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Electrokinetic–Adsorptive Remediation of Hydrocarbon-Contaminated Soil: Trade-Offs Between Strength, Durability and Fabric Evolution

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ABSTRACT

Electrokinetic remediation (EKR) is a promising technique for treating hydrocarbon contaminated soils; however, its implications for soil engineering behaviour are not fully understood. This study investigates the combined effects of electrokinetic transport and carbon-based permeable reactive barriers (charcoal and activated carbon) on contaminant removal, soil fabric evolution, and geotechnical performance. Crude oil contaminated soil with an initial total petroleum hydrocarbon (TPH) concentration of 78,600 mg/kg was treated under an electric gradient of 1 V/cm. Removal efficiencies of 81.4% and 84.6% were achieved for charcoal and activated carbon, respectively, with the latter showing faster remediation. Significant improvements were observed in compaction characteristics and bearing capacity, with California Bearing Ratio (CBR) increasing from 6.7% to 35.9–46.1%. However, remediation resulted in increased plasticity and very low durability under wet–dry cycling, indicating high susceptibility to moisture-induced degradation. These changes are attributed to removal of hydrocarbon coatings and subsequent particle aggregation, leading to reorganisation of soil fabric and enhanced soil–water interaction. The results reveal a fundamental trade off between contaminant removal and engineering performance: while electrokinetic remediation improves short term strength, it simultaneously increases plasticity and reduces durability. The findings highlight the need for post treatment stabilisation to render remediated soils suitable for structural applications.

Keywords: Electrokinetic remediation; Hydrocarbon-contaminated soil; Permeable reactive barrier; Soil fabric; Durability

1. INTRODUCTION

Soil contamination by petroleum hydrocarbons remains a significant environmental and geotechnical challenge, particularly in oil-producing regions where spillages introduce crude oil into near-surface soils (Rahman et al., 2010; Sani et al., 2024). Once deposited, hydrocarbons strongly adsorb onto soil particles and alter pore-fluid interactions, resulting in persistent contamination and degradation of soil behaviour (Prasanna & Shimna, 2016). Beyond environmental risks, these changes reduce the suitability of soils for engineering applications, particularly in road construction.

Crude oil contamination affects soil behaviour across scales. At the particle level, hydrocarbons coat mineral surfaces and modify interparticle forces by altering diffuse double layer interactions (Mohammad & Taghi, 2012; Swaroop & Rani, 2015). This translates into macroscopic changes in moisture content, consistency limits, and compaction characteristics, often accompanied by reductions in strength and durability (Akinwumi et al., 2014; Salimnezhad et al., 2021). Consequently, contaminated soils typically exhibit low bearing capacity and poor long-term performance, necessitating remediation prior to reuse (Suleiman et al., 2020).

Conventional remediation techniques, including soil washing, thermal desorption, and bioremediation, have shown variable effectiveness, particularly in fine-grained soils where low permeability and strong adsorption limit contaminant removal (Virkutyte et al., 2002; Streche et al., 2018). Electrokinetic remediation (EKR) (Figure1) has emerged as a promising alternative due to its ability to transport contaminants in low-permeability soils via electroosmosis and electromigration (Reddy,

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2013). However, its effectiveness for hydrocarbon-contaminated soils is limited by the low polarity and mobility of petroleum compounds, and by its reliance on transport rather than removal mechanisms (Muhsina & Chandrakaran, 2015).

To enhance EKR performance, permeable reactive barriers (PRBs) incorporating carbon-based materials have been widely proposed. Activated carbon provides high adsorption capacity due to its large surface area and functional groups, while charcoal offers a low-cost alternative with moderate adsorption performance (Li et al., 2010; Hong & Qingmei, 2022). Previous studies have shown that such filter media can significantly improve hydrocarbon removal during EKR. For example, Adebayo et al. (2025) reported removal efficiencies exceeding 80% using charcoal and activated carbon, while Adebayo et al. (2023) demonstrated corresponding improvements in compaction and bearing capacity.

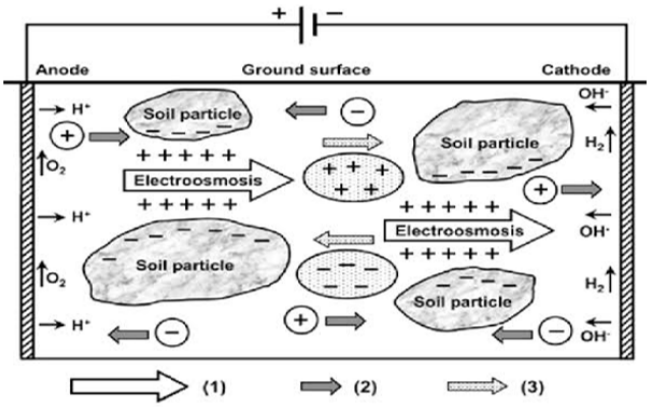

Figure 1: Schematic illustration of electrokinetic remediation (EKR) showing dominant transport mechanisms: (1) electroosmosis, (2) electromigration, and (3) electrophoresis (adapted from Reddy (2013)).

