

# Performance Evaluation of Vermi-Remediated Crude Oil Contaminated Soil on Compaction Characteristics When Stabilized with Cement Kiln Dust

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**Abstract-** *The compaction behaviour of crude oil-contaminated Black Cotton Soil (BCS) subjected to integrated vermi-remediation and Cement Kiln Dust (CKD) stabilization was investigated for potential subgrade applications. Black cotton soil was contaminated with crude oil at a rate of 75 cl per 10 kg of soil, vermi-remediated using Eisenia fetida earthworms for four weeks, and subsequently stabilized with CKD at 2%, 4%, 6%, and 8% by weight. Compaction tests were conducted under three compactive efforts: British Standard Light (BSL), West African Standard (WAS), and British Standard Heavy (BSH). Vermi-remediation reduced Total Petroleum Hydrocarbon (TPH) from 5200 mg/kg to 4033 mg/kg, representing a remediation efficiency of 22.44%. Compaction results revealed that Maximum Dry Density (MDD) generally increased with CKD content, rising from 1.63 to 1.70 Mg/m<sup>3</sup> (BSL), 1.77 to 1.81 Mg/m<sup>3</sup> (WAS), and 1.85 to 1.90 Mg/m<sup>3</sup> (BSH). Optimum Moisture Content (OMC) exhibited an initial increase at 2% CKD followed by a progressive reduction at higher CKD content, attributed to cementitious reactions forming Calcium Silicate Hydrate (CSH) and Calcium Aluminate Hydrate (CAH). MDD values at 6–8% CKD met the Nigerian General Specifications (NGS, 2016) requirements for subgrade materials under both BSL and BSH compaction. The study demonstrates that integrated vermi-remediation and CKD stabilization offers a sustainable, cost-effective strategy for improving the compaction behaviour of petroleum-contaminated soils for highway subgrade use.*

**Keywords:** *Crude oil contamination; Vermi-remediation; Cement Kiln Dust; Compaction characteristics; Maximum dry density; Optimum moisture content; Subgrade*

## I. INTRODUCTION

The rapid pace of industrialisation and population growth across developing nations has intensified demand for road infrastructure, necessitating

expanded use of available soils, including those that are contaminated or inherently problematic. Among these, black cotton soil (BCS), widely distributed across northern Nigeria and sub-Saharan Africa, presents significant geotechnical challenges owing to its expansive, high-plasticity nature. When further compromised by crude oil contamination arising from pipeline leakages, exploration activities, or vehicular spills, BCS becomes severely unsuitable as a pavement subgrade material (Uguru and Udubra, 2021).

Crude oil contamination degrades the engineering behaviour of soil by coating soil particles with hydrophobic hydrocarbons, altering inter-particle forces, reducing cohesion, and modifying compaction characteristics. In particular, petroleum hydrocarbons have been shown to reduce maximum dry density (MDD) and alter optimum moisture content (OMC), both of which are critical parameters governing subgrade performance (Shi et al., 2020a). The alteration of compaction behaviour in contaminated soils directly affects load-bearing capacity, settlement potential, and long-term durability of pavement systems constructed over such materials.

Conventional remediation strategies such as excavation and replacement are prohibitively expensive for large-scale road projects. Emerging biological and physico-chemical approaches offer cost-effective alternatives. Vermi-remediation, which exploits the bio-degradation capacity of earthworms, particularly *Eisenia fetida*, has gained recognition for its ability to reduce Total Petroleum Hydrocarbon (TPH) concentrations through enhanced microbial activity, soil aeration, and organic matter turnover (Rodriguez-Campos et al., 2019; Shi et al., 2020a).

However, biological remediation alone may not adequately restore engineering properties to meet construction standards, necessitating complementary chemical stabilization.

Cement Kiln Dust (CKD), an industrial by-product of the cement manufacturing process, is a calcium-rich material with pozzolanic properties. Its application to soils has been documented to improve compaction behaviour, reduce plasticity, and enhance strength through cation exchange, flocculation, and the formation of cementitious hydration products (Eberemu, 2011; Almuaythir and Abbas, 2023). When combined with prior vermi-remediation, CKD stabilization can address both contaminant reduction and engineering improvement synergistically.

