JOURNAL OF SCIENCE TECHNOLOGY AND EDUCATION 14(2), JUNE, 2026
E-ISSN: 3093-0898, PRINT ISSN: 2277-0011; Journal homepage: www.atbufstejoste.com

Stabilization of Vermiremediated Crude Oil-Contaminated Lateritic Soil Using Cement Kiln Dust for Landfill Liner and Cover Applications

J. E. Sani, M. A. Hamza, G. Moses, Z. I. Ummisawa
Department of Civil Engineering,
Nigerian Defence Academy (NDA), Kaduna, Nigeria

ABSTRACT

Crude oil pollution of tropical lateritic soils remains a persistent geo-environmental problem in oil-producing regions such as the Niger Delta of Nigeria, where spillage, pipeline vandalism and artisanal refining continually degrade soils that would otherwise be suitable for engineering use. This study evaluated the combined use of vermiremediation and cement kiln dust (CKD) stabilization to recondition crude oil-contaminated lateritic soil for use as a compacted liner and cover material in waste containment systems. Lateritic soil obtained from Shika, Zaria, Nigeria, was artificially contaminated with crude oil, bioremediated using the earthworm species Eudrilus eugeniae, and subsequently stabilized with 0, 2, 4, 6 and 8% CKD by dry weight of soil. Vermiremediation reduced the total petroleum hydrocarbon (TPH) content of the contaminated soil from 4500 to 3300 mg/kg, a removal efficiency of 27%. Stabilization with CKD produced a general reduction in liquid limit, from 54% at 0% CKD to a minimum of 43% at 8% CKD, and reduced the plasticity index from 21.7% to 16.9% at 6% CKD. Maximum dry density increased from 1.63 Mg/m³ under British Standard Light (BSL) compaction to a peak of 1.84 Mg/m³ at 4% CKD under British Standard Heavy (BSH) compaction, while optimum moisture content increased moderately with CKD content, consistent with the additional water demand for hydration and pozzolanic reaction. Unconfined compressive strength (UCS) improved markedly with treatment, rising from 170.2 kN/m² in the untreated soil to a maximum of 748.2 kN/m² at 6% CKD, +2% moulding water content and BSH compaction. Volumetric shrinkage strain (VSS) fell from 5.01% in the untreated soil to a minimum of 2.60% at 8% CKD, while hydraulic conductivity decreased with treatment, reaching values as low as 3.7 × 10^{-8} cm/s at 4-6% CKD under BSH compaction. Based on criteria commonly specified for compacted clay liners and covers (UCS ≥ 200 kN/m², VSS ≤ 4% and hydraulic conductivity ≤ 1 × 10^{-7} cm/s), vermiremediated crude oil-contaminated lateritic soil stabilized with 6% CKD satisfies the engineering requirements for use as a landfill liner and cover material, offering a low-cost, dual-mechanism route for the beneficial reuse of a petroleum-impacted soil together with an industrial by-product.

ARTICLE INFO
Article History
Received: January, 2026
Received in revised form: March, 2026
Accepted: March, 2026
Published online: June, 2026

KEYWORDS
Vermiremediation; Crude Oil Contamination; Cement Kiln Dust; Lateritic Soil; Atterberg Limits; Unconfined Compressive Strength; Volumetric Shrinkage Strain; Hydraulic Conductivity; Landfill Liner

INTRODUCTION

Soil is one of the most widely used natural construction materials, and the performance, durability and safety of geotechnical and geo-environmental structures depend fundamentally on its engineering properties. Residual lateritic soils are especially important in tropical regions, including much of Nigeria, where

Corresponding author: M. A. Hamza
jesani@nda.edu.ng
Department of Civil Engineering, Nigerian Defence Academy (NDA), Kaduna, Nigeria.

JOURNAL OF SCIENCE TECHNOLOGY AND EDUCATION 14(2), JUNE, 2026
E-ISSN: 3093-0898, PRINT ISSN: 2277-0011; Journal homepage: www.atbufstejoste.com

they are abundantly available and are routinely used in road construction, embankments and, increasingly, as compacted liner and cover material in engineered landfills (Osinubi et al., 2023). Where the natural soil falls short of the performance requirements of a given application, ground improvement techniques are employed to modify its index, compaction, strength and hydraulic properties.

Crude oil exploration, transportation and refining activities in Nigeria's Niger Delta and other producing regions have, however, left extensive areas of soil contaminated by spillage, pipeline vandalism, and illegal refining (Michael-Igoli et al., 2022). Crude oil is a complex mixture of aliphatic and cyclic hydrocarbons, resins and asphaltenes, several of which -- notably the polycyclic aromatic hydrocarbons (PAHs) -- are toxic, persistent and resistant to natural degradation because of their hydrophobic character (Thacharodi et al., 2023; Saeed et al., 2024). Their presence in soil alters basic geotechnical behaviour: hydrocarbon films coat soil particles, interfere with clay-water interaction, reduce shear strength, and generally render the soil unsuitable for direct engineering use (Akinwumi et al., 2023).

Among the range of remediation options available, vermiremediation -- the use of earthworms and their associated microbiota to accelerate the biodegradation of organic contaminants -- has attracted growing interest as a low-cost and environmentally benign technique. Through burrowing, ingestion and casting, earthworms aerate the soil, stimulate microbial populations and increase the enzymatic activity responsible for hydrocarbon breakdown, while simultaneously improving soil structure (Khan et al., 2023; Ansari et al., 2023; Poornima et al., 2024). Field and laboratory studies have reported total petroleum hydrocarbon (TPH) reductions ranging from about 30% to over 90%, depending on contaminant concentration, earthworm species, stocking density and exposure period (Li et al., 2023). Vermiremediation alone, however, rarely restores the soil to a level suitable for structural or barrier applications, since the residual hydrocarbon fraction and the altered clay fabric continue to depress strength and increase compressibility; a subsequent geotechnical stabilization step is therefore usually required.

Cement kiln dust (CKD), a fine-grained, calcium-rich by-product of Portland cement manufacture, is an attractive stabilizing agent for this purpose. It is generated in large quantities at cement plants, is considerably cheaper than ordinary Portland cement or hydrated lime, and its use as a stabilizer diverts an industrial waste stream from open dumping while lowering the net carbon footprint associated with conventional cement- or lime-based ground improvement (Chauhan et al., 2024; Yan et al., 2025). When mixed with fine-grained soils, the free lime and calcium sulphate in CKD promote cation exchange, flocculation and pozzolanic reactions that reduce plasticity, increase strength and lower permeability (Amadi and Eberemu, 2013; Osinubi et al., 2015). These same characteristics make CKD-treated lateritic soils attractive candidates for compacted clay liners and covers in waste containment systems, where regulatory practice typically requires a minimum unconfined compressive strength of about 200 kN/m^2, a volumetric shrinkage strain not exceeding 4%, and a saturated hydraulic conductivity no greater than 1×10^{-7} cm/s (Daniel and Wu, 1993; Amadi and Eberemu, 2013).

