



Effects of Varied Electrodes on Electrokinetic Remediation (EKR) of Crude Oil-Contaminated Lateritic Soil

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ABSTRACT: Crude oil contamination severely degrades the geotechnical properties of soils, rendering them unsuitable for engineering applications. This study investigates the effects of four electrode materials—carbon, stainless steel, platinum, and titanium—on the efficiency of Electrokinetic Remediation (EKR) of crude oil-contaminated lateritic soil obtained from an oilfield site in Nembe Creek, Bayelsa State, Nigeria. Laboratory EKR experiments were conducted using a direct current supply of 30 V with a voltage gradient of 0.5–2.0 V/cm, employing 0.1 M sodium sulphate as the anolyte and 0.05 M sodium dodecyl sulphate as the catholyte. Geotechnical characterisation, including Atterberg limits, particle size distribution, specific gravity, compaction (BSL, WAS, BSH), unconfined compressive strength (UCS), California Bearing Ratio (CBR), and Total Petroleum Hydrocarbon (TPH) analyses, was conducted on both contaminated and remediated soil samples in accordance with BS 1377 (1990). Results show that platinum electrode achieved the highest TPH removal efficiency of 80.34%, followed by titanium (77.81%), stainless steel (73.03%), and carbon (71.63%). Post-remediation UCS values ranged from 266.6 to 751.5 kN/m², with stainless steel recording the highest strength across all compactive effort levels; however, all values fell short of the 1,720 kN/m² base material threshold stipulated by TRRL (1977) but meeting the requirement for 687–1,373 kN/m² range recommended by Ingles and Metcalf (1972) for sub-base. The highest CBR value of 72% was attained with stainless steel at BSH energy level, meeting sub-base and sub-grade but not base material requirements of the Nigerian General Specifications (2016). Stainless steel electrodes are recommended for practical EKR applications due to their superior geomechanical performance, cost-effectiveness, and availability.

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KEY WORDS: Crude oil contamination; Electrokinetic remediation; Electrode materials; Lateritic soil; Total petroleum hydrocarbons; Geotechnical properties; Stainless steel electrode.

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1. INTRODUCTION

Crude oil contamination of soils resulting from petroleum exploration, production, and transportation activities has emerged as a critical geoenvironmental problem, particularly in oil-producing regions of sub-Saharan Africa. In the Niger Delta region of Nigeria, frequent pipeline ruptures, equipment failures, and oil spills from operational sites such as those managed by Aiteo Eastern

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Exploration and Production Limited in Nembe, Bayelsa State, have resulted in extensive soil contamination. Beyond ecological damage, crude oil contamination fundamentally alters the physical, chemical, and mechanical properties of soils, compromising their suitability for civil engineering applications (Akinwumi et al., 2014; Mohammad & Taghi, 2012).

Crude oil-contaminated (COC) soils are characterised by the presence of complex hydrocarbon compounds—including saturated (paraffins), unsaturated (olefins), and aromatic hydrocarbons such as benzene, toluene, and xylene—as well as heavy metals such as lead (Pb) and trace elements. These contaminants alter soil fabric by coating particles with hydrophobic films, modifying interparticle friction, increasing bulk density, changing Atterberg limits, reducing hydraulic conductivity, and diminishing shear strength (Arao et al., 2010 as cited in Haruna et al., 2023; Abdulrahman, 2023). Collectively, such alterations reduce bearing capacity, accelerate settlement, compromise slope stability, and impair drainage, creating significant engineering hazards.

Among the various remediation techniques developed for COC soils, Electrokinetic Remediation (EKR) has gained prominence as a promising in situ or ex situ method. EKR applies a low-level direct current (DC) across electrodes inserted into contaminated soil, generating electroosmotic flow, electromigration, and electrophoresis that mobilise and extract contaminants including heavy metals, radionuclides, and organic compounds from saturated or unsaturated soil matrices (Cameselle & Gouveia, 2018; Boulakradeche et al., 2021). Despite its demonstrated effectiveness, the performance of EKR is highly dependent on operational parameters, including electrode material, applied voltage gradient, electrolyte composition, and treatment duration.