Despite these advances, existing studies have largely examined contaminant removal and engineering performance separately. In practice, remediation alters not only contaminant levels but also soil microstructure, potentially influencing engineering behaviour in complex and sometimes conflicting ways. Particle aggregation and redistribution of fines during remediation may improve strength while simultaneously increasing plasticity and reducing durability (Salimnezhad et al., 2021). The implications of such microstructural changes for engineering performance remain insufficiently understood.

While previous studies (Adebayo et al., 2023, 2025) examined contaminant removal and engineering performance separately, this study integrates these aspects by linking electrokinetic transport mechanisms, changes in soil fabric, and geotechnical behaviour. This study addresses this gap by investigating the coupled effects of electrokinetic transport and carbon-based adsorption on contaminant removal, changes in soil fabric, and geotechnical behaviour. Specifically, the study evaluates the performance of charcoal and activated carbon as filter media in enhancing EKR of crude oil-contaminated soil, and examines the resulting changes in index properties and engineering characteristics. By linking remediation mechanisms to soil behaviour, the study provides insight into the trade-offs between environmental remediation and engineering performance, with implications for the reuse of treated soils in road construction.

2. MATERIALS AND METHODS

2.1 Soil sampling and initial characterisation

Crude oil-contaminated soil (COCS) was obtained from a depth of approximately 1.0 m at a pipeline spill location within the Nigerian Pipeline and Storage Company facility, Kaduna, Nigeria (10°24′6″ N, 7°29′32″ E). The sampling depth was selected to represent subsurface soils typically used for subgrade applications in road construction. The soil was air-dried, pulverised, and homogenised prior to testing.

Initial characterisation included determination of total petroleum hydrocarbon (TPH) content, index properties, and particle size distribution in accordance with BS 1377 (1990). The measured TPH concentration was 78,600 mg/kg, indicating severe hydrocarbon contamination.

2.2 Materials and reagents

Graphite electrodes (8 mm diameter, 300 mm length) were used due to their resistance to corrosion under electrokinetic conditions. A 0.01 M sodium hydroxide (NaOH) solution was employed as both anolyte and catholyte to maintain alkaline conditions and promote contaminant desorption.

Two carbon-based filter media were investigated: charcoal produced from hardwood pyrolysis and activated carbon obtained through thermal activation. Both materials were sieved to particle sizes between 150 and 300 μm to ensure comparable hydraulic and reactive behaviour. Distilled water was used throughout all experimental procedures.

2.3 Electrokinetic remediation setup

Electrokinetic remediation (EKR) was conducted using a laboratory-scale acrylic cell (400 mm × 200 mm × 300 mm) comprising a central soil compartment and two electrode chambers separated by perforated

partitions (Figure 2). The soil was placed in the central compartment and compacted at its optimum moisture content to simulate field conditions for low-permeability soils.

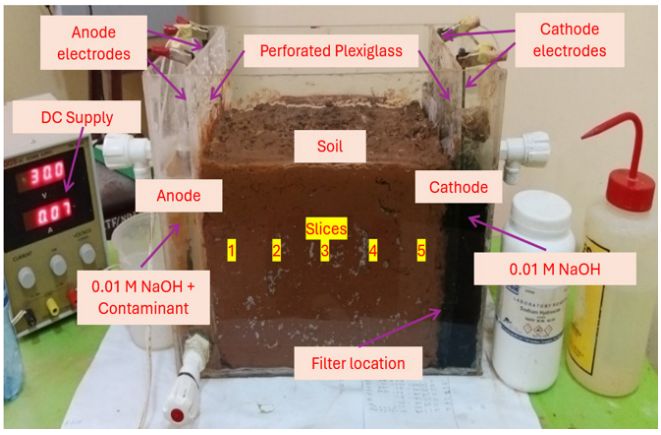

Figure 2: Laboratory-scale electrokinetic remediation setup showing electrode compartments, soil chamber, and placement of the carbon-based permeable reactive barrier adjacent to the cathode.

Graphite electrodes were installed in the anode and cathode chambers, and a direct current potential of 30 V was applied, corresponding to an electric gradient of approximately 1 V/cm across the soil specimen. The applied electric field induces electrokinetic transport processes, including electroosmosis, electromigration, and electrophoresis, which facilitate the movement of pore fluid and dissolved contaminants through the soil matrix (Gidudu & Chirwa, 2022).

