**Current Research Bulletin**

**Volume 03 Issue 07 July 2026, Page no: 239-245**

**Available Url: http://crbjour.org/**

**Article DOI: 10.55677/CRB/I7-02-CRB2026**

**e-ISSN: 3050-5933**
**p-ISSN: 3050-5925**

**Open Access**

# Strength Development and Microstructural Evolution of Electro-Kinetically Remediated Lead-Contaminated Lateritic Soil: Effect of Electrode Material

**John E. Sani*[1], Babatunde B. Abdulhafiz[2], George Moses[3], Faustinus Bayang[4]**
[1,2,3,4] Department of Civil Engineering, Nigerian Defence Academy, Kaduna, Nigeria

**Published Online:**
**18 July 2026**

**Article DOI:**
10.55677/CRB/I7-02-CRB2026

**ABSTRACT:** Lead (Pb) contamination of lateritic soils used for pavement construction compromises both the environmental quality and the geotechnical performance of the material. Electro-kinetic remediation (EKR) offers a low-energy route to decontaminate such soils, but the electrode material used can itself alter the resulting mechanical behaviour. This study evaluates the effect of aluminium, carbon and graphite electrodes on the unconfined compressive strength (UCS), California bearing ratio (CBR) and microstructure of a lead-contaminated lateritic soil from Birnin Gwari, Kaduna State, Nigeria. Scanning electron microscopy (SEM) with energy-dispersive X-ray analysis (EDS) was used to relate microstructural changes to the observed strength trends. The untreated soil classified as A-7-6 (CL) with a liquid limit of 48.0% and UCS of 225.3-335.0 kN/m² across British Standard Light (BSL), West African Standard (WAS) and British Standard Heavy (BSH) compactive efforts. After EKR, carbon-electrode treatment consistently produced the highest strength gains, raising the 7-day UCS to 364.0 kN/m² and the unsoaked CBR to 85% at BSH effort, exceeding the 80% threshold specified for lightly trafficked road bases. Aluminium-electrode treatment reduced strength relative to the untreated soil, while graphite gave intermediate performance. SEM micrographs showed a shift from the loosely aggregated, high-porosity fabric of the untreated soil toward a denser, more flocculated particle arrangement in the carbon-treated samples, consistent with the strength improvement; EDS confirmed a reduction in PbO content and enrichment in $Fe_2O_3$ accompanying carbon-electrode treatment. The results indicate that electrode selection is a controlling variable in EKR-based soil remediation for pavement applications, with carbon electrodes offering the best combination of contaminant removal and geotechnical suitability among the materials tested.



**KEY WORDS:** electro-kinetic remediation, lead-contaminated soil, electrode material, unconfined compressive strength, California bearing ratio, scanning electron microscopy

***Cite the Article:*** *Sani, J.E., Abdulhafiz, B.B., Moses, G., Bayang, F. (2026). Strength Development and Microstructural Evolution of Electro-Kinetically Remediated Lead-Contaminated Lateritic Soil: Effect of Electrode Material. Current Research Bulletin, 3(7), 239-245.* https://doi.org/10.55677/CRB/I7-02-CRB2026

## 1. INTRODUCTION

Heavy-metal contamination of soil, particularly by lead (Pb), is a persistent environmental problem arising from industrial activity, vehicular emissions and improper waste disposal. Because Pb has a soil persistence period estimated at 150-5000 years, contaminated soils that are reused for engineering works, such as road base and sub-base material, carry both an environmental liability and a risk of reduced mechanical performance. Electro-kinetic remediation (EKR) has emerged as a comparatively low-cost, low-impact technique for mobilising and removing heavy metals from fine-grained soils through electro-osmosis, electromigration and electrophoresis under a low-intensity direct current.