Previous studies have reported variable remediation outcomes depending on electrode type, yet comprehensive comparative investigations of electrode materials for crude oil-contaminated lateritic soils under standardised conditions remain limited. The electrode material directly influences electrochemical reactions at the electrode–soil interface, electrolyte chemistry, current efficiency, and ultimately, contaminant removal. Carbon electrodes offer economic advantages but are susceptible to degradation; stainless steel electrodes are corrosion-resistant and widely available; platinum electrodes provide high conductivity but at significant cost; and titanium electrodes are inert and durable, though also expensive.

This study, therefore, investigates the comparative effects of four electrode materials—carbon, stainless steel, platinum, and titanium—on EKR performance for crude oil-contaminated lateritic soil, with emphasis on TPH removal efficiency, index properties, compaction characteristics, strength parameters (UCS and CBR), and suitability for road pavement applications. The findings aim to inform optimal electrode selection for cost-effective and efficient EKR in field practice.

2. MATERIALS AND METHODS

2.1 Soil Sample Collection

A total of 250 kg of crude oil-contaminated lateritic soil was collected from an oilfield spill site in Nembe Creek, Nembe Local Government Area, Bayelsa State, Nigeria, operated by Aiteo Eastern Exploration and Production Limited. The topsoil was removed to a depth of 0.2 m to exclude surface vegetation. Contaminated soil was subsequently excavated from a depth of 0.6–1.0 m across a sampling area of approximately 1.81–2.5 m². Samples were sealed in airtight polythene bags and transported to the Civil Engineering Laboratory at the Nigerian Defence Academy (NDA), Kaduna, for processing. The natural moisture content of the contaminated samples was measured prior to air-drying for seven days before laboratory testing.

2.2 EKR Cell Design and Experimental Setup

The EKR experimental apparatus consisted of a rectangular Plexiglass cell (400 mm × 200 mm × 300 mm) divided into three compartments: two electrode chambers (each 100 mm × 200 mm × 200 mm) and a central soil chamber (300 mm × 200 mm × 200 mm). The electrode and soil compartments were separated by perforated Plexiglass partitions (30 cm × 8 mm diameter holes at 6 cm centre-to-centre spacing) lined with Whatman filter paper to prevent soil migration into the electrode chambers and to eliminate hydraulic gradients across the specimen (Cameselle & Gouveia, 2018; Hawal, 2017; Boulakradeche et al., 2021). Each electrode compartment had a 10 mm drainage hole to collect electro-osmotic flow (EOF) effluent, the volume of which was recorded daily. The setup was consistent with the EKR model described by Yu et al. (2019).

Four parallel EKR setups were operated simultaneously, each employing a different electrode material: carbon, stainless steel, platinum, and titanium (8 mm diameter, 300 mm length). A DC power supply (30 V, 5 A) was used, with actual voltage gradient in the range 0.5–2.0 V/cm, monitored using a digital multimeter. The central soil compartment was filled with 20 kg of air-dried contaminated soil at its optimum moisture content (OMC) to a height of 200 mm. Electrolyte reservoirs (1,065 mL each) containing 0.1 M sodium sulphate (Na₂SO₄) as the anolyte and 0.05 M sodium dodecyl sulphate (SDS) as the catholyte were used throughout the experiment. Citric acid served as a chelating agent to enhance contaminant mobility. The complete experimental design is summarised in Table 1.

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Table 1: EKR experimental programme and electrode configuration.

Code	Electrode	Voltage	VG (V/cm)	Anolyte	Catholyte	Mode	Duration (days)
EK1	Titanium	30 V	0.5–2.0	0.1 M Na ₂ SO ₄	0.05 M SDS	Continuous	7
EK2	Stainless Steel	30 V	0.5–2.0	0.1 M Na ₂ SO ₄	0.05 M SDS	Continuous	7
EK3	Platinum	30 V	0.5–2.0	0.1 M Na ₂ SO ₄	0.05 M SDS	Continuous	7
EK4	Carbon	30 V	0.5–2.0	0.1 M Na ₂ SO ₄	0.05 M SDS	Continuous	7

2.3 Laboratory Testing

All geotechnical and chemical tests on contaminated and EKR-remediated soil samples were conducted in accordance with BS 1377 (1990). The test programme comprised:

