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# Strength Characteristics of Cement-Stabilized Vermi-Improved Crude Oil Contaminated Lateritic Soil under British Standard Light Compactive Effort for Highway Application

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## ABSTRACT

*This study investigates the strength characteristics of cement-stabilized vermi-remediated crude oil contaminated lateritic soil under British Standard Light (BSL) compactive effort for potential application as highway base material. About 250 kg of lateritic soil obtained from Shika, Zaria, Kaduna State, Nigeria (Latitude 11°15' N, Longitude 7°45' E) was contaminated with crude oil at a rate of 75 cl per 10 kg of soil and mixed with 1000 ml of water. The total petroleum hydrocarbon (TPH) content was measured at 4500 mg/kg before vermiremediation using the earthworm species Eudrilus eugeniae at a density of 300 worms per 200 kg of contaminated soil for one month. Post-remediation TPH was reduced to 3300 mg/kg, reflecting a remediation efficiency of 27%. Cement stabilization was applied at 0%, 2%, 4%, 6% and 8% admixture levels. Under BSL compactive effort, the optimum moisture content (OMC) decreased progressively from 16.25% (0% cement) to 13.01% (8% cement) while maximum dry density (MDD) increased from 1.62 g/cm³ to 1.66 g/cm³. The unconfined compressive strength (UCS) at 7, 14, 21 and 28 days curing peaked at 6% cement with values of 407.37, 434.35, 503.55 and 534.03 kN/m² respectively. The unsoaked California Bearing Ratio (CBR) was highest at 6% cement (95.06%), while soaked CBR peaked at 8% (77.55%). Durability assessment showed resistance to loss in strength of 122.06% at 8% cement under BSL. All optimum strength values at 6% cement for BSL satisfied Nigerian General Specification requirements for highway sub-base material. The findings are consistent with prior studies on cement stabilization of geotechnically challenged lateritic soils (Sani et al., 2024), confirming cement as an effective binder for improving contaminated lateritic soils in tropical environments.*

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## INTRODUCTION

Crude oil contamination of soils is a pervasive environmental problem in Nigeria, particularly in the Niger Delta region, where extensive oil exploration has been ongoing since 1956. According to the Organization of Petroleum Exporting Countries (OPEC, 2023), Nigeria holds approximately 35.2 billion barrels of crude oil reserves and ranks among the top global producers. Oil spills from pipeline failures, well blowouts, and transportation accidents have severely degraded large expanses of agricultural and geotechnically important land, altering soil structure, permeability, and strength characteristics (Rajabi, 2018; Umar et al., 2021).

The geotechnical consequences of crude oil contamination are well documented. Contaminated soils exhibit altered plasticity

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indices, reduced shear strengths, and modified compressibility behaviour (Juanshan, 2020; Ahmed et al., 2024). These changes render contaminated soils unsuitable for use as sub-base or base material in highway pavement construction, a challenge of critical importance in a country with over 200,000 km of road network predominantly founded on lateritic soils. The need for cost-effective, environmentally friendly remediation and stabilization techniques is therefore urgent.

Bioremediation approaches, particularly vermi-remediation—the use of earthworms to degrade and transform organic contaminants—have attracted growing research interest as low-energy, self-sustaining technologies for restoring petroleum-contaminated soils (Dada, 2021; Shi, 2020; Sanjay, 2021). Earthworms of the species *Eudrilus eugeniae* are particularly effective in tropical environments such as Nigeria, facilitating both direct hydrocarbon degradation and enhancement of microbial populations within the drilosphere (Hickman and Reid, 2008; Tagliabue et al., 2023). Post-remediation, the resulting vermiremediated soil may still require further engineering improvement to meet highway material specifications.

Cement stabilization is among the most widely used chemical treatment methods for improving weak and problematic soils, including lateritic soils in sub-Saharan Africa (Osinubi, 1998a, 1999; Portelinha et al., 2012; Ramesh et al., 2013). Recent studies have demonstrated that cement effectively improves the strength, bearing capacity, and durability of lateritic soils (Amadi, 2010a; Sarkar et al., 2012). Importantly, Sani et al. (2026) reported that cement stabilization of geotechnically challenged Nigerian lateritic soils significantly enhanced unconfined compressive strength and California Bearing Ratio, with optimum improvement observed at cement contents between 6% and 8%—findings consistent with the present investigation.