To enhance contaminant capture, a 1 cm thick permeable reactive barrier (PRB) consisting of either charcoal or activated carbon was installed adjacent to the cathode between two filter papers (Figure 2). This configuration promotes adsorption of mobilised hydrocarbons as they migrate towards the cathode under electroosmotic flow. Two experimental configurations were evaluated: charcoal-enhanced EKR and activated carbon-enhanced EKR.

Sodium hydroxide (NaOH) was used as both the anolyte and catholyte to maintain alkaline conditions throughout the soil system and to minimise the development of strong pH gradients. In conventional electrokinetic systems, electrolysis reactions generate an acidic front at the anode and an alkaline front at the cathode, resulting in pronounced pH gradients that influence contaminant mobility (ITRC, 2024). The use of NaOH at both electrodes suppresses the formation of an acidic front and promotes a more uniform alkaline environment, which enhances desorption of hydrophobic hydrocarbons and supports electroosmotic flow by maintaining the negative surface charge of clay minerals (Bustos, 2014; Yang et al., 2023).

Remediation was conducted continuously until the stabilisation of key process indicators was observed. The remediation endpoint was defined based on the temporal behaviour of electric current, electrical conductivity (EC), and effluent flow. Specifically, remediation was considered complete when (i) the electric current exhibited minimal variation over successive measurements, and (ii) effluent flow from the cathode became negligible, indicating reduced electroosmotic transport and depletion of mobile ionic species. These indicators are commonly used in electrokinetic systems to identify the approach to equilibrium conditions and cessation of significant contaminant transport (Gidudu & Chirwa, 2022).

2.4 Monitoring of electrokinetic processes

The electrokinetic process was monitored through periodic measurements of electric current, pH distribution, electrical conductivity (EC), and effluent volume collected at the cathode. These parameters were used to assess ionic transport, electroosmotic flow, and contaminant mobilisation. At the end of each test, the soil specimen was extruded and divided into five equal segments along the flow direction for spatial analysis of contaminant removal.

2.5 Determination of total petroleum hydrocarbon

Total petroleum hydrocarbon (TPH) content was determined using a gravimetric cold extraction method with toluene. Approximately 25 g of oven dried soil was mixed with toluene, agitated, filtered, and subsequently dried at 50 °C. The TPH concentration was calculated using equation (1):

$$TPH = \frac{W_0 - W_1}{W_0} \times 10^6 \quad (1)$$

where W_0 and W_1 represent the initial and residual sample masses, respectively.

Removal efficiency was determined from equation 2 as:

$$Re = \frac{C_0 - C}{C_0} \times 100 \quad (2)$$

where C_0 and C are the initial and post-treatment TPH concentrations.

It is recognised that gravimetric extraction methods may underestimate TPH concentrations due to the potential loss of volatile hydrocarbon fractions during oven drying and solvent evaporation. Gravimetric methods predominantly quantify heavier, non volatile hydrocarbons, as lighter fractions can be lost during sample preparation and extraction processes (Sun et al., 2021). In addition, volatilisation is a key process governing the behaviour of petroleum hydrocarbons in soils, and lighter hydrocarbon fractions can be reduced prior to analysis through evaporation during sample handling (Wang et al., 2021).

Accordingly, the TPH values reported in this study are considered representative of the residual, predominantly non volatile hydrocarbon fraction. While this limitation may influence the absolute magnitude of measured TPH concentrations, the relative differences between untreated and remediated soils remain indicative of remediation performance under consistent testing conditions.

Future studies employing chromatographic techniques such as gas chromatography with flame ionisation detection (GC FID) or gas chromatography–mass spectrometry (GC–MS) would provide a more comprehensive quantification of both volatile and non volatile hydrocarbon fractions (Ezeani et al., 2022).

2.6 Determination of index properties

Index properties of untreated and remediated soils were determined in accordance with BS 1377 (1990), including natural moisture content, specific gravity, particle size distribution, and Atterberg limits. These parameters were used to evaluate changes in soil consistency following remediation

2.7 Compaction characteristics and bearing capacity

The compaction characteristics of the untreated and remediated soils were determined using the West African Standard (WAS) compaction method, which is widely adopted in geotechnical practice within West Africa for evaluating road construction materials. The test was conducted by compacting the soil in three layers within a standard mould, using a 4.5 kg rammer dropped from a height of 450 mm, with 10 blows applied per layer.

This procedure corresponds to a compactive effort of approximately 2700 kJ/m³. The WAS compaction energy is significantly higher than that of the British Standard Light (BSL) compaction method (approximately 600 kJ/m³) and is comparable to, though slightly lower than, the British Standard Heavy (BSH) compaction effort (approximately 2700–3000 kJ/m³). The use of WAS compaction therefore provides a level of energy representative of field compaction conditions for pavement materials in the regional context.

