



Remediation Efficiency, Index Properties, and Compaction Characteristics of Vermi-Remediated Crude Oil-Contaminated Black Cotton Soil Stabilized with Cement Kiln Dust

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ABSTRACT

Crude oil contamination severely degrades the geotechnical performance of expansive black cotton soil (BCS), rendering it unsuitable for engineering reuse, while conventional stabilizers such as cement and lime remain costly and carbon-intensive. This study evaluates vermi-remediation using *Eisenia fetida* as a low-cost biological pre-treatment for crude oil-contaminated BCS, followed by stabilization with 0–8% cement kiln dust (CKD), an industrial by-product, with a view to reuse as landfill liner and cover material. Total petroleum hydrocarbon (TPH) content was determined gravimetrically before and after a 36-day vermi-remediation period, while index properties (natural moisture content, specific gravity, particle size distribution, and Atterberg limits) and compaction characteristics (maximum dry density, MDD, and optimum moisture content, OMC) of the remediated soil treated with CKD were investigated under three compactive efforts — British Standard Light (BSL), West African Standard (WAS), and British Standard Heavy (BSH) — in accordance with BS 1377 (1990, 2016). Vermi-remediation reduced the average TPH concentration from 5200 mg/kg to 4033 mg/kg, corresponding to a removal efficiency of 22.43%. CKD treatment increased the liquid limit from 53.10% to 55.60%, the plastic limit from 20.90% to 27.10%, and specific gravity from 2.320 to 2.340, while the plasticity index decreased from 32.20% to 28.50% and fines content declined across all compactive efforts, an outcome attributed to flocculation and agglomeration induced by cementitious hydration products. MDD ranged from 1.60–1.90 g/cm³ and OMC from 11.00–19.36%, both within limits recommended for landfill liner and cover materials. The results demonstrate that combining biological remediation with waste-derived chemical stabilization is a viable, sustainable pathway for converting hydrocarbon-contaminated expansive soils into geotechnically acceptable barrier materials.

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INTRODUCTION

Soil contamination by crude oil is a major environmental and geotechnical challenge in petroleum-producing regions, particularly within Nigeria's Niger Delta and Middle Belt areas. Crude oil infiltration coats clay particles, breaks down interparticle bonds, and impairs compaction efficiency and load-bearing capacity (Nwankwoala

& Warmate, 2023). From a geotechnical standpoint, contaminated expansive soils exhibit reduced cohesion, increased compressibility, and pronounced volumetric instability (Ibrahim et al., 2023; Abiola & Eze, 2022). Black cotton soil (BCS) is a montmorillonite-dominated expansive clay characterized by pronounced shrink-swell

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behaviour, low shear strength, and high plasticity (Khan et al., 2024; Aliyu et al., 2023).

Crude oil contamination compounds these deficiencies, lubricating clay particles and further weakening interparticle bonding (Nwankwoala & Warmate, 2023), while its inherent susceptibility to differential settlement and cracking makes it unsuitable for use as landfill liner or cover material without adequate treatment (Onyia et al., 2025). Although conventional stabilizers such as cement and lime improve the properties of expansive soils, their high cost and carbon footprint limit sustainable large-scale application (Bamidele et al., 2024), motivating growing interest in industrial by-products such as cement kiln dust (CKD) as low-carbon alternatives (Muhammad et al., 2023; Khan et al., 2024).

Vermi-remediation — the use of earthworms such as *Eisenia fetida* to degrade organic contaminants — has attracted increasing attention as an environmentally benign treatment for hydrocarbon-polluted soils (Babalola & Ibrahim, 2021; Adhikari et al., 2022). Earthworms enhance soil aeration and support gut-associated microbial consortia that break down hydrocarbons, reducing total petroleum hydrocarbon (TPH) concentrations (Oluwatosin et al., 2023). However, vermi-remediated soils typically retain inadequate engineering strength owing to residual organic matter, necessitating subsequent mechanical or chemical stabilization for geotechnical reuse (Oluwatosin et al., 2023).

Cement kiln dust, a calcium oxide-rich particulate by-product of cement manufacture, reacts with aluminosilicate clay minerals to form cementitious calcium silicate hydrate (C–S–H) and calcium aluminate hydrate (C–A–H) products that reduce plasticity, control shrinkage, and lower hydraulic conductivity (Zhou et al., 2023; Muhammad et al., 2023). Soils stabilized with CKD have shown improved compaction characteristics and strength suitable for landfill liner and cover applications (Almuaythir & Abbas, 2023), and combining vermi-remediation with CKD stabilization offers a synergistic route to soils that are simultaneously environmentally safer and structurally competent (Adesina et al., 2024).