- (i) Particle Size Distribution – performed by wet sieving through BS No. 200 sieve (0.075 mm aperture) and hydrometer analysis.
- (ii) Atterberg Limits – liquid limit (LL), plastic limit (PL), plasticity index (PI), and linear shrinkage (LS) determined per BS 1377 Part 2.
- (iii) Specific Gravity (Gs) – determined using density bottles as per BS 1377 Part 2 using the formula: $G_s = (M_2 - M_1) / [(M_2 - M_1) - (M_3 - M_4)]$.
- (iv) Compaction – carried out at three energy levels: British Standard Light (BSL), West African Standard (WAS), and British Standard Heavy (BSH), per BS 1377 Part 4 and Nigerian General Specifications (1997).
- (v) Unconfined Compressive Strength (UCS) – conducted on cylindrical specimens (38.1 mm diameter × 76.2 mm length) compacted at OMC and cured for 7 days, per BS 1377 Part 7.
- (vi) California Bearing Ratio (CBR) – both unsoaked and soaked conditions, in 2,360 cm³ moulds at three compactive energy levels, per BS 1377 Part 4.
- (vii) Total Petroleum Hydrocarbon (TPH) – measured gravimetrically on three replicates per electrode type, both before and after EKR treatment. TPH removal efficiency was calculated as: $\text{Removal (\%)} = [(C_i - C_f) / C_i] \times 100$, where C_i and C_f are initial and final average TPH concentrations (mg/kg) respectively.
- (viii) X-Ray Fluorescence (XRF) Analysis – conducted to determine the elemental oxide composition of the contaminated soil.

3. RESULTS AND DISCUSSION

A comprehensive summary of all index, compaction, strength, and bearing ratio results for the crude oil-contaminated soil (COCS) and the four EKR-remediated samples is presented in Table 2. Detailed discussion of each property follows in subsequent subsections.

Table 2: Summary of geotechnical properties of contaminated and EKR-remediated soils.

Property	COCS	Carbon (ACAR)	Stainless Steel (ASTS)	Platinum (APLA)	Titanium (ATIT)
Index Properties					
Passing BS No. 200 sieve (%)	76.60	77.56	74.40	71.00	77.70
Natural moisture content (%)	13.70	13.70	13.70	13.70	13.70
Liquid limit, LL (%)	42.90	43.90	50.00	49.40	44.50
Plastic limit, PL (%)	27.10	27.32	28.30	25.80	25.14
Plasticity index, PI (%)	15.80	16.58	21.70	23.60	19.36
Linear shrinkage (%)	10.0	9.3	9.3	6.4	9.3
Specific gravity, G _s	2.26	1.80	1.25	1.29	2.50
AASHTO classification	A-7-6	A-7-6	A-7-6	A-7-6	A-7-6

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Property	COCS	Carbon (ACAR)	Stainless Steel (ASTS)	Platinum (APLA)	Titanium (ATIT)
USCS classification	CL	CL	CL	CL	CL
Maximum Dry Density (g/cm³)					
BSL	1.75	1.64	1.71	1.71	1.70
WAS	1.78	1.76	1.84	1.86	1.74
BSH	1.89	1.82	1.88	1.90	1.85
Optimum Moisture Content (%)					
BSL	14.44	18.99	17.13	15.50	18.75
WAS	14.30	16.23	15.00	12.62	15.93
BSH	12.00	15.20	13.25	11.90	12.40
Unconfined Compressive Strength (kN/m²)					
BSL (7-day curing)	110.10	88.87	175.35	136.58	89.30
WAS (7-day curing)	123.40	103.70	206.00	183.20	105.30
BSH (7-day curing)	143.68	113.30	250.50	210.40	117.90
CBR – Unsoaked (%)					
BSL	21.0	12.0	17.0	16.34	4.98
WAS	25.0	11.0	41.0	30.0	13.0
BSH	42.0	11.0	72.0	46.0	38.0
CBR – Soaked (%)					
BSL	15.0	9.0	4.0	4.0	5.1

COCS = Crude oil contaminated soil; ACAR = After carbon EKR; ASTS = After stainless steel EKR; APLA = After platinum EKR; ATIT = After titanium EKR; BSL = British Standard Light; WAS = West African Standard; BSH = British Standard Heavy.

