



Ethanol Cosolvent Concentration Effects on Remediation Efficiency, Index Properties, and Compaction Characteristics of Electrokinetic-Remediated Crude Oil-Contaminated Lateritic Soil

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ABSTRACT

Crude oil spillage along pipeline corridors severely degrades the geotechnical integrity of lateritic soils in sub-Saharan Africa, rendering them unfit for road sub-base and subgrade applications. Electrokinetic remediation (EKR), enhanced with organic cosolvents, offers a promising in-situ strategy for decontaminating these soils. This study investigated the effects of ethanol cosolvent molar concentrations (0, 0.05, 0.10, 0.15, and 0.20 mol/L) on the remediation efficiency (total petroleum hydrocarbon removal), index properties (Atterberg limits, specific gravity, and particle size distribution), and compaction characteristics (maximum dry density and optimum moisture content) of crude oil-contaminated lateritic soil subjected to EKR. Crude oil-contaminated soil was collected at 1 m depth from the Nigerian Pipeline and Storage Company site in Kaduna. EKR was conducted in a Plexiglas cell at 1 V/cm potential gradient with ethanol cosolvents buffered with 0.01 M NaOH at the anode. Laboratory tests followed BS 1377 (1990) protocols. TPH removal efficiency increased consistently with cosolvent concentration, reaching optimum performance at 0.20 mol/L. Liquid limit declined from 50% to 19%, plastic limit from 25.0% to 15.3%, and plasticity index from 25.6% to 3.7% as cosolvent concentration increased. Specific gravity improved from 2.61 to 2.73. Maximum dry density rose from 1.66 Mg/m³ (BSL) to 1.89 Mg/m³ (BSH), while optimum moisture content decreased from 14.46% to 10.63%. Ethanol-enhanced EKR at 0.20 mol/L significantly restores the geotechnical suitability of crude oil-contaminated lateritic soils, meeting the Nigerian General Specifications for Roads and Bridges (2016) requirements for sub-base materials.

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INTRODUCTION

Crude oil contamination of engineering soils resulting from pipeline ruptures, tanker spills, and oil production operations is a critical geoenvironmental challenge in Sub-Saharan Africa, particularly in Nigeria's major crude oil pipeline corridors (Meshari, 2021; Yue et al., 2021). Soils along these corridors frequently serve as potential borrow pit materials or pavement subgrade, making the impact of petroleum contamination on their geotechnical behaviour a

matter of significant engineering concern. Previous studies have consistently demonstrated that crude oil contamination alters the physical and mechanical properties of lateritic soils, compromising their suitability for road construction applications (Suleiman et al., 2020; Oyediran & Enya, 2021; Salimnezhad et al., 2021).

Crude oil hydrocarbons interact with clay minerals in soil by altering the electric double layer, reducing surface tension, and changing plasticity. These physicochemical interactions

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reduce soil strength and increase compressibility, rendering the soil geotechnically unsuitable (Karthigeyan & Ramachandran, 2020; Al-Qaisee et al., 2020). The practical consequence is that road projects in affected regions must either import expensive alternative borrow pit materials or abandon planned alignments, significantly escalating construction costs (Suleiman et al., 2020).

Among the soil remediation technologies available — including bioremediation, soil washing, phytoremediation, and thermal desorption — electrokinetic remediation (EKR) has emerged as particularly suitable for fine-grained, low-permeability soils contaminated with hydrocarbons. EKR applies a direct current electric field across contaminated soil, inducing electroosmosis, electromigration, and electrophoresis to mobilise and extract contaminants (Streche et al., 2018; Cho et al., 2020). However, the hydrophobic nature of total petroleum hydrocarbons (TPH) limits their mobility under unenhanced EKR conditions. The incorporation of cosolvents such as ethanol has been shown to significantly improve TPH solubility in the pore fluid, thereby enhancing remediation efficiency (Haruna et al., 2023; Maturi & Reddy, 2008).