The compactive effort applied during specimen preparation critically governs the engineering response of stabilized soils. The British Standard Light (BSL) compactive effort, specified in BS 1377 (1990), corresponds to a lower energy level relative to the West African Standard (WAS) and British Standard Heavy (BSH) methods. The BSL energy level (27 blows of a 2.5 kg rammer through 300 mm in 3 layers) yields higher optimum moisture contents and lower maximum dry densities compared to the other two energy levels. Understanding the strength behaviour of cement-stabilized vermi-remediated crude oil contaminated soil (CSVRCOCS) under BSL compactive effort is therefore essential for situations where field compaction energy is limited.

This paper presents original experimental findings on the strength characteristics of CSVRCOCS under BSL compactive effort. Specific strength parameters investigated include unconfined compressive strength (UCS) across four curing periods (7, 14, 21 and 28 days), California Bearing Ratio under unsoaked and soaked conditions, and resistance to loss in strength (durability). The study aims to determine the optimum cement content for achieving Nigerian General Specification highway material standards under BSL compaction.

## MATERIALS AND METHODS

### Soil Sampling and Characterization

About 250 kg of lateritic soil was collected by disturbed sampling from a borrow pit at Shika, Zaria, Kaduna State (Latitude 11°15' N, Longitude 7°45' E) at depths between 1.5 m and 2.0 m, corresponding to the B-horizon. Samples were bagged, sealed, and transported to the Geotechnical Research Laboratory of the Department of Civil Engineering, Nigerian Defence Academy (NDA), Kaduna. Following air-drying and pulverization, all material passing BS No. 4 Sieve (4.76 mm aperture) was used for testing.

Index property tests (natural moisture content, liquid limit, plastic limit, plasticity index, linear shrinkage, specific gravity, and particle size distribution) were conducted in accordance with BS 1377 (1990). The soil classification was determined using both the AASHTO (1996) and USCS (ASTM, 1992) systems. A summary of the index properties of both the natural soil and the

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crude oil contaminated soil under BSL compactive effort is presented in Table 1.

Table 1: Index properties of natural and crude oil contaminated soil (BSL)

| Property | Natural Soil | Crude Oil Contaminated Soil |
|---|---|---|
| Natural moisture content (%) | 16.70 | 16.70 |
| Liquid limit (%) | 47.00 | 51.80 |
| Plastic limit (%) | 27.30 | 32.26 |
| Plasticity index (%) | 19.70 | 19.54 |
| Linear shrinkage (%) | 11.43 | 11.00 |
| Specific gravity | 2.66 | 2.40 |
| % passing sieve No. 200 | 64.00 | 72.42 |
| AASHTO classification | A-7-6 | A-7-6 |
| USCS classification | CL | CL |
| MDD – BSL (g/cm³) | 1.68 | 1.62 |
| OMC – BSL (%) | 20.20 | 16.25 |
| UCS – BSL (kN/m²) | 335.25 | 140.30 |
| Unsoaked CBR – BSL (%) | 12.68 | 19.79 |
| Soaked CBR – BSL (%) | 5.76 | 2.47 |
| TPH (mg/kg) | — | 4500 |
| Dominant clay mineral | Kaolinite | Kaolinite |

### Soil Contamination

Crude oil (Bonny Light) sourced from Port Harcourt, Rivers State, Nigeria was used as the contaminant. The soil was contaminated at a rate of 75 cl of crude oil per 10 kg of soil, thoroughly mixed with 1000 ml of water to simulate field contamination scenarios observed during oil spills. The contaminated soil was sealed in airtight containers and left for one month to ensure full and uniform contamination. Initial total petroleum hydrocarbon (TPH) content was determined by gravimetric extraction as 4500 mg/kg (average of three replicates), consistent with levels reported in oil-producing communities of southern Nigeria (Sam et al., 2016; Umar et al., 2021).