While the individual effects of vermiremediation and of CKD stabilization have each received attention in the literature, few studies have examined the two techniques in combination, applied specifically to crude oil-contaminated lateritic soil intended for landfill barrier use. This study therefore investigated the index, compaction, strength, shrinkage and hydraulic conductivity characteristics of a vermiremediated crude oil-contaminated lateritic soil stabilized with 0-8% CKD, with the aim of establishing whether the treated soil meets the performance criteria required of compacted liner and cover materials. Specifically, the study sought to (i) determine the TPH removal efficiency achieved by vermiremediation, (ii) evaluate the effect of CKD content on the index and compaction properties of the vermiremediated soil, and (iii) assess the strength, shrinkage and

Corresponding author: M. A. Hamza
jesani@nda.edu.ng
Department of Civil Engineering, Nigerian Defence Academy (NDA), Kaduna, Nigeria.

JOURNAL OF SCIENCE TECHNOLOGY AND EDUCATION 14(2), JUNE, 2026
E-ISSN: 3093-0898, PRINT ISSN: 2277-0011; Journal homepage: www.atbufstejoste.com

hydraulic conductivity of the treated soil against established landfill barrier criteria.

MATERIALS AND METHODS

Materials

Lateritic soil

The lateritic soil used in this study was obtained by disturbed sampling from a borrow pit at Shika, Zaria, Kaduna State, Nigeria (latitude 11°15' N, longitude 7°45' E), from the B-horizon at a depth of between 1.5 and 2.0 m, where accumulation of material leached from the overlying A-horizon typically produces a more homogeneous, fines-rich material. The bulk sample was air-dried and pulverized to pass BS No. 4 sieve (4.76 mm aperture) before storage in sealed bags. The natural soil is light brown, fine-grained, with kaolinite as the dominant clay mineral, and classifies as CL (Unified Soil Classification System) or A-7-6 (AASHTO); its principal index properties are summarized in Table 1.

Crude oil

The crude oil used to simulate contamination was sourced from Port Harcourt, Rivers State, Nigeria, representative of the light, sweet crude typically associated with Niger Delta spillage incidents.

Cement kiln dust

The cement kiln dust (CKD) used as the stabilizing admixture was obtained from the BUA Cement plant (formerly the Sokoto Cement Company) in Sokoto State, Nigeria. Oxide analysis by X-ray fluorescence (Table 2) shows that the CKD is dominated by calcium oxide (53.23%), with appreciable sulphate (12.0%) and comparatively low silica and alumina contents relative to the parent soil, consistent with its established role as a source of free lime and calcium sulphate capable of driving cation exchange and pozzolanic reactions in fine-grained soils (Amadi and Eberemu, 2013).

Table 1: Oxide composition of the lateritic soil and cement kiln dust used in the study

Oxide	Lateritic soil (%)	Cement kiln dust (%)
SiO_2	41.05	16.05
Al_2O_3	24.16	4.16
Fe_2O_3	10.16	1.98
CaO	0.23	53.23
MgO	0.21	1.21
SO_3	1.04	12.00
Na_2O	1.37	1.37
K_2O	0.34	1.99
Loss on ignition (LOI)	19.35	9.35

Earthworms (Eudrilus eugeniae)

The earthworm species used for Verm remediation, Eudrilus eugeniae, was sourced from the Kaduna River axis around the Kabala Doki area of Kaduna State. This species is widely favoured for tropical vermiremediation work because of its tolerance of a broad range of organic contaminant concentrations and its high reproductive and burrowing activity (Khan et al., 2023).

Water

Potable water used for mixing and curing was obtained from the Soil Mechanics

Corresponding author: M. A. Hamza
jesani@nda.edu.ng
Department of Civil Engineering, Nigerian Defence Academy (NDA), Kaduna, Nigeria.

Laboratory of the Department of Civil Engineering, Nigerian Defence Academy, Kaduna.

Contamination and vermiremediation procedure

The air-dried, pulverized soil was artificially contaminated with crude oil at a rate of 75 cl of crude oil per 10 kg of soil, together with 1000 ml of water, thoroughly mixed and sealed for a period of one month to allow full contaminant-soil interaction. The contaminated soil was thereafter remediated using earthworms introduced at rates of 40, 50, 60, 70 and 80 worms per 40 kg of contaminated soil (equivalent to a total of 300 worms per 200 kg of soil), placed in perforated, aerated tanks for a further period of one month. The tanks were watered daily and monitored to sustain earthworm activity and survival throughout the remediation period.

Determination of total petroleum hydrocarbon (TPH)

TPH was determined by the gravimetric toluene cold-extraction method (USEPA Method 9071B), following the procedure reported by Khamehchiyan et al. (2007). Samples (2500 g) of air-dried soil, before and after vermiremediation, were extracted with 10 ml of toluene, stirred continuously for 30 minutes, left to stand in a fume cupboard for 2 hours, and filtered through Whatman No. 42 filter paper; the residue was oven-dried at 50°C. TPH content was computed as:

$$TPH\ (mg/kg) = [(W_0 - W_1) / \text{mass of sample}] \times 10^6 \quad (1)$$

where W_0 is the initial sample weight before extraction and W_1 is the sample weight after solvent extraction.

Determination of index properties (Atterberg limits)

Liquid limit (LL), plastic limit (PL) and plasticity index (PI) were determined for the natural, contaminated, vermiremediated and CKD-stabilized soils in accordance with BS 1377 (1990), Part 2. Liquid limit was determined using the Casagrande cup method, with the number of blows corresponding to a groove closure of 13 mm recorded across a range of moisture contents and the results plotted on a semi-logarithmic moisture content-blow count graph to obtain the value corresponding to 25 blows. Plastic limit was determined by rolling threads of soil to a diameter of about 3 mm until they crumbled. Plasticity index was computed as:

$$PI = LL - PL \quad (2)$$

Compaction characteristics

Compaction tests were performed on the natural and treated soils in accordance with BS 1377 (1990) Part 4, BS 1924 (1990) and the Nigerian General Specification (1997), using three compactive efforts: British Standard Light (BSL) -- 27 blows of a 2.5 kg rammer falling 300 mm on each of 3 layers in a 1000 cm³ mould; West African Standard (WAS) -- 10 blows of a 4.5 kg rammer falling 450 mm on each of 5 layers in the same mould; and British Standard Heavy (BSH) -- 27 blows of the 4.5 kg rammer on each of 5 layers. The maximum dry density (MDD) and optimum moisture content (OMC) for each compactive effort were obtained from the peak of the dry density-moisture content relationship, with dry unit weight computed as:

$$\rho_d = \rho_b / (1 + w) \quad (3)$$

where ρ_d is dry density, ρ_b is bulk density and w is moulding water content, expressed as a fraction.

Unconfined compressive strength (UCS)

UCS tests were carried out in accordance with BS 1377 (1990) Part 7. Specimens compacted at their respective OMC for each compactive effort were extruded and trimmed to cylinders 38.1 mm in diameter and 76.2 mm in length, cured for 48 hours, and loaded axially at a strain rate of 0.10 mm/min to failure. Tests were repeated at -2, 0, +2 and +4% of OMC to evaluate the influence of moulding water content. Compressive stress at any strain level was computed as:

$$\sigma = [R \times C^T \times (100 - E\%)] / (100 \times A_0) \quad (4)$$

where R is the load-ring reading, C^T is the load-ring calibration factor, E is the axial strain, and A_0 is the initial cross-sectional area of the specimen.