Despite individual studies on vermi-remediation and CKD stabilization, there is a paucity of research examining the compaction response of vermi-remediated crude oil-contaminated soils treated with CKD under varying compactive efforts. This study, therefore, investigates the compaction characteristics — specifically MDD and OMC — of vermi-remediated crude oil-contaminated black cotton soil stabilized with CKD at varying dosages and compactive energies, with a view to establishing optimum treatment conditions for subgrade applications.

## II. MATERIALS AND METHODS

### 2.1 Materials

#### 2.1.1 Black Cotton Soil

Representative samples of black cotton soil was collected from Gamadadi, Borno State, Nigeria, at coordinates 10.320163° N and 11.5484146° E. Samples were obtained from a depth range of 0.5 m to 1.5 m, after removing the topsoil to about 0.5 m. The natural soil was characterized by high plasticity index, low bearing capacity, and high moisture affinity, typical of montmorillonite-rich expansive clays prevalent in northern Nigeria.

#### 2.1.2 Crude Oil

Crude oil, a naturally occurring unrefined mixture of hydrocarbons, sulfur, nitrogen, and oxygen, was used to artificially contaminate the black cotton soil under controlled laboratory conditions to simulate field

contamination from pipeline incidents or exploration activities.

#### 2.1.3 Vermicomposting Earthworms

*Eisenia fetida* (red wiggler worm), known for its capacity to thrive in organic-rich, contaminated environments, was selected for the vermi-remediation phase. These earthworms enhance microbial degradation of organic contaminants by improving soil aeration, porosity, and biochemical activity (Maboeta and Van Rensburg, 2003).

#### 2.1.4 Cement Kiln Dust (CKD)

The CKD used in this study was sourced from BUA Cement (Sokoto Cement Factory), Sokoto State, Nigeria. CKD is a fine, alkaline by-product containing free lime, silica, alumina, and alkali sulphates, making it suitable for pozzolanic stabilization of soils.

### 2.2 Soil Contamination Procedure

Air-dried BCS was hand-sorted, pulverized, and sieved through a BS No. 4 sieve (4.76 mm aperture) to remove coarse particles. The processed soil was contaminated with crude oil at a rate of 75 cl per 10 kg of soil mixed with 1000 ml of water. The contaminated soil was sealed and cured for four weeks to allow full hydrocarbon penetration and saturation of the soil matrix.

### 2.3 Vermiremediation Procedure

Following the contamination period, the crude oil-contaminated BCS was introduced into perforated aerated tanks and inoculated with *Eisenia fetida* earthworms at a rate of 40 to 80 worms per 40 kg of contaminated soil, totalling approximately 300 worms per 200 kg of soil. The remediation was maintained for four weeks, with daily watering to sustain moisture and earthworm viability, and regular observations were recorded.

### 2.4 Stabilization with CKD

After vermi-remediation, the treated soil was mixed with CKD at proportions of 2%, 4%, 6%, and 8% by dry weight of soil. Mixing was carried out thoroughly to ensure uniform distribution of CKD throughout the soil mass prior to compaction testing.

### 2.5 Laboratory Testing

The following tests were conducted in accordance with applicable British Standard (BS) specifications:

- Total Petroleum Hydrocarbon (TPH) — gravimetric extraction method, before and after vermiremediation
- Atterberg Limits (Liquid Limit, Plastic Limit, Plasticity Index) — BS 1377-2
- Compaction Tests (MDD and OMC) — British Standard Light (BSL), West African Standard (WAS), and British Standard Heavy (BSH) compactive efforts — BS 1377-4

### III. RESULTS AND DISCUSSION

#### 3.1 Remediation Efficiency (TPH Analysis)

Total Petroleum Hydrocarbon (TPH) analysis was conducted by gravimetric method to quantify hydrocarbon content before and after vermiremediation. Results are presented in Tables 1a and 1b.