While the contaminant-removal efficiency of EKR has been widely studied, its effect on the post-treatment geotechnical behaviour of the soil, particularly strength, is comparatively less understood, and is strongly influenced by the electrode material used. Electrode choice affects the electrochemical reactions at the anode and cathode, the pH regime developed across the soil mass, and consequently the mineralogical and microstructural changes that govern strength (Mohammad et al., 2022; Zheng et al., 2024). This study therefore investigates the effect of aluminium, carbon and graphite electrodes on the unconfined compressive strength and California bearing ratio of a lead-contaminated lateritic soil after EKR, and uses scanning electron microscopy (SEM) with energy-dispersive X-ray spectroscopy (EDS) to relate the observed strength behaviour to underlying microstructural and elemental changes. The specific objectives are to (i) quantify the strength response (UCS and CBR) of the soil before and after EKR with each electrode material, and (ii) characterise the accompanying microstructural and compositional changes to explain the mechanisms responsible for strength gain or loss.

## 2. MATERIALS AND METHODS

### *2.1 Soil sample and materials*

The lead-contaminated lateritic soil used in this study was obtained by disturbed sampling at depths of 1.5-2.0 m from a mining site in Birnin Gwari Local Government Area, Kaduna State, Nigeria. The soil was air-dried, pulverised and stored prior to testing and EKR treatment. Aluminium, carbon and graphite rod electrodes, sourced from Jos, Plateau State, were used for the EKR treatments; citric acid served as the enhancing catalyst and distilled water as the process fluid.

### *2.2 Electro-kinetic remediation set-up*

EKR was carried out in locally fabricated plexiglass cells (400 mm x 200 mm x 300 mm) with a central soil compartment and two outer electrode compartments. For each electrode material, about 10 kg of soil was mixed with distilled water and placed in the cell, with two rod electrodes installed on each of the anode and cathode sides. Nitric acid was introduced at the cathode chamber, and effluent was collected at both chambers throughout treatment. A low-intensity direct current was applied, with current flow, effluent volume and soil pH monitored every 6 hours. Treatment continued for 10-13 days until the effluent volume and acidity stabilised, indicating that remediation was complete. The procedure was repeated independently for aluminium, carbon and graphite electrode sets, consistent with citric-acid-enhanced EKR configurations reported elsewhere (Sun et al., 2024).

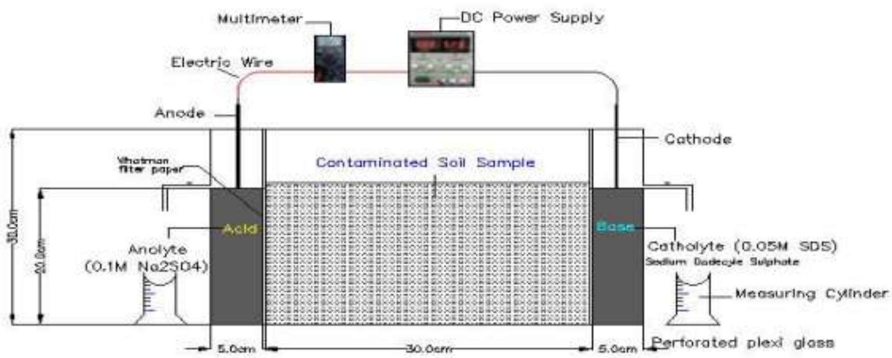


**Figure 1. Schematic diagram of the electro-kinetic remediation cell.**

### *2.3 Strength characterisation*

Index and compaction properties (moisture content, specific gravity, Atterberg limits, particle size distribution, maximum dry density and optimum moisture content) were determined in accordance with BS 1377 (1990) for the untreated and each EKR-treated soil, at British Standard Light (BSL), West African Standard (WAS) and British Standard Heavy (BSH) compactive efforts.

Unconfined compressive strength (UCS) was determined per BS 1377 (1990) Part 7. Specimens were compacted at their respective optimum moisture contents, extruded and trimmed to 38.1 mm diameter x 76.2 mm length cylinders, then wax-cured for 7, 14 and 28 days before being tested to failure in a Wykeham Farrance unconfined compression apparatus (Model WF20140) at a strain rate of 0.10 mm/min. California bearing ratio (CBR) was determined per BS 1377 (1990) for both soaked (24-hour immersion after 6-day cure) and unsoaked conditions, with the plunger penetrating the specimen at 1.3 mm/min; CBR was read at 2.5 mm and 5.0 mm penetration against the standard loads of 13.24 kN and 19.96 kN respectively.