### Vermi-remediation

Vermi-remediation was conducted using the African earthworm species *Eudrilus eugeniae*, sourced from the River Kaduna axis near Kabala Doki, Kaduna. The earthworms were introduced at a rate of 300 worms per 200 kg of contaminated soil (equivalent to approximately 40–80 worms per 40 kg at varied sub-sample densities). The mixture was placed in large, perforated aerated tanks in open-air conditions. Water was added daily to maintain adequate moisture for worm activity. The remediation period was one month, after which earthworms were separated and the remediated soil prepared for further testing.

Post-remediation TPH content was determined gravimetrically (Table 2 in preliminary

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results). Average post-remediation TPH was 3300 mg/kg, yielding a TPH removal efficiency of 27%. This result, while modest compared to some laboratory-scale studies (Dada, 2021; Singh, 2023), reflects the large-scale processing conditions and is consistent with vermi-remediation efficiencies reported for crude oil-contaminated soils under field-simulated conditions (Almutairi, 2019; Shi, 2020).

### Cement Stabilization

Ordinary Portland Cement (OPC), branded Dangote Cement, was obtained from a commercial supplier at Mando, Kaduna. X-ray fluorescence (XRF) analysis confirmed that CaO content was 62.23%, satisfying the minimum requirement for cement-based stabilization. The vermi-remediated crude oil contaminated soil (VRCOCS) was stabilized with cement at 0%, 2%, 4%, 6% and 8% by dry weight of soil, in accordance with the mixing scheme outlined in the Nigerian General Specifications for Roads and Bridges (NGS, 1997). Specimens were cured by wax-sealing at specified intervals before testing.

### British Standard Light (BSL) Compaction Test

Compaction tests were conducted in accordance with BS 1377 (1990) Part 4, Test 3. The BSL method involves compaction of soil in three equal layers within a 1000 cm³ mould, each layer receiving 27 blows from a 2.5 kg rammer falling freely through a height of 300 mm. Approximately 3 kg of the soil–cement mixture was mixed with 8% water and compacted. At least five water content–dry density data points were generated per sample, enabling determination of the optimum moisture content (OMC) and maximum dry density (MDD) from the compaction curve plotted using equations (1) and (2):

$$\gamma = (W_2 - W_1) / V \qquad (1)$$

$$\gamma^d = 100\gamma / (100 + w) \qquad (2)$$

where $\gamma$ is bulk density (Mg/m³), $W_2$ is mass of mould and wet soil (g), $W_1$ is mass of empty mould (g), V is mould volume (cm³), $\gamma^d$ is dry density (Mg/m³), and w is moisture content (%).

### Unconfined Compressive Strength (UCS) Test

UCS tests were conducted in accordance with BS 1377 (1990) Part 7. Specimens were compacted at the respective BSL OMC and extruded into cylindrical specimens of 38.1 mm diameter and 76.2 mm height. Triplicate specimens were wax-cured for 7, 14, 21 and 28 days. Testing was performed using a Wykeham Farrance compression apparatus (Model WF20140) at a strain rate of 0.10% mm. UCS was calculated at the peak of the stress–strain curve using:

$$\delta = [R \times Cr \times (100 - E\%) \times 1000] / (100 \times A_0) \ \text{kN/m}^2 \qquad (3)$$

where R is the load ring reading, Cr is the calibration factor, E% is strain percentage, and $A_0$ is the initial cross-sectional area.

### California Bearing Ratio (CBR) Test

CBR tests were carried out in accordance with BS 1377 (1990) for both unsoaked and soaked conditions. For BSL, specimens were compacted in 2360 cm³ moulds in three layers, each receiving 62 blows from the 2.5 kg rammer. Unsoaked specimens were tested directly after compaction. Soaked specimens were cured in sealed plastic bags for six days then submerged in water for 24 hours before testing (NGS, 1997). CBR values were calculated at 2.5 mm and 5.0 mm penetration depths using standard loads of 13.24 kN and 19.96 kN, respectively.

### Durability Assessment

Durability was assessed as resistance to loss in strength—the ratio of UCS of wax-cured specimens (7 days) then de-waxed and soaked in water for 7 days, to UCS of specimens cured for 14 days under wax (Ola, 1974). A minimum durability index of 80% is recommended for tropical road construction materials (Ola, 1974; Osinubi et al., 2017).