Although vermi-remediation and CKD stabilization have each been studied independently, their combined application to crude oil-contaminated expansive soils remains scarcely investigated, particularly in the Nigerian context (Oluwatosin et al., 2023). This paper addresses that gap by reporting the hydrocarbon removal efficiency of vermi-remediation and the resulting index properties and compaction characteristics of vermi-remediated, CKD-stabilized black cotton soil, evaluated in accordance with BS 1377 (1990; 2016) and the Nigerian General Specification (1997), with a view to establishing its suitability for landfill liner and cover applications.

MATERIALS AND METHODS

Soil, Crude Oil, and Cement Kiln Dust

Disturbed black cotton soil samples were obtained from Gamadadi, Borno State, Nigeria (10.320163° N, 11.5484146° E) at a depth of 1.5–2.0 m below the surface, air-dried, and pulverized to pass a BS No. 4 (4.76 mm) sieve. Bonny Light crude oil (API gravity \approx 35.9°), obtained from the Nigerian National Petroleum Corporation Limited depot, Port Harcourt, was used to artificially contaminate the soil at a rate of 0.75 L of crude oil per 10 kg of dry soil, with 1 L of water added to promote uniform distribution. The soil–oil mixture was homogenized and cured in sealed containers for one month to allow adequate soil–hydrocarbon interaction prior to treatment (Nduka et al., 2023). Cement kiln dust, a calcium oxide-rich by-product sourced from the BUA Cement Factory, Kalambaina, Sokoto State, Nigeria, was used as the chemical stabilizer at 0, 2, 4, 6, and 8% by dry weight of soil.

Vermi-Remediation Procedure

Vermi-remediation was carried out using *Eisenia fetida* (Tiger worm), selected for its tolerance of organic pollutants and proven biodegradation capacity (Adhikari et al., 2022). Adult, clitellate earthworms were acclimatized for one week before being introduced into the crude oil-contaminated soil at a density of 60 earthworms per 40 kg of soil (300 earthworms per

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200 kg batch). The soil–earthworm mixtures were held in perforated, shaded containers for 30 days, with daily moistening to sustain optimal moisture for earthworm survival and microbial hydrocarbon degradation.

Determination of Total Petroleum Hydrocarbon (TPH) Removal Efficiency

TPH content was determined before and after vermi-remediation using solvent extraction with dichloromethane followed by gas chromatography–mass spectrometry (GC–MS), following the procedure of Sani et al. (2023). The TPH removal efficiency was computed as:

$$\text{TPH(RE) (\%)} = \left[\frac{\text{TPHi} - \text{TPHf}}{\text{TPHi}} \right] \times 100 \dots(1)$$

where TPHi and TPHf are the initial and final TPH concentrations (mg/kg), respectively.

Determination of Index Properties

Natural moisture content, specific gravity, particle size distribution, and Atterberg limits (liquid limit, plastic limit, plasticity index, and linear shrinkage) were determined in accordance with BS 1377 (1990, 2016), Part 2, for the untreated soil and for the vermi-remediated soil treated with 0, 2, 4, 6, and 8% CKD. Specific gravity was determined using the density bottle method, with three replicate determinations averaged for each CKD dosage. Dry sieve analysis was performed on 200 g soil samples for each treatment level under the three compactive efforts described in Section 2.5, to evaluate the influence of CKD-induced flocculation on the fines fraction (percentage passing the 0.075 mm sieve).

Compaction Test

Standard laboratory compaction tests were performed on the vermi-remediated soil

treated with 0–8% CKD, in accordance with BS 1377: Part 4 (1990), using three compactive efforts: British Standard Light (BSL) — 2.5 kg rammer, 305 mm drop height, 3 layers, 27 blows per layer; West African Standard (WAS); and British Standard Heavy (BSH) — 4.5 kg rammer, 450 mm drop height, 5 layers, 27 blows per layer, all applied in a 1000 cm³ mould. For each compactive effort, the soil was compacted at progressively increasing moisture content, and the bulk and dry densities were computed from the mass of compacted soil and the oven-determined moisture content of each point. The maximum dry density (MDD) and optimum moisture content (OMC) were obtained from the peak of the resulting dry density–moisture content curve for each CKD dosage.