3.1 Chemical Composition and Initial Soil Characterisation

The XRF analysis of the crude oil-contaminated soil revealed silicon dioxide (SiO₂) and aluminium oxide (Al₂O₃) as the dominant elemental oxides, constituting 50.44% and 30.17% by mass respectively, consistent with a kaolinite-dominant lateritic soil profile. The elevated iron oxide (Fe₂O₃) content of 15.11% is characteristic of tropical lateritic soils. Loss on ignition (LOI) of 19.35% is indicative of the significant organic hydrocarbon content associated with crude oil contamination. Full XRF results are presented in Table 3.

Table 3: XRF chemical composition of crude oil-contaminated soil.

Elemental Oxide	Composition (%)
SiO ₂	50.44
Al ₂ O ₃	30.17
Fe ₂ O ₃	15.11
CaO	0.30
MgO	0.00
SO ₃	0.30
Na ₂ O	1.37

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Elemental Oxide	Composition (%)
K ₂ O	0.61
TiO ₂	1.69
P ₂ O ₅	0.01
MnO	0.07
LOI	19.35

The initial AASHTO classification of the contaminated soil was A-7-6, corresponding to clay of low plasticity (CL) under the Unified Soil Classification System (USCS), with a liquid limit of 42.9%, plastic limit of 27.1%, and plasticity index of 15.8%. These index values confirm the soil's fine-grained, clay-dominated character, with 76.60% of particles passing through the No. 200 sieve.

3.2 TPH Removal Efficiency

The initial average TPH concentration of the crude oil-contaminated soil was 5,933 mg/kg. Following EKR treatment with varied electrodes, TPH concentrations were significantly reduced in all four setups. Table 4 summarises the TPH removal efficiency for each electrode type.

Table 4: TPH removal efficiency of EKR with varied electrodes.

Sample	Avg. TPH (mg/kg)	TPH (mg/kg)	Removed (%)	Removal Efficiency (%)
Crude Oil Contaminated Soil (COCS)	5,933.00	—	—	—
Carbon electrode (ACAR)	1,683.33	4,249.67	71.63	71.63
Stainless steel electrode (ASTS)	1,600.00	4,333.00	73.03	73.03
Platinum electrode (APLA)	1,166.67	4,766.33	80.34	80.34
Titanium electrode (ATIT)	1,316.67	4,616.33	77.81	77.81

Platinum achieved the highest removal efficiency (80.34%), attributed to its superior electrochemical stability, high oxidative potential, and resistance to side reactions that could impede hydrocarbon breakdown. Titanium followed with 77.81%, consistent with its inert nature and oxide-layer stability. Stainless steel (73.03%) and carbon (71.63%) electrodes showed comparable but lower efficiencies. The relatively close performance of all four electrodes suggests that under the adopted experimental conditions, electrode electrochemical activity plays a secondary role to current density and electrolyte chemistry in driving contaminant mobilisation.

3.3 Index Properties

All EKR-remediated soil samples retained the same AASHTO (A-7-6) and USCS (CL) classification as the contaminated soil. Liquid limits increased post-EKR for stainless steel (50.0%) and platinum (49.4%) electrodes relative to the COCS (42.9%), while titanium (44.5%) and carbon (43.9%) showed marginal increases. The observed increases in liquid limit reflect the electrochemically induced mineralogical alterations and increased surface activity of clay particles during EKR treatment.

Plasticity index (PI) increased across all electrode types, with platinum EKR recording the highest PI of 23.6%, followed by stainless steel (21.7%), titanium (19.36%), and carbon (16.58%) (see Figure 1). An increased PI implies enhanced plasticity and water retention capacity, which is consistent with EKR-induced leaching of stabilising cations and pore fluid chemistry changes. Linear shrinkage reduced from 10% for COCS to 6.4% for platinum-treated soil, indicating a reduction in volumetric change potential.