### *2.4 Microstructural and elemental analysis*

Microstructural changes accompanying EKR treatment were examined using a PHENOM WORLD scanning electron microscope operated at 5 kV and 15 kV, at the Department of Chemical Engineering, Nigerian Building and Road Research Institute (NBRRI). Specimens compacted at BSH effort and cured for 7 and 28 days were sectioned, polished and carbon-coated to provide a conductive surface before imaging at spatial resolutions of 10 µm and 100 µm. Elemental composition of the untreated and each electrode-treated soil was determined by X-ray fluorescence (XRF) as bulk oxide composition, complementing the point and area analyses obtainable from energy-dispersive X-ray spectroscopy (EDS) during SEM.

## 3. RESULTS AND DISCUSSION

### *3.1 Index and physical properties*

The untreated soil is fine-grained, with 72.42% passing the BS No. 200 sieve, a liquid limit of 48.0%, plastic limit of 28.2%, plasticity index of 19.8% and specific gravity of 2.65. It classifies as A-7-6 under AASHTO and CL under the Unified Soil Classification System. Table 1 summarises the index properties of the untreated soil and the soil after EKR treatment with each electrode. Liquid and plastic limits generally fell after aluminium-electrode treatment but rose again with carbon and graphite electrodes, while plasticity index and linear shrinkage increased for all treated soils relative to the untreated soil, indicating some redistribution of clay-sized material and diffuse double-layer effects induced by the applied electric field.

**Table 1. Index and physical properties of untreated and EKR-treated lead-contaminated soil.**

| Property | Untreated soil | Al-electrode EKR | C-electrode EKR | Graphite-electrode EKR |
|---|---|---|---|---|
| % passing BS No. 200 sieve | 72.42 | 35.52 | 38.20 | 37.25 |
| Liquid limit (%) | 48.00 | 47.40 | 48.80 | 49.50 |
| Plastic limit (%) | 28.20 | 27.20 | 28.40 | 24.95 |
| Plasticity index (%) | 19.80 | 20.20 | 20.40 | 24.60 |
| Linear shrinkage (%) | 8.6 | 10.0 | 9.3 | 9.3 |
| Specific gravity | 2.65 | 2.53 | 2.57 | 2.56 |
| AASHTO / USCS class | A-7-6 / CL | A-7-6 / CL | A-7-6 / CL | A-7-6 / CL |

### *3.2 Unconfined compressive strength*

The untreated soil recorded 7-day UCS values of 225.25, 289.00 and 335.00 kN/m² for BSL, WAS and BSH compactive efforts respectively (Table 2). Carbon-electrode EKR produced the greatest strength gain among the three electrodes at every compactive effort, reaching 258.00, 272.75 and 364.00 kN/m² at BSL, WAS and BSH. Graphite-electrode treatment gave intermediate values (232.00-315.00 kN/m²), while aluminium-electrode treatment consistently reduced UCS below the untreated soil (201.17-282.25 kN/m²). None of the treatments met the 1710 kN/m² TRRL (1977) requirement for base-course material, or the 687-1373 kN/m² range specified for sub-base by Ingles and Metcalf (1972), indicating that EKR alone, without additional stabilisation, is insufficient to meet UCS-based base or sub-base specifications for this soil; comparable magnitudes of UCS gain have only been achieved for lead-contaminated soils through combined binder-based solidification/stabilisation approaches (Molaei et al., 2024).

