

## Index Properties and Compaction Characteristics of Cement-Stabilized Vermi-Remediated Crude Oil–Contaminated Black Cotton Soil for Highway Subgrade Applications

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### Abstract

Black cotton soil (BCS) contaminated with crude oil presents serious engineering and environmental challenges across oil-producing regions of Nigeria, particularly Borno State. Conventional stabilization of such soils without prior remediation is unsustainable and may not address hydrocarbon persistence. This study evaluates the index properties and compaction characteristics of vermi-remediated crude oil–contaminated black cotton soil stabilized with Ordinary Portland Cement (OPC) at 2%, 4%, 6%, and 8% by dry weight. Soil samples from Gamadadi, Borno State (10.320163°N, 11.5484146°E) were artificially contaminated at 8% crude oil by dry weight, bioremediated using *Eisenia fetida* earthworms over 30 days, and subsequently stabilized with cement. Laboratory tests—including Atterberg limits, specific gravity, particle size distribution (PSD), and proctor compaction under British Standard Light (BSL), West African Standard (WAS), and British Standard Heavy (BSH) efforts—were conducted in accordance with BS 1377 (1990). The vermi-remediation process achieved a total petroleum hydrocarbon (TPH) removal efficiency of 22.43%. The natural soil was classified as A-7-6 (19) (AASHTO) and CH (USCS), with a liquid limit (LL) of 57.8%, plasticity index (PI) of 29.15%, and specific gravity of 2.32. Cement addition progressively reduced LL from 55.0% to 48.0%, decreased PI from 25.37% to 13.68%, and reduced linear shrinkage from 16.43% to 12.86%. Specific gravity increased from 2.25 to 2.34 with cement content. Maximum dry density (MDD) exhibited a general decrease from 0–6% cement, then a slight recovery at 8%, across all compactive efforts (BSL: 1.63–1.62 Mg/m<sup>3</sup>; WAS: 1.77–1.74 Mg/m<sup>3</sup>; BSH: 1.85–1.83 Mg/m<sup>3</sup>). Optimum moisture content (OMC) increased from 0–6% cement and decreased slightly at 8%, with values consistently lower under higher compactive effort. Cement stabilization of vermi-remediated black cotton soil significantly improves index properties, though values remain above AASHTO base course thresholds. The treated soil demonstrates properties appropriate for use as subgrade and sub-base material, supporting sustainable reuse of petroleum-contaminated soils in highway construction.

**Keywords:** Black cotton soil; vermi-remediation; cement stabilization; Atterberg limits; compaction; crude oil contamination; highway subgrade

## 1. INTRODUCTION

Crude oil contamination of soils represents one of the most pervasive geoenvironmental challenges in oil-producing nations, with Nigeria's Niger Delta and its environs bearing a disproportionate burden. Over 5,000 oil spill cases were recorded between 2018 and 2022, releasing approximately 240,000 barrels of crude oil into surrounding ecosystems (NOSDRA, 2023). Beyond ecological damage, hydrocarbon contamination fundamentally alters the geotechnical

behavior of soils, increasing plasticity, reducing shear strength, decreasing permeability, and ultimately rendering affected soils unsuitable for construction applications (Ahmed et al., 2024; Oluwatuyi et al., 2023, Sani et al., 2026a).

Black cotton soil (BCS), or vertisol, is ubiquitous across Borno State and the broader semi-arid belt of northeastern Nigeria. Characterized by its high montmorillonite clay content, pronounced shrink–swell behavior, high plasticity index, and low bearing capacity, BCS is inherently problematic for highway engineering in its natural state (Garba & Yunana, 2023; Almuaythir et al., 2024, Sani et al., 2026b). When crude oil contamination is superimposed on these already challenging properties, the engineering performance deteriorates further, presenting a dual remediation-and-stabilization challenge (Jalal et al., 2023).

Vermi-remediation, the use of earthworms—particularly *Eisenia fetida*—to bioremediate contaminated soils, has emerged as a cost-effective, eco-friendly, and practically scalable alternative to conventional physicochemical remediation methods (Gong et al., 2023; Huang et al., 2024 Sani et al., 2026b). Earthworms enhance soil remediation through bioturbation, improved aeration, enzymatic fragmentation of hydrocarbons, and stimulation of hydrocarbon-degrading microbial communities (Adhikari et al., 2022). While vermi-remediation can reduce total petroleum hydrocarbon (TPH) levels substantially, residual contamination typically necessitates secondary treatment before the soil can meet highway material specifications.

Cement stabilization is a well-established technique for improving the engineering properties of weak and expansive soils. The addition of Ordinary Portland Cement (OPC) to BCS initiates hydration reactions producing calcium silicate hydrate (C–S–H) and calcium aluminate hydrate (C–A–H) gels, which bind soil particles, reduce plasticity, increase density, and improve bearing capacity (Kamaruddin et al., 2020; Osinubi et al., 2022). Applied to vermi-remediated BCS, cement stabilization offers a dual benefit: further hydrocarbon encapsulation and significant geotechnical improvement.

Despite growing interest in combining bioremediation with chemical stabilization for sustainable pavement subgrade preparation, there remains limited published data on the index properties and compaction behavior of vermi-remediated, cement-stabilized crude oil–contaminated BCS under multiple compactive efforts. This study addresses that gap through systematic laboratory investigation using British Standard Light (BSL), West African Standard (WAS), and British Standard Heavy (BSH) compaction energies, providing data directly relevant to Nigerian highway construction practice under the Nigerian General Specifications for Roads and Bridges (2016).

The specific objectives of this study are to: (i) determine the index properties (Atterberg limits, specific gravity, particle size distribution) of vermi-remediated crude oil–contaminated BCS with varying cement contents; and (ii) evaluate the compaction characteristics (MDD and OMC) of the treated soil under three compactive efforts.

## 2. LITERATURE REVIEW

### 2.1 Engineering Behavior of Black Cotton Soil

Black cotton soils are vertisols formed through the weathering of mafic parent materials under alternating wet-dry climatic cycles, resulting in deep, dark-colored clay soils with plasticity indices typically between 40% and 60% and pronounced shrink–swell characteristics (Rahman et al., 2023; Garba & Yunana, 2023). From an engineering perspective, BCS exhibits very low permeability ( $10^{-6}$  to  $10^{-8}$  cm/s), high compressibility, and low shear strength, making it unsuitable for direct use as a highway subgrade or base material without treatment (Moses, 2021). AASHTO (2022) classifies such soils as A-7-6, denoting poor subgrade quality, while USCS categorizes them as CH (high plasticity clay).