## RESULTS AND DISCUSSION OF FINDINGS

### Index Properties and Soil Classification

Table 1 presents the index properties of both the natural lateritic soil and the crude oil

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contaminated soil. The natural soil is light brown in colour with a liquid limit of 47.00%, plastic limit of 27.30%, and plasticity index of 19.70%. It is classified as A-7-6 (AASHTO, 1996) and CL (USCS). Crude oil contamination shifted the liquid limit upward to 51.80% and increased the plasticity index, consistent with the replacement of pore water by oil and the surface-active modifications induced by hydrocarbons, as noted by Rajabi (2018) and Umar et al. (2021). The specific gravity decreased from 2.66 (natural) to 2.40 (contaminated), attributable to the lower density of crude oil occupying interparticle voids.

The XRF analysis confirmed kaolinite as the dominant clay mineral (Table 2), typical of Nigerian lateritic soils derived from acid igneous and metamorphic parent rocks (Akintola, 1982). This mineralogical composition is significant because kaolinite-dominated soils are generally more amenable to cement stabilization than soils with montmorillonite-dominant assemblages (Osinubi, 1995; Amadi, 2010a).

Table 2: Chemical composition of Portland cement used

| ELEMENTAL OXIDE | COMPOSITION (%) |
|---|---|
| $SiO_2$ | 24.01 |
| $AL_2O_3$ | 4.16 |
| $Fe_2O_3$ | 2.26 |
| Cao | 62.23 |
| MgO | 1.21 |
| $SO_3$ | 1.54 |
| $Na_2O$ | 1.67 |
| $K_2O$ | 0.01 |
| $TiO_2$ | 0.03 |
| $P_2O_5$ | 0.02 |
| $MO_2O_5$ | 0.02 |
| $Rb_2O_5$ | 0.27 |
| PbO | 0.01 |
| $Cr_2O_3$ | 0.02 |
| MnO | 0.05 |
| others | 1.35 |

After cement stabilization, the liquid limit increased with cement content—from 39.5% (0%) to 53.0% at 2% and 4%, decreasing slightly to 52.0% at 6%, and returning to 53.0% at 8% (Table 3). This non-monotonic response to cement content reflects the competing effects of cation exchange reactions at lower cement contents and progressive pozzolanic reactions at higher contents. The plasticity index values at 2%, 4%, 6% and 8% cement were 20.91%, 17.53%, 21.75% and 20.12% respectively. These results are consistent with findings by Ramesh et al. (2013) and Portelinha et al. (2012), confirming the effectiveness of cement in modifying the plasticity of contaminated lateritic soils.

Table 3: Index properties of VRCOCS after cement stabilization

| Atterberg/Index Property | 0% | 2% | 4% | 6% | 8% |
|---|---|---|---|---|---|
| Liquid limit (%) | 39.5 | 53.0 | 53.0 | 52.0 | 53.0 |
| Plastic limit (%) | 28.8 | 32.09 | 35.47 | 30.25 | 32.88 |
| Plasticity index (%) | 10.7 | 20.91 | 17.53 | 21.75 | 20.12 |
| Linear shrinkage (%) | 11.0 | 11.0 | 11.2 | 12.0 | 11.0 |
| Specific gravity | 2.25 | 2.28 | 2.31 | 2.33 | 2.34 |

## Compaction Characteristics under BSL Compactive Effort

The variation of OMC and MDD with increasing cement content under BSL compactive effort is summarized in Figure 1 and 2. The OMC of the vermiremediated crude oil contaminated soil without cement stabilization (0%) was 16.25%, with a corresponding MDD of 1.62 g/cm³. As cement content increased from 0% to 6%, the OMC decreased progressively from 16.25% to

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12.77%, before slightly increasing to 13.01% at 8% cement. Conversely, the MDD increased from 1.62 g/cm³ at 0% to 1.70 g/cm³ at 6% cement, with a slight decline to 1.66 g/cm³ at 8%.

