

Index and Compaction Characteristics of Electrokinetically Remediated Crude Oil-Contaminated Lateritic Soil Using Different Electrode Materials

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Abstract- Crude oil contamination severely alters the index and compaction characteristics of lateritic soils, limiting their engineering reuse potential. Electrokinetic remediation (EKR) using different electrode materials offers a viable pathway to restore these properties; however, the electrode-specific influence on post-remediation index properties and compaction behaviour remains inadequately documented for Nigerian lateritic soils. Crude oil-contaminated lateritic soil was electrokinetically remediated over 20 days using graphite, carbon, and mild steel electrodes with sodium sulphate and SDS surfactant enhancement. Post-remediation index properties — specific gravity, particle size distribution, Atterberg limits — and compaction characteristics under British Standard Light (BSL), West African Standard (WAS), and British Standard Heavy (BSH) compactive efforts were determined following BS 1377 (1990). All remediated soils classified as lean clay (CL/A-7-6) with fines content 79.40–81.56%, liquid limits 41.91–45.78%, and plasticity indices 14.22–19.13%. Graphite produced the lowest PI (14.22%), reflecting superior hydrocarbon removal (73.34% TPH efficiency). Under BSL compaction, maximum dry density (MDD) ranged from 1.59–1.63 Mg/m³ with optimum moisture content (OMC) 25.23–29.71%. MDD consistently increased with compactive effort (BSL → WAS → BSH), while OMC decreased correspondingly. Graphite-treated soils exhibited the most stable plasticity and workability characteristics among the three electrode types. Conclusions: EKR effectively restores the index and compaction characteristics of crude oil-contaminated lateritic soil to ranges suitable for geotechnical reuse. Electrode material significantly influences the degree of plasticity reduction and densification achievable, with graphite demonstrating the most favourable overall index and compaction profile for engineered waste containment applications.

Keywords: Electrokinetic Remediation, Crude Oil Contamination, Lateritic Soil, Index Properties, Atterberg Limits, Compaction Characteristics, Electrode Materials.

I. INTRODUCTION

Crude oil contamination of lateritic soils in Nigeria constitutes one of the most widespread geoenvironmental challenges in the country, arising from pipeline failures, tank farm leakages, and artisanal refining activities. Beyond its ecological consequences, crude oil contamination fundamentally alters the engineering properties of affected soils — specifically their index characteristics and compaction behaviour — thereby restricting their reuse in geotechnical construction (Khamehchiyan et al., 2007; Adebayo et al., 2023).

Index properties, including particle size distribution, specific gravity, liquid limit, plastic limit, and plasticity index, govern the engineering classification and geotechnical suitability of fine-grained soils. Crude oil contamination is known to modify these parameters by coating soil particles with hydrophobic hydrocarbon films, altering Atterberg limits, and changing particle density (Das, 2016; Mitchell & Soga, 2005). Similarly, compaction characteristics — maximum dry density (MDD) and optimum moisture content (OMC) — are sensitive to hydrocarbon contamination, as petroleum residues interfere with particle–water interactions and reduce achievable dry densities (Khamehchiyan et al., 2007).

Electrokinetic remediation (EKR) applies a direct current across electrodes embedded in the contaminated soil, mobilising petroleum

hydrocarbons through electroosmosis, electromigration, and electrophoresis (Acar & Alshwabkeh, 1993; Reddy & Cameselle, 2009). While EKR has been widely studied for contaminant removal, its influence on the post-remediation index properties and compaction characteristics of crude oil-contaminated Nigerian laterite across different electrode materials — graphite, carbon, and mild steel — under varying compactive efforts has received limited systematic attention (Jibril et al., 2024; Imic, 2023).

This study addresses this gap by comprehensively characterising the index and compaction properties of EKR-treated crude oil-contaminated lateritic soil using three electrode materials under British Standard Light (BSL), West African Standard (WAS), and British Standard Heavy (BSH) compactive efforts, with direct comparisons to unremediated contaminated soil. The findings are contextualised for waste containment facility applications where soil workability, plasticity control, and compaction performance are critical design inputs.