A range of moisture contents was used to establish compaction curves for each soil condition, from which the optimum moisture content (OMC) and maximum dry density (MDD) were determined.

The bearing capacity of the soils was evaluated using the California Bearing Ratio (CBR) test conducted on samples compacted at their respective OMC and MDD under WAS compaction conditions. Both soaked and unsoaked CBR tests were performed in accordance with standard procedures to simulate field moisture conditions. For soaked tests, specimens were immersed in water for 24 hours prior to testing to assess the influence of moisture on load-bearing capacity.

The CBR values were obtained by measuring the load–penetration response of the soil and comparing the measured load at specified penetrations with standard values. The results provide an indication of the suitability of the soil for subgrade and sub-base applications in pavement design.

2.8 Durability assessment

Durability was evaluated using resistance to loss in unconfined compressive strength (UCS) under alternating wetting and drying conditions. Specimens were cured for 14 days under dry conditions, and for 7 days followed by 7 days of soaking. Durability was determined from equation 3 as:

$$Durability = \frac{UCS_{soaked}}{UCS_{unsoaked}} \times 100 \quad (3)$$

2.9 Limitations

This study was conducted using a laboratory-scale electrokinetic system and a single experimental configuration, with fixed parameters including permeable reactive barrier (PRB) thickness (1 cm), electric gradient (1 V/cm), electrolyte composition (NaOH), and system geometry. Consequently, the experimental programme does not include parametric variation of key operational

conditions such as electric gradient, barrier thickness, or electrolyte chemistry.

In addition, replicate testing was not performed, and each experimental condition was evaluated using a single specimen. Therefore, quantitative differences observed between treatment systems (e.g. charcoal and activated carbon) cannot be assessed statistically, and the variability associated with the measurements cannot be formally quantified.

The results presented in this study should therefore be interpreted primarily in terms of consistent trends and mechanistic behaviour rather than definitive quantitative comparisons. While the agreement between multiple independent indicators — including contaminant removal, particle size redistribution, compaction characteristics, and bearing capacity — suggests systematic behaviour, the absence of replication and statistical analysis limits the ability to generalise the observed differences.

Furthermore, the comparisons between charcoal and activated carbon reflect material-specific responses under the selected experimental conditions and should not be assumed to be universally applicable across different electrokinetic configurations. Electrokinetic processes are inherently sensitive to factors such as electric gradient, electrolyte composition, and boundary conditions, and variations in these parameters may significantly influence contaminant transport, adsorption efficiency, and soil behaviour.

Accordingly, the findings of this study are best understood as indicative of the coupled physicochemical and geotechnical processes occurring during electrokinetic–adsorptive remediation under the conditions investigated. Future research should incorporate replicate testing and statistical analysis, as well as systematic parametric studies involving variations in operating conditions, to evaluate the robustness, sensitivity, and broader applicability of the observed trends.

3. RESULTS AND DISCUSSION

3.1 Electrokinetic process behaviour

The electrokinetic process exhibited a progressive reduction in electric current with time for both systems, as shown in Figure 3. For the charcoal system, the current decreased from approximately 0.13 A at the start of remediation to about 0.06 A at the end of the process, while the activated carbon system showed a similar trend, decreasing from 0.12 A to approximately 0.05 A over a shorter duration.

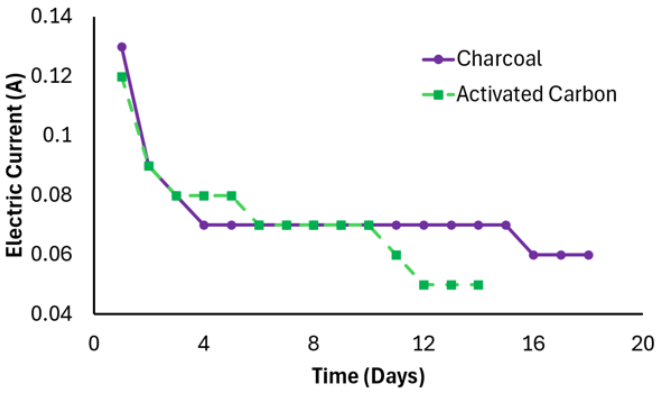

Figure 3: Variation of electric current with time during electrokinetic remediation of crude oil-contaminated soil using charcoal and activated carbon filter media

As illustrated in Figure 3, the current variation can be interpreted in three distinct stages. An initial rapid decline was observed during the early stages of remediation (Days 1–3), reflecting high ionic mobility and active contaminant transport. This was followed by a plateau phase (approximately Days 4–10), during which current values stabilised at around 0.07–0.08 A, indicating reduced availability of mobile ionic species and slower electrokinetic transport. In the final stage, a further decline in current was observed, with the activated carbon system reaching lower current values earlier than the charcoal system, consistent with its shorter remediation duration.