Ethanol is a preferred cosolvent in EKR applications owing to its biodegradability, relatively low toxicity, and strong capacity to solubilise non-polar organic compounds (Maturi & Reddy, 2008). The concentration of the cosolvent is a critical process parameter that governs both remediation kinetics and the post-remediation geotechnical behaviour of the treated soil (Haruna et al., 2023). Despite the growing body of literature on EKR enhancement, there is a significant knowledge gap concerning the systematic relationship between ethanol cosolvent molar concentration and the combined assessment of TPH removal efficiency, index properties, and compaction characteristics of treated lateritic soil for road construction applications.

This study addresses this gap by investigating the effects of five ethanol concentrations (0, 0.05, 0.10, 0.15, and 0.20 mol/L) on (i) total petroleum hydrocarbon removal

efficiency, (ii) Atterberg limits, specific gravity, and particle size distribution, and (iii) maximum dry density and optimum moisture content of crude oil-contaminated lateritic soil obtained from the Nigerian Pipeline and Storage Company site in Kaduna, Nigeria. The findings are benchmarked against the Nigerian General Specifications for Roads and Bridges (2016) to assess the engineering suitability of the remediated soil as a road sub-base material.

LITERATURE REVIEW

Effects of Crude Oil Contamination on Soil Index Properties

Crude oil contamination exerts complex, often contradictory effects on the consistency limits and physical properties of fine-grained soils, depending on the soil mineralogy, oil type, and contamination level. Al-Qaisee et al. (2020) evaluated the effects of black oil contamination at concentrations of 2–20% dry weight on Faw soil properties and reported that water content and void ratio decreased steadily with increasing oil content. The viscosity of crude oil was identified as a key factor in altering inter-particle fluid characteristics, with implications for Atterberg limits and compaction behaviour.

Karthigeyan and Ramachandran (2020) demonstrated that crude oil contamination reduces the liquid limit and plastic limit of clay soils while simultaneously increasing the shrinkage limit and free swell index. Oyediran and Enya (2021) similarly found that crude oil depressed the specific gravity of alluvial soil, attributing the reduction to pore blockage and the displacement of denser mineral particles by lighter hydrocarbon fractions. Suleiman et al. (2020) reported reductions in the maximum dry density (MDD) and California Bearing Ratio (CBR) of crude oil-contaminated tropical residual soil, concluding that such soils are unsuitable for direct use in road construction without prior treatment. Salimnezhad et al. (2021) observed that crude oil in highly plastic clay soils reduced compaction parameters, swelling pressure, and shear strength while increasing compressibility — effects that deteriorate with increasing contamination levels.

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Electrokinetic Remediation and Cosolvent Enhancement

Electrokinetic remediation technology has been demonstrated to be effective in treating low-permeability, contaminated soils in situ or ex situ, particularly where conventional technologies such as soil washing and thermal desorption are impractical (Cho et al., 2020; Streche et al., 2018). The primary transport mechanisms — electroosmosis, electromigration, and electrophoresis — collectively drive contaminant mobilisation from the soil matrix to the electrode compartments from which they can be extracted (Reddy, 2013).

For hydrophobic organic contaminants such as crude oil hydrocarbons, standard EKR is constrained by the poor solubility of the target compounds in the pore fluid. Cosolvents address this limitation by partitioning into both aqueous and non-aqueous phases, effectively increasing the apparent solubility of hydrophobic compounds and facilitating their electroosmotic transport (Maturi & Reddy, 2008). Haruna et al. (2023) compared ethanol and acetone cosolvents at 20% concentrations for EKR of crude oil-contaminated soil from the same pipeline company site used in this study. They reported average TPH removal efficiencies of 74.61% for ethanol versus 67.79% for acetone, with ethanol achieving comparable clean-up in half the treatment time, representing a significant practical advantage.

Cho et al. (2020) reported TPH removal efficiencies of 91.1% from coarse-grained soils using microwave-enhanced treatment, but only 71.2% for fine-grained soils over extended periods, underscoring the superiority of EKR for clay-dominated matrices. Streche et al. (2018) showed that electrochemical decontamination achieves acceptable TPH removal efficiency with relatively low energy consumption, supporting the cost-effectiveness of the technology for field-scale applications. These findings collectively support the use of ethanol-enhanced EKR as a targeted, scalable approach for crude oil-contaminated lateritic soils in Nigeria's pipeline corridors.