### 2.2 Crude Oil Contamination Effects on Soil Properties

Crude oil contains a complex mixture of saturates, aromatics (including BTEX compounds), resins, and asphaltenes (Speight, 2014). When released into soil, hydrocarbons form coatings on soil particles, disrupt inter-particle bonds, reduce pore fluid surface tension, and impair natural soil structure (Gertsen et al., 2024). Research by Oluwatuyi et al. (2023) demonstrated that crude oil contamination significantly increases the plasticity of lateritic soils in Nigeria, while concurrently reducing CBR and UCS values. Ahmed et al. (2024) reported that even moderate contamination levels can render black cotton soil unsuitable as a subgrade material without remediation and stabilization.

### 2.3 Vermo-Remediation of Petroleum-Contaminated Soils

Vermi-remediation leverages the physical, biochemical, and microbial-stimulating activities of earthworms to degrade petroleum hydrocarbons in contaminated soils. *Eisenia fetida* is the most widely studied species, demonstrating tolerance to hydrocarbon contamination and high reproductive efficiency (Almutairi, 2019; Chachina et al., 2016). Gong et al. (2023) and Huang et al. (2024) showed that earthworm burrowing increases soil aeration, improves aggregate stability, and enriches the hydrocarbon-degrading microbial community—collectively accelerating TPH mineralization. Typical removal efficiencies of 22–99% have been reported depending on initial contamination levels, earthworm density, and remediation duration (Chachina et al., 2018; Owagboriaye et al., 2019). However, vermi-



remediation is most effective at low-to-moderate contamination levels; heavily contaminated soils (TPH > 5,000 mg/kg) often require complementary treatment (Almutairi, 2019).

## 2.4 Cement Stabilization of Expansive and Contaminated Soils

The interaction of OPC with expansive soils involves cation exchange, flocculation, pozzolanic reactions, and cementation. Calcium from cement hydration replaces exchangeable cations on clay surfaces, reducing the diffuse double layer, decreasing plasticity, and inducing flocculation (Kamaruddin et al., 2020). These processes reduce the liquid limit, increase the plastic limit, and substantially lower the plasticity index. Osinubi et al. (2022) reported significant reductions in LL and PI of black cotton soil with increasing OPC content, alongside improvements in compressive strength. Das and Sobhan (2023) confirmed that cement stabilization effectively reduces the volume change potential of montmorillonite-rich soils. In contaminated soils, cement also provides solidification/stabilization (S/S) benefits by encapsulating residual hydrocarbons within the cementitious matrix, reducing their bioavailability and environmental mobility (Alvares et al., 2021).

## 2.5 Compaction Behavior of Cement-Stabilized Soils

Compaction characteristics—specifically MDD and OMC—are fundamental to the design and quality control of stabilized highway layers. Upon cement addition to clay soils, the MDD typically decreases initially due to the formation of a flocculated, open soil structure with increased inter-particle spacing (Subair et al., 2024; Ameen et al., 2024). At higher cement contents, a partial increase in MDD may occur as cementitious products fill inter-particle voids. The OMC generally increases with cement content up to an optimal level, reflecting the additional water demand for cement hydration and the altered soil structure, before decreasing slightly at higher dosages as the mixture stiffens (Fadugba et al., 2024). Higher compactive effort consistently produces greater MDD and lower OMC across all admixture levels, reflecting improved particle rearrangement under increased compaction energy (Subair et al., 2024).

# 3. MATERIALS AND METHODS

## 3.1 Materials

### 3.1.1 Soil

Disturbed soil samples were collected from Gamadadi, Borno State, Nigeria (coordinates: 10.320163°N, 11.5484146°E) at depths of 1.5–2.0 m after stripping 1.5 m of topsoil. Samples were sealed in polythene bags and sacks to preserve field moisture conditions. In the laboratory, samples were air-dried and pulverized to pass through a 4.75 mm BS sieve (No. 4).

### 3.1.2 Crude Oil

Bonny Light crude oil (API gravity  $\approx 35.9^\circ$ ), obtained from the Nigerian National Petroleum Company Limited (NNPCL) depot in Kaduna, was used to contaminate the soil at 8% by dry weight. The contaminated soil was sealed and aged for 14 days to simulate field contamination conditions (Goswami et al., 2022).

### 3.1.3 Earthworms

Mature *Eisenia fetida* (Tiger Worm) specimens with developed clitellum were sourced from a local vermiculture supplier in Kaduna. Worms were acclimatized in partially decomposed cow dung for one week prior to introduction into the contaminated soil for the 30-day vermi-remediation period.

### 3.1.4 Cement

Ordinary Portland Cement (OPC) classified as CEM I 42.5N (BS EN 197-1:2011) was used as the stabilizing agent, incorporated at 2%, 4%, 6%, and 8% by dry weight of soil. Chemical oxide analysis of the cement confirmed high CaO content (75.03%) and a low SiO<sub>2</sub>/CaO ratio characteristic of Portland clinker (see Table 1).

## 3.2 Experimental Methods

### 3.2.1 Total Petroleum Hydrocarbon (TPH) Determination

TPH content before and after vermi-remediation was quantified by solvent extraction using dichloromethane followed by gas chromatography–mass spectrometry (GC–MS) analysis as described by Bada et al. (2019). Removal efficiency was computed as: Removal efficiency (%) = [(Initial TPH – Final TPH) / Initial TPH]  $\times$  100.

### 3.2.2 Index Property Tests

All index property tests were conducted in accordance with BS 1377:1990, Part 2. The Atterberg limits—liquid limit (LL), plastic limit (PL), plasticity index (PI), and linear shrinkage (LS)—were determined using the Casagrande



apparatus and standard thread-rolling methods respectively. Specific gravity (Gs) was determined using the density bottle method (BS 1377:1990, Part 2). Particle size distribution (PSD) was assessed by dry sieving of air-dried samples mixed with cement (2%, 4%, 6%, 8%) and cured for 72 hours before testing.

### 3.2.3 Compaction Tests

Proctor compaction tests were performed using three compactive efforts: (i) British Standard Light (BSL): 27 blows of a 2.5 kg rammer from 300 mm, in 3 layers, in a 1000 cm<sup>3</sup> mould; (ii) West African Standard (WAS): 10 blows of a 4.5 kg rammer from 450 mm, in 5 layers; and (iii) British Standard Heavy (BSH): 27 blows of a 4.5 kg rammer from 450 mm, in 5 layers. Tests followed BS 1924 (1990) and Head (1994). Dry density was computed from bulk density and moisture content, and MDD and OMC were read from the moisture–density curve. Tests were conducted on vermi-remediated soil and on soil-cement mixtures at 2%, 4%, 6%, and 8% OPC.

### 3.3 Classification Standards

Soil classification followed AASHTO (2022) and ASTM (2023) standards. Highway material suitability was assessed against the Nigerian General Specifications for Roads and Bridges (2016), with reference to criteria from Ingles and Metcalf (1972) for base course UCS and from AASHTO (2022) for CBR, LL, PI, MDD, and OMC requirements.