Electrical conductivity (EC) exhibited a complementary trend, with an initial increase followed by a gradual decrease during the remediation process. The initial increase is attributed to mobilisation of dissolved ionic species into the pore fluid, while the subsequent decline reflects progressive removal of these species from the soil matrix. Similarly, effluent flow at the cathode decreased towards the end of the process, with cumulative volumes of 5,820 mL and 2,570 mL recorded for the charcoal and activated carbon systems, respectively. The reduction in effluent volume indicates diminished electroosmotic flow as the system approached equilibrium conditions.

pH values remained within the alkaline range throughout the process (10.1–11.1 for charcoal and 8.8–10.7 for activated carbon), reflecting the influence of the NaOH electrolyte and electrochemical reactions at the electrodes.

The combined temporal trends in current (Figure 3), EC, and effluent flow indicate that the electrokinetic system approached a quasi-steady state towards the end of the remediation period. Accordingly, the remediation endpoint was defined based on stabilisation of electric current and negligible effluent production, which are indicative of depletion of mobile ionic species and cessation of significant contaminant transport.

The remediation duration was 18 days for the charcoal system and 14 days for the activated carbon system under an applied electric gradient of 1 V/cm. As shown in Figure 3, the earlier decline in current observed for the activated carbon system is consistent with faster depletion of mobile species, suggesting more rapid progression towards equilibrium under the conditions investigated.

Although these durations are comparable to those reported in previous electrokinetic studies on hydrocarbon-contaminated soils, the relatively long treatment period highlights potential practical limitations, particularly in terms of energy consumption and operational cost. While energy consumption was not directly measured, the observed decline in current over time suggests a reduction in power demand as remediation progresses.

From an engineering perspective, the results indicate that electrokinetic–adsorptive remediation is effective for contaminant removal but may be better suited to controlled or site-specific applications where treatment duration is not the primary constraint. Further work incorporating detailed time-series monitoring, energy analysis, and optimisation of operating conditions is required to evaluate the scalability and economic feasibility of the process.

3.2 Contaminant removal efficiency

The results of soil bacteria count as shown in Table 2 demonstrate clear shifts in soil microbial dynamics following the application of cassava processing effluent (CPE) and its treated derivatives.

The spatial distribution of total petroleum hydrocarbon (TPH) removal along the soil column is presented in Figure 4. The soil was divided into five segments from the anode (slice 1) to the cathode (slice 5), allowing evaluation of contaminant removal as a function of position.

As shown in Figure 4, the charcoal system exhibits a clear spatial gradient, with TPH removal efficiency decreasing from 93.4% at the anode to 70% at the cathode. This trend reflects directional transport of contaminants driven by electroosmotic flow and electromigration, resulting in progressive movement of hydrocarbons towards the cathode.

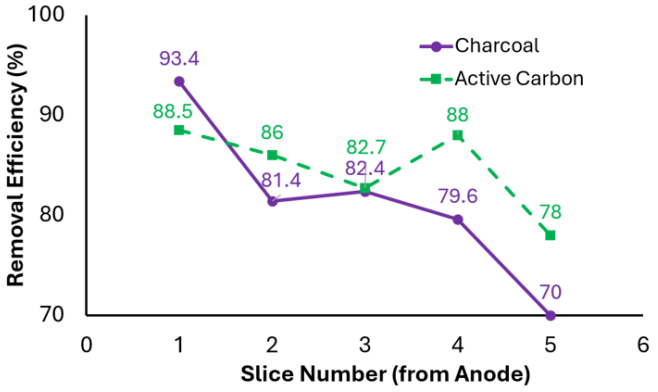

Figure 4: Spatial variation of total petroleum hydrocarbon (TPH) removal efficiency along the soil column for charcoal and activated carbon-enhanced electrokinetic remediation system

In contrast, the activated carbon system shows a more uniform removal profile across the soil column, with values ranging from 82.7% to 88.5%. This relatively consistent distribution suggests enhanced retention of mobilised hydrocarbons within the soil matrix due to adsorption within the permeable reactive barrier and surrounding soil.

The intermediate segments (slices 2–4) demonstrate gradual variation in TPH removal, confirming that contaminant transport occurs throughout the soil column rather than being confined to the electrode regions. The presence of these intermediate values provides clear evidence of a spatially distributed remediation process.