RESULTS AND DISCUSSION

Properties of Materials Used in the Study

Index properties of the natural soil

Preliminary test conducted on the natural properties of the soil reveal that the soil has low moisture content of 18.7% because the sample were collected before the raining season. The index properties of soil are summarized in table 1. The soil belongs to the CH group in the Unified Soil Classification System (ASTM, 1992) and A-7-6(11) soil group of the AASHTO soil classification system (AASHTO, 1986). The soil is greyish black colour (from wet to dry states) with a liquid limit of 52.10%, plastic limit of 20.90% and plasticity index of 32.20%. The oxide composition of the crude oil contaminated soil and oxide composition of CKD are shown in table 2 and 3 respectively.

Table 1: Physical properties of the vermin-remediated crude oil contaminated soil used for the study

Property	Quantity
Natural moisture content (%)	18.7
Percentage passing No 200	48.53
Liquid limit (%)	53.10
Plastic limit (%)	20.90
Plasticity index (%)	32.20
Linear shrinkage (%)	16.43

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Property	Quantity
Specific gravity	2.46
ASHTO Classification	A-7-6 (11)
USCS Classification	CL
Group Index (GI)	12
Maximum dry density (mg/m ³)	1.63
British Standard Light (BSL)	1.77
West African Standard (WAS)	1.85
British Standard Heavy (BSH)	
Optimum Moisture Content (mg/m ³)	18.22
British Standard Light (BSL)	15.80
West African Standard (WAS)	11.00
British Standard Heavy (BSH)	
Colour	Dark Brown
Dominant clay mineral	Montmorillonite

Table 2: Oxide Composition of Crude Oil Contaminated Black Cotton Soil

Element Oxide	Concentration (%)	Element Oxide	Concentration (%)
SiO ₂	60.59	TiO ₂	1.99
Al ₂ O ₃	18.41	P ₂ O ₅	0
Fe ₂ O ₃	11.89	Mn ₂ O ₅	0.02
CaO	2.51	Rb ₂ O ₅	0.03
MgO	0	PbO	0.02
SO ₃	0.142	Cr ₂ O ₃	0.03
Na ₂ O	1.37	MnO	0.26
K ₂ O	2.78	LOI	17.34

Table 4.4 Oxide Composition of Cement Kiln Dust (CKD)

Element Oxide	Concentration (%)	Element Oxide	Concentration (%)
SiO ₂	11.5	TiO ₂	0.39
Al ₂ O ₃	4.99	P ₂ O ₅	0.01
Fe ₂ O ₃	5.31	Mn ₂ O ₅	ND
CaO	75.03	Rb ₂ O ₅	0.03
MgO	0	PbO	0.04
SO ₃	1.18	Cr ₂ O ₃	0
Na ₂ O	0.43	MnO	0.15
K ₂ O	0.27	LOI	3.5

Remediation Efficiency of Vermi-Treatment

The gravimetric TPH analysis showed that the untreated crude oil-contaminated black cotton soil had an average TPH concentration of 5200 mg/kg, indicating substantial hydrocarbon

pollution capable of impairing soil aeration, microbial activity, and engineering behaviour (Adefemi & Adeleke, 2023). Following 30 days of vermi-remediation, the average TPH concentration declined to 4033 mg/kg (Figure 1a–

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b), corresponding to a removal efficiency of 22.43%, consistent with the range reported by

Nduka et al. (2023) for biologically treated hydrocarbon-impacted soils.