Corresponding author: M. A. Hamza
jesani@nda.edu.ng
Department of Civil Engineering, Nigerian Defence Academy (NDA), Kaduna, Nigeria.

JOURNAL OF SCIENCE TECHNOLOGY AND EDUCATION 14(2), JUNE, 2026
E-ISSN: 3093-0898, PRINT ISSN: 2277-0011; Journal homepage: www.atbufstejoste.com

Hydraulic conductivity

Hydraulic conductivity was measured using the falling-head permeameter recommended by Head (1994), on specimens compacted at each compactive effort and moulding water content, saturated for 48 hours prior to permeation while restrained from vertical swelling. Head readings were logged over a 24-hour permeation period at 4-hour intervals, and the coefficient of permeability computed as:

$$k = (2.303 \times a \times L) / (A \times t) \times \log_{10}(h_1/h_2) \qquad (5)$$

where a is the cross-sectional area of the standpipe, L is the specimen length, A is the specimen cross-sectional area, t is the elapsed time, and h_1 and h_2 are the initial and final standpipe water levels, respectively.

Volumetric Shrinkage Strain (VSS)

Specimens compacted at -2, 0, +2 and +4% of OMC for each compactive effort were extruded, measured for initial diameter and height using a vernier caliper accurate to 0.05 mm, and left to air-dry on a laboratory bench at 29 ± 2°C for 30 days, following the natural-drying approach considered more representative of field conditions than the air-conditioned drying used by Daniel and Wu (1993). Diameter and height were re-measured at the end of the drying period, and volumetric shrinkage strain computed from the change in specimen volume relative to the initial (moulded) volume.

RESULTS AND DISCUSSION

Index and strength properties of the natural and crude oil-contaminated soil

Table 1 compares the principal index, compaction and strength properties of the natural lateritic soil with those of the same soil after artificial contamination with crude oil, before any remediation or stabilization was applied. Contamination increased the liquid limit from 47.0% to 51.8% and the plastic limit from 27.3% to 32.3%, while the plasticity index remained broadly similar (19.7% to 19.5%). This behaviour is consistent with the coating of soil particles by hydrophobic hydrocarbon films, which alters surface activity and water-holding capacity without necessarily changing the range over which the soil remains plastic (Akinwumi et al., 2023).

More significantly, contamination reduced the unconfined compressive strength substantially -- from 335.3-537.0 kN/m² in the natural soil to only 119.3-146.7 kN/m² in the contaminated soil across the three compactive efforts -- reflecting the lubricating effect of the oil film on inter-particle contact and its interference with normal clay-water-cementitious bonding (Saeed et al., 2024). These reductions confirm that the contaminated soil, in its raw state, falls well short of the strength typically required for engineering use and motivates the combined remediation and stabilization approach adopted in this study.

Table 1: Index and strength properties of the natural and crude oil-contaminated lateritic soil

Property	Natural soil	Crude oil-contaminated soil
Percentage passing BS No. 200 sieve (%)	64.00	72.42
Liquid limit, LL (%)	47.00	51.80
Plastic limit, PL (%)	27.30	32.26
Plasticity index, PI (%)	19.70	19.50
Linear shrinkage (%)	11.43	11.00
Specific gravity	2.66	2.40
USCS classification	CL	CL
AASHTO classification	A-7-6 (12)	A-7-6 (12)

Corresponding author: M. A. Hamza
jesani@nda.edu.ng
Department of Civil Engineering, Nigerian Defence Academy (NDA), Kaduna, Nigeria.

JOURNAL OF SCIENCE TECHNOLOGY AND EDUCATION 14(2), JUNE, 2026
E-ISSN: 3093-0898, PRINT ISSN: 2277-0011; Journal homepage: www.atbufstejoste.com

Property	Natural soil	Crude oil-contaminated soil
MDD - BSL / WAS / BSH (Mg/m³)	1.68 / 1.76 / 1.87	1.62 / 1.63 / 1.86
OMC - BSL / WAS / BSH (%)	20.20 / 15.90 / 14.20	19.79 / 18.85 / 16.87
UCS - BSL / WAS / BSH (kN/m²)	335.3 / 409.0 / 537.0	140.3 / 146.7 / 119.3

Efficiency of crude oil contaminant removal by vermiremediation

Total petroleum hydrocarbon (TPH) is widely used as an index of petroleum contamination and of remediation performance (Ossai et al., 2020; Varjani et al., 2023). As shown in Table 2, the TPH concentration of the soil prior to vermiremediation averaged 4500 mg/kg across the three replicate samples. Following one month of treatment with Eudrilus eugeniae, the average TPH concentration fell to 3300 mg/kg (Table 3), corresponding to a removal efficiency of 27.0% for two of the three replicates and 24.0% for the third. This reduction is attributable to the combined action of earthworm burrowing, ingestion and casting, which aerates the soil, increases the surface area available for microbial colonization, and stimulates the native soil microbial community responsible for hydrocarbon biodegradation (Li et al., 2023; Adewuyi et al., 2022).

A removal efficiency in this range is consistent with values reported for short-duration (four- to eight-week) vermiremediation trials in the literature, which typically fall between about 20% and 45% before the process plateaus, with substantially higher removals reported only after several months of continuous treatment (Poornima et al., 2024; Ansari et al., 2023). While the 27% reduction achieved here is moderate rather than complete, it represents a meaningful first-stage reduction in contaminant loading ahead of the subsequent chemical stabilization step, and is broadly consistent with the view that vermiremediation is most effective as a pre-treatment rather than a stand-alone remediation strategy for heavily contaminated soils (Khan et al., 2023).

Table 2: Total petroleum hydrocarbon (TPH) of crude oil-contaminated soil before vermiremediation

S/N	Sample	Weight before extraction (mg)	Weight after extraction (mg)	Cycle	TPH (mg/kg)	Average TPH (mg/kg)
1	COCS1	10,000.00	9,560.00	4	4,400.00	4,500.00
2	COCS2	10,000.00	9,550.00	4	4,500.00	4,500.00
3	COCS3	10,000.00	9,550.00	4	4,500.00	4,500.00

Table 3: Total petroleum hydrocarbon (TPH) of crude oil-contaminated soil after vermiremediation

S/N	Sample	Weight before extraction (mg)	Weight after extraction (mg)	Cycle	TPH (mg/kg)	Average TPH (mg/kg)	Removal efficiency (%)
1	COCS1	10,000.00	9,680.00	4	3,200.00	3,300.00	27.00
2	COCS2	10,000.00	9,670.00	4	3,300.00	3,300.00	27.00
3	COCS3	10,000.00	9,660.00	4	3,400.00	3,300.00	24.00

Corresponding author: M. A. Hamza
jesani@nda.edu.ng
Department of Civil Engineering, Nigerian Defence Academy (NDA), Kaduna, Nigeria.