## 4. RESULTS AND DISCUSSION

### 4.1 Chemical Composition of Soil and Cement

The oxide compositions of the crude oil–contaminated black cotton soil and of the OPC used are summarized in Table 1. The soil is dominated by SiO<sub>2</sub> (60.59%) and Al<sub>2</sub>O<sub>3</sub> (18.41%), with significant Fe<sub>2</sub>O<sub>3</sub> (11.89%), consistent with lateritic influence. The high loss on ignition (LOI = 17.34%) indicates substantial organic and hydroxyl content. The OPC is predominantly CaO (75.03%), with low SiO<sub>2</sub> (14.42%), confirming its hydraulic binding potential and capacity for pozzolanic interaction with soil aluminosilicates.

Table 1. Oxide composition of crude oil–contaminated black cotton soil and OPC

Oxide	Soil (%)	Oxide	Soil (%)	OPC (%)
SiO <sub>2</sub>	60.59	TiO <sub>2</sub>	1.99	0.21
Al <sub>2</sub> O <sub>3</sub>	18.41	P <sub>2</sub> O <sub>5</sub>	0.00	–
Fe <sub>2</sub> O <sub>3</sub>	11.89	MnO	0.26	0.03
CaO	2.51	Rb <sub>2</sub> O <sub>5</sub>	0.03	–
MgO	0.00	PbO	0.02	0.04
SO <sub>3</sub>	0.14	Cr <sub>2</sub> O <sub>3</sub>	0.03	0.01
Na <sub>2</sub> O	1.37	Cl	–	0.15
K <sub>2</sub> O	2.78	LOI	17.34	–
CaO (OPC)	–	MgO (OPC)	–	1.30
SiO <sub>2</sub> (OPC)	–	CaO (OPC)	–	75.03

### 4.2 Removal Efficiency

The result of the 30 days of remediation shows earthworms reduced the hydrocarbon concentration by approximately 22.93% (removal efficiency), signifying a moderate yet meaningful remediation performance. The reduction implies that the vermi-remediation process is likely still in an active but intermediate stage of degradation, where easily degradable (light) hydrocarbon fractions have been partially removed, while the more complex and stable fractions remain. This aligns with the typical biodegradation pattern of petroleum contaminants, which proceeds from simple to more complex compounds over time (Abdulsalam, 2024).

In addition, the relatively high residual TPH suggests that remediation time was insufficient for complete mineralization, and that the process may benefit from extended duration, increased earthworm density, or the integration of complementary treatment methods such as organic amendments or chemical stabilization (Abdulsalam,



2024).

### 4.3 Index Properties of Vermi-Remediated Crude Oil–Contaminated Black Cotton Soil

#### 4.3.1 Natural Properties and Soil Classification

The preliminary index properties of the black cotton soil, contaminated with crude oil and subsequently subjected to vermi-remediation, are presented in Table 2. The natural moisture content of 10.68% is comparatively low, attributable to sample collection during the pre-rainy season. The soil recorded 72.42% passing the No. 200 sieve (0.075 mm), confirming a predominantly fine-grained, clay-rich matrix.

The liquid limit (LL = 57.8%), plastic limit (PL = 28.65%), plasticity index (PI = 29.15%), and linear shrinkage (LS = 16.43%) collectively indicate a highly plastic soil with moderate-to-high swell potential. These values classify the soil as A-7-6 (Group Index = 19) under AASHTO (2022), representing poor subgrade quality, and as CH (high plasticity clay) under the USCS. The specific gravity of 2.32 is below the 2.60–2.80 range recommended for base course materials by AASHTO (2022) and ASTM (2023), consistent with the organic influence and the low-density minerals characteristic of montmorillonite-rich soils. These findings are consistent with established literature on black cotton soil properties in northeastern Nigeria (Garba & Yunana, 2023; Moses, 2021; Almuaythir et al., 2024, Sani et al., 2026a, Sani et al., 2026b, Sani et al., 2026c).

Table 2. Summary of physical and engineering index properties of the vermi-remediated crude oil–contaminated black cotton soil

Property	Value
Natural moisture content (%)	10.68
Percentage passing No. 200 sieve (%)	72.42
Liquid limit LL (%)	57.80
Plastic limit PL (%)	28.65
Plasticity index PI (%)	29.15
Linear shrinkage LS (%)	16.43
Specific gravity G <sub>s</sub>	2.32
AASHTO classification	A-7-6 (19)
USCS classification	CH
MDD – BSL (g/cm <sup>3</sup> )	1.63
MDD – WAS (g/cm <sup>3</sup> )	1.77
MDD – BSH (g/cm <sup>3</sup> )	1.85
OMC – BSL (%)	18.22
OMC – WAS (%)	15.80
OMC – BSH (%)	11.00

#### 4.3.2 Effect of Cement on Atterberg Limits

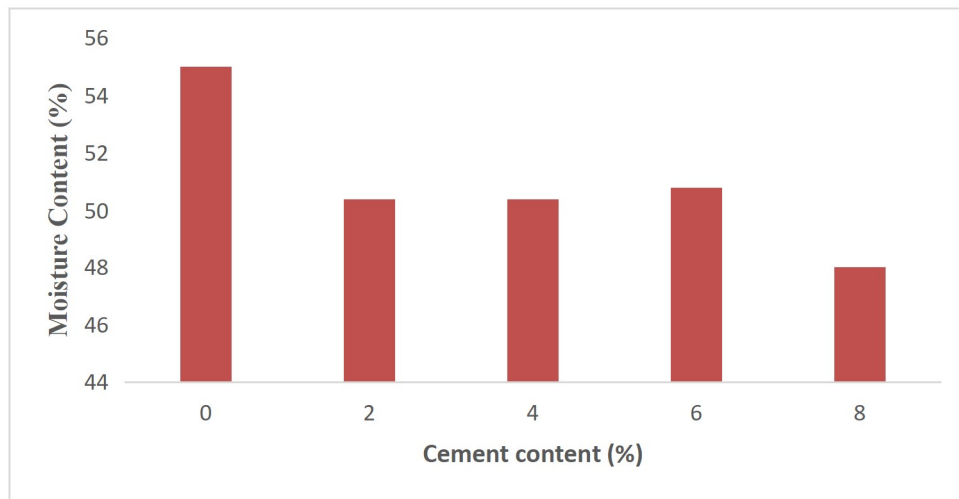
The variation of Atterberg limits with cement content for the vermi-remediated black cotton soil is summarized in Table 3 and illustrated graphically in Figures 1–4.

