© JUL 2026 | IRE Journals | Volume 10 Issue 1 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV10I1-1719688

Index Properties and Compaction Characteristics of Cement Kiln Dust-Stabilized, Vermi-Improved Crude Oil-Contaminated Lateritic Soil for Road Subgrade Application

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Abstract- Crude oil contamination degrades the index properties and compaction behaviour of lateritic soil, limiting its direct reuse as road subgrade material. This study presents the index properties and compaction characteristics of vermi-improved crude oil-contaminated lateritic soil stabilized with 0, 2, 4, 6 and 8% cement kiln dust (CKD). Lateritic soil obtained from Shika, Zaria, was artificially contaminated with Bonny Light crude oil, remediated using Eudrilus eugeniae earthworms, and subsequently stabilized with CKD. Vermi-improvement reduced the total petroleum hydrocarbon (TPH) concentration from 4500 mg/kg to 3300 mg/kg, a removal efficiency of 27.0%. Index property tests (dry sieve analysis, specific gravity and Atterberg limits) and compaction tests under British Standard Light (BSL), West African Standard (WAS) and British Standard Heavy (BSH) energies were conducted in accordance with BS 1377 (1990) and BS 1924 (1990). The untreated vermi-improved soil classified as A-7-6 (AASHTO) and CL (USCS), with a liquid limit of 54%, plasticity index of 21.7%, and specific gravity of 2.48. CKD addition progressively reduced the fines content passing the 0.075 mm sieve, from 3.9% to 1.5% (BSL), 2.9% to 0.8% (WAS), and 1.9% to 0.9% (BSH), while specific gravity increased to a peak of 2.62 at 6% CKD. The liquid limit decreased from 54% to 43% and the plasticity index fell from 21.7% to a minimum of 15.5% at 4% CKD, bringing the soil within Nigerian General Specification limits for subgrade materials. Maximum dry density increased with CKD content, peaking at 1.84 Mg/m3 at 4% CKD under BSH compaction, while optimum moisture content generally peaked around 4% CKD before declining at higher CKD contents. These trends confirm that CKD stabilization, combined with heavier compactive effort, produces the coarser gradation, reduced plasticity, and improved densification required for the reuse of vermi-improved crude oil-contaminated lateritic soil as road subgrade material.

Keywords: Lateritic Soil; Crude Oil Contamination; Vermiremediation; Cement Kiln Dust; Index Properties; Compaction Characteristics; Road Subgrade

I. INTRODUCTION

Crude oil contamination of lateritic soils used in road construction alters their gradation, plasticity, and compaction behaviour, often rendering the soil unsuitable for direct use as subgrade material without prior treatment. Contamination increases hydrophobicity, disrupts particle bonding, and reduces the achievable density of the compacted soil, thereby compromising subgrade performance under traffic loading (Khan et al., 2022; Li et al., 2021).

Vermiremediation using earthworms such as Eudrilus eugeniae provides an environmentally sustainable means of reducing total petroleum hydrocarbon (TPH) concentration in contaminated soils through the combined biological action of earthworms and indigenous soil microorganisms (Li et al., 2021; Khan et al., 2022; Sani et al., 2026a; Sani et al., 2026b). However, vermiremediation alone does not restore the index properties and compaction characteristics required for subgrade construction, necessitating further chemical stabilization.

Cement kiln dust (CKD), a calcium-rich industrial by-product of cement manufacture, offers a sustainable stabilizing alternative to conventional binders.

Its high calcium oxide content promotes cation exchange, flocculation and pozzolanic reactions that modify soil gradation, reduce plasticity, and improve compaction characteristics (Osinubi et al., 2023; Eberemu et al., 2024). The beneficial reuse of CKD as a soil stabilizer also reduces the environmental burden associated with its disposal.

Index properties (particle size distribution, specific gravity and Atterberg limits) and compaction characteristics (maximum dry density and optimum moisture content) are fundamental parameters governing the classification and subgrade suitability of a soil, since they directly determine achievable density, plasticity, and moisture-density relationships in the field (Osinubi & Medubi, 1997; Federal Ministry of Works, 1997).

While previous studies have examined crude oil contamination, vermiremediation and CKD stabilization of lateritic soils individually, limited work has documented how these indexes and compaction properties evolve when vermi-improved crude oil-contaminated lateritic soil is subsequently treated with CKD.

This study therefore presents and discusses the index properties and compaction characteristics of vermi-improved crude oil-contaminated lateritic soil stabilized with varying percentages of CKD, with the aim of establishing its suitability as a road subgrade material.