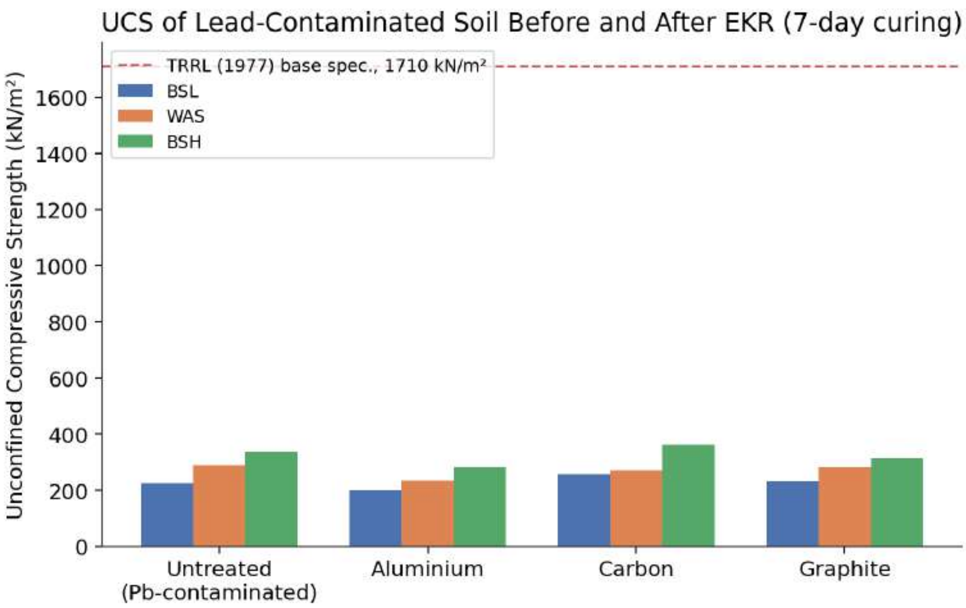


**Figure 2. Variation of unconfined compressive strength (7-day cure) with electrode material and compactive effort.**

### 3.3 California bearing ratio

Unsoaked CBR values increased markedly with carbon- and graphite-electrode treatment relative to the untreated soil at higher compactive effort: at BSH, unsoaked CBR rose to 85% for carbon and 72% for graphite, compared with 69% for the untreated soil, while aluminium reduced it to 40% (Table 2). The carbon-electrode value of 85% exceeds the 80% minimum recommended for base material under lightly trafficked roads by the Nigerian General Specifications for Roads and Bridges (2016). Soaked CBR values, in contrast, remained low across all treatments (4-16%), well below specification, reflecting continued moisture sensitivity of the remediated soil fabric despite the gains observed under unsoaked conditions.

**Table 2. UCS (7-day) and CBR results for untreated and EKR-treated soil across compactive efforts.**

| Electrode | Effort | UCS 7-day (kN/m²) | CBR unsoaked (%) | CBR soaked (%) |
|---|---|---|---|---|
| Untreated | BSL | 225.25 | 20 | 14 |
| | WAS | 289.00 | 26 | 12 |
| | BSH | 335.00 | 69 | 9 |
| Aluminium | BSL | 201.17 | 15 | 8 |
| | WAS | 235.00 | 52 | 12 |
| | BSH | 282.25 | 40 | 16 |
| Carbon | BSL | 258.00 | 17 | 12 |
| | WAS | 272.75 | 36 | 13 |
| | BSH | 364.00 | 85 | 12 |
| Graphite | BSL | 232.00 | 17 | 4 |
| | WAS | 280.90 | 41 | 5 |
| | BSH | 315.00 | 72 | 7 |