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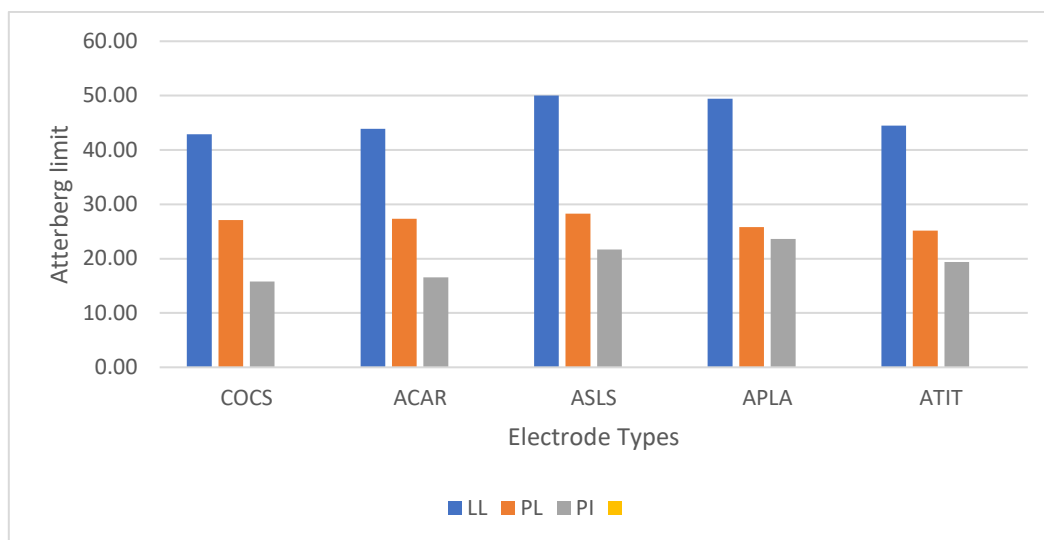


Fig. 1. Variation of Atterberg limit with varying electrodes for EKR remediation

The specific gravity values decreased after EKR treatment for carbon (1.80), stainless steel (1.25), and platinum (1.29) electrodes, compared to the original COCS value of 2.26. Only titanium EKR produced an increase (2.50) (see Figure 2). The reduction in specific gravity is attributed to the migration and removal of denser hydrocarbon-bound mineral particles during EKR, resulting in a lighter, more porous soil matrix. These findings are consistent with the observations of Oyediran and Enya (2021).

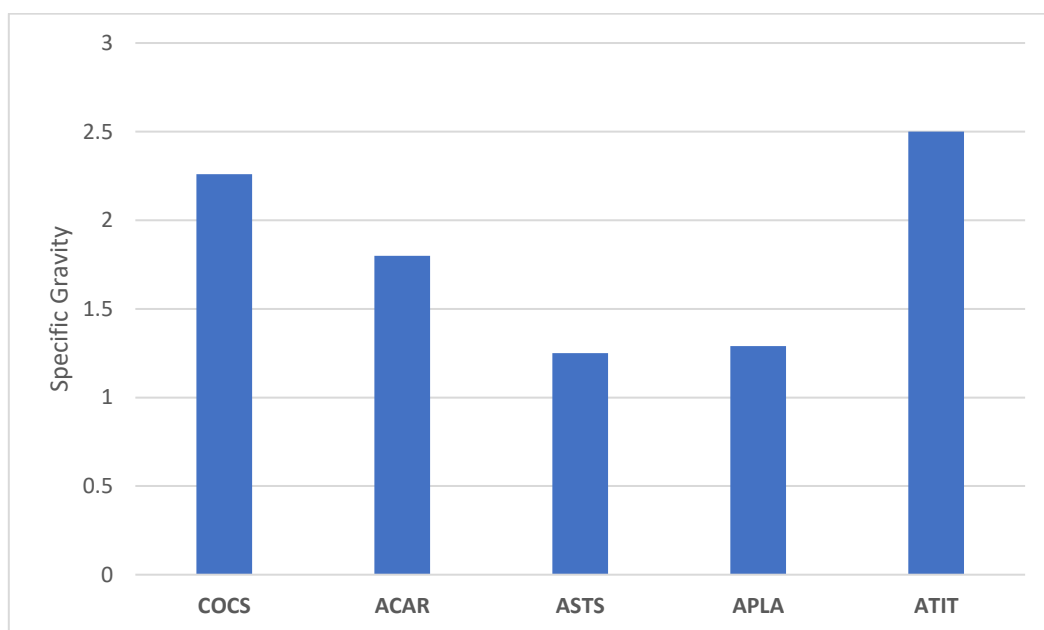


Figure 2: Specific Gravity of crude oil contaminated soil and varying electrode remediated soil with EKR