II. MATERIALS AND METHODS

2.1. Study Area and Soil Sampling

Disturbed lateritic soil samples were collected from a borrow pit at Shika, Zaria, Kaduna State, Nigeria (Latitude 11°15'N, Longitude 7°45'E) at depths of 0-1.5 m. The samples were air-dried and pulverized to pass the BS No. 4 sieve (4.76 mm aperture) in preparation for laboratory testing, in accordance with BS 1377 (1990).

2.2. Materials

Bonny Light crude oil obtained from Port Harcourt, Rivers State, was used for artificial contamination. Cement kiln dust (CKD), sourced from the former Sokoto Cement Factory (now BUA Cement) in Sokoto State, was used as the stabilizing admixture at 0, 2, 4, 6 and 8% by dry weight of soil. Eudrilus eugeniae earthworms, sourced from the Kaduna River axis around Kabala Doki, were used for the vermiremediation stage.

2.3. Contamination and Vermiremediation Pretreatment

The lateritic soil was artificially contaminated with crude oil at a rate of 75 cl per 10 kg of soil and 1000 ml of water, then cured for one month to achieve full contamination.

The contaminated soil was subsequently subjected to vermiremediation using Eudrilus eugeniae at a rate of 300 worms per 200 kg of contaminated soil in an aerated, perforated tank for one month, with daily moisture replenishment. Removal efficiency was determined gravimetrically from the initial and residual TPH concentrations.

This pretreatment step is described only briefly here, as the present study focuses on the resulting index properties and compaction characteristics of the vermi-improved soil under CKD stabilization.

2.4. Laboratory Testing Programme

Natural moisture content, specific gravity, particle size distribution (dry sieving) and Atterberg limits (liquid limit, plastic limit and plasticity index) were determined for the untreated vermi-improved soil and for soil treated with 0, 2, 4, 6 and 8% CKD, in accordance with BS 1377 (1990) Part 2 for the natural soil and BS 1924 (1990) for the CKD-treated soil.

Specific gravity was determined by the density bottle method, particle size distribution by dry sieving of oven-dried, wet-sieved retained fractions through a standard stack of sieves, and Atterberg limits using the Casagrande/cone penetrometer method (liquid limit) and thread-rolling method (plastic limit), with the plasticity index computed as the difference between the liquid and plastic limits.

Compaction characteristics were evaluated using British Standard Light (BSL), West African Standard (WAS) and British Standard Heavy (BSH) compactive efforts in accordance with BS 1377 (1990) Part 4 and the Nigerian General Specifications (1997). BSL compaction was achieved using 27 blows of a 2.5 kg rammer falling from 300 mm on each of three soil layers in a 1000 cm3 mould; WAS compaction used 10 blows of a 4.5 kg rammer falling from 450 mm on each of five layers; and BSH compaction used 27 blows of a 4.5 kg rammer on each of five layers, within the same mould volume.

For each compactive effort, approximately 3 kg of dry soil-CKD mixture was compacted at successive water contents incremented by 2% until a reduction in the bulk mass of the compacted soil was observed, after which the maximum dry density (MDD) and its corresponding optimum moisture content (OMC) were obtained from the peak of the dry density-moisture content curve.

III. RESULTS AND DISCUSSION

3.1. Index Properties of the Untreated Vermi-Improved Crude Oil-Contaminated Soil

The natural lateritic soil, prior to contamination, recorded 64.0% passing the BS No. 200 sieve, a liquid limit of 47.0%, plastic limit of 27.3%, plasticity index of 19.7% and specific gravity of 2.66, classifying as CL (USCS) and A-7-6 (AASHTO), with kaolinite as the dominant clay mineral.

Following crude oil contamination, the percentage passing the 0.075 mm sieve increased to 72.42%, the liquid limit rose to 51.8%, and specific gravity decreased to 2.40, reflecting the influence of hydrocarbon contamination on particle density and consistency.

After vermiremediation, which reduced TPH concentration from 4500 mg/kg to 3300 mg/kg (a removal efficiency of 27.0%), the vermi-improved soil recorded a liquid limit of 54%, plastic limit of 32.26%, plasticity index of 21.7%, and specific gravity of 2.48, still classifying as CL (USCS) and A-7-6 (AASHTO), with a group index of 12.

This vermi-improved condition served as the baseline (0% CKD) for the cement kiln dust stabilization reported in this study.