JOURNAL OF SCIENCE TECHNOLOGY AND EDUCATION 14(2), JUNE, 2026
E-ISSN: 3093-0898, PRINT ISSN: 2277-0011; Journal homepage: www.atbufstejoste.com

Effect of cement kiln dust on the Atterberg limits of the vermiremediated soil

Liquid limit

Figure 1 shows the variation of liquid limit with CKD content for the vermiremediated crude oil-contaminated soil. The untreated soil (0% CKD) recorded a liquid limit of 54%, appreciably higher than that of the uncontaminated soil (Table 1), reflecting residual organic matter and fine particle activity carried over from contamination (Akinwumi et al., 2023). Addition of 2% CKD produced an immediate and substantial reduction in liquid limit, to 44%, consistent with rapid cation exchange between the calcium ions supplied by the CKD and the exchangeable cations on the clay surfaces, which reduces the double-layer thickness and the water-holding capacity of the clay fraction (Oti and Kinuthia, 2023). A modest increase to 46% and 48% was recorded at 4% and 6% CKD respectively, before a further decrease to 43% -- the lowest value recorded in the study -- at 8% CKD, at which point sufficient cementitious compounds had likely formed to bind fine particles into larger, less water-retentive aggregates.

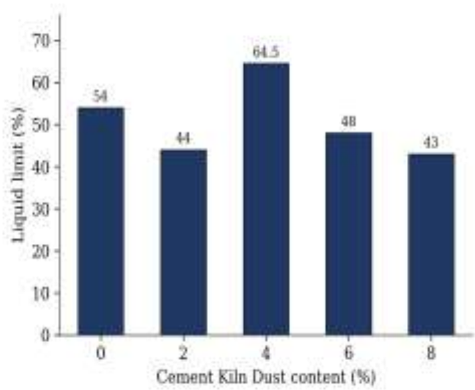

Fig. 1: Variation of liquid limit with CKD content

Plastic Limit

The plastic limit of the untreated soil (Figure 2) was 32.3%, decreasing sharply to 23.5% at 2% CKD, in agreement with the rapid cation-exchange response reported by Ochepo and Mohammed (2023) for CKD-treated tropical soils. With further CKD addition, the plastic limit increased progressively to 29.0% and 31.1% at 4% and 6% CKD respectively, before declining again to 24.8% at 8% CKD. The non-monotonic response reflects the competing influences of early flocculation (which tends to lower the plastic limit) and progressive cementation of the fabric at intermediate CKD contents (which tends to raise it), a pattern also noted by Eberemu et al. (2022) for contaminated soils undergoing simultaneous chemical stabilization.

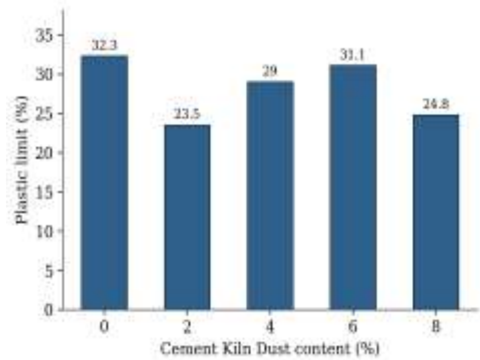

Fig. 2: Variation of plastic limit with CKD content

Plasticity Index

The plasticity index of the untreated soil (Figure 3) was 21.7%, indicating medium plasticity. A slight reduction to 20.5% was observed at 2% CKD, attributable to the immediate flocculating action of calcium ions released from the CKD (Alhassan et al., 2023). At 4% CKD, the plasticity index rose sharply to 35.5%, the highest value recorded in the study; this point departs from the otherwise decreasing trend and, since it coincides with the transitional dosage at which cation exchange and early cementation act simultaneously on the clay fabric, it should be interpreted with some caution pending confirmatory testing.

From 4% CKD onward, however, the plasticity index fell consistently, to 16.9% at 6% CKD and 18.2% at 8% CKD, indicating that higher CKD contents progressively suppressed the plastic behaviour of the fines through more complete cementation (Adeyanju et al., 2024). The plasticity index values obtained at 6% and 8%

Corresponding author: M. A. Hamza
jesani@nda.edu.ng
Department of Civil Engineering, Nigerian Defence Academy (NDA), Kaduna, Nigeria.

CKD fall within the range generally regarded as suitable for compacted liner and cover materials, which typically calls for low-to-moderate plasticity to balance workability against excessive shrink-swell behaviour (Daniel and Wu, 1993).

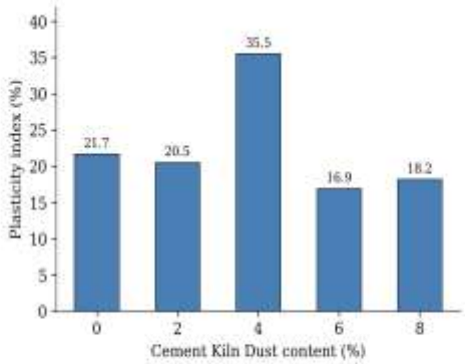

Fig. 3: Variation of plasticity index with CKD content

COMPACTION CHARACTERISTICS

Maximum Dry Density

Figure 4 presents the variation of maximum dry density (MDD) with CKD content for the three compactive efforts. Under BSL compaction, MDD increased only marginally, from 1.63 Mg/m³ in the untreated soil to a peak of 1.65 Mg/m³ at 6% CKD, before falling slightly at 8% CKD. Under WAS compaction, MDD remained relatively stable between 1.65 and 1.66 Mg/m³ up to 6% CKD, before rising markedly to 1.74 Mg/m³ at 8% CKD. The most pronounced response was recorded under BSH compaction, where MDD increased from 1.69 Mg/m³ in the untreated soil to a peak of 1.84 Mg/m³ at 4% CKD, before declining to 1.78 Mg/m³ and 1.76 Mg/m³ at 6% and 8% CKD respectively.

The general increase in MDD with CKD addition reflects the filling of soil voids by fine CKD particles and the flocculation of clay particles into a more open, compaction-responsive fabric, an effect that is amplified at higher compactive energy because greater energy input is better able to overcome the increased inter-particle friction introduced by early cementation (Eberemu et al., 2024; Ibrahim et al., 2022). The subsequent decline in MDD beyond the optimum CKD dosage under BSH compaction is consistent with the lower specific gravity of CKD relative to the soil solids it replaces, which becomes the dominant effect once sufficient cementitious bonding has already been established.

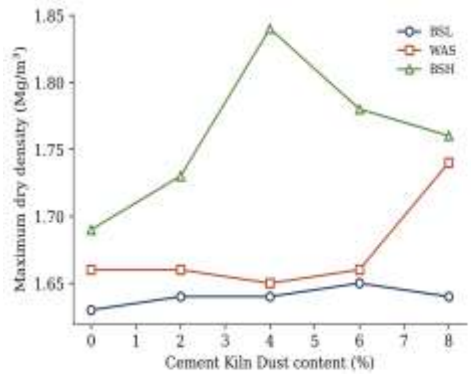

Fig. 4: Variation of maximum dry density with CKD content for BSL, WAS and BSH compactive efforts

Optimum moisture content

The corresponding optimum moisture content (OMC) results are presented in Figure 5. Under BSL compaction, OMC increased from 18.87% at 0% CKD to a peak of 19.92% at 4% CKD, before decreasing slightly at higher dosages. A similar pattern was observed under WAS compaction, with OMC increasing from 17.18% to 18.69% at 4% CKD. Under BSH compaction, OMC rose from 15.78% at 0% CKD to 17.26% at 2% CKD, before decreasing to 16.82% and 16.59% at 4% and 6% CKD respectively, and rising again slightly to 17.02% at 8% CKD. The initial increase in OMC with CKD content reflects the additional water demand associated with hydration of the free lime and calcium sulphate in the CKD and the accompanying pozzolanic reactions, while the subsequent plateau or mild decrease suggests that, once a sufficient concentration of cementitious reaction products has formed within the soil matrix, further increases in CKD content contribute proportionally less additional water demand (Ibrahim et al., 2022).