Table 1a: Total Petroleum Hydrocarbon (TPH) of crude oil contaminated soil (Before vermiremediation)

S/ no	Soil Sample	Weight Before Extraction (mg)	Weight After Extraction (mg)	Cycle (C)	TPH (mg/kg)	Average TPH (mg/kg)
1.	CC BCS 1	10,00 0.00	9480. 00	4	520 0	
2.	CC BCS 1	10,00 0.00	9470. 00	4	530 0	5200 .00
3.	CC BCS 1	10,00 0.00	9480. 00	4	520 0	

Table 1b: Total Petroleum Hydrocarbon (TPH) of crude oil contaminated soil (After vermiremediation)

S/	Soi	Wei	Wei	C	TP	Ave	TPH
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no	Sample	Weight Before Extraction (mg)	Weight After Extraction (mg)	Cycle (C)	TPH (mg/kg)	Removal Efficiency (%)
1.	CR BC S 1	10,0 00.0 0	9610 .00	4	390 0.0 0	
2.	CR BC S 1	10,0 00.0 0	9590 .00	4	410 0.0 0	403 3 22.4 4%
3.	CR BC S 1	10,0 00.0 0	9590 .00	4	410 0.0 0	

The average TPH of the crude oil-contaminated BCS was 5200 mg/kg prior to remediation. Following four weeks of vermiremediation, TPH was reduced to 4033 mg/kg, yielding a remediation efficiency of 22.44%. Although this level of reduction confirms that earthworms meaningfully degrade petroleum hydrocarbons through enhanced microbial activity and soil aeration, the residual TPH indicates that vermiremediation alone does not achieve complete restoration. This observation reinforces the need for CKD stabilization to address the remaining engineering deficiencies arising from petroleum contamination of the soil matrix (Rodriguez-Campos et al., 2019).

The partial TPH reduction is consistent with findings by Shi et al. (2020a), who noted that vermiremediation efficiency depends on earthworm species, soil moisture, temperature, and contamination level. Notwithstanding the incomplete remediation, the biological treatment altered soil structure through earthworm-induced bioturbation, which is expected to influence subsequent compaction behaviour.

#### 3.2 Index Properties

Atterberg limits were determined to characterize the plasticity state of the soil at each treatment stage, as plasticity directly influences water retention and

hence compaction behaviour. The variation of the Atterberg limits of Vermi-remediated Block Cotton Soil stabilized with cement kiln dust is shown in Figure 1.

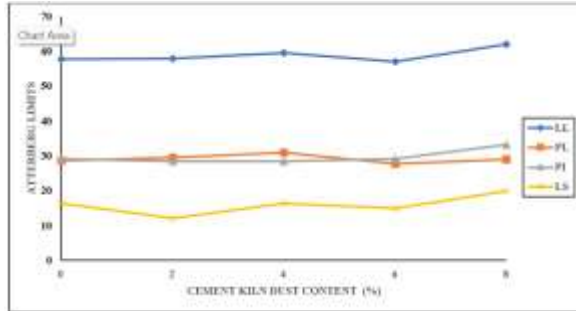


Figure 1: Variation of Atterberg Limits of Vermi-remediated Crude oil contaminated Black Cotton soil with Cement Kiln Dust content

The Liquid Limit (LL) of the vermi-remediated BCS ranged from approximately 58% to 62% with increasing CKD content. The marginal increase at 8% CKD is attributed to unreacted CKD fines absorbing water and the persistence of the expansive montmorillonite clay mineralogy, which resists significant LL reduction at low to moderate stabilizer dosages (Adeyanju, 2019).

The Plastic Limit (PL) increased from approximately 28% to 31%, reflecting an improvement in soil workability. This is attributed to calcium ion ( $\text{Ca}^{2+}$ ) cation exchange, which promotes flocculation of clay particles, reducing their affinity for water and increasing the PL. The Plasticity Index (PI) showed an initial decrease at 2–4% CKD due to flocculation and formation of cementitious compounds (CSH), followed by a slight increase at 6–8% CKD due to unreacted CKD fines. Overall, the reduction in PI at lower CKD levels is favourable for compaction performance, as lower plasticity soils typically achieve higher densities at lower moisture contents.

### 3.3 Compaction Characteristics

#### 3.3.1 Maximum Dry Density (MDD)

The variation of Maximum Dry Density (MDD) of vermi-remediated crude oil-contaminated black cotton soil stabilized with CKD under three compactive efforts — British Standard Light (BSL),

West African Standard (WAS), and British Standard Heavy (BSH) — is presented in Figure 2.