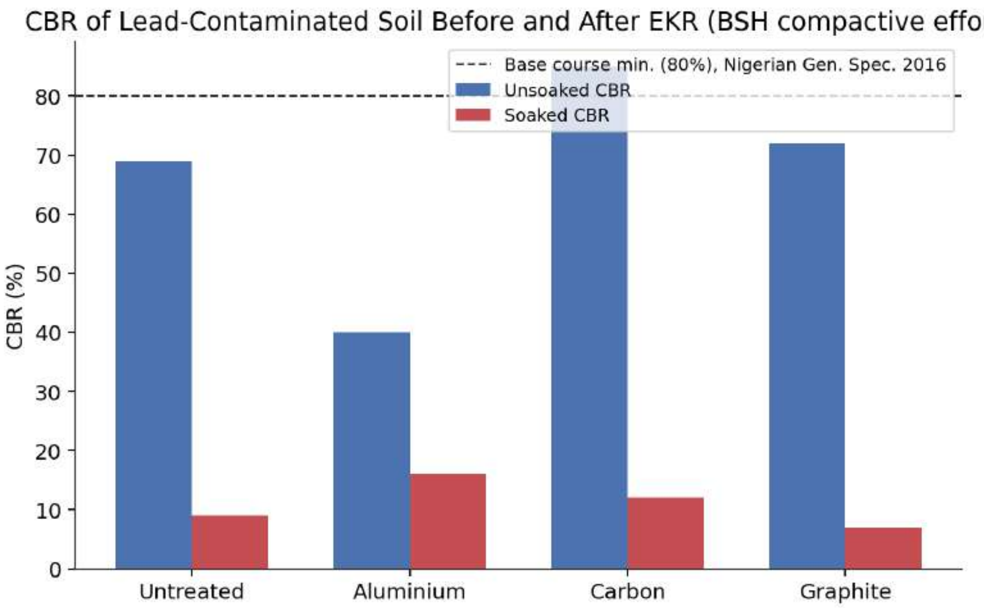


**Figure 3. Soaked and unsoaked CBR at BSH effort for untreated and EKR-treated soil.**

### 3.4 Microstructural evidence (SEM)

SEM micrographs of the untreated lead-contaminated soil (Figure 4) show a loosely packed, heterogeneous particle fabric with visible inter-particle voids, consistent with its comparatively low bulk strength. After EKR treatment, the aluminium-electrode sample (Figure 5) retained a relatively open, poorly bonded fabric, corroborating its lower measured UCS and CBR values relative to the untreated soil. In contrast, the carbon-electrode sample (Figure 6) exhibits a visibly denser, more flocculated arrangement with reduced void space and greater particle-to-particle contact, aligning with its superior strength performance. The graphite-electrode sample (Figure 7) shows an intermediate fabric, denser than the aluminium sample but less compact than the carbon sample, consistent with its intermediate strength ranking.

These microstructural trends support the strength results: electrode material governs the electrochemical environment (pH gradients, ion migration pathways) during EKR, which in turn controls the degree of particle flocculation, cementation or dispersion in the treated soil. The carbon electrode appears to promote geochemical alteration and diffuse-double-layer reorganisation that favours particle aggregation, while the aluminium electrode's dissolution products may instead disperse fines and weaken inter-particle bonding, consistent with recent findings that electrode material and its corrosion/dissolution behaviour are a primary determinant of remediation-induced microstructural change (Naseer et al., 2025).