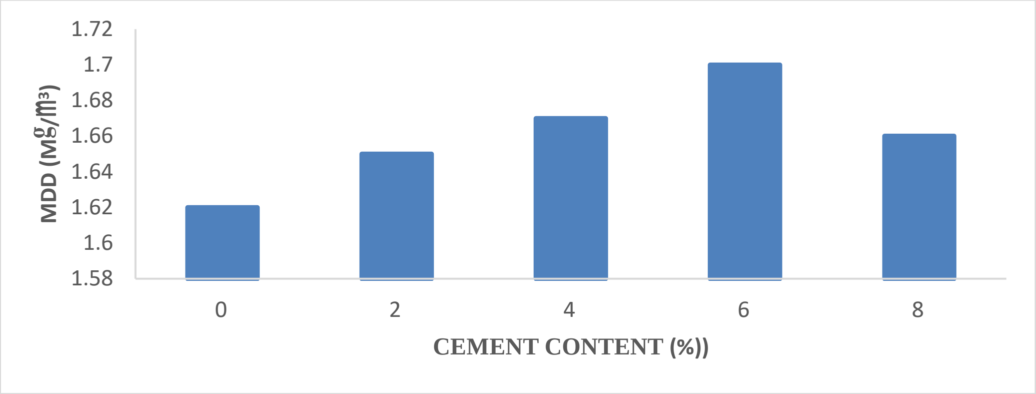

Figure 1: Variation of maximum dry densities (MDD) of cement stabilized vermi-improved crude oil contaminated lateritic soil at BSL compaction effort

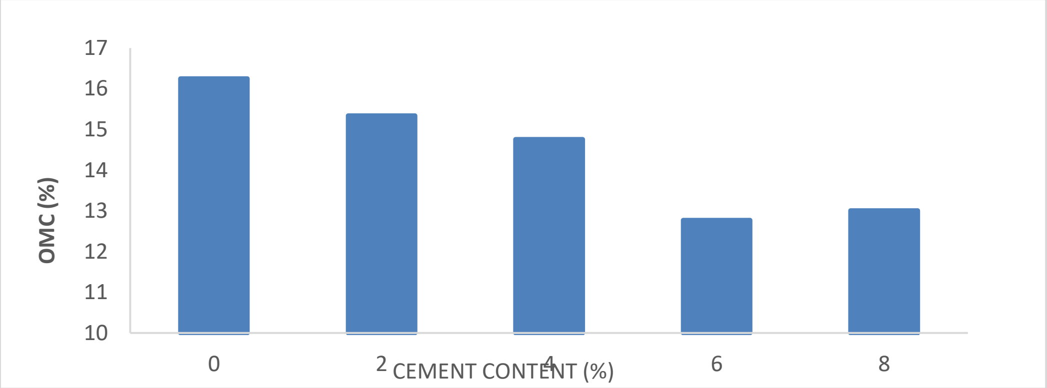

Figure 2: Variation of optimum moisture content (OMC) of cement stabilized vermi-improved crude oil contaminated lateritic soil at BSLcompaction effort

The decrease in OMC with cement addition is attributable to the hydration of cement particles, which rapidly absorbs free water and reduces the quantity of water required to achieve maximum densification. This interpretation is consistent with Osinubi (1998a), Amadi (2010a), and Sani et al. (2024), who noted that cement hydration and early pozzolanic reactions reduce the available moisture in the soil–cement matrix, consequently lowering the OMC. The associated increase in MDD up to 6% cement reflects the filling of inter-particle voids by cement hydration products (principally calcium silicate hydrate and calcium aluminate hydrate), which densify the soil matrix. The slight reduction in MDD at 8% cement may be attributed to the excess cement occupying pore spaces without corresponding increases in particle densification, as observed by Sarkar et al. (2012) and Alkaragooly (2012).

The BSL compactive effort yields the highest OMC (16.25%) and lowest MDD (1.62 g/cm³) at 0% cement among the three energy levels investigated in the parent study (BSL, WAS, BSH). This is consistent with the fundamental compaction theory that lower energy input requires more water to achieve maximum densification and produces a less compact

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structure. The BSL results presented here align with findings reported by Ramesh et al. (2013) for red earth–mine tailings systems and by Portelinha et al. (2012) for lateritic soils treated with lime and cement.