##### 4.3.2.1 Liquid Limit

The liquid limit of the vermi-remediated black cotton soil decreased progressively from 55.0% (0% cement) to 48.0% at 8% cement, with values recorded at 50.4%, 54.4%, and 50.8% at 2%, 4%, and 6% cement respectively (Figure 1). Despite some fluctuation at 4% cement—attributable to heterogeneous flocculation kinetics—the overall downward trend confirms that cement addition reduces soil-water affinity through cation exchange, flocculation, and initial cementation (Das & Sobhan, 2023; Osinubi et al., 2022; Sani et al., 2026c). However, all LL values exceeded the ≤ 30% threshold specified for base course materials by AASHTO (2022) and ASTM (2023), indicating that the treated soil remains unsuitable for base course application on the basis of liquid limit alone. These findings align with reports by Oluwatuyi et al. (2023); and Subair et al. (2024), who documented similar reductions in LL upon cement addition



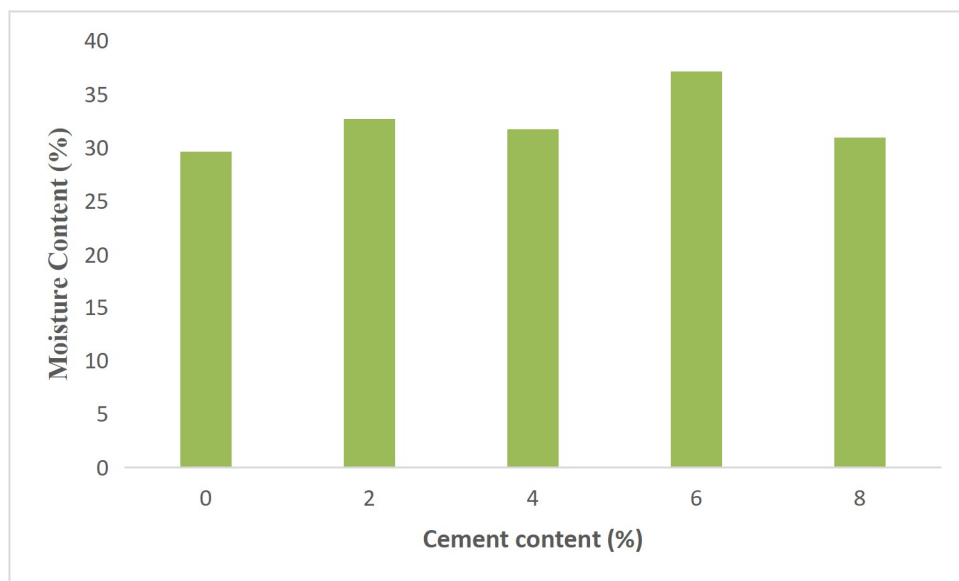
to expansive soils.



**Figure 1: Variation of Liquid Limit with Cement Content**

**4.3.2.2 Plastic Limit**

The plastic limit increased with cement addition, rising from 29.63% at 0% cement to a peak of 37.12% at 6% cement, before declining to 30.95% at 8% cement (Figure 2). This increase reflects cement-induced flocculation, particle bonding, and reduced clay activity, all of which necessitate higher moisture before the soil transitions to its plastic state (Behzad & Abolfazl, 2021). The values obtained exceeded the 10–20% range specified for base course materials (AASHTO, 2022; ASTM, 2023), but the upward trend is consistent with established observations that cement stabilization raises the plastic limit of clay soils by modifying inter-particle interactions (Fatemeh et al., 2021; Das & Sobhan, 2023).



**Figure 2: Variation of Plastic Limit with Cement Content**

**4.3.2.3 Plasticity Index**

The plasticity index decreased substantially from 25.37% at 0% cement to a minimum of 13.68% at 6% cement, with a slight increase to 17.05% at 8% cement (Figure 3). This overall reduction of approximately 46% in PI indicates a marked improvement in soil workability and reduced expansive potential. The reduction is primarily attributed to the combined effect of decreasing LL and increasing PL, driven by flocculation and cementitious bonding (Fatemeh et al., 2021; Oluwatuyi et al., 2023). Notwithstanding, all PI values exceeded the  $\leq 6\%$  limit for base course materials specified by AASHTO (2022) and ASTM (2023), consistent with the finding that 8% cement alone is insufficient to meet base course plasticity requirements for a CH-classified soil. These results concur with those of Osinubi et al. (2022) and Subair et al. (2024), who reported progressive PI reduction with cement addition in Nigerian expansive soils.

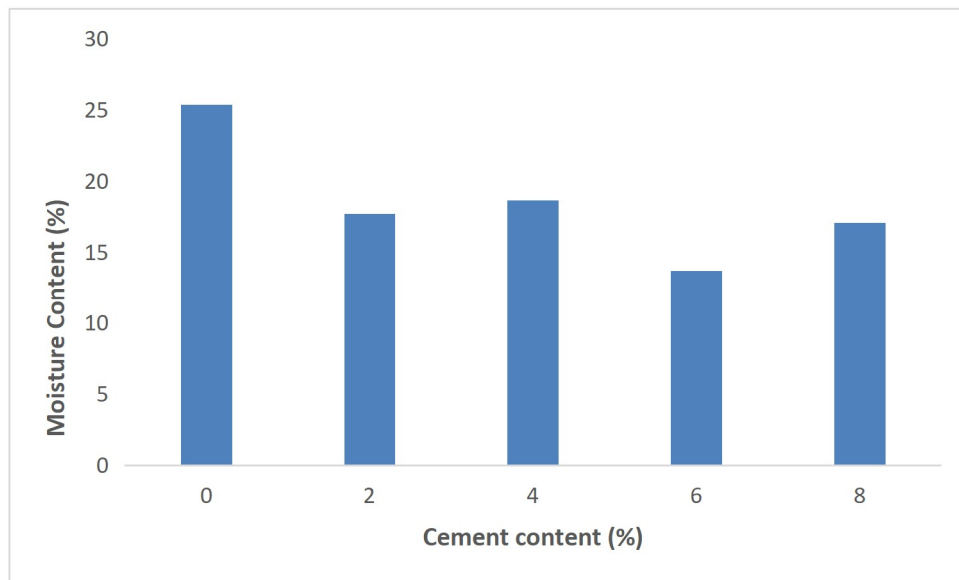


Figure 3: Variation of Plasticity Index with Cement Content

4.3.2.4 Linear Shrinkage

Linear shrinkage decreased monotonically with cement content, from 16.43% (0% cement) to 12.86% at 8% cement (Figure 4). This reduction is attributed to cement-induced flocculation, particle bonding, reduction in clay activity, and void filling by cementitious products, all of which decrease the capillary forces driving shrinkage during drying (Oluwatuyi et al., 2023; ASTM, 2023). The improvement in volumetric stability is significant for highway applications, as excessive shrinkage can lead to longitudinal cracking in pavement layers. These findings are consistent with those of Oluwatuyi et al. (2023), who reported analogous reductions in linear shrinkage with cement stabilization of Nigerian expansive soils.