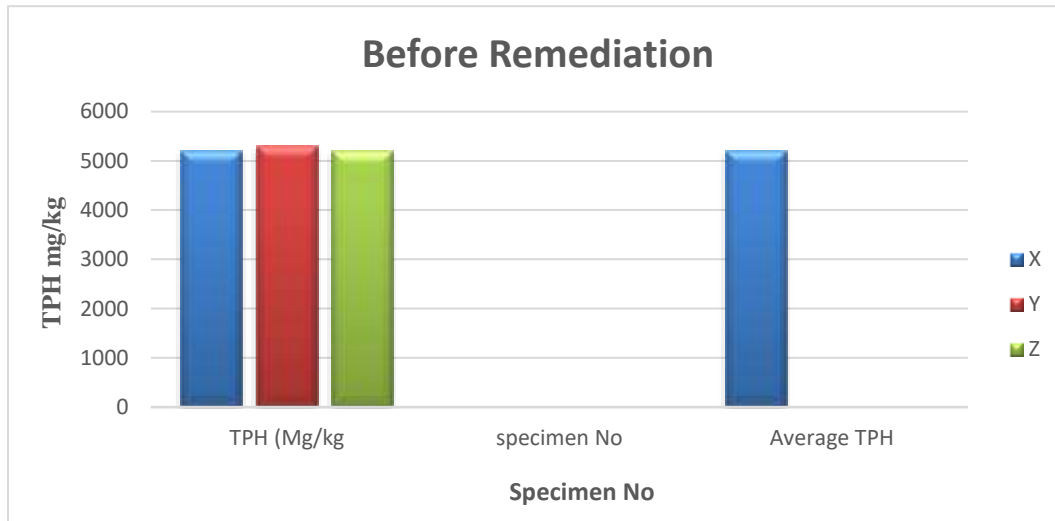


Figure 1a: Total petroleum hydrocarbon (TPH) content of crude oil–contaminated black cotton soil before remediation

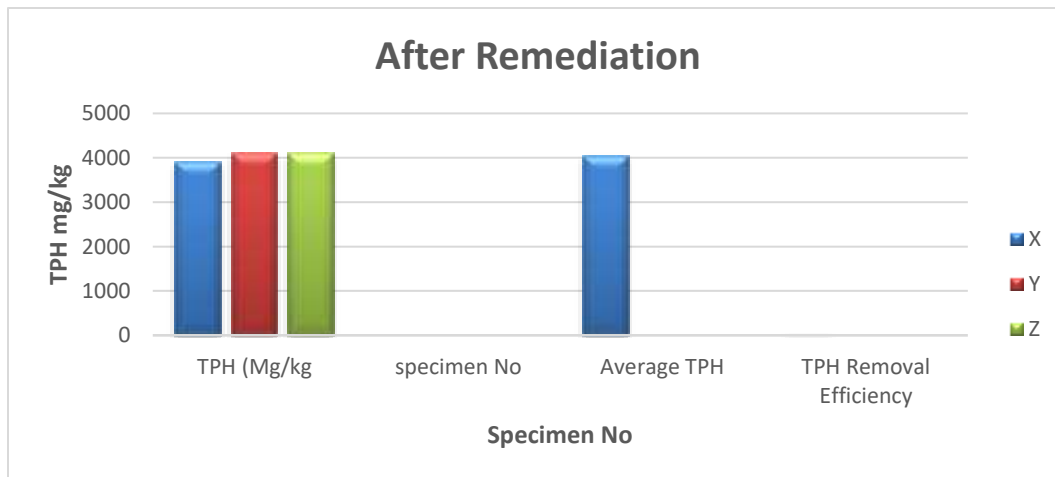


Figure 1b: Total petroleum hydrocarbon (TPH) content of vermi-remediated crude oil–contaminated black cotton soil

The reduction in TPH is attributed to the combined burrowing and gut-microbial action of *Eisenia fetida*, which enhances soil aeration and facilitates microbial breakdown of complex hydrocarbon molecules into simpler, less toxic compounds (Oluwatosin et al., 2023). Although the 22.43% removal efficiency reflects only partial

remediation, it confirms that vermi-remediation is a viable, low-cost, and environmentally benign pre-treatment step, whose efficiency could be further enhanced by optimizing remediation duration, earthworm density, and moisture regime prior to subsequent chemical stabilization (Babalola & Ibrahim, 2021).

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Index Properties of the Untreated and CKD-Treated Vermi-Remediated Soil

The natural (untreated) soil had a low natural moisture content of 18.70%, attributed to sample collection prior to the rainy season, a liquid limit of 53.10%, plastic limit of 20.90%, and plasticity index of 32.20%, classifying it as CL/A-7-6 (group index 12) under the Unified Soil

Classification System and AASHTO systems, respectively, confirming its highly plastic, expansive character (Ibrahim et al., 2023). The particle size distribution curve of the contaminated soil (Figure 2) shows 48.53% of particles finer than the 0.075 mm sieve, typical of fine-grained expansive clays.