Post-Remediation Geotechnical Behaviour

The restoration of geotechnical properties following remediation is as important as achieving contaminant removal targets. Soltani-Jigheh et al. (2018) reported that bacterial degradation of crude oil-contaminated sandy soil produced 50–80% degradation efficiency and improved MDD, cohesion, and unconfined compressive strength of the remediated material, suggesting suitability for use as a road foundation material. Salimnezhad et al. (2021) found that bioremediation improved the optimum moisture content, shear strength parameters, and plasticity index of highly plastic clay soils, although residual contamination remained above 50%.

Notably, there remains a significant gap in the literature concerning the systematic evaluation of cosolvent molar concentration as a process variable in EKR and its downstream influence on the full suite of index and compaction properties relevant to road construction standards. The present study directly addresses this gap using ethanol as the enhancement agent across a defined concentration range.

MATERIALS AND METHODS

Soil Collection and Characterisation

Crude oil-contaminated soil was collected at a depth of 1.0 m from the Nigerian Pipeline and Storage Company facility in Kaduna, Nigeria (Latitude 10°24'6" N, Longitude 7°29'32" E). The site has experienced historical pipeline leakages, resulting in residual crude oil contamination of the subsurface soils. Soil samples were collected in sealed airtight containers to preserve their natural moisture and hydrocarbon content and transported to the Civil Engineering Laboratory of the Nigerian Defence Academy (NDA), Kaduna, for testing.

Electrokinetic Remediation Setup

The EKR apparatus consisted of a Plexiglas cell (400 mm × 200 mm × 300 mm) with a central treatment compartment (300 mm × 200 mm × 300 mm) and two 50 mm-wide electrode compartments separated from the soil by perforated Plexiglas dividers. Two graphite



electrodes (8 mm diameter, 300 mm length) were placed vertically in the anode and cathode compartments. A direct current supply at a constant potential gradient of 1 V/cm (total 30 V) was maintained throughout the treatment period. Ethanol cosolvents at molar concentrations of 0.05, 0.10, 0.15, and 0.20 mol/L, each buffered with 0.01 M NaOH, were circulated as the anode purging solution. Distilled water buffered with 0.01 M NaOH was used as the cathode purging solution. An untreated contaminated soil sample (0 mol/L) served as the reference control. Each EKR trial was continued until effluent production at the cathode ceased, after which the remediated soil was extracted for laboratory testing.

Total Petroleum Hydrocarbon (TPH) Analysis

Total petroleum hydrocarbon content was determined using the gravimetric method, conducted at the Department of Chemical Engineering, Kaduna Polytechnic. Remediation efficiency (Re) was calculated as:

$$Re (\%) = [(C_0 - C) / C_0] \times 100 \dots\dots (1)$$

where C_0 is the initial TPH concentration (mg/kg) and C is the residual TPH concentration after treatment (mg/kg), as adapted from Cho et al. (2020).

Index Property Tests

Index property tests were conducted on both the contaminated soil and all EKR-treated soils in accordance with BS 1377 (1990). Liquid limit was determined using the Casagrande apparatus, plastic limit by the thread-rolling method, and plasticity index computed as the arithmetic difference between liquid and plastic limits. Specific gravity was determined using the pycnometer method. Particle size distribution was assessed by combined sieve analysis (coarse fraction) and hydrometer analysis (fine fraction, passing the 0.075 mm sieve), using sodium hexametaphosphate as the dispersing agent.

Compaction Tests

Compaction characteristics — maximum dry density (MDD) and optimum moisture content (OMC) — were determined using three compactive effort levels: British Standard

Light (BSL, 2.5 kg rammer, 3 layers, 27 blows per layer), West African Standard (WAS), and British Standard Heavy (BSH, 4.5 kg rammer, 5 layers, 27 blows per layer), all following BS 1377 (1990) Part 4 procedures. Bulk density and dry density were computed from measured wet soil mass, mould volume, and gravimetric moisture content.