1.1 Research Objectives

The specific objectives of this study are to: (i) determine the effect of graphite, carbon, and mild steel electrodes on the post-EKR index properties — specific gravity, particle size distribution, Atterberg limits — of crude oil-contaminated lateritic soil; (ii) evaluate the compaction characteristics (MDD and OMC) of EKR-remediated soils under BSL, WAS, and BSH compactive efforts; (iii) compare the index and compaction performance of electrode-specific EKR treatments against unremediated contaminated soil; and (iv) provide electrode-specific recommendations for waste containment facility applications based on index and compaction performance.

II. MATERIALS AND METHODS

2.1 Soil and Contamination

Lateritic soil samples representative of Nigerian tropical laterite were collected, air-dried, disaggregated, and sieved through a 4.75 mm BS sieve. Crude oil contamination was simulated under controlled laboratory conditions using Niger Delta

crude oil, mixed uniformly with soil at a predetermined percentage by weight to replicate field contamination scenarios encountered in petroleum-producing zones of Nigeria. All tests were performed in conformance with BS 1377 (1990) and Nigerian General Specifications (1997).

2.2 Electrokinetic Remediation

EKR was conducted for 20 days in separate experimental cells for each electrode type — graphite, carbon, and mild steel — under identical boundary conditions. Sodium sulphate (Na_2SO_4) and sodium dodecyl sulphate (SDS) were used as the electrolyte and surfactant enhancer respectively. A low-voltage direct current was applied continuously, and pore fluid pH was monitored at regular intervals throughout the treatment period to track electrochemical evolution. Total petroleum hydrocarbon (TPH) removal was assessed by gravimetric analysis at the end of each treatment.

2.3 Index Property Testing

Post-EKR index tests included: (i) specific gravity by pycnometer method; (ii) particle size distribution by combined wet sieving and hydrometer analysis; (iii) liquid limit (LL) by Casagrande cup method; (iv) plastic limit (PL) by thread rolling; (v) plasticity index ($\text{PI} = \text{LL} - \text{PL}$); and (vi) linear shrinkage (LS) using shrinkage mould and oven drying. All index tests followed BS 1377 (1990) Part 2. Soil classification was performed using both USCS (ASTM D2487) and AASHTO (1986) systems.

2.4 Compaction Testing

Compaction tests were conducted on EKR-remediated soils following BS 1377 (1990) Part 4 and Nigerian General Specifications (1997) using three compactive efforts: British Standard Light (BSL) — 2.5 kg rammer, 3 layers, 27 blows per layer; West African Standard (WAS) — 4.5 kg rammer, 5 layers, 10 blows per layer; and British Standard Heavy (BSH) — 4.5 kg rammer, 5 layers, 27 blows per layer. For each test, at least five specimens were prepared across a range of moisture contents, and bulk densities were calculated from measured mass and volume. Dry density was computed from bulk density and moisture content.

MDD and OMC were determined from the peak of the dry density–moisture content curve.

III. RESULTS AND DISCUSSION

3.1 Index Properties of the soil

The index properties of the soil used is presented in Table 1.

Table 1: Index Properties of EKR-Remediated Crude Oil-Contaminated Lateritic Soils by Electrode Type

Property	Graphite	Carbon	Mild Steel
A. Particle Properties			
Specific Gravity	1.785	2.028	1.801
Fines Content (%)	79.40	80.94	81.56
Sand Fraction (%)	20.60	19.06	18.44
Clay Fraction (%)	4.29	4.22	4.42
B. Atterberg Limits			
Liquid Limit, LL (%)	41.91	43.33	45.78
Plastic Limit, PL (%)	27.69	25.61	26.65
Plasticity Index, PI (%)	14.22	17.72	19.13
Linear Shrinkage (%)	6.85	7.40	7.89
C. Soil Classification			
USCS Classification	CL	CL	CL
AASHTO Classification	A-7-6	A-7-6	A-7-6
Soil Description	Lean Clay	Lean Clay	Lean Clay

Note: LL = Liquid Limit; PL = Plastic Limit; PI = Plasticity Index; CL = Lean Clay (USCS); A-7-6 = AASHTO classification. All tests per BS 1377 (1990) Part 2.