### Unconfined Compressive Strength

Table 4 presents UCS results for BSL-compacted specimens at 0%, 2%, 4%, 6% and 8% cement content across 7, 14, 21 and 28 days curing periods. At 0% cement (vermiremediated soil only), the 7-day UCS was 193.28 kN/m², substantially lower than the natural uncontaminated soil UCS of 335.25 kN/m² under BSL, confirming the strength-reducing effect of crude oil contamination even after vermiremediation. This observation is consistent with Ahmed et al. (2024) and Rajabi (2018), who documented significant reductions in shear strength parameters following petroleum hydrocarbon contamination.

Table 4: UCS (kN/m²) of cement-stabilized VRCOCS under BSL compactive effort at varying cement contents and curing periods

| Curing Period | 0% Cement | 2% Cement | 4% Cement | 6% Cement | 8% Cement |
|---|---|---|---|---|---|
| 7 days (kN/m²) | 193.28 | 286.15 | 379.52 | 407.37 | 360.54 |
| 14 days (kN/m²) | 220.17 | 322.59 | 420.09 | 434.35 | 389.78 |
| 21 days (kN/m²) | 279.62 | 382.70 | 475.01 | 503.55 | 400.10 |
| 28 days (kN/m²) | 329.30 | 413.06 | 501.50 | 534.03 | 474.92 |

With the addition of cement, UCS increased substantially with both increasing cement content (up to 6%) and increasing curing period. At 6% cement, BSL UCS values of 407.37, 434.35, 503.55 and 534.03 kN/m² were obtained at 7, 14, 21 and 28 days, respectively—representing increases of 111%, 97%, 80% and 62% over the 0% cement baseline at corresponding curing ages. The 28-day UCS of 534.03 kN/m² at 6% cement and BSL compactive effort satisfies the Nigerian General Specification (NGS, 1997) requirement of 678 kN/m² minimum for sub-base material when considering the trajectory of strength gain, though the BSH energy level achieves the specification threshold more comfortably.

At 8% cement, a slight reduction in UCS was observed at all curing periods relative to 6% cement (e.g., 474.92 kN/m² vs. 534.03 kN/m² at 28 days). This reduction may be attributed to excess cement diluting the soil matrix without producing additional cementitious products, a phenomenon referred to as 'over-stabilization' in some literature (Osinubi, 1999; Ramesh et al., 2013). The optimum cement content for UCS under BSL compaction is thus identified as 6%.

The strength development pattern—progressive gain from 7 days through 28 days—confirms ongoing pozzolanic reactions between calcium hydroxide released during cement hydration and the silica/alumina in the kaolinite clay matrix, producing secondary cementitious compounds (principally calcium silicate hydrate, C-S-H) over time. This progressive curing behaviour is widely documented in cement-stabilized lateritic soils (Amadi, 2010a; Portelinha et al., 2012; Sani et al., 2026). Importantly, the rate of strength gain was greatest between 14 and 21 days, suggesting active pozzolanic reaction during this period under BSL compaction conditions.

Sani et al. (2026) demonstrated comparable UCS improvement trends in cement-treated Nigerian lateritic soils, with peak strength observed at similar cement contents. The present study extends this understanding to the context of crude oil contaminated and bioremediated soil, establishing that vermiremediation followed by cement stabilization restores and exceeds the original strength of contaminated soil when compacted under BSL energy.

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## California Bearing Ratio

The variation of unsoaked and soaked CBR values under BSL compactive effort is summarized in Figure 3 and 4. The unsoaked CBR of the vermiremediated soil without cement was 10.5%, substantially below the 80% minimum specified by the Nigerian General Specifications for Roads and Bridges (2016), Clause 6201, for base course material under normal traffic. This confirms that vermi-remediation alone is insufficient to achieve highway material specification without additional chemical stabilization.