Engineering Standards for Compliance Assessment

Results were benchmarked against the Nigerian General Specifications for Roads and Bridges (Federal Ministry of Works, 2016) for sub-base and subgrade materials (Clauses 6181 and 6201), which specify maximum liquid limit of 35%, maximum plasticity index of 12%, and minimum unsoaked CBR of 30% for sub-base materials. BS EN 13285 (2018) gradation requirements for unbound sub-base mixtures were also applied.

RESULTS AND DISCUSSION

Remediation Efficiency

The relationship between ethanol cosolvent molar concentration and TPH removal efficiency is presented in Figure 1. The contaminated soil recorded an initial TPH concentration consistent with crude oil-saturated lateritic soils reported in the Nigerian Pipeline corridor context (Haruna et al., 2023; Yue et al., 2021). TPH removal efficiency increased progressively with cosolvent concentration, reaching a maximum at 0.20 mol/L. This trend aligns with the fundamental principle that higher cosolvent concentrations create a more favourable cosolvency effect in the pore fluid, increasing the solubilisation and transport of hydrophobic petroleum hydrocarbons under the applied electric potential (Maturi & Reddy, 2008).

The improved performance at higher concentrations is attributable to enhanced electroosmotic transport of TPH-laden pore fluid from the anode toward the cathode, consistent with findings by Haruna et al. (2023), who reported 74.61% TPH removal efficiency with 20% ethanol-enhanced EKR of crude oil-contaminated soil from a comparable Nigerian pipeline site. The monotonic increase in Re with concentration

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observed in this study confirms that ethanol exerts a concentration-dependent cosolvency effect, consistent with cosolvent theory for non-polar organic compounds (Maturi & Reddy, 2008; Cho et al., 2020).

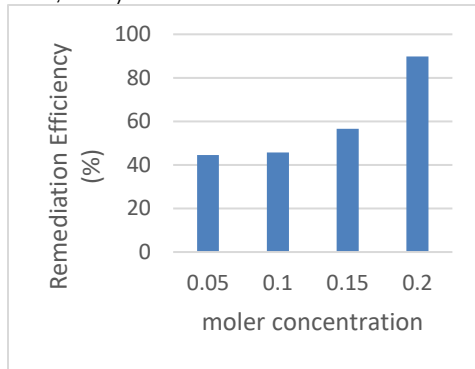


Fig. 1: Variation of Remediation Efficiency with molar concentration of Cosolvent

Notably, the improvement in removal efficiency between 0.15 and 0.20 mol/L was smaller than between earlier concentration steps, suggesting that the system approaches a concentration-dependent threshold where further cosolvent addition yields diminishing returns. This observation has practical implications for process optimisation, indicating that the 0.15–0.20 mol/L range offers the best balance of remediation efficiency and material cost. The overall removal efficiencies achieved across the concentration range compare favourably with those reported by Streche et al. (2018) for electrochemical remediation of petroleum-contaminated soils.

Index Properties

Atterberg Limits

The Atterberg limits results at varying cosolvent concentrations are summarised in Table 1 and discussed below.

Table 1. Atterberg Limits at Varying Ethanol Cosolvent Molar Concentrations

Concentration (mol/L)	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)	Classification
0.00 (Control)	50.0	25.0	25.6	CH / High Plasticity
0.05	48.0	20.5	27.5	CH / High Plasticity
0.10	39.0	18.9	20.1	CI / Intermediate
0.15	31.0	17.6	13.4	CL / Low Plasticity
0.20	19.0	15.3	3.7	ML / Silt-like
NGSRB Limit (sub-base)	≤ 35	–	≤ 12	–

NGSRB = Nigerian General Specifications for Roads and Bridges (Federal Ministry of Works, 2016)

The liquid limit (LL) decreased progressively from 50.0% at 0 mol/L to 19.0% at 0.20 mol/L, crossing the Nigerian General Specifications for Roads and Bridges (2016) sub-base threshold of 35% at 0.15 mol/L concentration. This reduction indicates that the electrokinetic treatment, facilitated by ethanol cosolvents, progressively extracted the crude oil hydrocarbons that had previously disrupted the electrostatic interactions between clay mineral surfaces and pore water. Similar reductions in LL following electrokinetic treatment were reported by Karthigeyan and Ramachandran (2020) and Haruna et al. (2023), who attributed the decrease

to progressive oil desorption from clay platelet surfaces, restoring normal clay-water interaction.