3.4 Compaction Characteristics

3.4.1 Maximum Dry Density (MDD)

The MDD values for COCS under BSL, WAS, and BSH energy levels were 1.75, 1.78, and 1.89 g/cm³, respectively. Post-EKR treatment, MDD values generally decreased for the carbon electrode (1.64, 1.76, 1.82 g/cm³) but increased for platinum under WAS and BSH (1.86, 1.90 g/cm³) (see Figure 3), with stainless steel and titanium showing intermediate values. The slight reduction in MDD for most electrodes is attributable to the porous, low-density nature of the remediated soil matrix resulting from hydrocarbon extraction. The platinum electrode achieved the highest BSH-MDD of 1.90 g/cm³, suggesting that the intense electrochemical reactions under platinum catalysis restructured the soil fabric into a denser configuration under heavy compaction.

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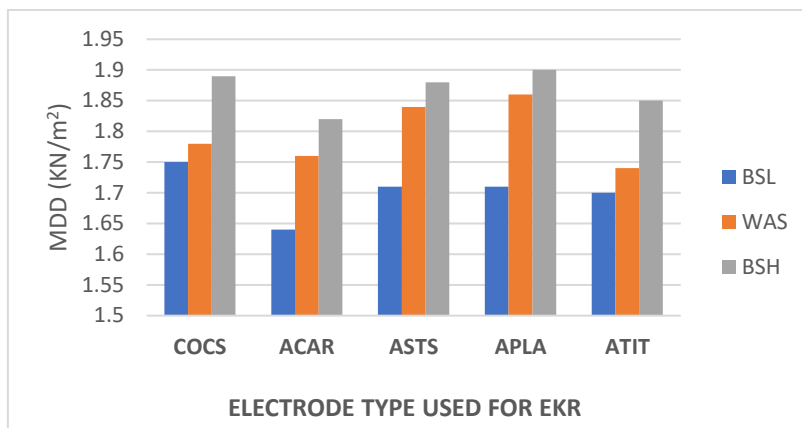


Figure 3: Variation of maximum dry density of varying electrode for BSL, WAS, BSH compactive effort

3.4.2 Optimum Moisture Content (OMC)

OMC values increased across all electrode types after EKR relative to COCS values (BSL: 14.44%, WAS: 14.30%, BSH: 12.00%). The highest OMC under BSL was recorded for carbon (18.99%), while platinum produced the lowest post-remediation OMC (BSL: 15.50%) (see Figure 4). The general increase in OMC after EKR is consistent with increased moisture absorption capacity resulting from altered pore structure and clay mineral surface activity during electrokinetic treatment. The inverse OMC–MDD relationship was maintained throughout all electrode types, validating the compaction data quality.

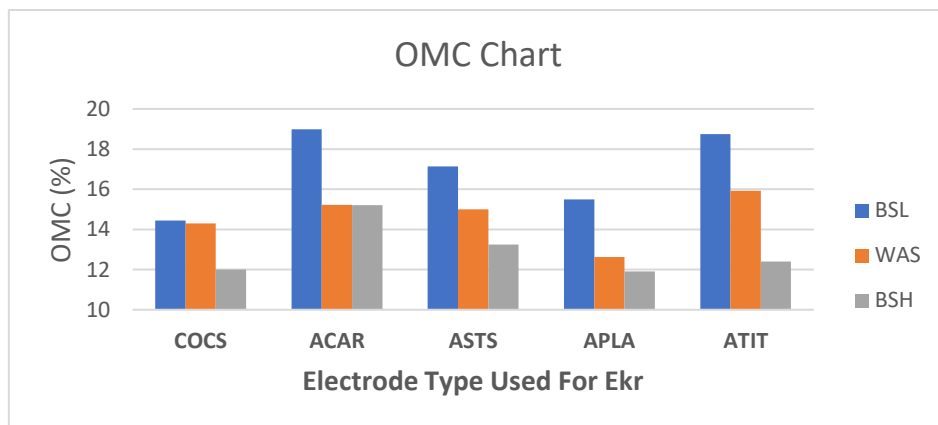


Figure 4: Variation of optimum moisture content of varying electrodes of EKR for BSL, WAS, BSH compactive effort

3.5 Unconfined Compressive Strength (UCS)

The UCS of EKR-remediated soils at 7-day curing under BSL, WAS, and BSH compactive efforts is shown in Figure 5. Stainless steel electrode consistently produced the highest UCS values across all energy levels: 526.1 kN/m² (BSL), 618.0 kN/m² (WAS), and 751.5 kN/m² (BSH). Carbon and titanium electrodes yielded the lowest UCS values in the range of 266.6–339.0 kN/m².