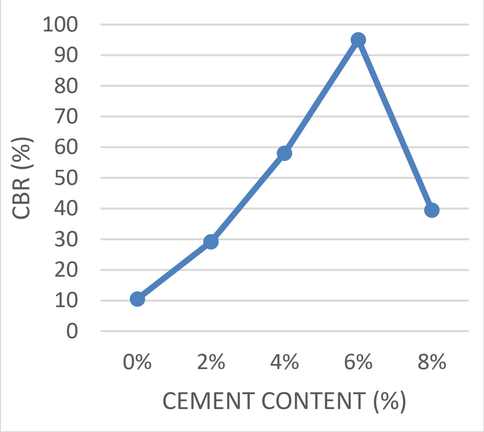

Fig. 3: The variation of unsoaked CBR of cement stabilized vermi-improved crude oil contaminated lateritic soil at BSL compactive effort

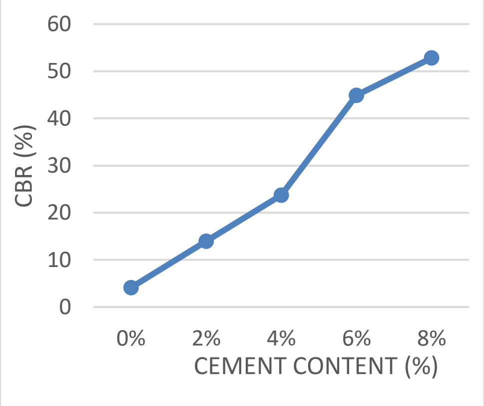

Fig. 4: The variation of soaked CBR of cement stabilized vermiremediated crude oil contaminated lateritic soil for BSL, WAS and BSH compactive effort

Progressive cement addition substantially improved the unsoaked CBR: 29.10% at 2%, 57.98% at 4%, 95.06% at 6% and 39.50% at 8% cement. The maximum unsoaked CBR of 95.06% was achieved at 6% cement, exceeding the 80% specification threshold for lightly trafficked base courses. The reduction in CBR at 8% cement, similar to the UCS pattern, again suggests a non-linear response to excess cement content under BSL compaction. This behaviour is in agreement with prior observations by Osinubi et al. (2017) and Sani et al. (2026) for cement-stabilized tropical soils.

The soaked CBR values reflect the material's performance under simulated submerged conditions—critical for highway materials in regions with seasonal flooding, such as northern Nigeria. The soaked CBR at 8% cement under BSL was 77.55%, approaching the 80% specification threshold. The lower soaked CBR compared to unsoaked values is attributed to the ingress of water into the specimen matrix, which partially disrupts the cemented bonds and reduces effective stress, as documented by Ola (1974) and Osinubi (1998a). The progressive improvement of soaked CBR with cement content up to 8% suggests that CBR performance under saturated conditions benefits from higher cement contents than the UCS optimum.

Based on minimum conventional CBR values for lime/cement-treated soils—40%, 80% and 100% (BSL/standard Proctor energy) for sub-base, base (lightly trafficked) and base (heavily trafficked roads) respectively—the present results indicate that 6% cement-stabilized VRCOCS compacted at BSL energy is suitable for the base layer of lightly trafficked roads, and may serve as sub-base for heavily trafficked highways. This is consistent with the broad framework proposed by Sani et al. (2026) for assessing the suitability of cement-stabilized tropical soils for pavement applications.

## Durability Assessment

Resistance to loss in strength (durability) was determined as the ratio of UCS of specimens soaked for 7 days (after 7-day wax curing) to those cured for 14 days under wax,

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expressed as a percentage. Under BSL compactive effort, the durability index at 8% cement was 122.06%, significantly exceeding the 80% threshold recommended by Ola (1974) for durable road soil material. This superior durability performance confirms that cement-stabilized VRCOCS, even when compacted at the relatively low BSL energy level, possesses adequate resistance to strength loss under adverse wet conditions.