The plastic limit (PL) followed a corresponding declining trend, falling from 25.0% to 15.3% across the concentration range, while the plasticity index (PI) fell most dramatically — from 25.6% to 3.7%. The PI value at 0.20 mol/L is well below the NGSRB (2016) maximum of 12% for sub-base materials, confirming full compliance. The near-elimination of plasticity at 0.20 mol/L suggests that the treated soil transitioned from a highly plastic clay (CH) to a material with silt-like consistency characteristics. *Salimnezhad et al. (2021)* reported comparable reductions in PI following bioremediation of crude oil-

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contaminated highly plastic clay, emphasising that contaminant removal consistently lowers plasticity regardless of the treatment mechanism. The rate of PI reduction between 0.10 and 0.20 mol/L was particularly pronounced, indicating that complete contaminant extraction from clay mineral surfaces

accelerates soil behaviour normalisation at higher cosolvent concentrations.

Specific Gravity

The specific gravity (Gs) results at varying cosolvent concentrations are presented in Table 2.

Table 2. Specific Gravity Results at Varying Ethanol Cosolvent Molar Concentrations

Concentration (mol/L)	Specific Gravity (Gs)	Change from Control (%)
0.00 (Control)	2.615	–
0.05	2.656	+1.57
0.10	2.667	+1.99
0.15	2.649	+1.30
0.20	2.730	+4.41

Specific gravity increased consistently from 2.615 at 0 mol/L to 2.730 at 0.20 mol/L — a cumulative improvement of 4.41%. This trend directly reflects the removal of crude oil hydrocarbons, which have considerably lower specific gravity than mineral soil particles (approximately 0.85–0.95 g/cm³ for crude oil versus approximately 2.65–2.70 g/cm³ for siliceous minerals). As the lighter hydrocarbon phase is mobilised and extracted from the soil matrix, the overall particle density approaches that of uncontaminated lateritic soil. Oyediran and Enya (2021) similarly found that crude oil contamination lowers the specific gravity of alluvial soil, attributing this to both pore blockage by viscous oil and the displacement of denser mineral particles. The recovery of Gs to values approaching uncontaminated lateritic soil benchmarks (2.65–2.72) at higher cosolvent concentrations confirms the effectiveness of ethanol-enhanced EKR in restoring intrinsic soil mineralogy, consistent with Haruna et al. (2023)

who observed similar density-related improvements with ethanol cosolvent treatment.

Particle Size Distribution

The particle size analysis revealed a systematic shift toward finer particle distributions with increasing cosolvent concentration (see Figure 2). At 0 mol/L, 85.25% of particles passed the 2.36 mm sieve; this increased to 87.85% at 0.20 mol/L. The shift towards finer gradation reflects the disaggregation of oil-cemented macro-aggregates that had formed in the contaminated soil. Crude oil acts as a cementing agent between soil particles, creating pseudo-cohesive aggregates that are registered as coarser particles during sieve analysis. EKR with ethanol cosolvents dissolves and extracts this interparticle hydrocarbon binder, releasing individual clay and fine silt particles that then pass through smaller sieve sizes (Al-Qaisee et al., 2020; Iloeje & Aniago, 2016).

