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Influence of Electrode Type on the Engineering Properties of Lead Contaminated Soil Subjected to Electro-Kinetic Remediation

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ABSTRACT: This study evaluated the effectiveness of electrokinetic remediation (EKR) using aluminium, carbon, and graphite electrodes in improving the environmental and geotechnical properties of lead-contaminated soil. The untreated soil was classified as A-7-6 according to the AASHTO classification system and CL (lean clay) under the Unified Soil Classification System (USCS), indicating a fine-grained soil with moderate plasticity. The results demonstrated that electrokinetic remediation effectively removed lead and other contaminants from the soil. The aluminium electrode achieved the highest PbO removal efficiency of 84.20%, followed by the carbon (82.60%) and graphite (68.80%) electrodes. Significant removal efficiencies were also recorded for Fe_2O_3, Cr_2O_3, SO_3, and K_2O, confirming the effectiveness of the remediation process. Furthermore, the engineering properties of the soil improved following remediation. The liquid limit decreased from 48.0% in the untreated soil to 45.3%, 46.2%, and 41.4% for the aluminium-, carbon-, and graphite-treated soils, respectively, while the plasticity index reduced from 19.8% to 18.8%, 16.7%, and 15.6%. Similarly, the specific gravity increased from 2.41 to 2.57, 2.53, and 2.58, respectively. The findings demonstrate that electrokinetic remediation using aluminium, carbon, and graphite electrodes significantly enhanced both the environmental quality and engineering performance of the lead-contaminated soil, with the aluminium electrode exhibiting the highest lead removal efficiency.

KEY WORDS: electrokinetic remediation (EKR), Specific gravity, Atterberg limit, sieve analysis, aluminium, carbon, and graphite electrodes.

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1.0 INTRODUCTION

Soil pollution is one of the major environmental concerns in developing countries due to the ungoverned disposal of liquid and solid wastes. Primary pollutants such as metals, organic compounds, pesticides, antibiotics, and even radioactive substances are predominantly toxic in their characteristics (Selvi, and Aruliah, 2018). Consequently, they have the potential to directly harm the environment, living organisms, and human health, as well as adversely affect economic activities and the overall well-being of society (Sharma et al., 2023). It is therefore essential to develop remediation solutions capable of sustaining environmental quality for present and future generations, particularly in developing countries where the existing rate of decontamination remains insufficient to keep pace with the scale of contamination (Sharma et al., 2023).

Heavy metals are introduced into the environment through various natural sources, including geological weathering, volcanic eruptions, mineral weathering, and continental dust (Amir et al., 2021). Anthropogenic activities are, however, the dominant contributors, with the improper discharge of toxic metal-rich effluents from tanneries, mining operations, thermal power plants, and pharmaceutical and chemical industries constituting the major sources of water and soil pollution (Oves et al., 2019). Lead, in particular, is among the most hazardous of these contaminants owing to its persistence, non-biodegradability, and potential to bioaccumulate in soil, water, and living organisms, posing serious risks to human health and ecosystem functioning even at relatively low concentrations.

Electrokinetic remediation (EKR) is a soil decontamination technology that was developed in the 1980s. Owing to its high remediation efficiency, low risk of secondary contamination, low energy consumption, and suitability for in-situ application, it is widely regarded as a "green remediation technology" (Jiang & Shukui, 2019). The technique involves the application of a low-intensity direct current across electrodes inserted into contaminated soil, inducing electromigration, electro-osmosis, and electrophoresis, which mobilise and transport pollutants toward the electrodes for subsequent collection and removal. EKR has been applied predominantly to soils contaminated with heavy metals such as cadmium, copper, lead, and zinc, with more limited application to soils contaminated with radioactive elements such as uranium (Jiang & Shukui, 2019).

The efficiency of EKR is strongly influenced by operational factors, among which electrode material is one of the most critical, since it governs electrochemical reactions at the electrode-soil interface, the current distribution within the soil mass, and the extent of contaminant mobilisation (Kumar & Singh, 2022; Gidudu & Chirwa, 2022). While previous studies have examined the influence of electrode configuration, voltage gradient, and enhancement additives on EKR performance (Zhang et al., 2024; Sani et al., 2023 a & b), comparatively fewer studies have systematically evaluated how different electrode materials simultaneously affect both contaminant removal efficiency and the residual geotechnical properties of the treated soil. This gap is particularly significant for tropical lateritic soils, whose engineering behaviour after remediation determines their suitability for reuse in geotechnical applications such as road subgrades and embankments. This study therefore investigates the influence of aluminium, carbon, and graphite electrodes on the removal efficiency of lead and associated contaminants from lead-contaminated soil, and evaluates the corresponding changes in the geotechnical index properties of the soil, including particle size distribution, Atterberg limits, linear shrinkage, and specific gravity. The findings are expected to guide the selection of cost-effective and technically suitable electrode materials for the electrokinetic remediation of heavy metal-contaminated soils in similar geo-environmental settings.