Table 1: Index Properties of the Untreated Vermi-Improved Crude Oil-Contaminated Lateritic Soil (0% CKD)

Property	Value
Passing BS No. 200 sieve (%)	72.42
Liquid limit (%)	54.00
Plastic limit (%)	32.26
Plasticity index (%)	21.70
Specific gravity, Gs	2.48
USCS classification	CL
AASHTO classification	A-7-6
Group index	12
Colour	Dark brown
Dominant clay mineral	Kaolinite

3.2. Effect of CKD Content on Particle Size Distribution

Dry sieve analysis showed a consistent reduction in fines content (percentage passing the 0.075 mm sieve) with increasing CKD content across all three compactive efforts (Figure 1). Under BSL compaction, fines decreased from 3.9% (0% CKD) to 0.9%, 1.2%, 1.4% and 1.5% at 2%, 4%, 6% and 8% CKD respectively.

Under WAS compaction, fines decreased from 2.9% to 1.3%, 0.6%, 0.9% and 0.8% at the same CKD contents, while under BSH compaction, fines decreased from 1.9% to 1.0%, 0.6%, 0.8% and 0.9%.

This reduction in fines reflects cation exchange and flocculation reactions in which calcium ions (Ca2+) released from CKD replace weaker exchangeable cations (Na+, K+) on clay surfaces, compressing the diffuse double layer and promoting particle aggregation.

Pozzolanic reactions between soil silica/alumina and CKD calcium compounds further contribute to the formation of cementitious bonds (calcium silicate hydrate and calcium aluminate hydrate) that bind fine particles into larger, sieve-retained aggregates.

The lowest fines contents across all three compactive efforts were generally recorded around 4-6% CKD, consistent with an optimum flocculation-cementation balance, beyond which excess unreacted CKD particles produced a marginal rise in fines at 8%

(Osinubi & Nwaiwu, 2005; Okonkwo et al., 2021; Olawale et al., 2021; Sani et al., 2026a; Sani et al., 2026b).

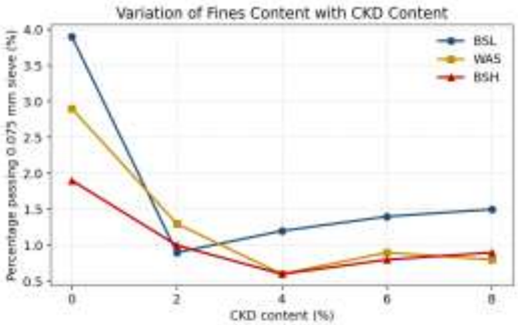

Figure 1: Variation of Fines Content (Percentage Passing 0.075 mm Sieve) with CKD Content under BSL, WAS and BSH Compactive Efforts

3.3. Effect of CKD Content on Specific Gravity

Specific gravity increased progressively from 2.48 (0% CKD) to 2.54, 2.60 and 2.62 at 2%, 4% and 6% CKD respectively, before decreasing slightly to 2.58 at 8% CKD (Figure 2), representing an overall improvement of approximately 5.6% at the peak.

This increase reflects the incorporation of denser calcium-rich mineral constituents from CKD into the soil matrix, progressively replacing lighter, hydrocarbon-affected particles (Osinubi et al., 2023; Eberemu et al., 2024; Sani et al., 2026a; Sani et al., 2026b).

The marginal decline at 8% CKD suggests that beyond the optimum stabilization level, excess CKD particles do not fully participate in pozzolanic reactions and instead reduce the efficiency of particle packing, consistent with the trend observed for fines content and, as discussed subsequently, for compaction behaviour.

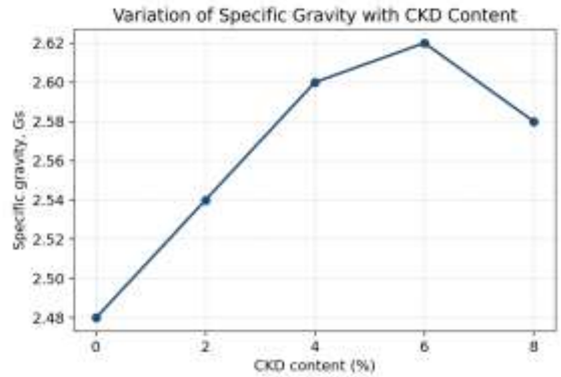

Figure 2: Variation of Specific Gravity with CKD Content

3.4. Effect of CKD Content on Atterberg Limits

The liquid limit decreased from 54% (0% CKD) to 44%, 44.5%, 48% and a minimum of 43% at 2%, 4%, 6% and 8% CKD respectively, an overall reduction of approximately 20.4% (Figure 3). The plastic limit decreased from a maximum of 32.3% (0% CKD) to a minimum of 23.5% at 2% CKD, before rising again to 29.0% at 4% and 31.1% at 6%, then falling to 24.8% at 8% CKD.