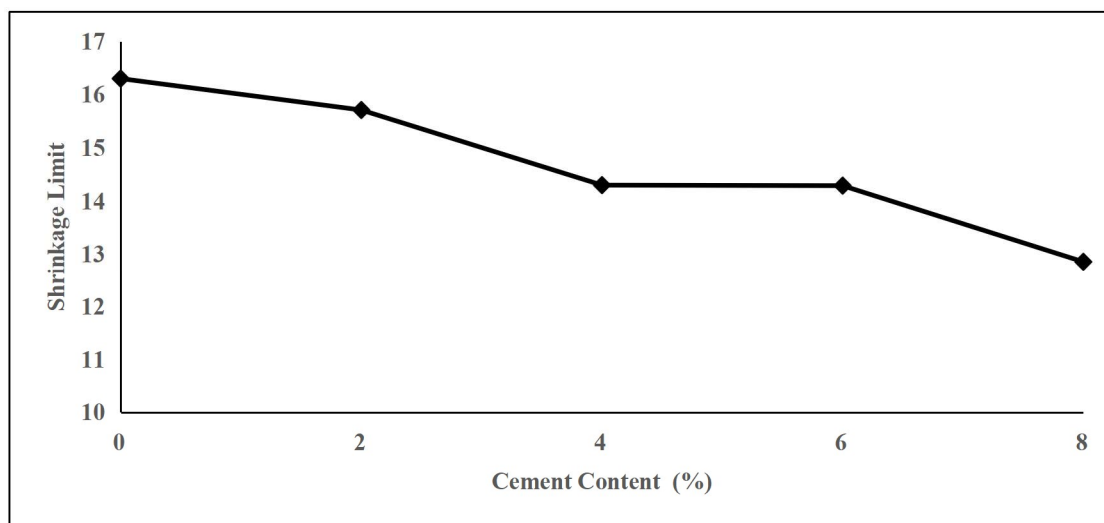


Figure 4: Variation of Linear Shrinkage with Cement Content

Table 3. Atterberg limits and specific gravity of vermi-remediated crude oil-contaminated black cotton soil with cement content

Cement (%)	LL (%)	PL (%)	PI (%)	LS (%)
0	55.00	29.63	25.37	16.43
2	50.40	32.72	17.68	15.71
4	54.40	31.75	18.65	14.29
6	50.80	37.12	13.68	14.29



8	48.00	30.95	17.05	12.86
AASHTO Base $\leq$	30.00	10–20	6.00	–

### 4.3.3 Specific Gravity

Specific gravity increased from 2.25 (2% cement) to 2.34 (8% cement), compared to 2.32 for the untreated vermi-remediated soil (Figure 5). This trend reflects the higher specific gravity of OPC ( $\approx 3.15$ ) and the progressive formation of denser cementitious products within the soil matrix (Oyediran & Enya, 2021). Despite the increase, all values remained below the 2.60–2.80 range recommended for base course materials by AASHTO (2022) and ASTM (2023), suggesting that the low-density organic and clay minerals in the BCS continue to govern the composite specific gravity even at 8% cement content. The results agree with findings by Oyediran and Enya (2021) on similar Afrotropical expansive soils.

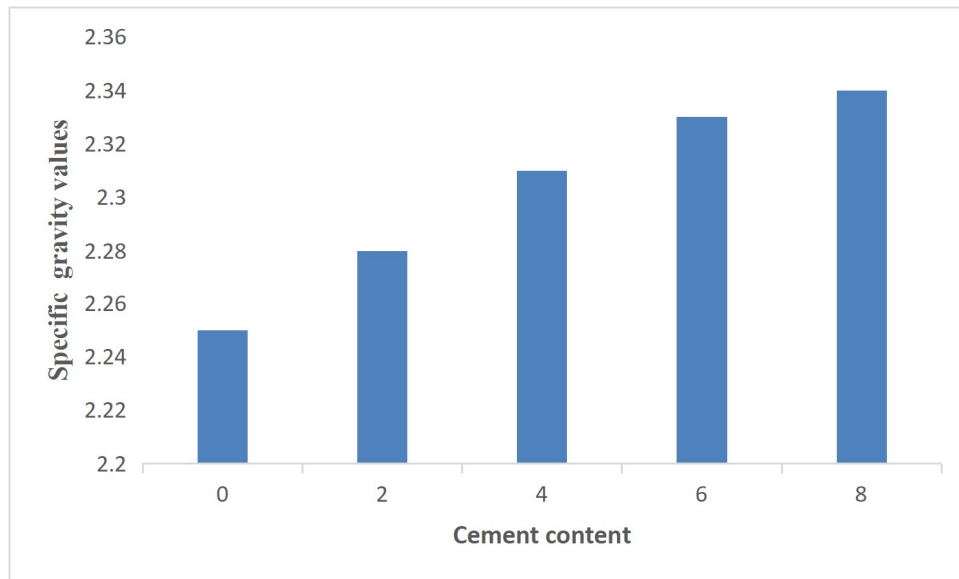


Figure 5: Variation of Specific Gravity with Cement Content

### 4.3.4 Particle Size Distribution

Particle size distribution analysis by dry sieving revealed that cement addition reduced the percentage of particles passing the No. 200 sieve (0.075 mm) from 72.42% in the natural soil. Under BSL compaction, fines content values of 0.10%, 0.25%, 0.10%, and 1.45% were recorded at 2%, 4%, 6%, and 8% cement respectively. Similar patterns were observed under WAS (0.30%, 1.20%, 0.30%, 2.80%) and BSH (0.25%, 0.25%, 2.55%, 0.65%) compaction energies (Figures 6a–6c).

The reduction in fines content from natural to cement-treated soil is attributable to flocculation, agglomeration, and cementation, which bind fine clay particles into coarser aggregates that no longer pass the No. 200 sieve (Amu et al., 2020; Sani, 2012). The slight increase in fines at 6–8% cement under some compactive efforts reflects the presence of unhydrated fine cement particles and partial disintegration of cemented clusters. These observations confirm that cement stabilization fundamentally transforms the grading of the soil from a fine-grained clay matrix to a cemented, coarse-like structure—a prerequisite for improved drainage and strength. These findings are consistent with those of Sani (2012) and Osinubi et al. (2020).