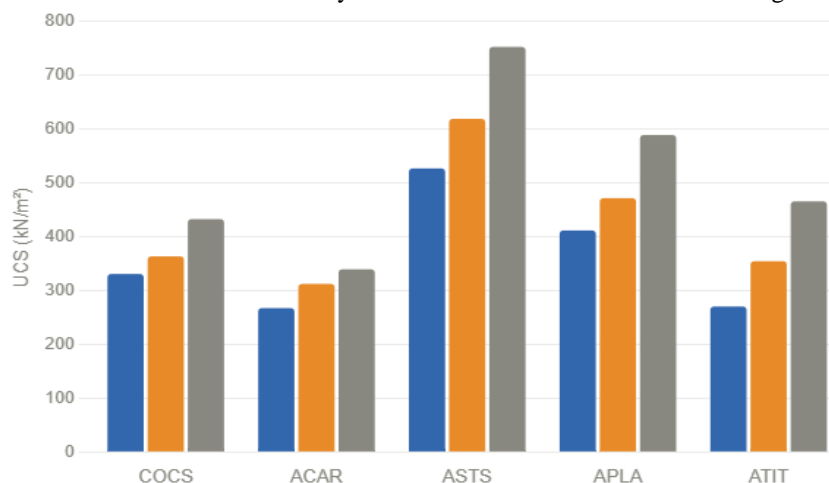


Figure 5: Variation of Unconfined Compressive Strength with varying electrode EKR for BSL, WAS and BSH compactive efforts respectively

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The superior strength achieved with stainless steel may be attributed to the release of iron ($\text{Fe}^{2+}/\text{Fe}^{3+}$) and nickel (Ni) ions during electrolytic oxidation of the electrode, which facilitate pozzolanic reactions and cation exchange within the clay mineral lattice, thereby strengthening interparticle bonds. This geochemical interaction, combined with ionic concentration changes in the diffuse double layer, results in improved particle-to-particle structural rearrangement (Adebayo et al., 2023).

However, all UCS values fall substantially below the minimum threshold of 1,720 kN/m² specified by TRRL (1977) for base course stabilisation but met the requirement for 687–1,373 kN/m² range recommended by Ingles and Metcalf (1972) for sub-base at BSH with Stainless Steel electrodes

This indicates that EKR alone, without additional stabilisation, is insufficient to qualify remediated soils for structural pavement layers.

3.6 California Bearing Ratio (CBR)

The unsoaked CBR results showed that EKR remediation with stainless steel electrodes produced the highest CBR values at all compactive effort levels (see Figure 6): 17% (BSL), 41% (WAS), and 72% (BSH). Platinum followed with 16.34% (BSL), 30% (WAS), and 46% (BSH). The CBR values for carbon and titanium electrodes were markedly lower, with titanium recording the least CBR of 4.98% under BSL.

The unsoaked BSH-CBR value of 72% for stainless steel, although not meeting the 80% minimum specified by the Nigerian General Specifications for Roads and Bridges (2016, Clause 6201) for base course, satisfies the requirements for sub-base ($\geq 30\%$) and sub-grade ($\geq 5\%$) applications. Soaked CBR values were considerably lower for all electrode types under BSL (ranging from 4.0% to 9.0%), reflecting the sensitivity of the remediated soil to moisture ingress—an important consideration for design in tropical, high-rainfall environments.

The observed ranking of stainless steel > platinum > carbon > titanium in CBR performance is broadly consistent with the UCS results and confirms stainless steel as the most geomechanically effective electrode for EKR treatment under the adopted experimental conditions.