Because the plasticity index is the numerical difference between the liquid and plastic limits, these combined trends produced a general decline in plasticity index, from 21.7% (0% CKD) to 20.5% (2%), a minimum of 15.5% (4%), 16.9% (6%) and 18.2% (8% CKD).

The overall reduction in liquid limit and plasticity index with CKD addition reflects cation exchange and flocculation-agglomeration reactions that reduce the surface area and water affinity of the clay fraction, consistent with the reduction in fines content discussed in Section 3.2 (Osinubi et al., 2023; Eberemu et al., 2024; James et al., 2023; Sani et al., 2026a; Sani et al., 2026b).

The minimum plasticity index of 15.5% recorded at 4% CKD indicates the most effective stabilization level with respect to consistency improvement, with a mild rebound at higher CKD contents attributed to excess, incompletely reacted CKD particles.

Importantly, the untreated vermi-improved soil exceeded the Nigerian General Specification liquid limit ceiling of 50% for subgrade materials, whereas all CKD-treated samples (2-8%) recorded liquid limits below this threshold, confirming that CKD stabilization is necessary and effective in bringing the soil within specification for subgrade use.

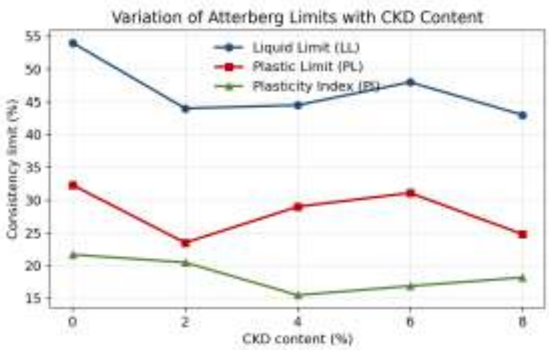

Figure 3: Variation of Atterberg Limits with CKD Content

3.5. Compaction Characteristics

3.5.1. Maximum Dry Density

Maximum dry density (MDD) increased with CKD content under all three compactive efforts, although the magnitude and location of the peak value differed by compactive effort. Under BSL compaction, MDD increased slightly from 1.63 Mg/m3 (0% CKD) to a peak of 1.65 Mg/m3 at 6% CKD, before decreasing marginally to 1.64 Mg/m3 at 8% CKD (see Figure 4).

Under WAS compaction, MDD remained relatively stable between 1.65 and 1.66 Mg/m3 up to 6% CKD, before increasing significantly to 1.74 Mg/m3 at 8% CKD. Under BSH compaction, MDD increased markedly from 1.69 Mg/m3 (0% CKD) to a peak of 1.84 Mg/m3 at 4% CKD, before decreasing to 1.78 Mg/m3 and 1.76 Mg/m3 at 6% and 8% CKD respectively.

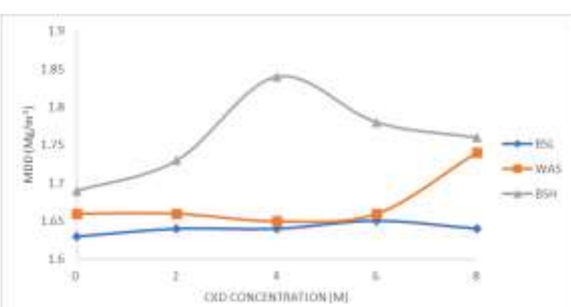

Figure 4: Variation of Maximum Dry Density with CKD Content

The general increase in MDD with CKD addition is attributed to calcium-induced flocculation and improved particle packing, which allow a greater mass of soil solids to occupy a given compacted volume.

The substantially higher MDD values obtained under BSH compaction compared with BSL and WAS confirm the dominant influence of compactive effort on densification, since higher compactive energy achieves more effective particle interlocking and void reduction (Eberemu et al., 2024).

The peak MDD of 1.84 Mg/m3 at 4% CKD under BSH compaction identifies this combination as the point of most effective densification, beyond which excess CKD, being less dense than the soil solids it partially replaces, produced a mild reduction in dry density (James et al., 2023; Sani et al., 2026a; Sani et al., 2026b).

3.5.2. Optimum Moisture Content

Optimum moisture content (OMC) generally increased with CKD content up to 4%, before declining at higher CKD contents. Under BSL compaction, OMC increased from 18.87% (0% CKD) to a peak of 19.92% at 4% CKD, then decreased to 18.32% and 18.82% at 6% and 8% CKD respectively.