2.0 MATERIALS AND METHODS

2.1 Materials

2.1.1 Lateritic soil

The lead contaminated soil used for this study was collected by method of disturbed sampling from a lead contaminated soil deposit located at Awe mine site in Awe local Government area of Nasarawa state at (Latitude $11^{0}15'$ N and longitude 7^{0} 45' E). The soil sample was collected at depths of between 1.5 m and 2.0 m below the natural ground surface using hand-dug trial pits.

2.1.2 Water

Tap water used in the study was collected from the Soil Laboratory of the Department of Civil Engineering, Nigerian Defence Academy, Kaduna, Nigeria.

2.1.3 Electrodes

The electrodes used for the EKR test were graphite, aluminium and carbon electrodes and they were all obtained from Jos, Plateau state of Nigeria.

2.1.4 Citric acid

The citric acid used for the EKR as the catalyst was purchased from the open market at Bayyajidda street, Kaduna central market, Kaduna.

2.1.5 Distilled water

The distilled water used for the EKR test was obtained from chemical engineering laboratory of Kaduna Polytechnic, Tudun Wada, Kaduna.

2.1.6 Electro kinetic Cell

Two (2) number of locally fabricated Electro kinetic cell made from a clear plexiglass plate of dimension 400mm by 200mm by 300mm, with a middle internal partition of dimension 300mm by 200mm by 300mm fabricated with two outer partitions, 50mm by 200mm by 300mm at the two ends available at NDA EKR laboratory.

2.2.1: Methods

2.2.1: EKR Set Up

During the electrokinetic remediation of the lead-contaminated soil, the elapsed time, current flow, effluent generated at both the anode and cathode chambers, and the soil pH were monitored and recorded, as shown in Plate 1. About 10 kg of lead-contaminated soil was thoroughly mixed with distilled water for each test and placed in separate EKR tanks, and four electrode rods (two at the anode and two at the cathode) were connected to the setup. Each EKR tank was first lined with filter paper before the mixed soil sample was placed in it. Citric acid was then introduced into the cathode chamber as an enhancement agent, and beakers were positioned at both chamber outlets to collect the effluent generated during remediation. The setup was connected to a direct current power source and allowed to remediate, with the system monitored and readings taken every 24 hours. The process was continued until the effluent ceased to be generated, indicating that the soil had been fully remediated, or when the current measured remained constant with time. The process typically lasted between 10 and 30 days. The same procedure was repeated for the aluminium and carbon electrode setups.

Plate 1: EKR setup for Aluminium electrode

2.2.2 Particle size distribution

Particle size analysis was performed in accordance with BS 1377; 1990 Part 2. To obtain the particle size distribution, dry sieving was performed on 200g of soil sample. The same procedure was carried out on all remediated soils

2.2.3 Specific gravity

The specific gravity was determined using the BS 1377 (1990) test (B) for fine–grained soils. The density bottle and stopper were weighed precisely to the nearest 0.001g (m_1). The air dried soil was placed in the density bottle, and the bottle, contents, and cover were all weighed as m_2. After adding just enough water to cover the soil, the solution was gently stirred to remove any air bubbles. After that, the bottle was completely filled and covered. The covered bottle was then wiped dry, and the entire assembly was weighed to the nearest 0.001g (as m_3). The bottle was then emptied, completely refilled with water, wiped dry, and weighed to the nearest 0.001 g (m_4). Equation (2) was used to calculate the specific gravity:

$$G_S = \frac{m_2 - m_1}{(m_4 - m_1) - (m_3 - m_1)} \quad (1)$$

The same procedure was repeated for all of the EKR treated soils.

2.2.4 Atterberg limits

The test consists of determining the liquid limits, plastic limits, and plasticity index for natural and stabilized soils. They were also carried out in accordance with BS 1377 (1990) Part 2 Test1 (A) for natural.

2.2.4.1 Liquid limit

For the liquid limit (LL) test, the soil sample was air-dried, and 200 g was sieved through a BS No. 40 sieve (425 µm openings). The sieved soil was thoroughly mixed with water on a flat glass plate to form a homogeneous paste. This mixture was placed in the Casagrande apparatus cup, leveled parallel to the base, and a groove was cut through its centre using the grooving tool. The crank was turned to lift and drop the cup, allowing the two sides of the soil to meet at the bottom of the groove. The number of blows required for the groove to close was recorded, and a small portion of the soil was taken to determine its moisture content.

The test was repeated across a range of moisture contents, from relatively dry to wet states. The results were plotted on a semi-logarithmic graph of moisture content versus number of blows, and the liquid limit was determined as the moisture content corresponding to 25 blows.