3.2 Total Petroleum Hydrocarbon (TPH) Removal Efficiency

Before examining index and compaction properties, it is instructive to note the TPH removal context, as residual contamination directly influences post-EKR geotechnical behaviour. Graphite electrodes achieved the highest TPH removal (73.34%), followed by mild steel (53.67%) and carbon (30.67%) as illustrated in Figure 1. Graphite's chemical inertness and high

electrical conductivity sustained efficient electroosmotic flow and contaminant mobilisation without electrode corrosion (Cameselle, 2015; Reddy & Cameselle, 2009). These removal differences underpin the observed variations in post-remediation index and compaction properties across electrode types.



Figure 1: TPH removal efficiency (%) by electrode material

3.3 Specific Gravity

Specific gravity values of EKR-remediated soils were substantially lower than typical uncontaminated laterite ($G_s \approx 2.65\text{--}2.72$): graphite 1.785, carbon 2.028, and mild steel 1.801 (Table 1; Figure 2). The unremediated contaminated soil recorded $G_s = 2.661$, and all electrode treatments showed reduction attributable to residual hydrocarbon presence within the soil matrix lowering particle density (Cameselle, 2015; Sani et al., 2023; Sani et al., 2026). Carbon's relatively higher G_s reflects greater matrix compaction from ion migration and electrical double-layer compression induced during EKR (Yeung & Gu, 2011). Mild steel's intermediate G_s indicates partial hydrocarbon removal offset by heavier $\text{Fe}^{2+}/\text{Fe}^{3+}$ corrosion deposits occupying pore space. Graphite's lowest G_s reflects the most extensive crude oil desorption from particle surfaces, loosening the microstructure.

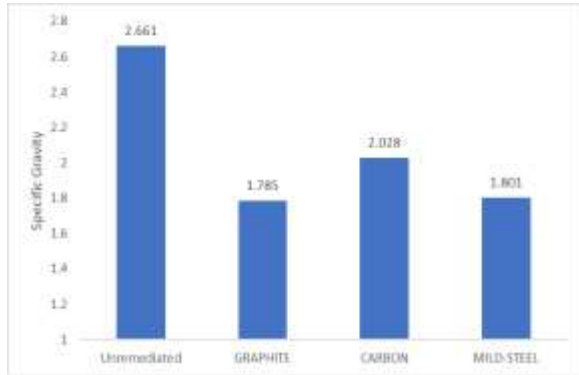
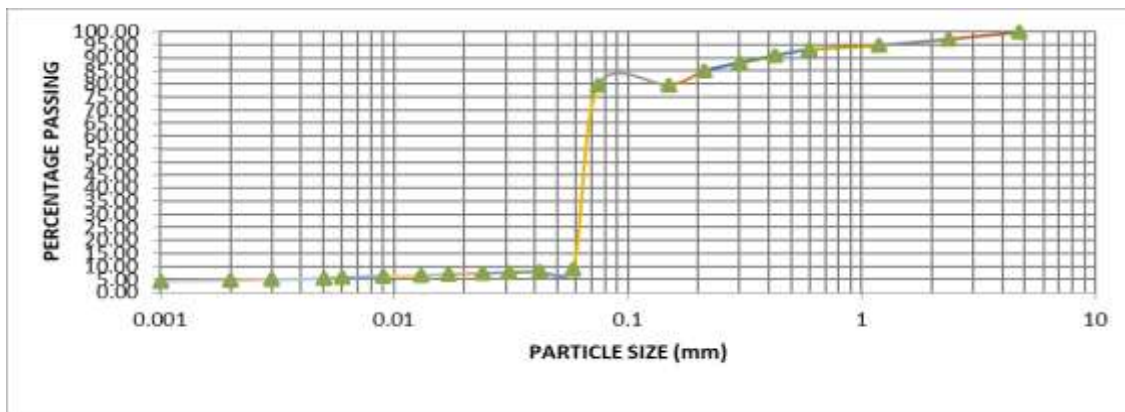