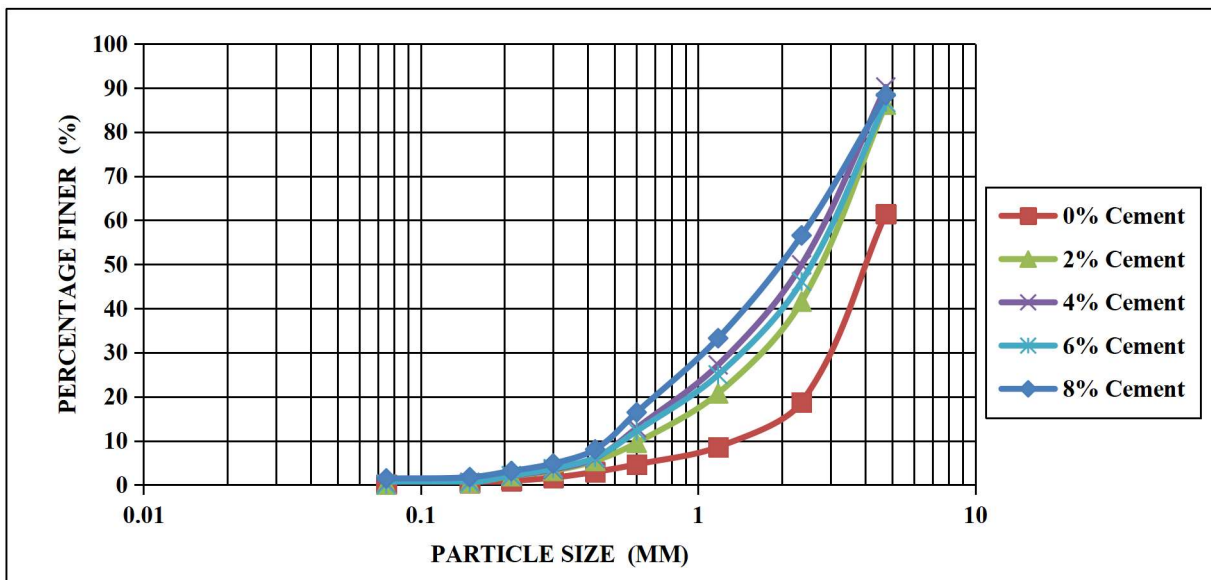


Figure 6a: Particle Size Distribution – BSL Compaction

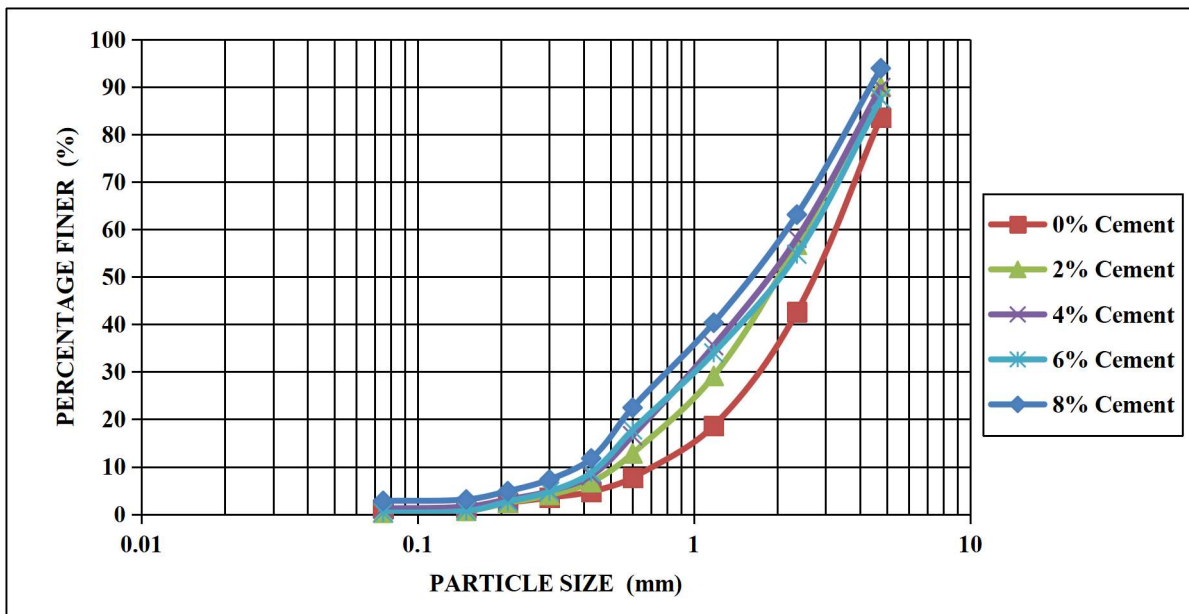


Figure 6b: Particle Size Distribution – WAS Compaction

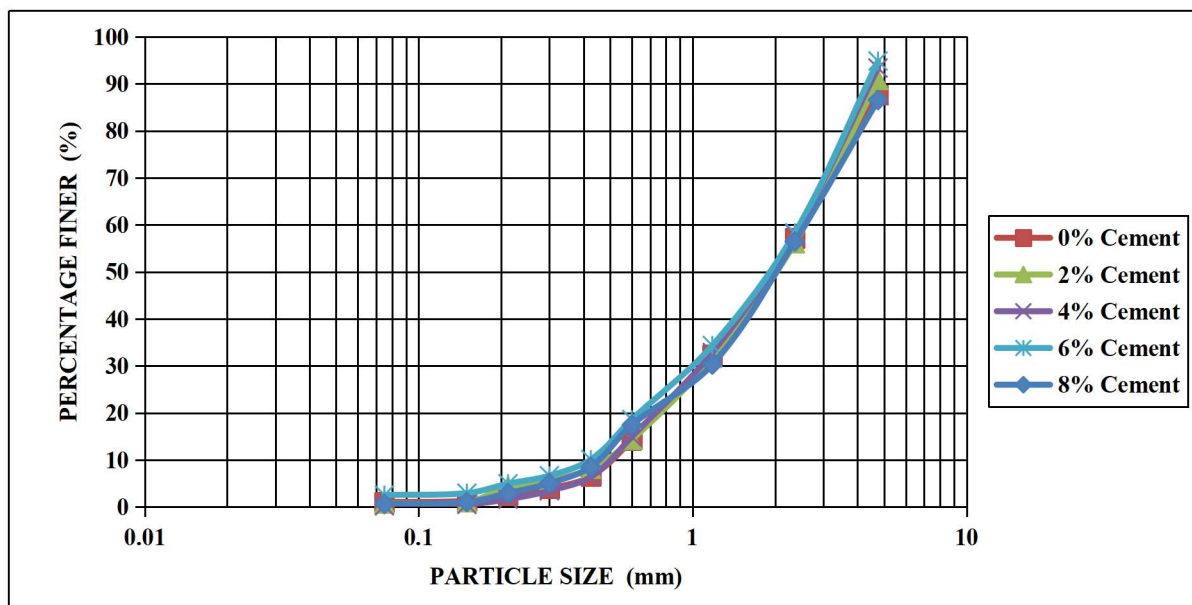


Figure 6c: Particle Size Distribution – BSH Compaction

#### 4.4 Compaction Characteristics

##### 4.4.1 Maximum Dry Density (MDD)

The variation of MDD with cement content under BSL, WAS, and BSH compactive efforts is presented in Table 4 and Figure 7. Under BSL, MDD decreased from 1.63 g/cm<sup>3</sup> (0% cement) through 1.62, 1.60, 1.60 g/cm<sup>3</sup> at 2%, 4%, 6% cement respectively, before recovering to 1.62 g/cm<sup>3</sup> at 8% cement. A similar pattern was observed under WAS (1.77 → 1.75 → 1.72 → 1.70 → 1.74 g/cm<sup>3</sup>) and BSH (1.85 → 1.83 → 1.80 → 1.80 → 1.83 g/cm<sup>3</sup>).