2.2.4.2 Plastic Limit

A portion of the soil retained from the liquid limit test was used to determine the plastic limit (PL). The soil was first shaped into a ball and then rolled between the palms and fingers until it reached a slightly drier consistency than that used for the liquid limit. The sample was divided into four equal portions, and each portion was rolled into a thread between the thumb and forefinger. The threads were further rolled on a glass plate using the fingers until their diameter was reduced to approximately 3 mm, usually after five to ten forward and backward movements. Rolling continued until the threads began to crack and crumble both longitudinally and transversely. The crumbled soil was collected in a moisture container, and its moisture content was determined

2.2.4.3 Plasticity index

Plasticity index (PI) of the soil is referred to the difference between the liquid limit (LL) of the soil and the corresponding plastic limit (PL). The plasticity index was calculated as:

$$PI = LL - PL \tag{2}$$

Where:
PI =Plasticity Index (%)
LL =Liquid Limit (%)
PL = Plastic Limit (%)

2.2.4.4 Linear shrinkage

The linear shrinkage test was carried out following Test 5 of BS 1377 (1990). Approximately 125 g of soil passing the BS No. 40 sieve (425 µm openings) was mixed with water to form a homogeneous paste, with the water content corresponding to the soil's liquid limit. The paste was placed into a shrinkage mould and gently vibrated to remove air pockets. The soil surface was levelled with a spatula and then air-dried at 60 °C until it visibly shrank away from the mould. Final drying was completed in an oven at 105–100 °C. After cooling, the length of the soil sample was measured, and the linear shrinkage was calculated using Equation (3).

$$\text{Linear Shrinkage} = \frac{(\text{Initial lenght - Dried lenght})}{\text{Initial Length}} \times 100\,\% \tag{3}$$

The same procedure was repeated for all the percentages of the admixtures.

3.0 RESULTS AND DISCUSSION

3.1 Effectiveness of Electrokinetic Remediation on Removal efficiency

The effectiveness of electrokinetic remediation (EKR) in removing contaminants from lead-contaminated soil shown in figure 1 was found to depend on the electrode material used. The results showed varying removal efficiencies for the different elemental oxides following remediation. For V_2O_5, the aluminium electrode achieved the highest removal efficiency (61.24%), followed by the carbon (58.23%) and graphite (53.40%) electrodes. The superior performance of the aluminium electrode may be attributed to anodic dissolution, which enhances contaminant removal through the generation of coagulant species (Wang et al., 2023).

For Fe_2O_3, the graphite electrode recorded the highest removal efficiency (80.14%), compared with 67.40% for the carbon electrode and 51.32% for the aluminium electrode. This suggests that the graphite electrode provided a stable conductive surface that sustained electrokinetic reactions and enhanced iron migration (Li et al., 2023). In contrast, the highest removal efficiencies for SO_3 (72.60%), MnO (66.30%), and K_2O (70.30%) were obtained using the carbon electrode, indicating that its favourable electrochemical properties and high electrical conductivity promoted the migration of these ionic species under the applied electric field (Zhang et al., 2024; Zhao et al., 2023; Ahmed et al., 2024).

The aluminium electrode also exhibited the highest removal efficiency for Cr_2O_3 (79.50%), which may be attributed to the acidic conditions generated during electrolysis that enhanced chromium mobilization (Kumar & Singh, 2022). For chloride (Cl), only slight differences were observed among the electrodes, with the graphite electrode recording the highest removal efficiency (61.30%), followed closely by the carbon (60.20%) and aluminium (59.30%) electrodes. This relatively small variation suggests that chloride removal is influenced primarily by its high mobility under the applied electric field rather than by the type of electrode material used (Luo et al., 2022).

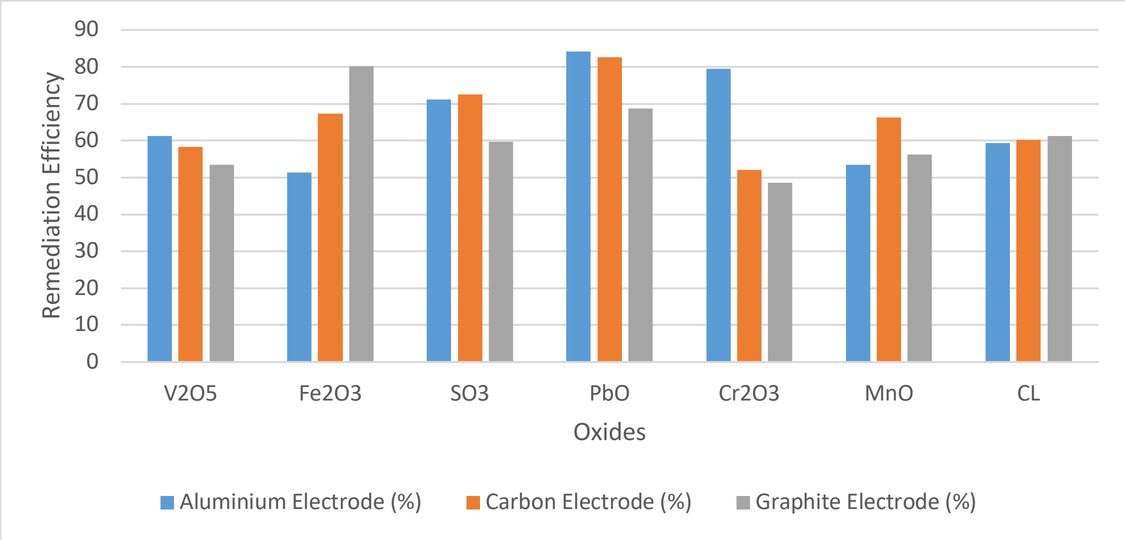

Figure 1 Removal efficiency of the lead contaminated soil using three different electrode