Under WAS compaction, OMC increased from 17.18% to a peak of 18.69% at 4% CKD before declining slightly at higher CKD contents. Under BSH compaction, OMC remained lower than under BSL and WAS throughout, ranging between 15.78% and 17.26% (see Figure 5).

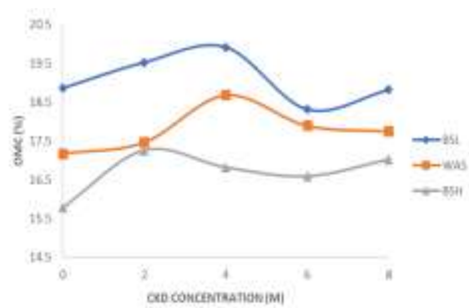

Figure 4: Variation of Optimum Moisture Content with CKD Content

The initial rise in OMC to a peak at 4% CKD reflects the additional water demand of calcium oxide hydration and pozzolanic reactions, which is greatest at this intermediate stabilization level. Beyond 4% CKD, the decline in OMC under BSL and WAS compaction is attributed to progressive flocculation and aggregation, which reduces the total particle surface area available for water adsorption (James et al., 2024).

Across all CKD contents, OMC followed the order BSL > WAS > BSH, confirming the inverse relationship between compactive effort and optimum moisture content: greater compactive energy rearranges particles into a denser configuration with less water required to expel air voids (Eberemu et al., 2023).

3.6. Engineering Significance for Road Subgrade Application

The reduction in fines content and plasticity index, together with the increase in specific gravity and maximum dry density, indicate that CKD stabilization improves the gradation, consistency and densification behaviour of vermi-improved crude oil-contaminated lateritic soil in a manner directly relevant to road subgrade performance.

The untreated vermi-improved soil exceeded the Nigerian General Specification liquid limit ceiling of 50% for subgrade materials, whereas all CKD-treated samples satisfied this requirement, confirming that stabilization is necessary for compliant subgrade use.

The consistently lower plasticity index and the peak densification obtained around 4-6% CKD under British Standard Heavy compaction identify this combination as the most favourable index and compaction condition, supporting the use of moderate CKD contents (4-6%) with heavy compactive effort for field application.

IV. CONCLUSION

This study evaluated the index properties and compaction characteristics of vermi-improved crude oil-contaminated lateritic soil stabilized with 0-8% cement kiln dust. Vermiremediation reduced total petroleum hydrocarbon content from 4500 mg/kg to 3300 mg/kg, a removal efficiency of 27.0%, providing the baseline material for stabilization.

The untreated vermi-improved soil classified as CL (USCS) and A-7-6 (AASHTO), with a liquid limit of 54%, plasticity index of 21.7%, and specific gravity of 2.48, exceeding the Nigerian General Specification liquid limit ceiling for subgrade materials.

CKD addition progressively reduced fines content passing the 0.075 mm sieve under all three compactive efforts, increased specific gravity to a peak of 2.62 at 6% CKD, reduced the liquid limit to a minimum of 43% at 8% CKD, and reduced the plasticity index to a minimum of 15.5% at 4% CKD, bringing all treated samples within specification limits.

Compaction results showed that maximum dry density increased with CKD content, peaking at 1.84 Mg/m3 at 4% CKD under British Standard Heavy compaction, while optimum moisture content generally peaked around 4% CKD before declining at higher contents, following the expected order BSL > WAS > BSH.

These findings demonstrate that vermiremediation combined with CKD stabilization at 4-6% under heavy compactive effort produces the most favourable index and compaction characteristics for the reuse of crude oil-contaminated lateritic soil as road subgrade material.

V. RECOMMENDATIONS

1. Vermiremediation should be adopted as a pre-treatment step for crude oil-contaminated lateritic soils prior to chemical stabilization, given its demonstrated reduction in hydrocarbon load ahead of CKD treatment.
2. CKD contents of 4-6% are recommended as the optimum stabilization range, based on the peak specific gravity, minimum plasticity index, and peak maximum dry density observed within this range.
3. British Standard Heavy (BSH) compactive effort is recommended for field application, as it consistently produced the highest maximum dry

density and the most favourable densification response to CKD addition.

4. Field compaction should target moisture contents close to the laboratory-determined optimum moisture content for the selected CKD content and compactive effort, to achieve the densities reported in this study.
5. Further studies should examine the long-term durability of the index and compaction properties of CKD-stabilized, vermi-improved soil under field exposure and wetting-drying cycles.

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