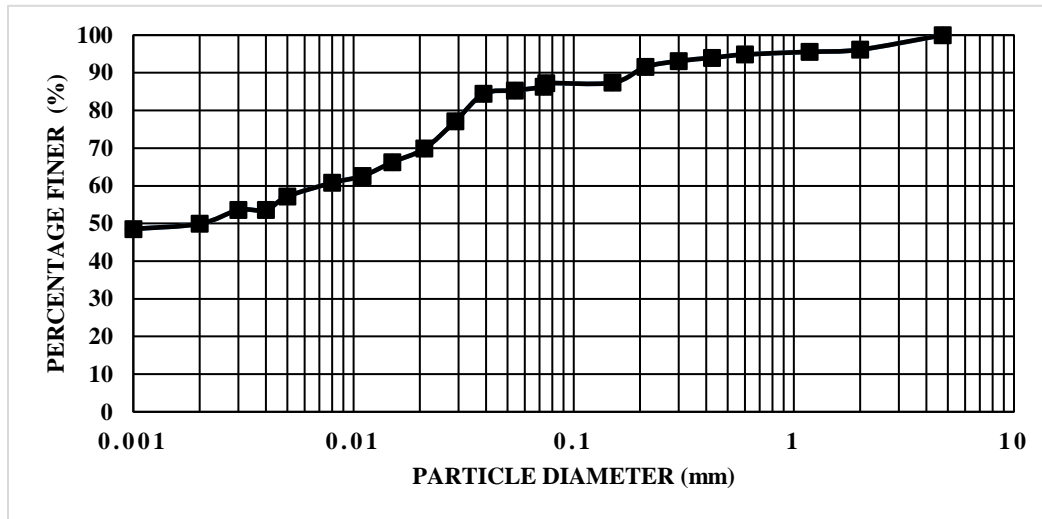


Figure 2: Particle size distribution curve of crude oil-contaminated black cotton soil

Dry sieve analysis of the vermi-remediated soil treated with 0–8% CKD under the BSL, WAS, and BSH compactive efforts consistently showed a decrease in the percentage of fines with increasing CKD content — for example, from 1.6% to 0.35% under BSL between 0% and 8% CKD. This reduction is attributed to cement hydration products acting as nucleation sites that promote flocculation and agglomeration of clay particles into coarser aggregates, a trend consistent with the findings of Oyelakin (2010), Sani (2012), and Osinubi et al. (2021).

The variation of Atterberg limits with CKD content is presented in Figure 3. The liquid limit increased steadily from 53.10% at 0% CKD to 55.60% at 8% CKD, while the plastic limit rose

from 20.90% to 27.10% over the same range, both increases attributable to the hydration of CKD constituents and the greater water demand of cation-exchange and flocculation reactions. Conversely, the plasticity index decreased from 32.20% to 28.50%, reflecting reduced clay activity and improved workability, while linear shrinkage increased from 12.14% to 20.00%, with a slight fluctuation, due to increased fines-related water retention and incomplete stabilization at higher CKD dosages. All obtained values (liquid limit 53.10–55.60%; plasticity index 28.50–32.20%; linear shrinkage 12.14–20.00%) fall within the ranges generally recommended for landfill liner and cover material, and are consistent with the findings of Sharma et al. (2023) and Amadi (2010).

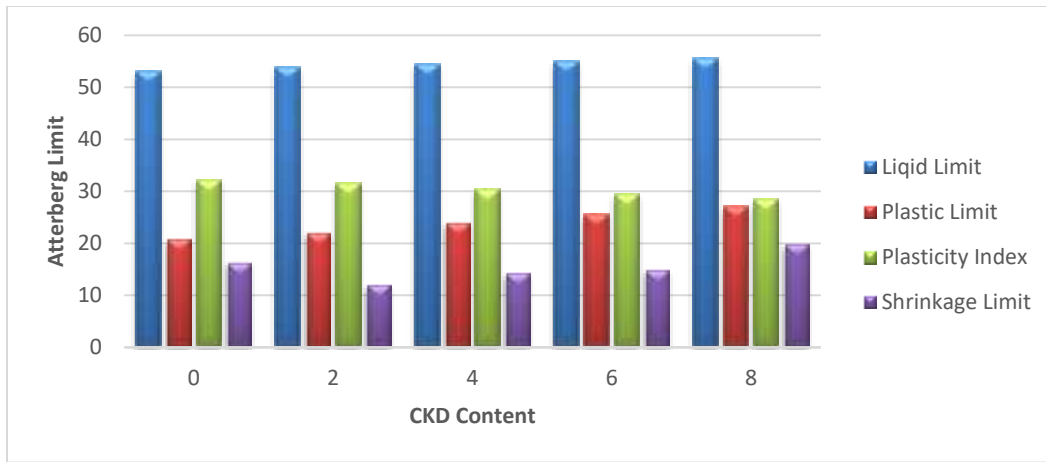


Figure 3: Variation of Atterberg limits of vermi-remediated crude oil-contaminated black cotton soil with CKD content