Figure 2: Specific gravity of remediated soils by electrode material

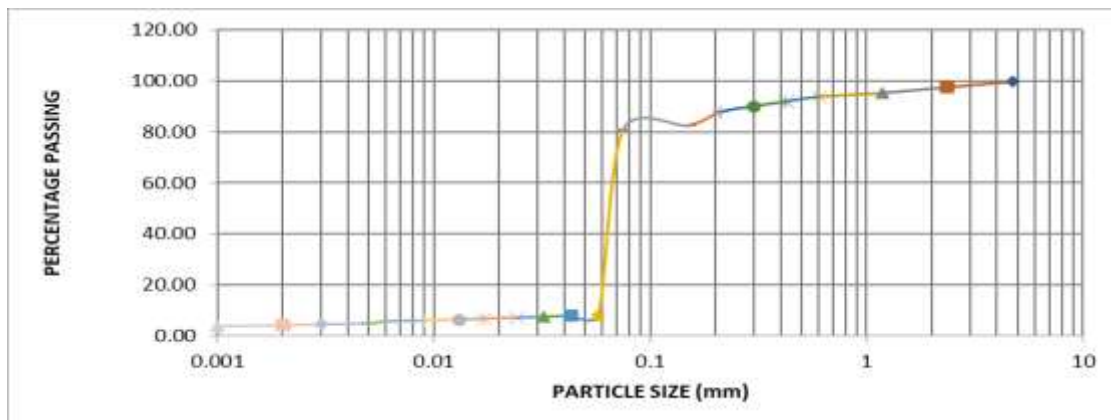
3.4 Particle Size Distribution

Particle size analysis confirmed that all EKR-remediated soils remained predominantly fine-grained, with fines content (passing 0.075 mm sieve) ranging from 79.40% (graphite) to 81.56% (mild steel) as shown in Table 1 and Figure 3. Sand

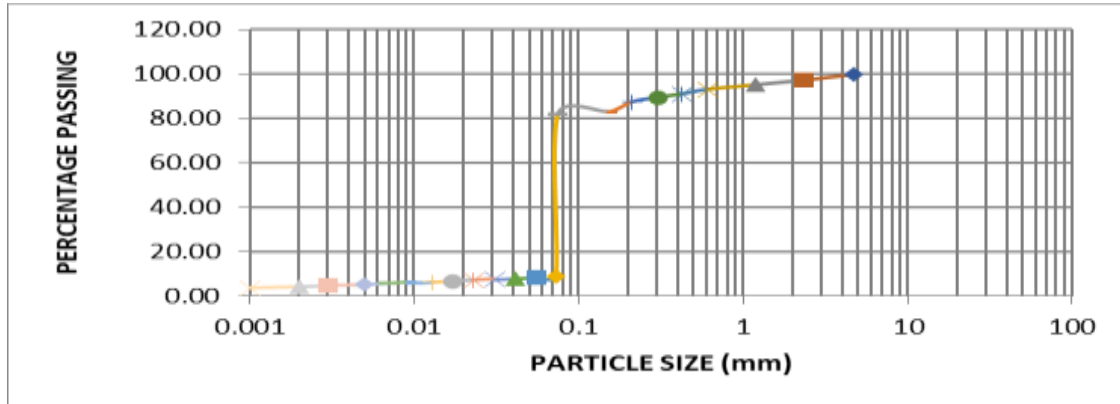
fractions were 20.60% (graphite), 19.06% (carbon), and 18.44% (mild steel), while clay fractions were narrow across all treatments: 4.29% (graphite), 4.22% (carbon), and 4.42% (mild steel). The slight increase in fines for mild steel-treated soils is attributable to electrochemical dispersion of aggregates resulting from iron dissolution and elevated pH altering double-layer forces on clay particles (Boulakradeche et al., 2022). Graphite's marginally lower fines content reflects more stable particle structure consistent with superior hydrocarbon removal and reduced electrochemical alteration. The dominance of fines across all electrode treatments confirms compatibility with compacted clay liner design criteria (Das, 2016; Sani et al., 2023; Sani et al., 2026).