3.1.2 Current behaviour

Electric current is one of the most important operational parameters in electrokinetic remediation (EKR) because it reflects the movement of ions through the soil matrix and provides valuable information on contaminant transport and the progression of the remediation process which is shown in figure 2. For the aluminium electrode, the current decreased from 0.31 A on Day 1 to 0.06 A by Day 23, indicating a gradual reduction in ionic conductivity as contaminants were removed and the concentration of mobile ions within the soil decreased. The carbon electrode recorded an initial current of 0.28 A, which steadily declined to 0.03 A by Day 23 and remained relatively constant until Day 27. The consistently lower current values observed for the carbon electrode, compared with the aluminium and graphite electrodes, may be attributed to its relatively stable electrochemical behaviour and lower electrode reactivity (Zhang et al., 2024).

The graphite electrode exhibited an initial current of 0.30 A, which gradually decreased to 0.06 A by Day 22 and further declined to 0.04 A between Days 25 and 27. Although the overall trend showed a progressive decrease in current, a slight increase was observed between Days 9 and 10, during which the current increased from 0.16 A to approximately 0.18 A before continuing its downward trend. This temporary increase may be associated with enhanced ion migration and the release of dissolved ions into the pore fluid during the remediation process (Li et al., 2023).

Comparison of the three electrode materials shows that the aluminium electrode produced the highest initial current (0.31 A), followed closely by the graphite electrode (0.30 A) and the carbon electrode (0.28 A). The higher current recorded with the aluminium electrode may be attributed to electrochemical reactions involving partial dissolution of the electrode surface, which increased the concentration of charge-carrying ions within the soil system and enhanced electrical conductivity (Kumar & Singh, 2022).