Specific gravity increased slightly and non-monotonically from 2.320 at 0% CKD to a maximum of 2.340 at 6–8% CKD (Figure 4), a trend attributed to the incorporation of denser CKD particles, void-filling effects, and the formation of dense cementitious reaction products, consistent with the observations of Alhassan and Mustapha (2007) and Amadi (2010). The highest specific gravity, coinciding with the CKD dosage identified as optimum in strength terms (6%), suggests a denser, better-packed soil matrix favourable for containment applications.

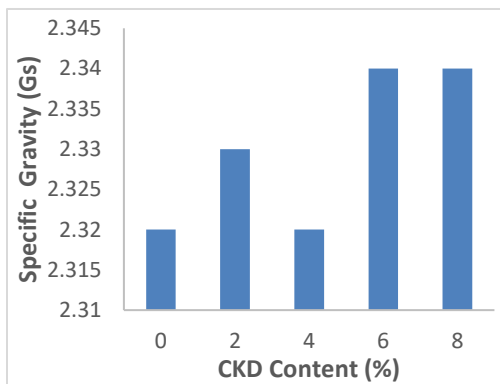


Figure 4: Variation of specific gravity of vermi-remediated crude oil-contaminated black cotton soil with CKD content.

Compaction Characteristics

The variation of maximum dry density (MDD) with CKD content for the three compactive efforts is shown in Figure 5. Under BSL compaction, MDD initially decreased from 1.63 g/cm³ at 0% CKD to 1.60 g/cm³ at 2% CKD, before rising to 1.70 g/cm³ at 8% CKD. A similar non-monotonic trend was observed for WAS (1.73–1.83 g/cm³) and BSH (1.83–1.90 g/cm³) compaction, with BSH consistently producing the highest MDD, followed by WAS and then BSL.

The initial decline in MDD is attributed to CKD particles occupying void spaces and inducing flocculation of clay particles through ion exchange, while the subsequent increase reflects improved particle packing and pore-space reduction as pozzolanic reactions progress. The overall MDD range obtained (1.60–1.90 g/cm³) falls within the acceptable range of 1.50–1.90 g/cm³ specified by ASTM D698, and is consistent with the findings of Adeyemi and Ogunsanwo (2001) and Alhassan and Mustapha (2007).

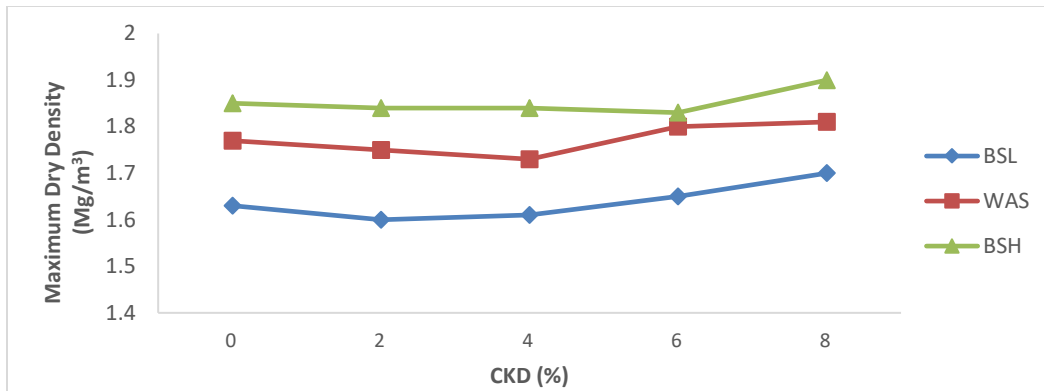


Figure 5: Variation of maximum dry density of vermi-remediated crude oil–contaminated black cotton soil with CKD content for BSL, WAS, and BSH compactive efforts