(a) PSD for graphite electrode



(b): PSD for carbon electrode



(C): PSD for mild steel electrode

Figure 3: Particle size distribution — fines content comparison by electrode

3.5 Atterberg Limits

3.5.1 Liquid Limit

Liquid limit (LL) values varied with electrode type: graphite 41.91%, carbon 43.33%, and mild steel 45.78% (Table 1; Figure 4). All three values were lower than the unremediated contaminated soil LL of approximately 49.20%, confirming that EKR treatment reduces the moisture-holding capacity at the liquid state — an indication of improved engineering behaviour. Graphite's lowest LL reflects reduced surface charge and water affinity resulting from greater hydrocarbon removal, which stripped lubricating films from particle surfaces and enabled tighter packing with lower moisture requirement (Das, 2016). Mild steel's highest LL is attributed to iron dissolution increasing clay surface charge and expanding the diffuse double-layer thickness (Mitchell & Soga, 2005; Boulakradeche et al., 2022; Sani et al., 2023; Sani et al., 2026), which increases inter-particle moisture demand. Carbon's intermediate LL indicates partial stabilisation of clay surface chemistry.

3.5.2 Plastic Limit and Plasticity Index

Plastic limit (PL) values were 27.69% (graphite), 25.61% (carbon), and 26.65% (mild steel), showing relatively small variation across electrode types (Table 1; Figure 4). This indicates that electrode material predominantly influences soil behaviour at higher moisture contents (liquid limit region) rather than at the plastic boundary, consistent with the literature (Das, 2021; Mitchell & Soga, 2005; Sani et al., 2023; Sani et al., 2026). Plasticity index (PI)

values were 14.22% (graphite), 17.72% (carbon), and 19.13% (mild steel). Graphite achieved the lowest PI, indicating reduced compressibility and swelling potential. With LL of 41.91–45.78% and PI of 14.22–19.13%, all soils classify as lean clay (CL) under USCS and A-7-6 under AASHTO, confirming their geotechnical suitability for liner and cover applications under appropriate compaction control.

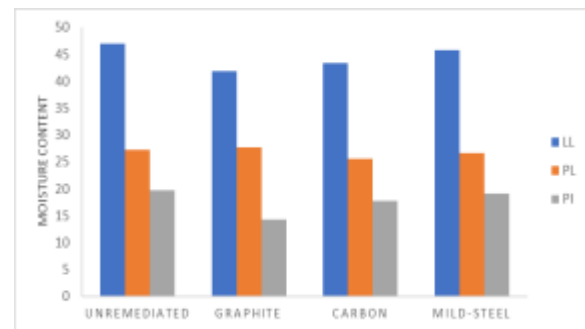


Figure 4: Atterberg limits (LL, PL, PI) by electrode material

3.6 Compaction Characteristics

3.6.1 Maximum Dry Density (MDD)

Maximum dry density values for all three electrodes under all three compactive efforts are summarised in Table 2 and Figure 5. Under BSL compaction: graphite 1.63, carbon 1.59, and mild steel 1.62 Mg/m³. Under WAS: graphite 1.66, carbon 1.68, mild steel 1.69 Mg/m³. Under BSH: graphite 1.71, carbon 1.80, mild steel 1.86 Mg/m³. MDD increased consistently with compactive effort across all electrode types (BSL < WAS < BSH), reflecting reduced pore space and increased unit weight with higher energy input — consistent with classical

compaction theory (Das, 2016; Asadollahfardi & Rezaee, 2019; Sani et al., 2023; Sani et al., 2026). Mild steel showed the strongest densification response to increasing compactive effort (1.62 to 1.86 Mg/m³ range), likely due to iron precipitation clogging macro-pores and facilitating tighter particle packing. Carbon's large MDD increase from BSL to BSH (1.59 to 1.80 Mg/m³) reflects responsive particle rearrangement under increasing energy. Graphite's more modest MDD range (1.63 to 1.71 Mg/m³) reflects a more stable soil fabric, with superior hydrocarbon removal producing a less compressible matrix.