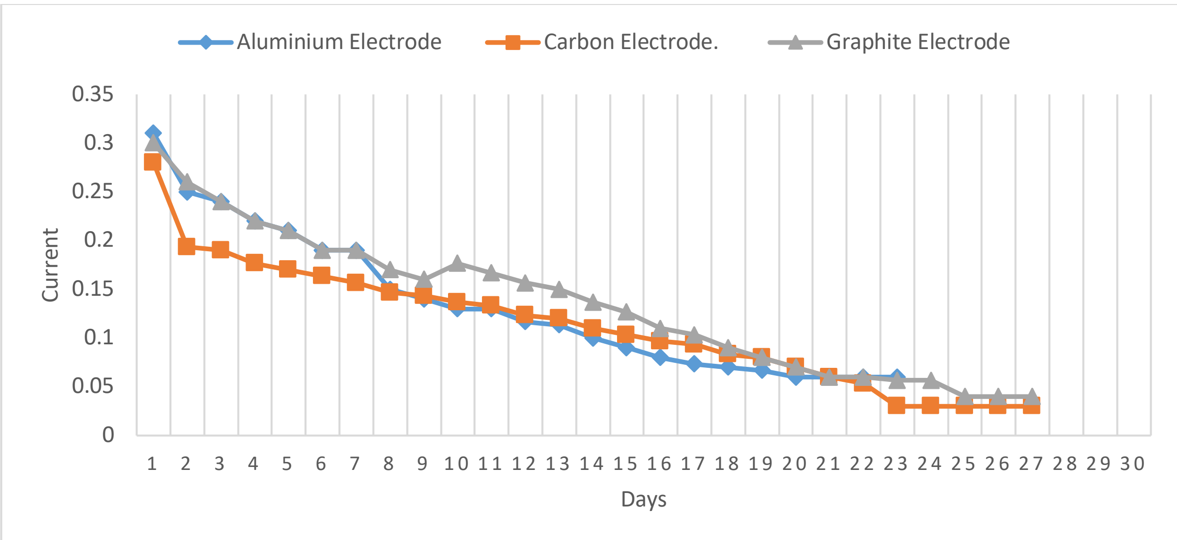

Figure 2 current behaviour during the electrokinetic remediation (EKR) process

3.1.3 pH behavior

The pH of the soil shown in figure 3 is one of the most critical parameters influencing the efficiency of electrokinetic remediation (EKR) because it governs the solubility, mobility, adsorption, desorption, and precipitation of heavy metals within the soil matrix. During electrokinetic remediation, electrolysis reactions at the electrodes generate hydrogen ions (H^+) at the anode and hydroxyl ions (OH^-) at the cathode, creating acidic and alkaline fronts that migrate through the soil. For the aluminium electrode, the initial pH was 5.97 on Day 1 and increased slightly to 6.57 on Day 3 before decreasing steadily to approximately 4.00 on Day 8. This reduction in pH can be attributed to the production of hydrogen ions at the anode during water electrolysis, resulting in the development of acidic conditions within the soil (Wang et al., 2023). After Day 8, the pH gradually increased, reaching values between 6.0 and 6.7 during the later stages of remediation. This increase may be associated with the migration of hydroxyl ions from the cathode and the buffering capacity of the soil. The carbon electrode exhibited an initial pH of 6.17, which remained relatively stable during the first few days of remediation before gradually decreasing to 4.53 by Day 9. The decline in pH indicates the formation of acidic conditions resulting from anodic oxidation and the continuous generation of hydrogen ions (Zhang et al., 2024). Thereafter, slight fluctuations in pH were observed, reflecting the combined effects of hydroxyl ion migration and soil buffering reactions. The graphite electrode recorded an initial pH of 5.73, which decreased to approximately 4.57 by Day 5 and remained within the acidic range throughout most of the remediation period. Compared with the aluminium and carbon electrodes, the graphite electrode exhibited relatively smaller pH fluctuations, suggesting a more stable electrochemical environment during treatment. The slight increase in pH observed between Days 10 and 12, when the pH rose above 5.4, may be attributed to the migration of hydroxyl ions from the cathode and buffering reactions involving soil constituents (Chen et al., 2023).

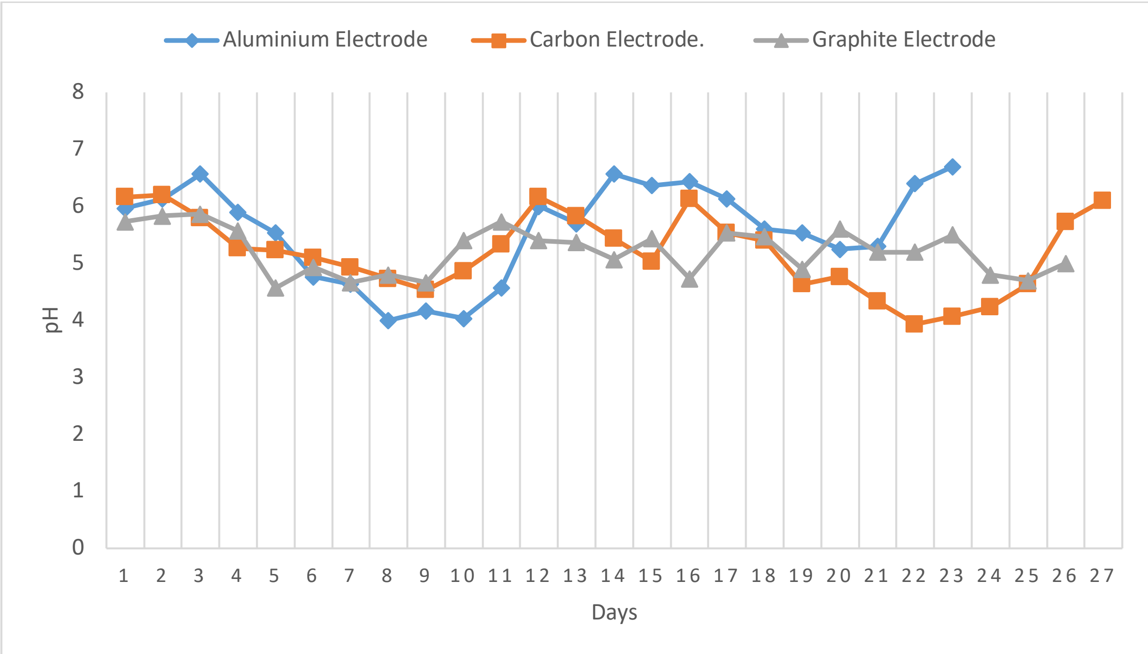

Figure 3: pH behaviour during the electrokinetic remediation (EKR) process

3.2 Particle size distribution

Fines are defined as the fraction of soil particles that pass through the No. 200 (0.075 mm) sieve and consist primarily of silt- and clay-sized particles. The number of fines present in a soil significantly influences its engineering properties, particularly hydraulic conductivity, plasticity, and compressibility. Soils with very low fines content generally lack sufficient silt and clay particles to achieve low hydraulic conductivity. The results of the dry sieve analysis for the untreated lead-contaminated soil and the electrokinetically remediated soils using graphite, aluminium, and carbon electrodes are presented in Figure 4. The percentage of fines obtained for all four samples was very similar, indicating that electrokinetic remediation had little or no effect on the particle size distribution of the soil. This trend can be attributed to the fact that the same soil was used throughout the study, with only the electrode material varied during the electrokinetic remediation process. Consequently, while the remediation process effectively removed contaminants, it did not significantly alter the gradation or fines content of the soil.