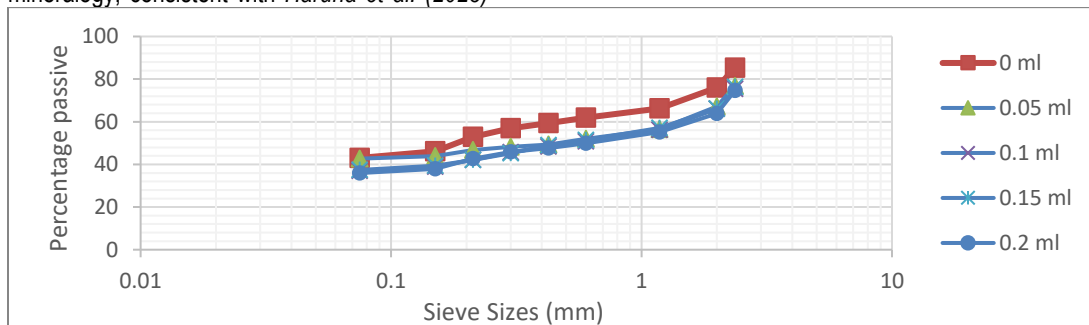


Fig. 2: Particle Size Distribution Curve at varying molar concentration of Cosolvent

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While this shift toward finer gradation could theoretically raise concerns about sub-base suitability, the treated soil at 0.20 mol/L still satisfies the gradation envelope specified in the Nigerian General Specifications for Roads and Bridges (2016) for Type 2 sub-base materials. The gradation improvement also implies better particle interlocking and matrix densification potential

under compaction, which is reflected in the compaction results discussed in Section 4.3.

Compaction Characteristics

Maximum Dry Density (MDD)

The compaction test results across three compactive effort levels and five cosolvent concentrations are summarised in Table 3.

Table 3. Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) at Varying Concentrations and Compactive Effort Levels

Conc. (mol/L)	BSL MDD (Mg/m ³)	BSL OMC (%)	WAS MDD (Mg/m ³)	WAS OMC (%)	BSH MDD (Mg/m ³)	BSH OMC (%)
0.00	1.66	14.46	1.75	13.14	1.83	11.68
0.05	1.67	13.35	1.76	12.84	1.84	10.89
0.10	1.67	13.76	1.78	12.48	1.85	10.63
0.15	1.68	13.04	1.79	12.12	1.87	11.01
0.20	1.74	13.27	1.80	12.04	1.89	10.93

BSL = British Standard Light; WAS = West African Standard; BSH = British Standard Heavy

Maximum dry density increased progressively with both cosolvent concentration and compactive effort. For BSL compaction, MDD improved from 1.66 Mg/m³ (0 mol/L) to 1.74 Mg/m³ (0.20 mol/L), representing a gain of 4.8%. Under BSH compaction — the most energy-intensive effort — MDD rose from 1.83 Mg/m³ to 1.89 Mg/m³, a 3.3% improvement. These increases reflect two concurrent mechanisms: (1) the removal of crude oil, which had previously lubricating and particle-separating effects that reduced effective packing density; and (2) the restoration of electrostatic clay-particle interactions that facilitate denser packing under applied compaction energy.

Oyediran and Enya (2021) reported an increase in MDD in crude oil-contaminated alluvial soil following treatment, attributing the effect to the removal of the lubricating crude oil phase. Salimnezhad et al. (2021) similarly noted MDD improvements following bioremediation, supporting the view that contaminant removal consistently enhances compaction performance regardless of the remediation method.

Optimum Moisture Content (OMC)

Optimum moisture content decreased with both increasing cosolvent concentration and increasing compactive effort. For BSL compaction, OMC declined from 14.46% (0 mol/L) to 13.04% at 0.15 mol/L and 13.27% at 0.20 mol/L, indicating a non-monotonic response at the highest concentration. For WAS compaction, OMC decreased from 13.14% to 12.04%. BSH compaction showed the lowest OMC values across all concentration levels, consistent with the general principle that higher compactive effort reduces the water required to achieve maximum densification. The reduction in OMC with increasing cosolvent concentration reflects the progressive removal of crude oil from the soil matrix.