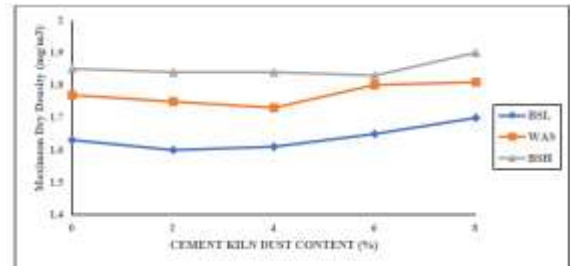


Figure 2: Variation of Maximum Dry Density of Vermi-remediated Crude oil contaminated Black Cotton soil with Cement Kiln Dust content

For BSL compaction, MDD increased from a natural value of 1.63  $\text{Mg}/\text{m}^3$  to a peak of 1.70  $\text{Mg}/\text{m}^3$  at 8% CKD. For WAS compaction, MDD rose from 1.77  $\text{Mg}/\text{m}^3$  to 1.81  $\text{Mg}/\text{m}^3$  at 8% CKD. Under BSH compaction, the highest densities were recorded, rising from 1.85  $\text{Mg}/\text{m}^3$  to a peak of 1.90  $\text{Mg}/\text{m}^3$  at 8% CKD content. Table 2 presents a summary of MDD and OMC values across all treatment levels.

Table 2: Summary of MDD and OMC Values for Vermi-remediated Crude Oil Contaminated BCS Stabilized with CKD

Compactive Effort	Natural	2% CKD	4% CKD	6% CKD	8% CKD	NGS Req.
BSL	MDD ( $\text{Mg}/\text{m}^3$ )	1.63	1.61	1.63	1.67	$\geq 1.70$
	OMC (%)	18.2	19.3	18.7	16.8	—
WAS	MDD ( $\text{Mg}/\text{m}^3$ )	1.77	1.7	1.7	1.7	—
	OMC (%)	—	19.3	18.7	16.8	—

	—	5	7	9	1	
	15.8	—	—	—	—	
		16.6	16.1	16.0	15.9	
BSH	1.85	1.8	1.8	1.8	1.9	≥1.90
	—	3	5	8	0	
	11.0	—	—	—	—	
		14.2	13.9	13.8	13.7	

The initial reduction in MDD observed at 2–4% CKD is attributable to flocculation and agglomeration of clay particles induced by Ca<sup>2+</sup> ions from CKD. This process creates a more open, bulkier soil structure with a higher void ratio and consequently lower dry density. At this stage, the modified inter-particle arrangement reduces compaction efficiency, a behaviour well documented in lime- and CKD-stabilized clays (National Lime Association, 2004).

The progressive increase in MDD at 6–8% CKD is driven by two interacting mechanisms: (i) the void-filling effect, whereby fine CKD particles occupy inter-aggregate pore spaces; and (ii) cementitious reactions producing Calcium Silicate Hydrate (CSH) and Calcium Aluminate Hydrate (CAH), which bind soil particles into a denser, more rigid matrix. The higher specific gravity of CKD particles relative to the remediated soil also contributes to increasing the unit weight of the compacted mass (James et al., 2021).

The effect of compactive effort on MDD is consistently observed across all CKD dosages, with BSH producing significantly higher dry densities than WAS and BSL. This is consistent with basic compaction theory: greater applied energy reduces air voids more effectively and forces particles into closer packing. The petroleum hydrocarbon residuals (residual TPH of 4033 mg/kg) present in the vermi-remediated soil introduce a lubricating effect between soil particles, which at lower compactive efforts moderates achievable density. However, under BSH energy, this lubrication effect is overcome by the applied compactive force, enabling near-complete particle densification.

The MDD values achieved at 6–8% CKD under both BSL (1.67–1.70 Mg/m<sup>3</sup>) and BSH (1.88–1.90 Mg/m<sup>3</sup>) satisfy the Nigerian General Specifications (NGS, 2016) minimum subgrade requirement of 1.70–1.90 Mg/m<sup>3</sup>. This confirms that the combined treatment protocol renders the formerly contaminated soil suitable for highway subgrade use. These findings agree with Akinwumi et al. (2020), who reported that combined biological and chemical stabilization improves soil structure and densification, thereby increasing MDD. Ochebo et al. (2022) similarly noted that industrial waste stabilizers, including CKD, improve particle rearrangement and reduce void ratio, enhancing compaction efficiency.