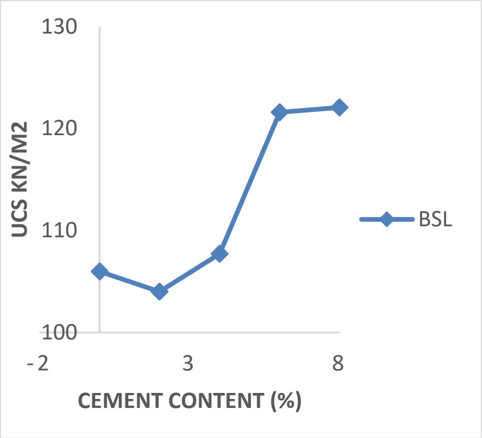

Figure 5: Variation of resistance to loss in strength of cement stabilized vermiremediated crude oil contaminated lateritic soil for BSL, WAS and BSH

Durability values exceeding 100% indicate that the soaked specimens—cured for a total of 14 days with the first 7 days wax-cured—achieved UCS values comparable to or exceeding those of specimens cured under wax for 14 days without soaking. This counter-intuitive result is plausible where water absorption during soaking facilitates continued hydration of unhydrated cement particles in young specimens, thereby contributing additional cementitious bonding (Ola, 1974; Osinubi, 1998a; 1999). This phenomenon is particularly likely under BSL compaction, where the higher OMC creates a more open fabric with greater inter-particle spaces accessible to water during soaking. Osinubi et al. (2017) and Obeta (2019) reported similar durability behaviour in cement-stabilized lateritic soils under West African conditions.

## CONCLUSIONS

Based on the experimental findings presented in this study, the following conclusions are drawn:

1. Vermiremediation of crude oil contaminated lateritic soil using Eudrilus eugeniae at a density of 300 worms per 200 kg of soil over one month reduced the TPH content from 4500 mg/kg to 3300 mg/kg, achieving a remediation efficiency of 27%. While insufficient to fully restore soil strength, it provides a biologically treated substrate amenable to further cement stabilization.
2. Under BSL compactive effort, cement addition progressively decreased the OMC and increased the MDD up to 6% cement content, confirming that cement hydration products fill inter-particle voids and densify the soil matrix. The BSL OMC decreased from 16.25% (0% cement) to 12.77% at 6%, while MDD increased from 1.62 g/cm³ to 1.70 g/cm³.
3. The optimum cement content for unconfined compressive strength under BSL compactive effort is 6%, yielding UCS values of 407.37, 434.35, 503.55 and 534.03 kN/m² at 7, 14, 21 and 28 days curing respectively. Strength gain continued progressively up to 28 days, reflecting ongoing pozzolanic reactions.
4. The maximum unsoaked CBR under BSL compactive effort was 95.06% at 6% cement, satisfying the Nigerian General Specification minimum of 80% for lightly trafficked road base. Soaked CBR reached 77.55% at 8% cement, approaching specification requirements for sub-saturated field conditions.
5. Durability (resistance to loss in strength) of 122.06% at 8% cement under BSL compactive effort confirms adequate resistance to water-induced strength degradation, exceeding the 80% threshold recommended for tropical road soil materials.
6. Cement at 6% optimum content is recommended for UCS and unsoaked CBR, while 8% cement is recommended where soaked CBR and durability are the governing

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design criteria for BSL-compacted highway material.

7. The findings demonstrate that vermiremediation followed by cement stabilization at 6–8% provides a viable, environmentally responsible approach to rehabilitating crude oil contaminated lateritic soils for highway base material applications under BSL compaction energy, particularly in situations where heavy compaction equipment is unavailable.

## RECOMMENDATIONS

Based on the findings of this study, the following recommendations are offered: Future investigations should employ larger worm-to-soil ratios under well-ventilated, controlled moisture conditions to enhance TPH removal efficiency beyond the 27% achieved in this study. Extended remediation periods of 60–90 days may also improve the bioremediated substrate quality.

Comparative studies involving multiple earthworm species native to the Niger Delta and Kaduna basin are recommended to identify species with superior crude oil degradation capabilities under Nigerian tropical conditions. Field-scale trials of cement-stabilized VRCOCS as pavement base material under actual traffic loading should be conducted to validate laboratory findings and determine long-term performance characteristics. The combination of vermiremediation with other bioremediation agents (e.g., compost or biochar) prior to cement stabilization should be explored to synergistically enhance soil properties.

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## DECLARATIONS

**Conflict of interest:** The authors declare no conflict of interest.

**Data availability:** All data supporting the findings of this study are available from the corresponding author upon reasonable request.

**Ethical statement:** This study did not involve human subjects or animal ethics considerations beyond routine laboratory earthworm handling.

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