The corresponding variation of optimum moisture content (OMC) is shown in Figure 6. Under BSL compaction, OMC decreased from 19.36% at 2% CKD to 16.80% at 8% CKD; under WAS compaction, OMC increased slightly from 15.80% at 0% CKD to 16.65% at 2% CKD before declining to 15.84% at 8% CKD; and under BSH compaction, OMC rose from 11.00% at 0% CKD to 14.70% at 6% CKD before falling to 13.80% at 8% CKD. These trends reflect the dual effect of

CKD in filling soil voids and promoting flocculation, which reduces the water demand for compaction, counterbalanced by the higher initial water requirement for densification under heavier compactive effort. The obtained OMC range (11.00–19.36%) falls within the acceptable range of 15.00–30.00% recommended by ASTM D698 for the majority of the treatment levels, and the results are in agreement with Adeyemi and Ogunsanwo (2001) and Alhassan and Mustapha (2007).

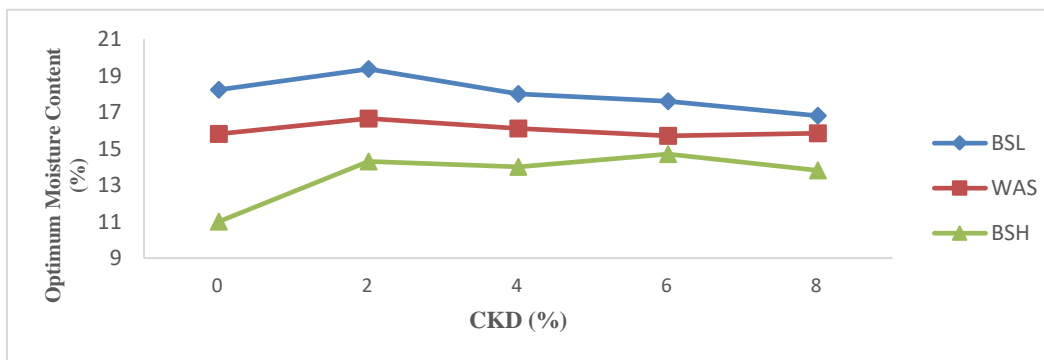


Figure 6: Variation of optimum moisture content of vermi-remediated crude oil–contaminated black cotton soil with CKD content for BSL, WAS, and BSH compactive efforts

Collectively, the compaction results indicate that increasing compactive effort (BSL → WAS → BSH) consistently raises MDD and lowers OMC, while CKD addition governs a secondary, non-monotonic adjustment driven by competing void-filling/flocculation and particle-packing mechanisms. Because both MDD and

OMC remained within the ranges recommended for landfill liner and cover material across all CKD dosages and compactive efforts, the vermi-remediated, CKD-stabilized black cotton soil demonstrates suitable compactibility for such applications.

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CONCLUSION

This study evaluated the remediation efficiency, index properties, and compaction characteristics of crude oil-contaminated black cotton soil treated by vermi-remediation using *Eisenia fetida* and subsequently stabilized with 0–8% cement kiln dust. Vermi-remediation achieved a 22.43% reduction in total petroleum hydrocarbon content over 30 days, confirming its potential as a low-cost, environmentally friendly biological pre-treatment, albeit one whose efficiency could be enhanced through further optimization of remediation duration, earthworm density, and moisture conditions.

CKD stabilization increased the liquid limit, plastic limit, and specific gravity of the vermi-remediated soil while reducing plasticity index and fines content, reflecting flocculation and cementitious hydration reactions that improved the soil's index characteristics. Compaction testing across British Standard Light, West African Standard, and British Standard Heavy efforts showed maximum dry density and optimum moisture content values of 1.60–1.90 g/cm³ and 11.00–19.36%, respectively, both within limits recommended for landfill liner and cover materials. Overall, the findings demonstrate that combining biological vermi-remediation with waste-derived CKD stabilization offers a sustainable and technically viable strategy for converting hydrocarbon-contaminated expansive soils into geotechnically acceptable materials for landfill barrier applications, with 6% CKD content identified as an efficient dosage balancing index and compaction performance.

Further studies are recommended to optimize vermi-remediation parameters (duration, earthworm density, and moisture regime) to improve hydrocarbon removal efficiency, and to extend the present laboratory findings through field-scale trials to validate the practical performance of vermi-remediated, CKD-stabilized black cotton soil as a landfill liner and cover material.

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