Under the conditions investigated, the activated carbon system exhibits slightly higher and more uniform removal efficiency across the profile compared with the charcoal system. This behaviour may be attributed to the higher surface area and adsorption capacity of activated carbon, which enhances retention of mobilised hydrocarbons during electrokinetic transport.

While the activated carbon system exhibited slightly higher removal efficiency and shorter remediation duration, it also produced a substantially lower cumulative effluent volume (2,570 mL) compared with the charcoal system (5,820 mL). This indicates reduced electroosmotic flow in the activated carbon system under the conditions investigated.

The lower effluent volume may be attributed to increased adsorption and possible flow resistance associated with the activated carbon barrier, which can restrict pore fluid movement. Reduced electroosmotic flow implies that contaminant transport through the soil matrix may be less extensive, potentially influencing the spatial redistribution of hydrocarbons.

This highlights an important trade-off between contaminant transport and retention during electrokinetic–adsorptive remediation. In the charcoal system, higher electroosmotic flow promotes greater movement of contaminants through the soil, resulting in a more pronounced spatial gradient. In contrast, the activated carbon system appears to favour localised adsorption and retention, leading to a more uniform removal profile but with reduced fluid transport.

From an engineering perspective, these results suggest that while activated carbon enhances removal efficiency through adsorption, reduced electroosmotic flow may influence the spatial homogeneity of remediation, particularly in larger systems. The balance between electroosmotic transport and adsorption capacity therefore represents a key consideration in the design and optimisation of electrokinetic remediation systems.

Finally, the results indicate that electrokinetic–adsorptive remediation produces a spatially varying contaminant removal profile governed by coupled transport and adsorption processes.

3.3 Changes in soil index properties and soil fabric

3.3.1 Moisture content and specific gravity

The specific gravity of the contaminated soil (2.28) is lower than the typical range for fine-grained lateritic soils (2.60–2.80), which is attributed to the presence of low-density hydrocarbon contaminants occupying pore spaces and coating particle surfaces. Following remediation, the specific gravity increased to 2.56–2.61, consistent the natural moisture content increased from 11.8% for the contaminated soil to 23.6% and 25.9% for the charcoal and activated carbon treated soils, respectively. This increase reflects enhanced soil–water interaction following remediation, as removal of hydrocarbon coatings exposes clay mineral surfaces and increases the soil's affinity for water, with removal of hydrocarbons and restoration of the mineral soil matrix.

The low initial value may also be influenced by entrapped hydrocarbons and incomplete air displacement during testing. Although replicate measurements were not conducted, the consistent increase in specific gravity, together with reductions in TPH content and corresponding changes in other soil properties, indicates that the observed variation primarily reflects contamination effects rather than inherent soil characteristics.

3.3.2 Particle size distribution and changes in soil fabric

The contaminated soil consists of 68.94% sand, 10.25% silt, and 20.81% clay. Following electrokinetic remediation, the clay fraction decreased markedly to approximately 1–2%, with a corresponding increase in the silt fraction to about 33–35%, while the sand fraction remained largely unchanged.

This apparent reduction in clay content is more plausibly attributed to aggregation of clay particles into larger clusters rather than actual loss of mineral fines. The redistribution of particles from the clay to silt fraction indicates flocculation and particle association, consistent with modification of interparticle forces during remediation.

This interpretation is supported by the stability of sand content, the increase in specific gravity, and the observed improvements in compaction and bearing capacity, all of which suggest retention of mineral constituents alongside structural reorganisation.

However, it is important to note that this interpretation is based on indirect evidence from particle size distribution and macroscopic soil properties. Direct microstructural confirmation using techniques such as scanning electron microscopy (SEM) or X ray diffraction (XRD) was not undertaken. The observed changes should therefore be regarded as indicative of aggregation and fabric transformation rather than definitive proof.

3.3.3 Atterberg limits

The liquid limit increased from 30.4% for the contaminated soil to 35.0–35.8% following remediation, while the plasticity index increased from 7.3% to 14.6–18.8%. These changes reflect enhanced clay–water interaction following removal of hydrocarbon coatings, which increases the soil's affinity for moisture.

The increase in plasticity index is consistent with greater clay activity and interparticle interaction, likely associated with aggregation and modification of surface forces. However, this increase has important implications for engineering performance. The remediated soils exceed typical specification limits for subgrade and sub base materials, indicating increased susceptibility to

moisture induced deformation and reduced long-term stability.

These results highlight a key trade-off: while remediation improves particle interaction and strength-related behaviour, it simultaneously increases plasticity and moisture sensitivity. Consequently, improvements in California Bearing Ratio (CBR) alone may not be sufficient to ensure engineering suitability, particularly under conditions of variable moisture.