Corresponding author: M. A. Hamza
jesani@nda.edu.ng
Department of Civil Engineering, Nigerian Defence Academy (NDA), Kaduna, Nigeria.

JOURNAL OF SCIENCE TECHNOLOGY AND EDUCATION 14(2), JUNE, 2026
E-ISSN: 3093-0898, PRINT ISSN: 2277-0011; Journal homepage: www.atbufstejoste.com

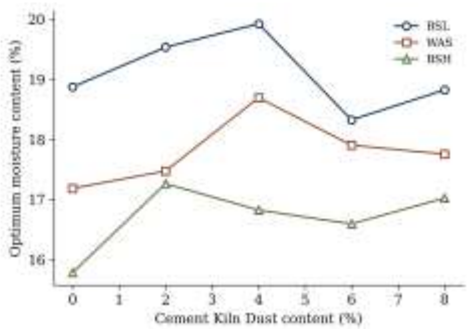

Fig. 5: Variation of optimum moisture content with CKD content for BSL, WAS and BSH compactive efforts

Unconfined Compressive Strength

Figure 6 presents the unconfined compressive strength (UCS) of the treated soil as a function of CKD content, moulding water content (-2, 0, +2 and +4% of OMC) and compactive effort. Under BSL compaction, UCS increased from a range of 170.2-187.1 kN/m² in the untreated soil to 246.6-299.2 kN/m² at 2% CKD, with further but comparatively modest gains at higher CKD contents. Under WAS compaction, UCS values at 6% CKD reached as high as 503.1 kN/m² at +4% moulding water content. The largest gains were recorded under BSH compaction, where UCS rose from 200.7-213.8 kN/m² in the untreated soil to a maximum of 748.2 kN/m² at 6% CKD and +2% moulding water content -- more than a four-fold increase over the untreated condition.

This combination of optimum stabilizer content, favourable moisture availability and high compactive effort evidently produced the most efficient particle packing and the most complete development of cementitious bonds, in agreement with the findings of Yusuf et al. (2023) and Mohammed et al. (2024), who reported that higher compactive efforts increase particle contact and reduce void ratio, thereby enhancing the effectiveness of chemical stabilization. A mild decline in UCS at 8% CKD across most conditions is consistent with the diminishing-returns behaviour widely reported once the optimum stabilizer dosage is exceeded, at which point excess unreacted CKD particles can weaken rather than strengthen the compacted fabric (Hassan et al., 2024).

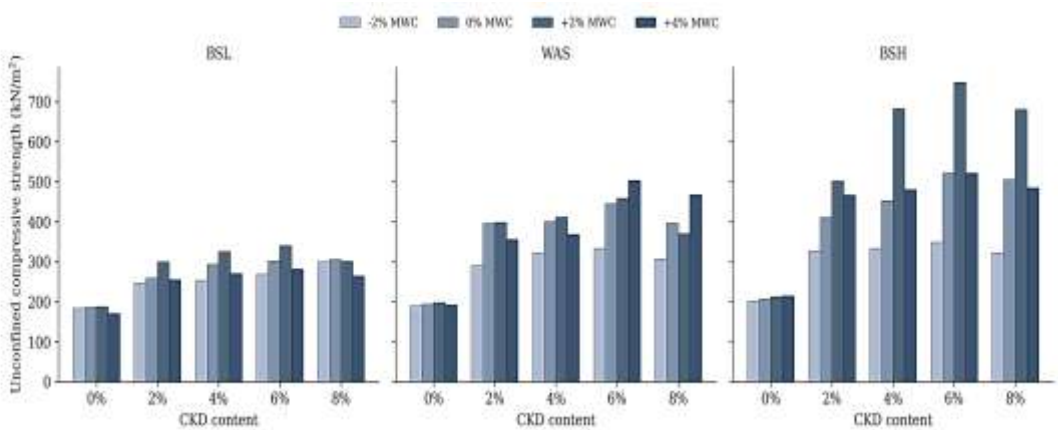

Fig. 6: Variation of unconfined compressive strength with CKD content for BSL, WAS and BSH compactive efforts at -2, 0, +2 and +4% of OMC

Volumetric Shrinkage Strain

The volumetric shrinkage strain (VSS) of the treated soil, plotted against moulding water content for each CKD dosage, is shown in Figures 7-11. In the untreated soil (Figure 7), VSS increased with moulding water content under all three compactive efforts, from 4.03% to 5.01% under BSL compaction, from 4.01% to 4.40% under WAS compaction, and from 3.61% to 4.00% under BSH compaction, consistent with the

Corresponding author: M. A. Hamza
jesani@nda.edu.ng
Department of Civil Engineering, Nigerian Defence Academy (NDA), Kaduna, Nigeria.

JOURNAL OF SCIENCE TECHNOLOGY AND EDUCATION 14(2), JUNE, 2026
E-ISSN: 3093-0898, PRINT ISSN: 2277-0011; Journal homepage: www.atbufstejoste.com

greater capillary tension that develops during drying as more water is removed from a wetter starting condition (Osinubi et al., 2022).

Progressive addition of CKD produced a consistent reduction in VSS at every moulding water content (Figures 8-11): at 2% CKD, values fell to 3.70-4.00% across the three compactive efforts; at 4% CKD, to 3.03-3.92%; and at 6% CKD, to 3.10-3.54%. The lowest values were recorded at 8% CKD under BSH compaction (Figure 11), where VSS ranged from 2.60% to 2.90%. This behaviour reflects the formation of a stable cementitious skeleton -- rich in calcium silicate and calcium aluminate hydration products -- that restrains the volumetric contraction which would otherwise accompany moisture loss, a mechanism also reported by Alhassan et al. (2024), Usman et al. (2023) and Musa et al. (2024) for CKD-treated tropical soils. Against the commonly cited liner criterion of VSS not exceeding 4% (Daniel and Wu, 1993), soils treated with 4% CKD and above consistently satisfied the requirement across all three compactive efforts, identifying 4-8% CKD as the range within which shrinkage-cracking risk in service would be acceptably low.