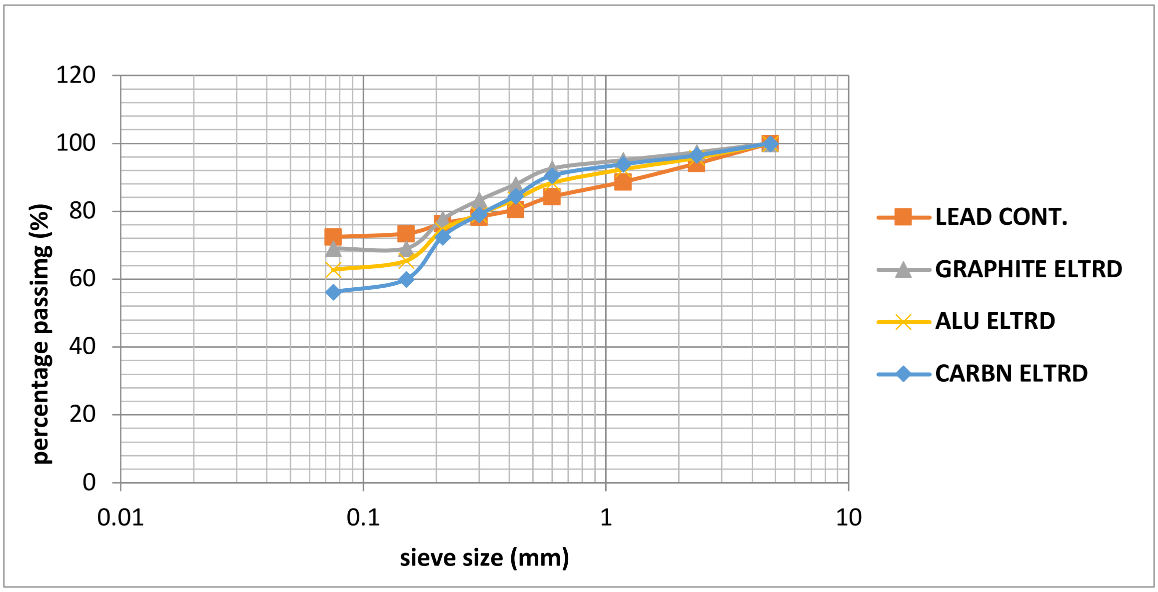

Fig. 4: Particle size distribution curve for lead contaminated and varying electrode EKR remediation

3.3 Atterberg Limit test

3.3.1 Liquid Limits

The variation in the liquid limit (LL) of the lead-contaminated soil before and after electrokinetic remediation using different electrode materials is presented in Figure 5. The untreated lead-contaminated soil recorded a liquid limit of 48.0%. Following electrokinetic remediation, the liquid limit decreased to 45.3%, 46.2%, and 41.4% for the aluminium-, carbon-, and graphite-treated soils, respectively. The reduction in liquid limit indicates that electrokinetic remediation improved the consistency characteristics of the contaminated soil by reducing its water-holding capacity and plastic behaviour. This improvement can be attributed to the removal of lead and other contaminants from the soil matrix, which altered the physicochemical interactions between soil particles and pore water (Li et al., 2023). Among the electrode materials investigated, the graphite electrode produced the greatest reduction in liquid limit (41.4%), followed by the aluminium electrode (45.3%), while the carbon electrode recorded the highest liquid limit among the remediated soils (46.2%). These results suggest that the graphite electrode was the most effective in enhancing contaminant removal and improving the consistency characteristics of the soil. From a geotechnical engineering perspective, a lower liquid limit is desirable because it is associated with reduced compressibility, lower swelling potential, and improved soil stability. Therefore, the reduction in liquid limit following electrokinetic remediation indicates enhanced engineering performance and increased suitability of the treated soil for pavement and foundation applications. This observation is consistent with the findings of Chen et al. (2023).