The initial decrease in MDD from 0–6% cement is attributable to flocculation and aggregation of clay particles upon cement hydration, which creates an open, loose soil structure with higher void ratios that reduces density under the same compaction energy (Subair et al., 2024; Ameen et al., 2024). The partial recovery at 8% cement reflects progressive cementation and void filling by hydrated calcium silicate and aluminate products, which consolidate the soil matrix and restore some density. As expected, MDD increased consistently with compactive effort, from BSL through WAS to BSH, due to improved particle rearrangement and reduced air voids under higher energy input (Osinubi et al., 2022; Fadugba et al., 2024; Sani et al., 2026a, Sani et al., 2026b, Sani et al., 2026c)).

Comparing against AASHTO (2022) and ASTM (2023) requirements, MDD values even under BSH (1.80–1.85 g/cm<sup>3</sup>) fall below the 1.90–2.20 g/cm<sup>3</sup> specified for base course materials, though they are within the 1.60–1.85 g/cm<sup>3</sup> range for subgrade use. These results are consistent with findings by Subair et al. (2024) and Ameen et al. (2024) on cement-stabilized expansive soils, and corroborate the established principle that cement stabilization of highly plastic clays initially reduces MDD before improvements manifest with higher dosages and curing.

Table 4. Maximum dry density (MDD) and optimum moisture content (OMC) of vermi-remediated crude oil-contaminated black cotton soil with cement content under BSL, WAS, and BSH compaction

Cement (%)	MDD BSL (g/cm <sup>3</sup> )	MDD WAS (g/cm <sup>3</sup> )	MDD BSH (g/cm <sup>3</sup> )	OMC BSL (%)	OMC WAS (%)	OMC BSH (%)	Base Course MDD (g/cm <sup>3</sup> ) [AASHTO, 2022]
0	1.63	1.77	1.85	18.22	15.80	11.00	1.90–2.20
2	1.62	1.75	1.83	18.41	16.21	14.71	
4	1.60	1.72	1.80	18.65	16.66	14.94	
6	1.60	1.70	1.80	19.08	17.11	15.40	
8	1.62	1.74	1.83	18.50	16.61	15.10	



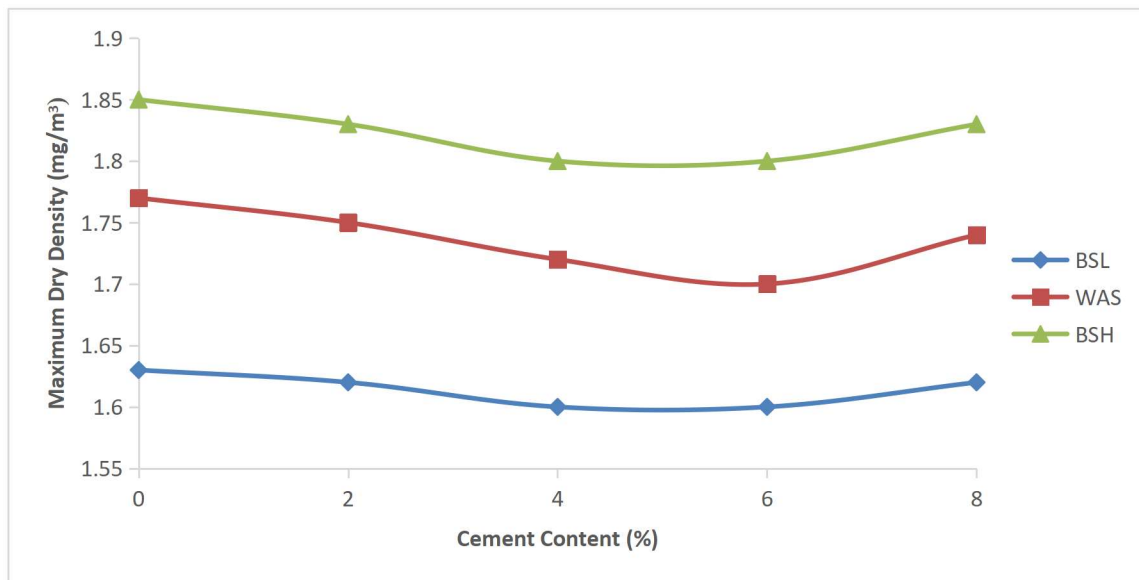


Figure 7: Variation of Maximum Dry Density (MDD) with Cement Content

#### 4.4.2 Optimum Moisture Content (OMC)

The OMC generally increased with cement content from 0–6% across all compactive efforts, with a slight decrease at 8% cement (Figure 8; Table 4). Under BSL, OMC increased from 18.22% (0% cement) to 19.08% at 6% cement, before decreasing to 18.50% at 8% cement. Under WAS, OMC rose from 15.80% to 17.11% at 6% cement, and decreased to 16.61% at 8%. Under BSH, the increase was most pronounced, rising from 11.00% to 15.40% at 6% cement, and declining to 15.10% at 8%.

The observed increase in OMC with cement content up to 6% is governed by two mechanisms: (i) the additional water demand required for OPC hydration and pozzolanic reactions, and (ii) the altered flocculated soil structure, which requires more moisture to lubricate inter-particle contacts during compaction. The slight decrease at 8% cement reflects the stiffening of the mix as cementation proceeds and the mixture becomes less plastic, requiring less water for densification (Ameen et al., 2024; Fadugba et al., 2024). The consistent decrease in OMC from BSL through WAS to BSH confirms that higher compaction energy reduces the moisture needed for achieving maximum density, consistent with classical soil mechanics and recent literature (Subair et al., 2024; Osinubi et al., 2022; Sani et al., 2026a, Sani et al., 2026b, Sani et al., 2026c).

Notably, the OMC value under BSH at 0% cement (11.00%) falls within the 8–12% range recommended for base course materials by AASHTO (2022), ASTM (2023), and the Federal Ministry of Works and Housing (FMWN, 2023). Higher cement contents push OMC above this range, indicating that while compaction energy can bring OMC into the acceptable band, cement addition at doses above 0% under BSH energy may necessitate moisture management during field compaction.