Compared to the unremediated contaminated soil (estimated BSL MDD ≈ 1.56 Mg/m³), all EKR-treated soils showed improved densification, with MDD gains of 0.03–0.06 Mg/m³ under BSL, confirming that EKR treatment restores and enhances the compactability of crude oil-contaminated laterite.

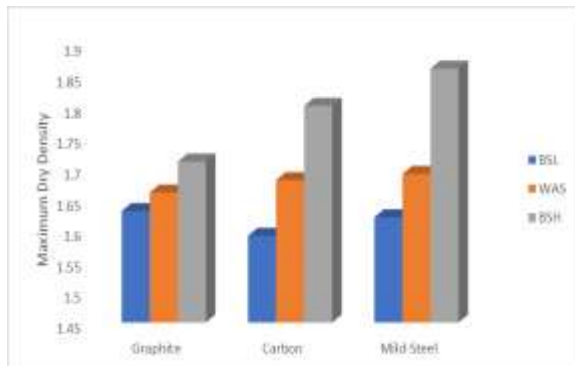


Figure 5: Maximum dry density (MDD) under BSL, WAS, and BSH by electrode type)

3.6.2 Optimum Moisture Content (OMC)

OMC followed an inverse trend to MDD across compactive efforts, decreasing in the order BSL > WAS > BSH for all electrode types (Table 2; Figure 6). Under BSL: graphite 28.60%, carbon 25.23%, mild steel 29.71%. Under WAS: graphite 18.04%, carbon 18.97%, mild steel 20.64%. Under BSH: graphite 12.84%, carbon 16.23%, mild steel 13.23%. This progressive OMC reduction with increasing compactive effort reflects the reduction in inter-particle void space requiring less water for lubrication, consistent with fundamental compaction mechanics (Das, 2016). The high BSL OMC values (25–30%) are characteristic of fine-grained lateritic

soils with elevated plasticity indices and reflect the high water retention capacity of the clay mineral matrix post-EKR. For field applications under BSL-equivalent compaction (e.g., cover system construction with light rollers), these elevated OMC values must be accounted for in water content specification to achieve target dry densities. Carbon showed the lowest BSL OMC (25.23%), potentially attributable to residual hydrocarbon films acting as partial lubricants, reducing the water demand at peak density. The results is in consistent with the findings of Sani et al., (2023) and Sani et al., 2026).

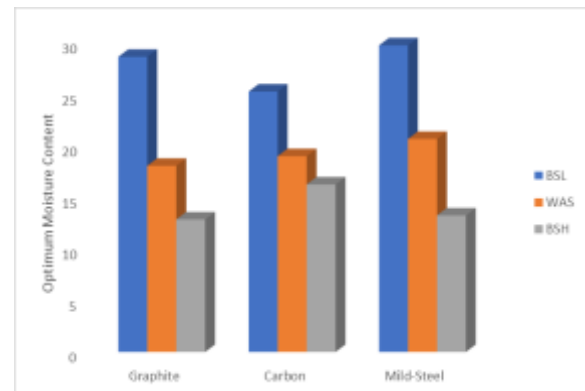


Figure 6: Optimum moisture content (OMC) under BSL, WAS, and BSH by electrode type

IV. DISCUSSION: IMPLICATIONS FOR WASTE CONTAINMENT DESIGN

The index and compaction properties of EKR-remediated crude oil-contaminated lateritic soils have direct implications for their suitability as construction materials in waste containment facilities. Geotechnical design of compacted clay liners (CCLs) and cover systems requires soils of controlled plasticity, consistent compaction response, and adequate density to achieve target hydraulic conductivities (Daniel & Koerner, 1995; Rowe, 2012).

The lean clay (CL) classification of all EKR-treated soils under USCS, with PI values of 14.22–19.13%, places them within the preferred plasticity window for CCL materials — high enough for cohesive barrier behaviour but low enough to avoid excessive shrink–swell risk (Das, 2016; Mitchell & Soga, 2005). Graphite-treated soils with PI of 14.22%

represent the optimal balance, offering reduced swelling potential, lower OMC (28.60% at BSL), and stable compaction response. This makes graphite-treated soils particularly well-suited for cover layer applications where desiccation cracking risk associated with high-PI soils must be minimised.