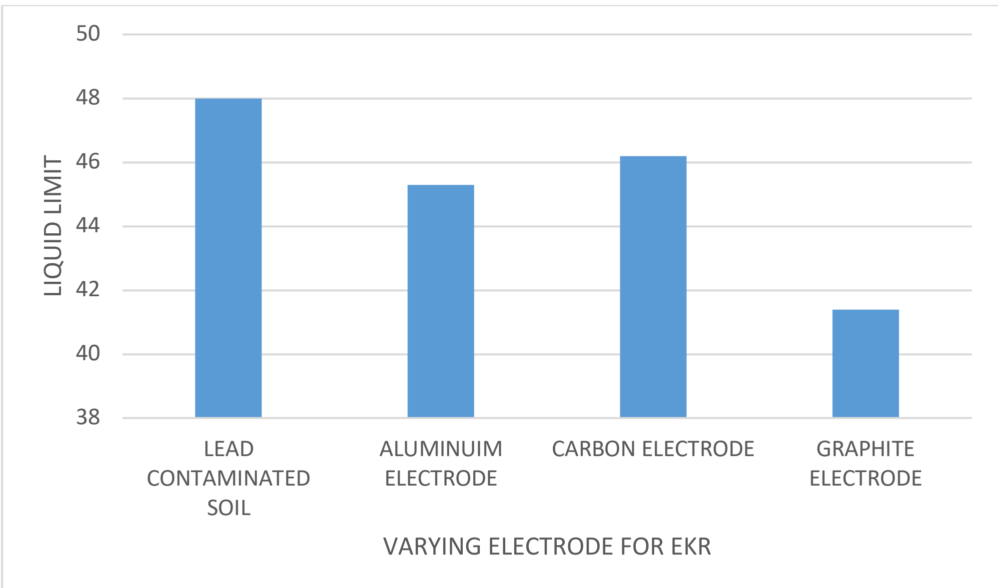

Fig. 5. Variation of liquid limit with varying electrodes for EKR remediation

3.3.2 Plastic limit (PL)

The variation in the plastic limit (PL) of the lead-contaminated soil before and after electrokinetic remediation using different electrode materials is presented in Figure 6. The untreated lead-contaminated soil recorded a plastic limit of 28.2%. Following electrokinetic remediation, the plastic limit changed to 26.5%, 29.5%, and 25.8% for the aluminium-, carbon-, and graphite-treated soils, respectively. The results indicate that the aluminium and graphite electrodes reduced the plastic limit of the contaminated soil, whereas the carbon electrode produced a slight increase. The reduction in plastic limit observed with the aluminium and graphite electrodes suggests that electrokinetic remediation modified the physicochemical interactions between soil particles and pore water through the removal of lead and other contaminants. This modification reduced the moisture content required for the soil to transition from a semi-solid to a plastic state, thereby improving its consistency characteristics (Li et al., 2023). Among the electrode materials investigated, the graphite electrode recorded the lowest plastic limit (25.8%), followed by the aluminium electrode (26.5%), while the carbon electrode recorded the highest value (29.5%). The lower plastic limit obtained with the graphite electrode indicates that it was more effective in modifying the soil structure and enhancing contaminant removal, resulting in improved engineering behaviour of the treated soil (Chen et al., 2023). Overall, the observed changes in plastic limit demonstrate that electrokinetic remediation has a significant influence on the consistency properties of lead-contaminated soil, thereby improving its suitability for geotechnical and pavement engineering applications.