### 3.3.2 Optimum Moisture Content (OMC)

The variation of Optimum Moisture Content (OMC) of CKD-stabilized vermi-remediated BCS under the three compactive efforts is presented in Figure 3.

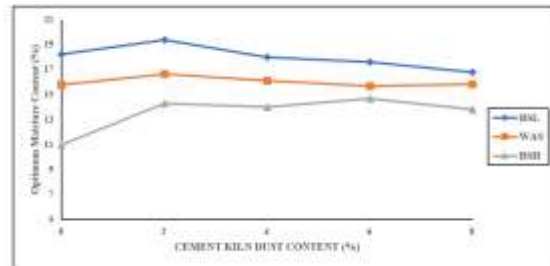


Figure 3: Variation of Optimum Moisture Content of Vermi-remediated Crude oil contaminated Black Cotton soil with Cement Kiln Dust content.

For BSL compaction, OMC rose from 18.2% (natural) to a peak of 19.3% at 2% CKD, thereafter declining progressively to 16.8% at 8% CKD. For WAS compaction, OMC increased slightly from 15.8% to 16.6% at 2% CKD before returning to approximately 15.9% at 8% CKD. Under BSH compaction, OMC increased notably from 11.0% to 14.2% at 2% CKD, then fluctuated and settled to approximately 13.7% at 8% CKD.

The initial increase in OMC at 2% CKD is explained by the same flocculation mechanism responsible for the MDD reduction at lower CKD contents. As Ca<sup>2+</sup> ions promote clay particle aggregation, the resulting flocculated structure has an increased surface area relative to the original dispersed arrangement, demanding more water for inter-particle lubrication

during compaction. Additionally, CKD hydration consumes water directly, further elevating the apparent water requirement during this phase (Adeyanju, 2019).

The subsequent decrease in OMC at 6–8% CKD reflects the progressive dominance of cementitious reactions. As CSH and CAH form, the soil's affinity for free water is reduced: the hydration products bond water into the solid phase and reduce the volume of pore space available to free water. Simultaneously, the void-filling effect of CKD improves particle packing efficiency, requiring less inter-particle moisture for adequate lubrication and compaction. The residual petroleum hydrocarbons also act as a partial water substitute in the lubrication role, contributing to the overall reduction in water demand at higher treatment levels.

The consistently lower OMC values observed under BSH compaction compared to WAS and BSL are fully consistent with compaction theory: higher compactive energy reduces the water needed to overcome inter-particle friction and achieve maximum density. This relationship holds across all CKD levels, confirming that compactive effort is an independent variable significantly influencing OMC response.

The interaction between residual crude oil hydrocarbons and the CKD stabilisation mechanism is noteworthy. The non-polar hydrocarbon residues in the vermi-remediated soil compete with water at the clay particle surface, modifying the effective OMC. At lower CKD dosages, this competition is more pronounced because fewer Ca<sup>2+</sup> ions are available for cation exchange, meaning the clay surface retains a significant hydrocarbon coating that reduces its water affinity. At higher CKD contents, extensive cation exchange and pozzolanic reactions displace hydrocarbons from particle surfaces, increasing hydrophilicity and stabilising the OMC at a lower equilibrium value.

These trends are in agreement with Akinwumi et al. (2020), who reported that bioremediation combined with chemical stabilisation initially increases moisture demand due to structural changes in soil, followed by a decrease as cementitious reactions

become dominant. Ochepeo et al. (2022) similarly found that industrial waste stabilisers reduce OMC at higher dosages due to improved particle arrangement and reduced void ratio. James et al. (2021) further emphasised that stabilisation of expansive soils with industrial by-products typically reduces OMC at higher additive contents due to decreased water affinity of the treated matrix.

#### IV. DISCUSSION

The integrated treatment of vermi-remediation followed by CKD stabilisation produced measurable and consistent improvements in the compaction behaviour of crude oil-contaminated black cotton soil. Table 3 summarises the key compaction and remediation outcomes.