3.4 Engineering properties

3.4.1 Compaction characteristics

Compaction results show that maximum dry density increased from 1.94 g/cm³ to 1.96–1.99 g/cm³, while optimum moisture content decreased from 13.9% to 12.0–12.5%. These changes suggest enhanced particle packing and reduced lubrication effects resulting from hydrocarbon removal. Similar trends have been reported by Akinwumi et al. (2014), confirming that remediation improves compaction behaviour.

3.4.2 California bearing ratio

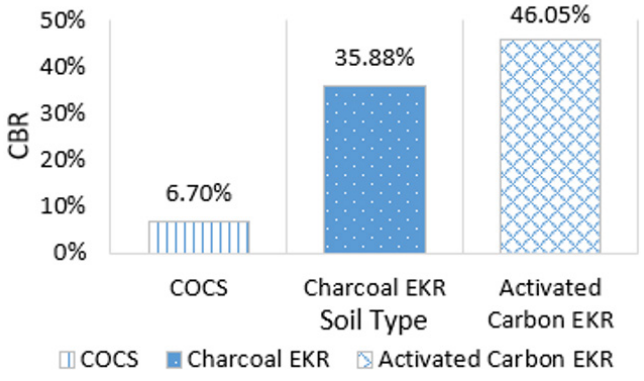

Figure 5: Soaked California Bearing Ratio (CBR) values of untreated (crude oil-contaminated soil, COCS) and electrokinetically remediated soils

The soaked CBR obtained at WAS energy level increased significantly from 6.7% (COCS) to 35.88% (charcoal) and 46.05% (activated carbon) as shown in figure 5. The values obtained from the remediated samples exceed the 20% minimum requirement for Type 2 sub-base materials for lightly trafficked Nigerian roads (Nigerian General Specifications for Road and Bridges, 2016). The increase in CBR may be attributed to improved particle contact and reduced hydrocarbon interference with soil skeleton stability.

3.4.3 Durability performance

The durability of the soils, expressed as the ratio of soaked to unsoaked unconfined compressive strength (UCS), remained very low despite improvements in strength-related properties. As shown in Table 1, durability increased from 8.57% for the contaminated soil to 10.10–15.24% for the remediated soils, which is significantly below the typical requirement for road construction materials. These results indicate poor resistance to degradation under wet–dry cycling conditions.

Table 1: Unconfined Compressive Strength (UCS) results

Soil Condition	UCS (Unsoaked) (kPa)	UCS (Soaked) (kPa)	Durability (%)
COCS	448.00	38.40	8.57
Charcoal EKR	633.60	64.00	10.10
Activated Carbon EKR	1049.60	160.00	15.24

The low durability values primarily reflect substantial loss of strength upon soaking rather than low initial strength. Although unsoaked UCS increased following remediation, the soaked UCS values remained very low, indicating high susceptibility of the soil structure to moisture-induced weakening.

This behaviour is attributed to several interacting factors. The increase in plasticity index following remediation indicates enhanced water affinity and moisture retention, promoting softening and loss of strength under saturated conditions. In addition, removal of hydrocarbon coatings exposes clay mineral surfaces, increasing their interaction with water and leading to swelling and shrinkage during wet–dry cycles. These volumetric changes can disrupt interparticle bonds and weaken the soil fabric.

Furthermore, the transition to a flocculated structure, while beneficial for strength under dry conditions, may produce a more open pore network that facilitates moisture ingress and accelerates degradation during cyclic exposure. These mechanisms collectively explain the apparent contradiction between improved strength and poor durability.

From an engineering perspective, durability represents the governing limitation for practical application of the remediated soils. Despite improvements in compaction and bearing capacity, the material remains

highly vulnerable to long-term environmental loading, particularly under conditions of moisture fluctuation.

3.5 Integrated mechanistic interpretation

The results of this study demonstrate that electrokinetic–adsorptive remediation induces coupled physicochemical processes that simultaneously influence contaminant removal and soil engineering behaviour. These changes arise primarily from modification of pore fluid chemistry, interparticle forces, and soil fabric.

Removal of hydrocarbon coatings from particle surfaces restores clay–water interactions and modifies interparticle forces, promoting aggregation and a transition from a dispersed to a flocculated structure. The observed shift in particle size distribution, characterised by a reduction in clay fraction and corresponding increase in silt-sized particles, is consistent with the formation of aggregated clusters rather than loss of mineral fines.

It should be noted that the interpretation of changes in soil fabric is based on indirect evidence derived from particle size distribution, index properties, and mechanical behaviour. Although these observations are consistent with aggregation and fabric transformation, direct microstructural confirmation was not undertaken. Techniques such as scanning electron microscopy (SEM), X-ray diffraction (XRD), or dispersed particle size analysis would be required to verify the extent and nature of these changes. The proposed mechanism should therefore be regarded as an evidence-supported interpretation rather than definitive proof.