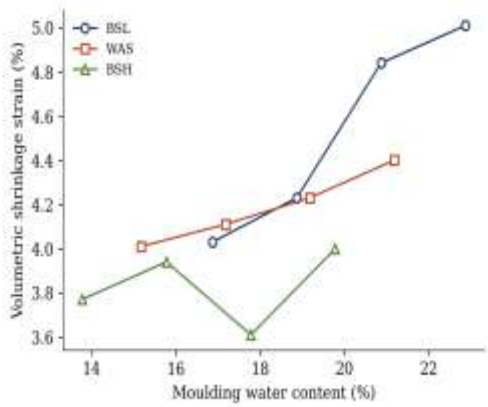

Fig. 7: Variation of volumetric shrinkage strain with moulding water content at 0% CKD

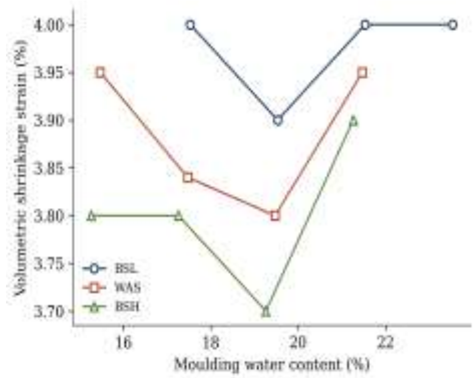

Fig. 8: Variation of volumetric shrinkage strain with moulding water content at 2% CKD

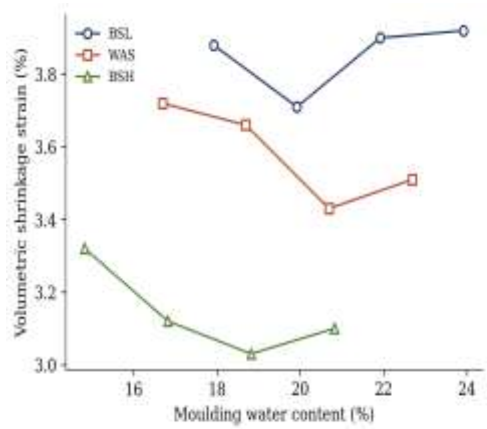

Fig. 9: Variation of volumetric shrinkage strain with moulding water content at 4% CKD

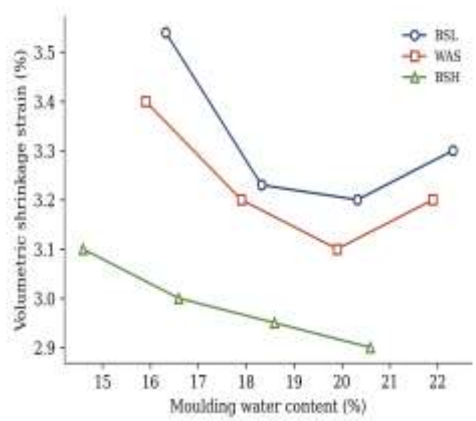

Fig. 10: Variation of volumetric shrinkage strain with moulding water content at 6% CKD

Corresponding author: M. A. Hamza
jesani@nda.edu.ng
Department of Civil Engineering, Nigerian Defence Academy (NDA), Kaduna, Nigeria.

JOURNAL OF SCIENCE TECHNOLOGY AND EDUCATION 14(2), JUNE, 2026
E-ISSN: 3093-0898, PRINT ISSN: 2277-0011; Journal homepage: www.atbufstejoste.com

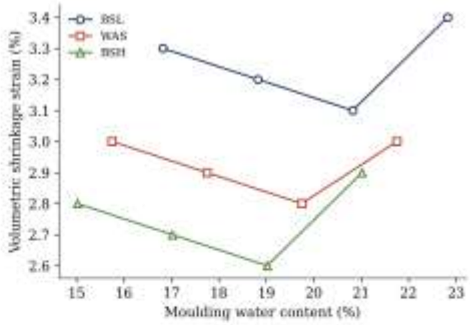

Fig. 11: Variation of volumetric shrinkage strain with moulding water content at 8% CKD

Hydraulic Conductivity

Figures 12-16 present the variation of hydraulic conductivity with moulding water content at each CKD dosage. In the untreated soil (Figure 12), hydraulic conductivity under BSH compaction was consistently of the order of 1.2 × 10^{-7} cm/s, already an order of magnitude lower than the values recorded under the lighter BSL and WAS efforts (of the order of 10^{-7} to 10^{-6} cm/s), reflecting the denser, less interconnected pore structure produced by heavier compaction. The addition of CKD produced a further, systematic reduction in hydraulic conductivity under all three compactive efforts, most markedly under BSH compaction, where average values fell from about 1.2 × 10^{-7} cm/s in the untreated soil to a minimum of around 3.7-5.7 × 10^{-8} cm/s at 4% CKD (Figure 14), before rising only marginally at 6% and 8% CKD to remain within the same order of magnitude (Figures 15 and 16).

This reduction is attributable to progressive pore filling by CKD fines and hydration products, together with flocculation of the clay fraction into a coarser, less continuous pore network (Mohammed et al., 2024). The comparable, low hydraulic conductivity sustained across the 4-8% CKD range indicates that excess unreacted CKD at the higher dosages did not materially compromise barrier performance, even though it began to reduce UCS gains, as noted in Section 3.5. Overall, hydraulic conductivity values in the 10^{-8} cm/s range at CKD contents of 4% and above comfortably satisfy the widely adopted regulatory ceiling of 1 × 10^{-7} cm/s for compacted clay liners and covers (Amadi and Eberemu, 2013), confirming the suitability of the CKD-stabilized, vermiremediated soil as a hydraulic barrier material.

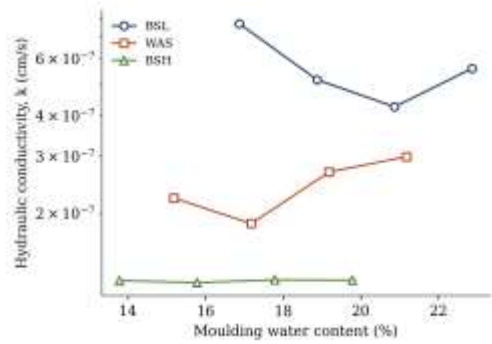

Fig. 12: Variation of hydraulic conductivity with moulding water content at 0% CKD

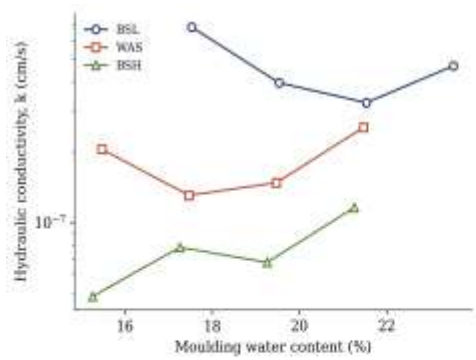

Fig. 13: Variation of hydraulic conductivity with moulding water content at 2% CKD

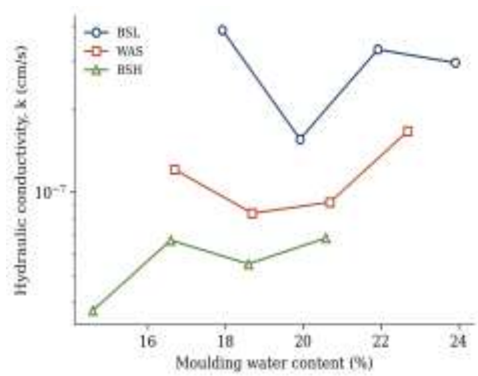

Fig. 14: Variation of hydraulic conductivity with moulding water content at 4% CKD

Corresponding author: M. A. Hamza
jesani@nda.edu.ng
Department of Civil Engineering, Nigerian Defence Academy (NDA), Kaduna, Nigeria.