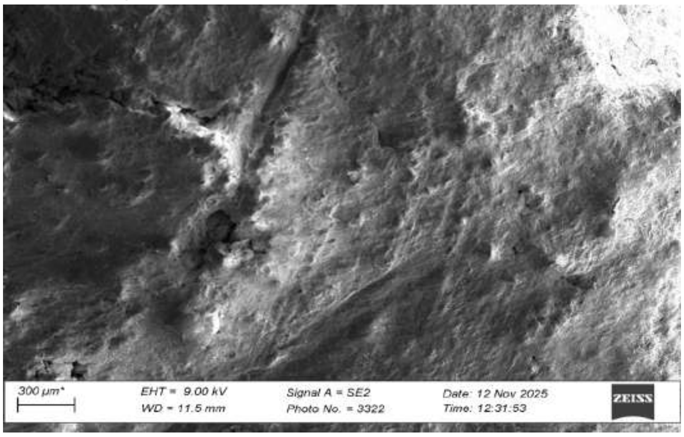


**Figure 4. SEM micrograph of untreated lead-contaminated soil (BSH, 7-day cure).**

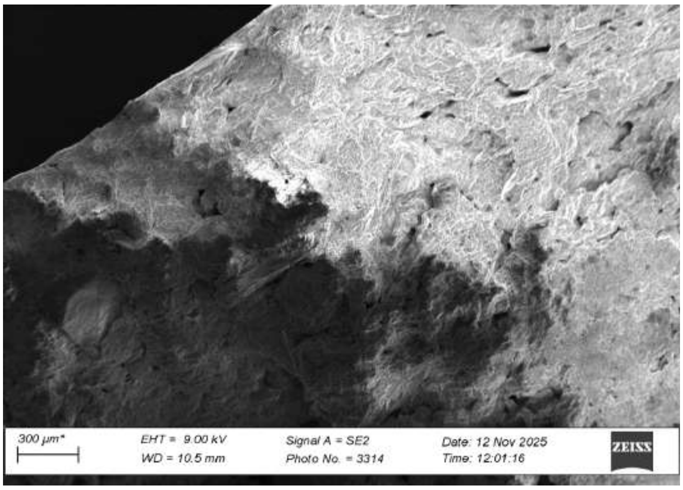


**Figure 5. SEM micrograph of aluminium-electrode EKR-treated soil (BSH, 7-day cure).**

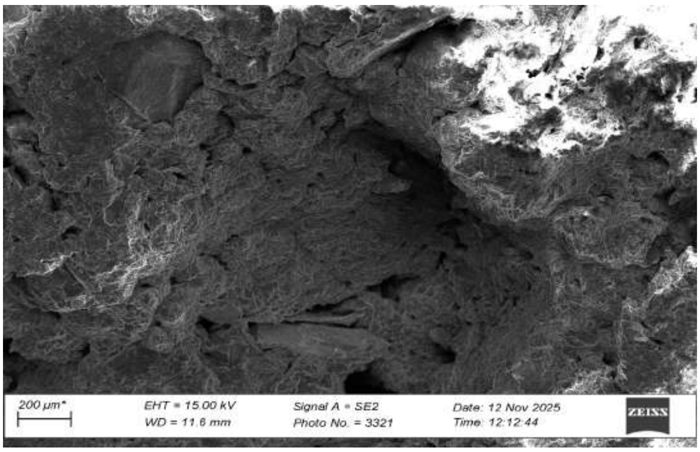


**Figure 6. SEM micrograph of carbon-electrode EKR-treated soil (BSH, 7-day cure).**

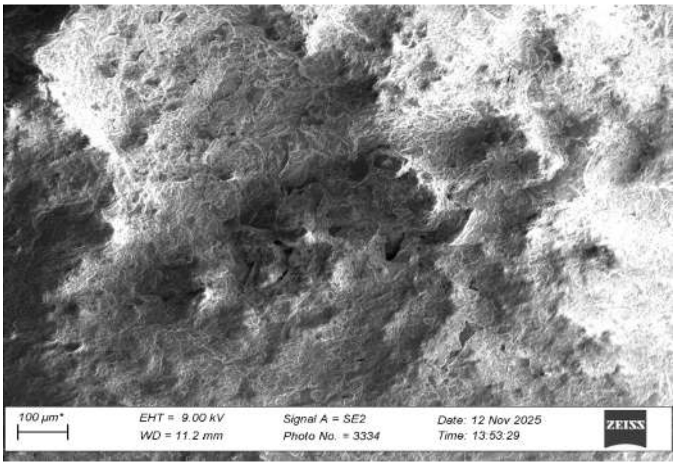


**Figure 7. SEM micrograph of graphite-electrode EKR-treated soil (BSH, 7-day cure).**

### *3.5 Elemental composition (XRF/EDS)*

Bulk oxide composition (Table 3) shows that $SiO_2$ and $Al_2O_3$ fractions decreased after EKR treatment with all three electrodes relative to the untreated soil, while $Fe_2O_3$ increased substantially, most notably for the aluminium-electrode sample (26.29% vs 14.64% in the untreated soil). PbO content fell from 0.103% in the untreated soil to 0.02-0.075% after treatment, confirming lead mobilisation and removal by EKR across all electrode types, with the greatest reduction observed for the aluminium electrode. This decoupling, where aluminium gives the greatest contaminant removal but the weakest strength gain, indicates that contaminant-removal efficiency and geotechnical performance are governed by partly independent mechanisms, and that electrode selection for field application should weigh both criteria rather than remediation efficiency alone.

**Table 3. Bulk oxide composition of untreated and EKR-treated lead-contaminated soil (XRF).**

| Oxide | Untreated (%) | Al-electrode (%) | C-electrode (%) | Graphite (%) |
|---|---|---|---|---|
| $SiO_2$ | 51.46 | 41.561 | 43.200 | 41.215 |
| $Al_2O_3$ | 28.76 | 22.752 | 26.135 | 25.916 |
| Fe2O3 | 14.64 | 26.286 | 21.720 | 24.783 |
| $K_2O$ | 3.083 | 2.710 | 2.710 | 2.219 |
| $TiO_2$ | 1.90 | 3.722 | 3.616 | 3.486 |
| CaO | 0.482 | 0.369 | 0.795 | 0.272 |
| PbO | 0.103 | 0.02 | 0.025 | 0.075 |