Table 3: Summary of Treatment Outcomes for Vermi-remediated Crude Oil Contaminated BCS Stabilized with CKD

Parameter	Before Treatment	After Treatment (8% CKD, BSH)
TPH	5200 mg/kg	4033 mg/kg (22.44% reduction)
MDD (BSL)	1.63 Mg/m <sup>3</sup>	1.70 Mg/m <sup>3</sup>
MDD (WAS)	1.77 Mg/m <sup>3</sup>	1.81 Mg/m <sup>3</sup>
MDD (BSH)	1.85 Mg/m <sup>3</sup>	1.90 Mg/m <sup>3</sup>
OMC (BSL)	18.2%	16.8% at 8% CKD
OMC (WAS)	15.8%	15.9% at 8% CKD
OMC (BSH)	11.0%	13.7% at 8% CKD
NGS MDD Requirement	—	Met at 6–8% CKD

The role of vermiremediation in modifying subsequent compaction response deserves specific attention. Beyond reducing TPH by 22.44%, the earthworm activity induced structural bioturbation of

the soil: earthworm casts are known to be more granular and porous than surrounding soil, improving aeration, porosity, and water drainage capacity (Xiao et al., 2022). These structural modifications likely created a more receptive matrix for CKD interaction, facilitating the distribution of calcium ions through the soil mass and promoting more uniform flocculation and cementitious binding.

The pattern of MDD increase with compactive effort across all CKD levels demonstrates that compaction quality control is critical when using this combined treatment for subgrade construction. While 6–8% CKD achieves NGS-compliant MDD under BSL and BSH compaction, the WAS intermediate results suggest that field compaction equipment must be selected and operated to deliver energy levels at least equivalent to WAS specifications to reliably meet minimum density requirements.

From a sustainability perspective, the use of CKD an industrial solid waste as a soil stabiliser reduces disposal burden on cement factories while valorising a by-product that would otherwise contribute to landfill and environmental contamination. Combined with vermi-remediation, which uses biological organisms rather than chemical reagents, the overall treatment protocol represents a low-carbon, resource-efficient approach to managing contaminated soils for infrastructure purposes.

## V. CONCLUSION

This study examined the compaction behaviour of vermi-remediated crude oil-contaminated black cotton soil stabilized with Cement Kiln Dust (CKD) at 2–8% under three compactive efforts (BSL, WAS, BSH). The following conclusions are drawn:

- Vermiremediation using *Eisenia fetida* reduced TPH from 5200 mg/kg to 4033 mg/kg, achieving a remediation efficiency of 22.44%, confirming the biological treatment's effectiveness in partially degrading petroleum hydrocarbons.
- Maximum Dry Density (MDD) generally increased with CKD content across all compactive efforts, with peak values of 1.70, 1.81, and 1.90 Mg/m<sup>3</sup> achieved under BSL, WAS, and BSH compaction respectively at 8% CKD.

- Optimum Moisture Content (OMC) exhibited an initial increase at 2% CKD due to flocculation-induced water demand, followed by a progressive reduction at 6–8% CKD attributable to cementitious reactions (CSH and CAH formation) reducing soil's water affinity.
- MDD values at 6–8% CKD satisfied the Nigerian General Specifications (NGS, 2016) requirement of 1.70–1.90 Mg/m<sup>3</sup> for subgrade materials under BSL and BSH compaction.
- The combined treatment demonstrates the synergistic benefit of biological remediation and chemical stabilisation in restoring the compaction characteristics of petroleum-contaminated expansive soils for sustainable highway subgrade construction.

## RECOMMENDATIONS

- Field compaction trials should be conducted to validate laboratory compaction findings and establish appropriate equipment specifications for field implementation.
- Future research should investigate the long-term durability of compacted vermi-remediated CKD-stabilised soil under cyclic wetting and drying conditions.
- The optimisation of earthworm species, density, and exposure period should be further explored to maximise TPH reduction efficiency prior to CKD stabilisation.
- The economic viability of the combined treatment approach relative to conventional excavation and replacement should be quantified for cost-benefit analysis in large-scale road projects.
- Government agencies and road construction practitioners in petroleum-producing regions should consider adopting this integrated approach as a standard protocol for managing contaminated subgrade soils.

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