JOURNAL OF SCIENCE TECHNOLOGY AND EDUCATION 14(2), JUNE, 2026
E-ISSN: 3093-0898, PRINT ISSN: 2277-0011; Journal homepage: www.atbufstejoste.com

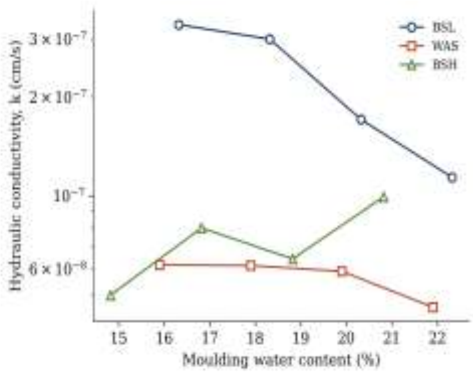

Fig. 15: Variation of hydraulic conductivity with moulding water content at 6% CKD

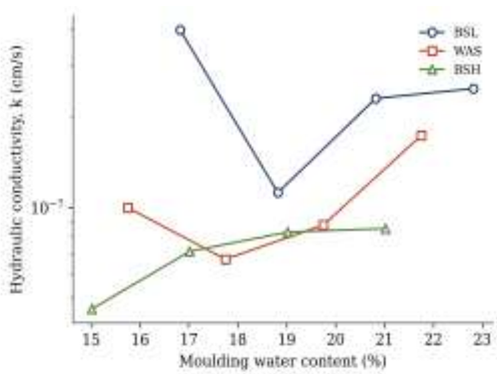

Fig. 16: Variation of hydraulic conductivity with moulding water content at 8% CKD

Suitability for landfill liner and cover applications

Taken together, the results indicate that CKD stabilization of the vermiremediated crude oil-contaminated soil produced simultaneous improvement across all three criteria conventionally used to judge the suitability of a compacted clay barrier material: strength, shrinkage and hydraulic conductivity (Daniel and Wu, 1993; Amadi and Eberemu, 2013). While the lowest hydraulic conductivity was recorded at 4% CKD, the 6% CKD dosage produced the highest UCS (748.2 kN/m², more than three and a half times the 200 kN/m² minimum commonly specified for liner materials), a VSS of 3.10-3.54% under BSH compaction (well within the 4% limit), and a hydraulic conductivity that remained solidly within the 10^{-8} cm/s range.

On balance, therefore, 6% CKD represents the most defensible optimum dosage for this application, offering the best overall combination of strength and shrinkage control while sacrificing very little in hydraulic performance relative to the 4% dosage. These findings support the technical feasibility of using vermiremediation as a biological pre-treatment step, followed by CKD stabilization, to convert a crude oil-contaminated lateritic soil that would otherwise be regarded as waste into a serviceable barrier material for landfill liner and cover construction -- a beneficial-reuse pathway that simultaneously addresses soil contamination and the disposal of an industrial by-product.

CONCLUSION

This study evaluated the combined effect of vermiremediation and cement kiln dust (CKD) stabilization on the geotechnical properties of a crude oil-contaminated lateritic soil, with a view to its use as a landfill liner and cover material. The following conclusions are drawn:

1. Vermiremediation using Eudrilus eugeniae reduced the total petroleum hydrocarbon content of the contaminated soil from 4500 to 3300 mg/kg, a removal efficiency of 27%, confirming its value as a low-cost biological pre-treatment step ahead of chemical stabilization.
2. Stabilization with CKD progressively reduced the liquid limit and, beyond an intermediate dosage of 4%, reduced the plasticity index of the vermiremediated soil, reflecting cation exchange, flocculation and cementation of the clay fraction.
3. Maximum dry density increased with CKD content and compactive effort, peaking at 1.84 Mg/m³ at 4% CKD under BSH compaction, while optimum moisture content increased moderately, consistent with the water demand of hydration and pozzolanic reactions.
4. Unconfined compressive strength increased more than four-fold with treatment, from 170.2 kN/m² in the

Corresponding author: M. A. Hamza
jesani@nda.edu.ng
Department of Civil Engineering, Nigerian Defence Academy (NDA), Kaduna, Nigeria.

untreated soil to a maximum of 748.2 kN/m² at 6% CKD, +2% moulding water content and BSH compaction, exceeding the 200 kN/m² minimum typically specified for compacted liners.

5. Volumetric shrinkage strain decreased consistently with CKD content, from 5.01% in the untreated soil to 2.60% at 8% CKD; soils treated with 4% CKD and above satisfied the commonly adopted 4% shrinkage-strain limit for liner materials.
6. Hydraulic conductivity decreased by roughly an order of magnitude with CKD treatment, reaching values in the range of 3.7-8 × 10^{-8} cm/s at 4-8% CKD under BSH compaction, well below the 1 × 10^{-7} cm/s ceiling generally required of compacted clay barriers.
7. Considering strength, shrinkage and hydraulic conductivity together, a dosage of 6% CKD offers the best overall balance of performance, and vermiremediated crude oil-contaminated lateritic soil stabilized at this dosage is judged suitable for use as a landfill liner and cover material.

Beyond its immediate geotechnical findings, the study demonstrates a practical, low-cost route for the beneficial reuse of both a petroleum-contaminated soil and an industrial by-product that would otherwise require costly disposal, offering a sustainable alternative to conventional liner materials in oil-producing regions such as the Niger Delta. Future work should extend the moulding-water-content and CKD-dosage matrix, incorporate long-term durability and contaminant-retention (batch equilibrium adsorption) testing, and evaluate field-scale performance of the stabilized soil under realistic leachate exposure conditions.

REFERENCES

Adewuyi, G. O., Akinyemi, O. O., & Adebayo, A. A. (2022). Vermiremediation of petroleum hydrocarbon-contaminated soils: Earthworm-microbial interactions and remediation efficiency. Environmental Technology & Innovation, 28, 102731.

Adeyanju, E. A., Eberemu, A. O., & Osinubi, K. J. (2024). Engineering behaviour of cement kiln dust-stabilized lateritic soils for sustainable waste containment applications. International Journal of Geotechnical Engineering, 18(2), 175-188.

Akinwumi, I. I., Booth, C. A., & Diwa, D. (2023). Influence of petroleum contamination on the consistency and geotechnical properties of lateritic soils. Environmental Earth Sciences, 82, 214.

Alhassan, M., Eberemu, A. O., & Osinubi, K. J. (2023). Improvement of shrinkage characteristics of lateritic soils treated with cement kiln dust for landfill barrier systems. Geotechnical and Geological Engineering, 41(6), 5149-5165.

Alhassan, M., Mohammed, S. A., & Eberemu, A. O. (2024). Volumetric stability of cement kiln dust-stabilized tropical soils for landfill liner applications. International Journal of Pavement Research and Technology, 17(1), 95-108.