## 4. CONCLUSION

Electrode material was found to be a controlling variable in the strength and microstructural outcome of electro-kinetic remediation of lead-contaminated lateritic soil. Carbon electrodes produced the greatest gains in unconfined compressive strength and unsoaked California bearing ratio, meeting the 80% CBR threshold for base material under lightly trafficked roads, and this was corroborated by a denser, more flocculated microstructure observed by SEM. Graphite electrodes gave intermediate strength performance, while aluminium electrodes reduced strength relative to the untreated soil despite achieving the greatest reduction in lead oxide content. None of the treatments, however, satisfied UCS-based specifications for base or sub-base material, and soaked CBR values remained below specification for all treatments, indicating that EKR alone is not sufficient for unconditional reuse of this soil in pavement layers and that supplementary stabilisation should be considered where soaked strength governs design. Overall, the results demonstrate that electrode selection should be guided jointly by contaminant-removal efficiency and geotechnical performance, with carbon electrodes offering the most favourable balance among the materials examined.

## REFERENCES

1. AASHTO (1996). Standard Specification for Transportation Materials and Methods of Sampling and Testing. American Association of State Highway and Transportation Officials, Washington, D.C.
2. ASTM (1992). Standard Classification of Soils for Engineering Purposes (Unified Soil Classification System). American Society for Testing and Materials.

3. British Standards Institution (1990). BS 1377: Methods of Test for Soils for Civil Engineering Purposes, Parts 2, 4 and 7. BSI, London.
4. Butcher, F. and Sailie, E. L. (1984). Testing soils for use as road construction materials. Nigerian Society of Engineers Technical Transactions.
5. Clare, A. G. (2012). Principles and applications of scanning electron microscopy in materials characterisation. Journal of Materials Science, 47(2), 401-415.
6. Edeh, J. E. and Amadi, A. A. (2014). Geotechnical properties of lateritic soils stabilised with locally derived admixtures. Nigerian Journal of Engineering Research and Development, 7(1), 22-31.
7. Goldstein, J. (2003). Scanning Electron Microscopy and X-ray Microanalysis. 3rd ed. Springer, New York.
8. Ingles, O. G. and Metcalf, J. B. (1972). Soil Stabilization: Principles and Practice. Butterworths, Sydney.
9. Mohammad, N., Moghal, A. A. B., Rasheed, R. M. and Almajed, A. (2022). Critical review on the efficacy of electrokinetic techniques in geotechnical and geoenvironmental applications. Arabian Journal of Geosciences, 15(8), 781.
10. Molaei, M. A., Miraki, H., Morovati, M., Ghadir, P. and Javadi, A. A. (2024). Solidification/stabilization of lead-contaminated soil using alkali-activated volcanic ash. Environmental Science and Pollution Research, 31(26), 38465-38484.
11. Naseer, U., Du, Z. P., Ahmad, A., Farooq, S., Yousaf, M. and Yue, T. X. (2025). Advanced electrode materials in electrokinetic technology for remediation of heavy metal-contaminated soil: recent progress and challenges. Advanced Sustainable Systems, 9(8), 2500197.
12. Nigerian General Specifications for Roads and Bridges (2016). Federal Ministry of Works, Abuja.
13. Osinubi, K. J. and Medubi, A. B. (1997). Lime stabilisation of tropical black clay for road construction. Journal of Environmental Sciences, 1(1), 12-19.
14. Oyediran, I. A. and Enya, A. (2021). Effect of contamination on the index and geotechnical properties of remediated soils. International Journal of Geo-Engineering, 12, 4.
15. Sun, Z., Xu, S., Zhang, J., Eugene, B. D. and Li, S. (2024). Effect of electrode positioning on electrokinetic remediation of contaminated soft clay with surface electrolyte. Toxics, 12(10), 758.
16. TRRL (1977). A Guide to the Structural Design of Bituminous-Surfaced Roads in Tropical and Sub-Tropical Countries. Transport and Road Research Laboratory, Crowthorne.
17. Zheng, X., Li, Q., Wang, Z. and Chen, M. (2024). Remediation of heavy metals contaminated soil by enhanced electrokinetic technology: A review. Arabian Journal of Chemistry, 17(6), 105773.