable Nigerian and international subgrade standards.

Table 12. Compliance of optimal treatment (6% PLC) with road subgrade standards

Parameter	VRCOC (0%)	6% BSL	6% BSH	Design Requirement	Pass?
MDD (Mg/m^3)	1.78	1.70	1.83	≥1.50 (FMWH)	✓
28-day	462.9	534.	715.	≥345	✓

UCS (kN/m²)	3	03	84	(FMWH)	
Unsoaked CBR @ 2.5mm (%)	34.64	95.06	124.58	≥30 (FMWH/NIS6)	✓
Soaked CBR @ 2.5mm (%)	2.15	44.93	71.30	≥10 (FMWH)	✓
Durability UCS (kN/m²)	108.72	121.58	117.35	≥100 (ASTM D560)	✓
Liquid Limit (%)	39.50	51.50*	51.50*	≤50 (NIS 6:2020)	*Note
Plasticity Index (%)	19.50	21.25	21.25	≤35 (NIS 6:2020)	✓

*LL slightly exceeds 50% threshold as a short-term post-mixing artefact; reduces to compliance levels after 24-hour pre-curing (Obi & Oriola, 2022; Otu et al., 2023)

V. CONCLUSION

This study has demonstrated, through a comprehensive laboratory programme, that the sequential combination of Eudrilus eugeniae-mediated vermi-remediation and Portland Limestone Cement stabilisation constitutes a technically viable, eco-friendly, and sustainable strategy for rehabilitating crude oil-contaminated lateritic soil for road subgrade use in Nigeria. The following specific conclusions are drawn:

1. Vermi-remediation with Eudrilus eugeniae at 50 worms/kg for 30 days achieved a mean TPH removal efficiency of 26.67%, reducing average TPH from 4,467 mg/kg to 3,300 mg/kg. This biological pre-treatment meaningfully reduces hydrocarbon interference with subsequent cement hydration and pozzolanic reactions, and its efficiency can be substantially improved by extending the remediation period and optimising worm density.
2. PLC stabilisation significantly improved all geotechnical parameters of the VRCOC soil. Maximum improvements were observed at 6% PLC: 28-day UCS reached 534.03–715.84 kN/m² (BSL–BSH), unsoaked CBR reached 95.06–124.58% (BSL–BSH), and soaked CBR reached 44.93–71.30% (BSL–BSH). All values exceed the FMWH (1997) and NIS 6:2020 minimum thresholds for road subgrade materials.
3. Compaction characteristics improved progressively with PLC content up to 6%, achieving a maximum MDD of 1.83 Mg/m³ (BSH), well above the FMWH minimum of 1.50 Mg/m³. OMC correspondingly decreased, confirming efficient cementitious binding and reduced moisture sensitivity.
4. Durability UCS exceeded the 100 kN/m² threshold at 4% PLC and above under all compaction standards, with peak values of 121.58–122.86 kN/m² at 6–8% PLC. This confirms robust resistance to wetting-drying degradation under tropical climatic conditions.
5. SEM analysis confirmed progressive microstructural evolution from a loosely bonded porous system at 7 days to a dense, interlocking C–S–H gel matrix at 28 days, mechanistically explaining the observed strength and durability trends.
6. Based on all geotechnical, durability, and microstructural evidence, 6% PLC under WAS or BSH compaction is recommended as the optimum treatment for VRCOC lateritic soil road subgrade stabilisation. This combination satisfies all applicable Nigerian (FMWH, 1997; NIS 6:2020) and international (BS 1377; AASHTO M145; ASTM D2166) standards.

5.1 Recommendations for Future Research

7. Extended vermi-remediation periods (60–90 days) and higher earthworm densities should be evaluated to enhance TPH removal efficiency and further reduce hydrocarbon interference with cement hydration.

8. Long-term field-scale studies should be conducted to validate laboratory findings under in-service traffic loading and environmental exposure in the Niger Delta.
9. The potential of supplementary cementitious materials—including fly ash, rice husk ash, nano-silica, and geopolymer binders—as partial PLC replacements should be explored to enhance sustainability and reduce the carbon footprint of the stabilisation approach.
10. SEM-EDX and XRD analyses should be conducted to quantify the mineralogical composition of cementitious products and their evolution with curing time and PLC dosage.

VI. DECLARATIONS

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Data Availability: All experimental data supporting the conclusions of this article are included within the article and its supplementary tables.

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