Amadi, A. A., & Eberemu, A. O. (2013). Potential application of lateritic soil stabilized with cement kiln dust (CKD) as liner in waste containment structures. Geotechnical and Geological Engineering, 31(4), 1221-1230.

Ansari, A., Wrights, J., & Jaikishun, S. (2023). Earthworms in bioremediation of soils contaminated with petroleum hydrocarbons. In H. A. Mupambwa, L. N. Horn, & P. N. S. Mnkeni (Eds.), Vermicomposting for Sustainable Food Systems in Africa (pp. 349-368). Springer Nature Singapore.

Chauhan, R., Suman, A., & Singh, S. (2024). Optimizing soil performance: Using cement kiln dust along with polymer integration for soil stabilization. Current World Environment, 19(3).

Corresponding author: M. A. Hamza
jesani@nda.edu.ng
Department of Civil Engineering, Nigerian Defence Academy (NDA), Kaduna, Nigeria.

Daniel, D. E., & Wu, Y. K. (1993). Compacted clay liners and covers for arid sites. Journal of Geotechnical Engineering, 119(2), 223-237.

Eberemu, A. O., Osinubi, K. J., & Yakubu, D. (2022). Geotechnical evaluation of contaminated and stabilized tropical soils for environmental containment systems. Environmental Geotechnics, 9(5), 501-515.

Eberemu, A. O., Osinubi, K. J., & Alhassan, M. (2024). Strength and compaction characteristics of industrial by-product stabilized tropical soils. Transportation Geotechnics, 45, 101158.

Hassan, M. B., Ijimdiya, T. S., & Osinubi, K. J. (2024). Effect of stabilizer dosage beyond optimum on the strength behaviour of treated lateritic soils. Journal of Materials in Civil Engineering, 36(4), 04024022.

Head, K. H. (1994). Manual of soil laboratory testing (2nd ed., Vol. 1). Pentech Press.

Ibrahim, A. M., Osinubi, K. J., & Eberemu, A. O. (2022). Moisture-density relationships of cement kiln dust-treated lateritic soils under different compactive efforts. International Journal of Geotechnical Engineering, 16(10), 1198-1210.

Khamehchiyan, M., Charkhabi, A. H., & Tajik, M. (2007). Effects of crude oil contamination on geotechnical properties of clayey and sandy soils. Engineering Geology, 89(3-4), 220-229.

Khan, M. A., Ali, S., & Rehman, K. (2023). Vermiremediation of petroleum hydrocarbon-contaminated soils: Recent advances and future prospects. Chemosphere, 334, 138918.

Li, X., Zhang, Y., Wang, J., Liu, H., & Chen, H. (2023). Advances in vermiremediation of hydrocarbon-contaminated soils: Mechanisms, influencing factors, and engineering applications. Journal of Environmental Management, 337, 117713.

Michael-Igoli, J. A., Nwankwoala, H. O., & Oborie, E. (2022). Environmental and human health implications of crude oil contamination in tropical soils: A review. Environmental Challenges, 9, 100626.

Mohammed, S. A., Eberemu, A. O., & Osinubi, K. J. (2024). Engineering performance of cement kiln dust-treated lateritic soils for landfill liner applications. Environmental Geotechnics, 11(2), 203-219.

Musa, A. A., Eberemu, A. O., & Osinubi, K. J. (2024). Volumetric shrinkage characteristics of cement kiln dust stabilized tropical soils under different compactive efforts. International Journal of Geotechnical Engineering, 18(3), 289-304.

Ochepo, J., & Mohammed, S. A. (2023). Influence of cement kiln dust on the consistency limits and engineering behaviour of tropical lateritic soils. Journal of Materials in Civil Engineering, 35(11), 04023315.

Osinubi, K. J., Moses, G., & Liman, A. S. (2015). The influence of compactive effort on compacted lateritic soil treated with cement kiln dust as hydraulic barrier material. Geotechnical and Geological Engineering, 33(3), 523-535.

Osinubi, K. J., Eberemu, A. O., & Yohanna, P. (2022). Volumetric shrinkage behaviour of compacted tropical soils used as hydraulic barriers. Geotechnical and Geological Engineering, 40(4), 2031-2048.

Osinubi, K. J., Eberemu, A. O., & Alhassan, M. (2023). Cement kiln dust stabilization of tropical soils for sustainable geoenvironmental applications. Environmental Geotechnics, 10(5), 467-484.

Ossai, I. C., Ahmed, A., Hassan, A., & Hamid, F. S. (2020). Remediation of soil and water contaminated with petroleum hydrocarbon: A review. Environmental Technology & Innovation, 17, 100526.

Corresponding author: M. A. Hamza
jesani@nda.edu.ng
Department of Civil Engineering, Nigerian Defence Academy (NDA), Kaduna, Nigeria.

JOURNAL OF SCIENCE TECHNOLOGY AND EDUCATION 14(2), JUNE, 2026
E-ISSN: 3093-0898, PRINT ISSN: 2277-0011; Journal homepage: www.atbufstejoste.com

Oti, J. E., & Kinuthia, J. M. (2023). Effect of cement kiln dust stabilization on the consistency and strength properties of fine-grained soils. Construction and Building Materials, 391, 131932.

Poornima, S., Rajan, R., & Kumar, V. (2024). Vermiremediation of petroleum-contaminated soils using earthworms: Recent developments and future perspectives. Journal of Environmental Management, 352, 120011.

Saeed, H., Nalbantoglu, Z., & Uygar, E. (2024). A comprehensive review of hydrocarbon contaminated soil behavior, geotechnical properties and potential remediation. Soil and Sediment Contamination: An International Journal, 34, 1-45.

Thacharodi, D., Praveen, K., & Suresh, P. (2023). Environmental fate and ecotoxicological impacts of petroleum hydrocarbons in contaminated soils: A review. Environmental Science and Pollution Research, 30(38), 89674-89696.

United States Environmental Protection Agency. (1996). Method 9071B: n-Hexane extractable material (HEM) for sludge, sediment, and solid samples. U.S. Environmental Protection Agency.

Usman, A. D., Eberemu, A. O., & Osinubi, K. J. (2023). Influence of cement kiln dust on the hydraulic and shrinkage behaviour of compacted tropical soils. Environmental Geotechnics, 10(6), 612-626.

Varjani, S., Kumar, G., Rene, E. R., & Bhatia, S. K. (2023). Bioremediation of petroleum hydrocarbon-contaminated environments: Recent advances and future perspectives. Bioresource Technology, 369, 128353.

Yan, Q., Peng, B., Li, W., Wang, B., Zuo, J., Lv, G., & Wang, T. (2025). Low-carbon stabilization of expansive soils using cement kiln dust and calcium carbide slag: Mechanisms and performance. Frontiers in Earth Science, 13, 1554812.

Yusuf, M. A., Eberemu, A. O., & Osinubi, K. J. (2023). Influence of compactive effort on the engineering behaviour of stabilized lateritic soils. Transportation Geotechnics, 42, 101063.

Corresponding author: M. A. Hamza
jesani@nda.edu.ng
Department of Civil Engineering, Nigerian Defence Academy (NDA), Kaduna, Nigeria.