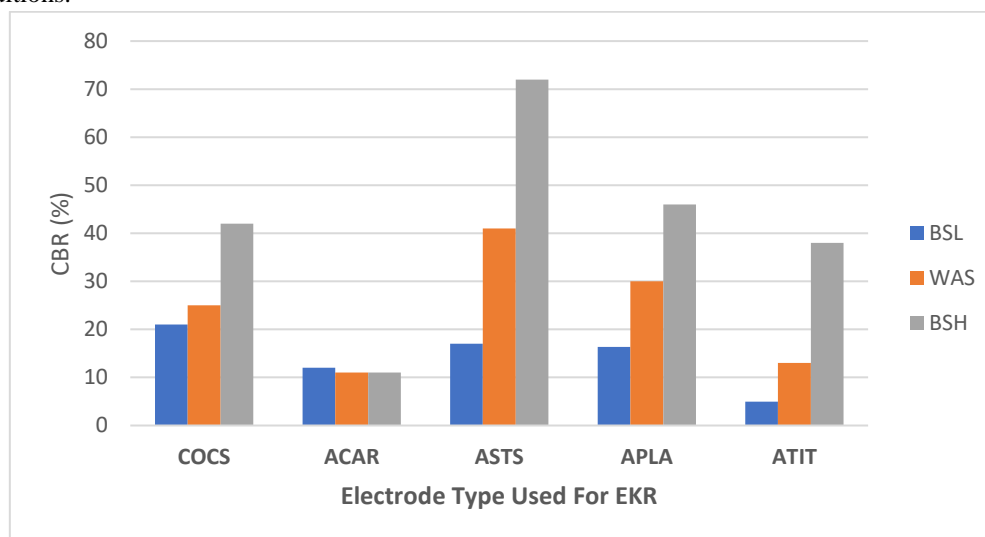


Figure 6: CBR of varied electrode EKR stabilized crude oil contaminated lateritic soil for BSL, WAS and BSH compactive effort.

4. CONCLUSIONS

This study evaluated the effects of four electrode materials—carbon, stainless steel, platinum, and titanium—on the electrokinetic remediation (EKR) performance of crude oil-contaminated lateritic soil from Nembe Creek, Bayelsa State, Nigeria. Based on the experimental results, the following conclusions are drawn:

- (i) Platinum electrode achieved the highest TPH removal efficiency of 80.34%, followed by titanium (77.81%), stainless steel (73.03%), and carbon (71.63%), demonstrating that all four electrode types are effective in significantly reducing total petroleum hydrocarbon content through EKR.
- (ii) The crude oil-contaminated soil and all EKR-remediated samples were classified as A-7-6 (AASHTO) and CL (USCS), with no change in soil classification after remediation. The EKR process altered Atterberg limits, specific gravity, and compaction characteristics in a manner consistent with hydrocarbon extraction and electrochemically induced mineralogical changes.
- (iii) Stainless steel electrode produced the highest unconfined compressive strength across all compactive effort levels, reaching a maximum of 751.5 kN/m² under BSH and also met the requirement of 687–1,373 kN/m² range recommended by Ingles and Metcalf (1972) for sub-base.
- (iv) The highest CBR of 72% was achieved with stainless steel at BSH compactive effort, meeting sub-base and sub-grade requirements of the Nigerian General Specifications (2016) but not the 80% minimum for base course.

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(v) Stainless steel electrode is recommended as the most practical and cost-effective option for field-scale EKR of crude oil-contaminated soils, given its superior geomechanical performance, wide availability, and significantly lower cost compared to platinum and titanium.

5. RECOMMENDATIONS

Based on the findings of this study, the following recommendations are made:

- (i) Future studies should investigate the combined effect of EKR and supplementary stabilisation techniques (e.g., lime, cement, or geopolymer binders) to enhance UCS and CBR values to levels that satisfy base course pavement specifications.
- (ii) The effect of treatment duration beyond 7 days on EKR efficiency and post-remediation soil strength should be investigated, as longer treatment periods may improve both contaminant removal and geomechanical performance.
- (iii) Pilot-scale and field EKR trials using stainless steel electrodes are recommended to validate the laboratory findings under realistic subsurface conditions and to assess long-term stability of remediated soils.
- (iv) The economic viability of platinum versus stainless steel electrodes should be assessed through a life-cycle cost analysis, particularly for large-scale remediation projects in the Niger Delta.

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