The progressive increase in MDD with compactive effort across all electrode treatments confirms that field compaction equipment selection significantly influences the density achievable in EKR-remediated laterite. For liner applications requiring high density, BSH-equivalent compaction (heavy vibratory roller compaction in the field) is essential, particularly for carbon and mild steel-treated soils which show the greatest MDD gains under high compactive effort (1.80 and 1.86 Mg/m³ respectively at BSH). Where only BSL-equivalent compaction is feasible — for instance, in remote or constrained construction environments — the MDD range of 1.59–1.63 Mg/m³ still represents an improvement over contaminated unremediated soil and provides acceptable liner subgrade performance when complemented with appropriate geosynthetic barrier components.

The high BSL OMC values (25–30%) characteristic of all EKR-treated soils require careful moisture conditioning protocols in field construction. Water addition to achieve target OMC must account for evaporative losses in the hot, dry climatic conditions typical of northern Nigerian construction sites, and soil should be compacted within a moisture content window of OMC ± 2% to ensure consistent MDD achievement. This specification is particularly critical for mild steel-treated soils which, despite achieving the highest BSH MDD (1.86 Mg/m³), show the most variable OMC response across compactive efforts (13.23–29.71%), increasing the risk of under- or over-compaction in field conditions.

V. CONCLUSIONS

This study systematically characterised the index and compaction properties of crude oil-contaminated lateritic soil electrokinetically remediated with graphite, carbon, and mild steel electrodes under BSL, WAS, and BSH compactive efforts. The following conclusions are drawn:

1. EKR effectively restored the index properties of crude oil-contaminated lateritic soil. All electrode treatments produced lean clay (CL/A-7-6) materials with fines content 79.40–81.56% and plasticity indices 14.22–19.13%, within the preferred range for compacted clay liner construction.
2. Electrode material significantly influenced post-EKR index behaviour. Graphite achieved the lowest PI (14.22%), liquid limit (41.91%), and most stable specific gravity (1.785), attributable to its superior TPH removal efficiency (73.34%) which stripped hydrocarbon films from particle surfaces.
3. MDD increased consistently with compactive effort for all electrode treatments (BSL → WAS → BSH), confirming that higher compaction energy is required to achieve target liner densities. BSH compaction produced the highest MDD values: mild steel 1.86, carbon 1.80, and graphite 1.71 Mg/m³.
4. OMC decreased with increasing compactive effort for all electrode treatments. BSL OMC values of 25.23–29.71% are high relative to typical lateritic soils, reflecting elevated clay mineral moisture retention post-EKR, and must be accounted for in field moisture conditioning protocols.
5. Graphite-treated soils exhibited the most stable and predictable index and compaction profile across all compactive efforts, making them the preferred electrode treatment for waste containment facility applications requiring consistent geotechnical performance.
6. All EKR-treated soils showed improved MDD and reduced LL, PL, and PI relative to the unremediated crude oil-contaminated baseline, confirming that EKR treatment enhances the geotechnical workability and compactability of contaminated Nigerian laterite.

VI. RECOMMENDATIONS

- Graphite electrodes are recommended as the primary EKR electrode for waste containment applications, offering the most favourable combination of low PI (14.22%), low LL

(41.91%), and stable compaction response across all compactive efforts.

- Field compaction of EKR-treated lateritic soils should target BSH-equivalent energy (heavy vibratory compaction) to achieve MDD values of 1.71–1.86 Mg/m³ suitable for compacted clay liner design. Where only lighter compaction is feasible, composite liner systems with geomembranes should supplement the compacted soil barrier.
- Moisture conditioning should be carried out within OMC ± 2% to account for the elevated and variable OMC values of EKR-treated soils (25–30% at BSL). Particular caution is required for mild steel-treated soils, which exhibit the widest OMC variation across compactive efforts.
- Future studies should investigate the long-term index property stability of EKR-treated soils under sustained leachate exposure and wetting–drying cycles, to assess whether post-remediation PI and LL values remain stable under service conditions in waste containment liner applications.

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