The inferred microstructural changes enhance interparticle contact and reduce the lubricating effects of hydrocarbons, leading to improved compaction characteristics and increased California Bearing Ratio (CBR). However, these benefits are accompanied by a corresponding increase in soil plasticity, reflecting enhanced water affinity and clay activity following remediation.

The rise in plasticity index beyond typical specification limits has significant implications for engineering performance. While the remediated soils exhibit improved strength, the increased plasticity indicates greater susceptibility to moisture-induced deformation and instability under field conditions. This highlights a limitation in relying solely on strength-based parameters for assessing material suitability.

Durability results further reinforce this limitation, demonstrating that the remediated soils are highly sensitive to moisture exposure. The substantial reduction in strength under soaked conditions reflects the combined effects of increased plasticity, enhanced water absorption, and exposure of clay mineral surfaces. In addition, the flocculated structure, while beneficial for strength under dry conditions, may facilitate moisture ingress and accelerate degradation during cyclic environmental loading.

These findings reveal a fundamental trade-off associated with electrokinetic remediation of hydrocarbon-contaminated soils. While contaminant removal improves short-term mechanical performance through enhanced particle interaction, it simultaneously increases plasticity and reduces resistance to environmental degradation, thereby limiting long-term performance. This interaction between physicochemical processes and engineering response highlights the need to evaluate remediated soils holistically rather than relying on isolated performance indicators.

It should also be noted that these interpretations are based on a single experimental configuration without replicate testing. Consequently, the observed relationships between changes in soil fabric, contaminant removal, and engineering behaviour should be interpreted as indicative of the mechanisms operating under the conditions investigated, rather than as universally applicable outcomes. Electrokinetic processes are sensitive to factors such as electric gradient, electrolyte composition, and barrier configuration, which may influence system behaviour.

From an engineering perspective, the results indicate that electrokinetic–adsorptive remediation is effective in improving contaminant conditions and short-term strength, but does not, on its own, produce a material suitable for durable structural applications. Additional stabilisation measures are therefore required to reduce plasticity, enhance bonding, and improve resistance to environmental degradation. Future work should focus on integrating remediation with stabilisation strategies, along with direct microstructural analysis and parametric studies, to validate and generalise the observed behaviour.

4. CONCLUSION

This study evaluated the effectiveness of electrokinetic–adsorptive remediation using charcoal and activated carbon permeable reactive barriers for the treatment of hydrocarbon contaminated soil, with emphasis on contaminant removal and the resulting changes in soil behaviour.

Electrokinetic remediation achieved substantial reduction in hydrocarbon content, with removal efficiencies exceeding 80% for both systems. Activated carbon demonstrated slightly higher removal efficiency and shorter remediation duration than charcoal, although this was accompanied by reduced electroosmotic flow, indicating a trade off between contaminant transport and adsorption.

Remediation was associated with significant changes in soil behaviour. Improvements in compaction characteristics and California Bearing Ratio (CBR) indicate enhanced particle interaction and short term strength following removal of hydrocarbon coatings. However, these benefits were offset by a marked increase in plasticity, with plasticity index values exceeding typical specification limits for subgrade and sub base materials. This indicates increased susceptibility to moisture induced deformation.

Durability performance represented the principal limitation of the remediated soils. Despite improved unsoaked strength, durability values remained very low due to significant strength loss under soaked conditions, indicating poor resistance to environmental degradation. These findings demonstrate that improvements in strength alone are insufficient to ensure long term engineering suitability.

The combined results reveal a fundamental trade off associated with electrokinetic remediation of hydrocarbon contaminated soils. While contaminant removal improves short term mechanical performance, it simultaneously increases plasticity and reduces resistance to moisture induced deterioration. This highlights the need to evaluate both strength and durability when assessing remediated soils for engineering applications.
From an engineering perspective, electrokinetic–adsorptive remediation should be regarded as a pre treatment technique rather than a standalone solution for producing construction ready materials. The remediated soils are likely to require additional stabilisation to reduce plasticity and improve durability prior to use. Effective stabilisation of similar fine grained soils is typically achieved using lime contents of approximately 2–8% or cement contents of approximately 3–10% by dry weight of soil, depending on soil characteristics and performance requirements (Bell, 1996; Imoh et al., 2025).

Finally, the findings of this study are based on a single experimental configuration without replicate testing and should therefore be interpreted in terms of consistent trends rather than definitive quantitative relationships. Further research incorporating replicate testing, systematic variation of operating conditions, and direct microstructural analysis is required to validate and extend the applicability of the observed behaviour.

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