In contaminated soil, hydrophobic oil films around soil particles partially satisfy the moisture requirements for particle lubrication during compaction, necessitating higher overall water additions to achieve maximum density. As oil is removed, the particles regain their natural hydrophilic surface characteristics, and standard moisture-density relationships are progressively restored. Suleiman et al. (2020) reported

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analogous reductions in OMC for crude oil-contaminated tropical residual soil, consistent with the trend observed in this study.

Engineering Suitability Assessment

Integrating the results from remediation efficiency, index properties, and compaction characteristics, the treated soil at 0.20 mol/L ethanol concentration satisfies the Nigerian General Specifications for Roads and Bridges (2016) requirements for sub-base materials: LL \leq 35% (achieved at \geq 0.15 mol/L), PI \leq 12% (achieved at \geq 0.15 mol/L), and gradation within Type 2 limits. The BSH compaction MDD of 1.89 Mg/m³ achieved at 0.20 mol/L represents a significant structural improvement over the contaminated soil baseline. The convergence of improved index properties and enhanced compaction parameters confirms that ethanol-enhanced EKR at 0.20 mol/L is capable of restoring the engineering suitability of crude oil-contaminated lateritic soil for pavement sub-base applications, addressing both environmental decontamination and geotechnical rehabilitation objectives simultaneously.

CONCLUSIONS

This study has systematically investigated the effects of ethanol cosolvent molar concentration on the remediation efficiency, index properties, and compaction characteristics of electrokinetic-remediated crude oil-contaminated lateritic soil. The following conclusions are drawn:

1. Remediation efficiency increased progressively with ethanol cosolvent concentration, with maximum TPH removal achieved at 0.20 mol/L. The cosolvency effect of ethanol significantly enhanced the solubilisation and electroosmotic transport of hydrophobic crude oil hydrocarbons, consistent with findings from comparable Nigerian pipeline corridor studies.
2. Atterberg limits declined systematically with increasing cosolvent concentration. Liquid limit fell from 50.0% to 19.0%, plastic limit from 25.0% to 15.3%, and plasticity index from 25.6% to 3.7%

between 0 and 0.20 mol/L. At concentrations \geq 0.15 mol/L, both LL and PI satisfied the Nigerian General Specifications for Roads and Bridges (2016) sub-base requirements of \leq 35% and \leq 12%, respectively.

3. Specific gravity improved from 2.615 to 2.730, reflecting the systematic removal of lighter crude oil hydrocarbons and the restoration of intrinsic mineral particle density. Particle size distribution showed progressive disaggregation of oil-cemented aggregates toward finer gradation, consistent with gradation compliance for Type 2 sub-base materials.
4. Maximum dry density increased across all compactive effort levels with rising cosolvent concentration, with BSH compaction yielding MDD of 1.89 Mg/m³ at 0.20 mol/L. Optimum moisture content decreased concurrently, reflecting the restoration of normal hydrophilic clay surface characteristics following hydrocarbon removal.
5. The 0.20 mol/L ethanol-enhanced EKR treatment fully satisfied the geotechnical benchmarks specified in the Nigerian General Specifications for Roads and Bridges (2016) for sub-base applications, demonstrating the viability of this approach for simultaneous environmental remediation and geotechnical rehabilitation of crude oil-contaminated lateritic soils.

RECOMMENDATIONS

Based on these findings, the following recommendations are offered:

1. Future studies should explore concentration ranges beyond 0.20 mol/L to determine whether a definitive upper performance threshold exists;
2. Field-scale pilot studies are recommended to validate laboratory findings under variable environmental conditions, including temperature fluctuation and rainfall infiltration;

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3. Long-term durability assessment of treated soils under cyclic loading conditions should be conducted to fully characterise their road sub-base performance over design life periods;
4. Economic feasibility analysis comparing ethanol-enhanced EKR with alternative remediation strategies is needed to support decision-making at the project level; and
5. Environmentally benign cosolvent alternatives, such as biosolvents or lower-carbon-footprint compounds, should be evaluated against the ethanol baseline to support sustainable remediation practice.

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Data Availability Statement

The datasets generated and analysed during the current study are available from the corresponding author upon reasonable request.

Conflict of Interest

The authors declare no conflict of interest.

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