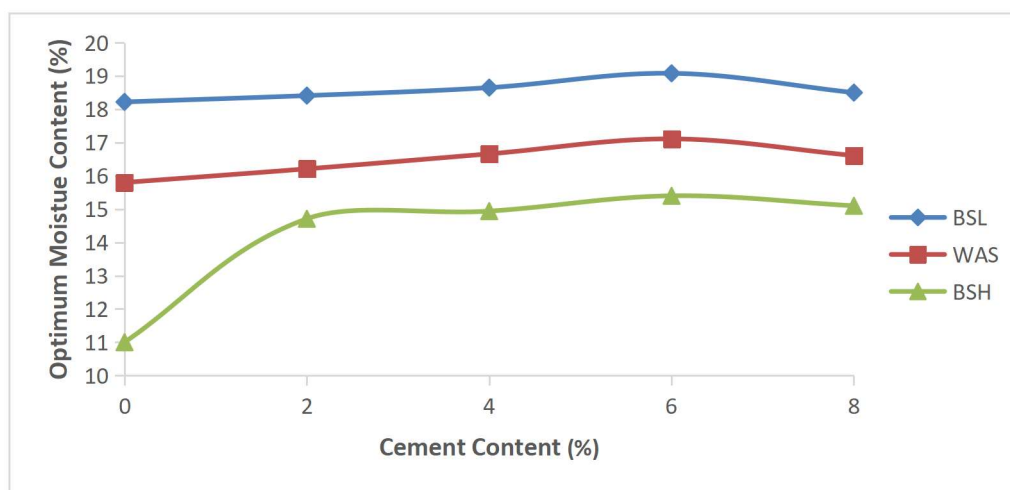


Figure 8: Variation of Optimum Moisture Content (OMC) with Cement Content



### 4.5 Implications for Pavement Material Suitability

Table 5 synthesizes the key index property and compaction results against AASHTO (2022) criteria for subgrade, sub-base, and base course classification. The vermi-remediated, cement-stabilized BCS consistently meets subgrade requirements for MDD (1.60–1.85 g/cm<sup>3</sup>), and the progressive reduction in LL, PI, and LS with increasing cement content indicates progressive improvement toward sub-base and base course suitability. However, given that LL values (48.0–55.0%) and PI values (13.68–25.37%) substantially exceed AASHTO base course thresholds (LL ≤ 30%, PI ≤ 6%), cement stabilization at the tested dosages (2–8%) is insufficient to qualify the soil as a base course material on plasticity criteria alone.

These findings have important practical implications: (i) cement-stabilized vermi-remediated BCS is suitable for use as a compacted subgrade or improved subgrade layer in Nigerian highway construction; (ii) higher cement dosages (>8%) or the combined use of cement with supplementary cementitious materials such as fly ash, ground granulated blast furnace slag (GGBS), or calcium carbide waste may be needed to achieve base course plasticity targets; and (iii) the BSH compactive effort consistently produced the best index property responses and MDD values, and should be specified in field compaction specifications for this material.

Table 5. Suitability assessment of vermi-remediated cement-stabilized crude oil-contaminated BCS against AASHTO (2022) and Ingles & Metcalf (1972) criteria

Property	Study value (0–8% OPC)	Subgrade	Sub-base	Base course
LL (%)	48.0–55.0	≤ 50	≤ 35 ✘	≤ 30 ✘
PL (%)	29.63–37.12	15–30 ✘	12–25 ✘	10–20 ✘
PI (%)	13.68–25.37	≤ 20 ✓	≤ 12	≤ 6
MDD (g/cm <sup>3</sup> )	1.60–1.85 (BSL-BSH)	1.60–1.85 ✓	1.75–2.00 ✓	1.90–2.20
OMC (%)	11.0–19.1 (BSH-BSL)	12–18 ✓	10–15 ✓	8–12 ✓
Gs	2.25–2.34	2.40–2.70 ✘	2.50–2.70 ✘	2.60–2.80 ✘

✓: Marginally satisfied

✘: Not satisfied

## 5. CONCLUSIONS

The following conclusions are drawn from this study on the index properties and compaction characteristics of cement-stabilized vermi-remediated crude oil-contaminated black cotton soil from Gamadadi, Borno State, Nigeria:

- Vermi-remediation using *Eisenia fetida* over 30 days achieved a TPH removal efficiency of 22.43%, reducing the initial TPH from 5,233.33 mg/kg to 4,033.33 mg/kg. While meaningful, this partial remediation underscores the need for complementary chemical stabilization.
- The vermi-remediated BCS was classified as A-7-6 (GI = 19) (AASHTO) and CH (USCS), with LL = 57.8%, PI = 29.15%, LS = 16.43%, and Gs = 2.32—confirming its highly plastic, expansive nature and poor subgrade quality in its natural state.
- Cement stabilization progressively reduced LL from 55.0% to 48.0%, decreased PI from 25.37% to 13.68%, and reduced linear shrinkage from 16.43% to 12.86% with increasing OPC content (2–8%). Specific gravity increased from 2.25 to 2.34. Despite improvement, all values remained above AASHTO base course thresholds.
- MDD decreased with cement content from 0–6% due to flocculation and open soil structure formation, with a partial recovery at 8% attributed to cementitious bonding and void filling. The decrease in MDD was consistent across BSL, WAS, and BSH efforts. MDD values (1.60–1.85 g/cm<sup>3</sup> under BSH) satisfy subgrade requirements but fall short of base course specifications.
- OMC increased with cement content from 0–6% and decreased slightly at 8%, reflecting the competing effects of water demand for hydration and reduced need for moisture in a stiffer mixture. OMC consistently decreased with increasing compactive effort. Only the BSH condition at 0% cement (OMC = 11.0%) met the 8–12% range for base course materials.
- The cement-stabilized vermi-remediated BCS is suitable for use as a compacted subgrade and improved sub-base material. Higher cement dosages (>8%) or the use of supplementary cementitious materials may be needed to achieve base course classification under Nigerian highway specifications.



## 5.1 Recommendations

Future investigations should: (i) examine the effect of cement dosages beyond 8% (up to 12–15%) on the index and compaction properties; (ii) assess the combined effect of OPC with supplementary materials such as fly ash, GGBS, or calcium carbide waste on the plasticity of vermi-remediated BCS; (iii) extend vermi-remediation periods beyond 60 days and/or increase earthworm density to achieve higher TPH removal before stabilization; and (iv) conduct field pilot tests to validate laboratory compaction results under realistic traffic loading conditions.

## DECLARATIONS

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**Conflicts of interest:** The authors declare no conflicts of interest.

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

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