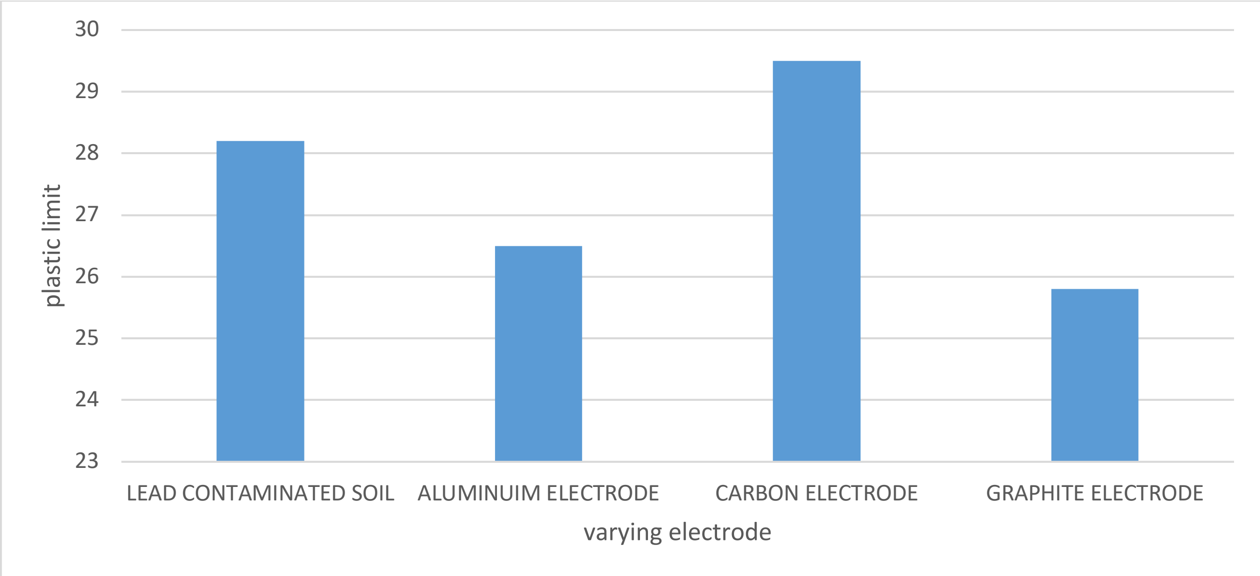

Fig. 6. Variation of plastic limit with varying electrodes for EKR remediation

3.3.3 Plasticity index

The variation in the plasticity index (PI) of the lead-contaminated soil before and after electrokinetic remediation using different electrode materials is presented in Figure 7. The untreated lead-contaminated soil recorded a plasticity index of 19.8%. Following electrokinetic remediation, the plasticity index decreased to 18.8%, 16.7%, and 15.6% for the aluminium-, carbon-, and graphite-treated soils, respectively. This reduction in plasticity index indicates that electrokinetic remediation significantly improved the consistency characteristics of the contaminated soil by reducing its plasticity. The plasticity index represents the range of moisture content over which a soil exhibits plastic behaviour and is an important indicator of its engineering performance (Chen et al., 2023). A lower plasticity index generally reflects a reduction in clay activity and an improvement in soil workability and dimensional stability. The observed decrease in plasticity index can be attributed to the removal of lead and other contaminants during the electrokinetic remediation process, which altered the physicochemical interactions between soil particles and reduced their affinity for water. Among the electrode materials investigated, the graphite electrode produced the greatest reduction in plasticity index, decreasing it from 19.8% to 15.6%, followed by the carbon electrode (16.7%) and the aluminium electrode (18.8%). This suggests that the graphite electrode was the most effective in improving the consistency characteristics of the contaminated soil. From a geotechnical perspective, lower plasticity index values are desirable because they are associated with reduced compressibility, lower shrink–swell potential, improved stability, and enhanced suitability for engineering applications such as pavement subgrades, embankments, and foundation materials. These findings are consistent with those reported by Li et al. (2023), who observed that electrokinetic remediation significantly improved the engineering behaviour of contaminated soils by reducing their plasticity characteristics.

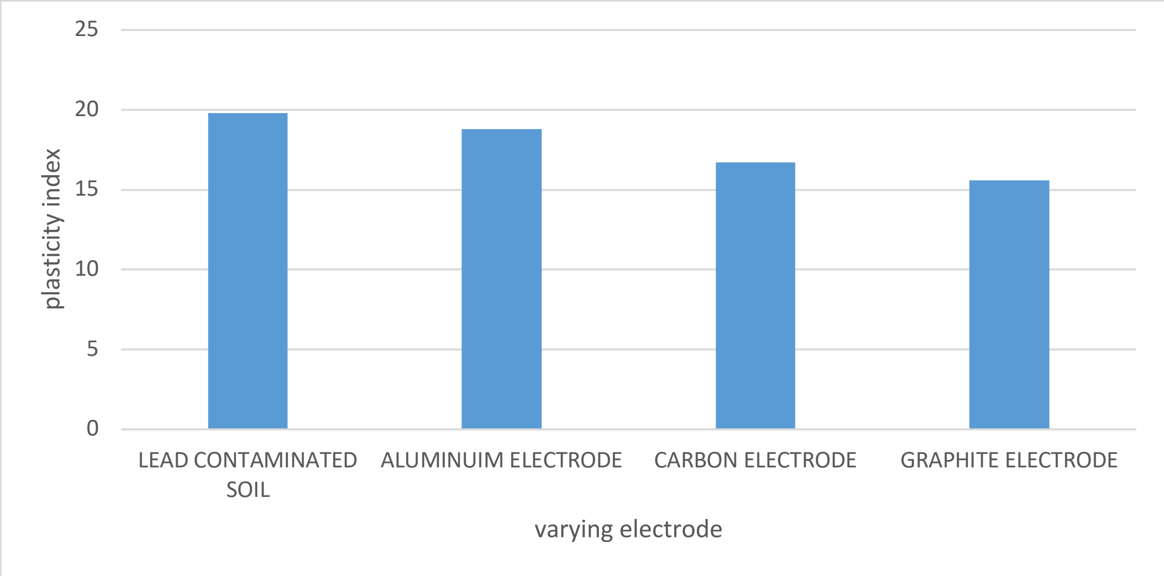

Fig. 7. Variation of plasticity index with varying electrodes for EKR remediation

3.3.4 Linear Shrinkage

The variation in the linear shrinkage of the lead-contaminated soil and the electrokinetically remediated soils treated with different electrode materials is presented in Figure 8. The untreated lead-contaminated soil recorded a linear shrinkage of 11.9%, while the soils remediated using graphite, aluminium, and carbon electrodes recorded values of 11.2%, 11.18%, and 11.2%, respectively. The slight reduction in linear shrinkage following electrokinetic remediation indicates an improvement in the volumetric stability of the soil. This reduction can be attributed to the removal of lead contaminants, which altered the soil structure and reduced its tendency to undergo shrinkage upon drying. Lower linear shrinkage values are desirable in geotechnical engineering because they indicate a reduced potential for volume change, cracking, and deformation under varying moisture conditions. The observed trend is consistent with the findings of Edeh and Amadi (2014), who reported that soil improvement techniques reduce shrinkage characteristics and enhance the engineering performance of treated soils.

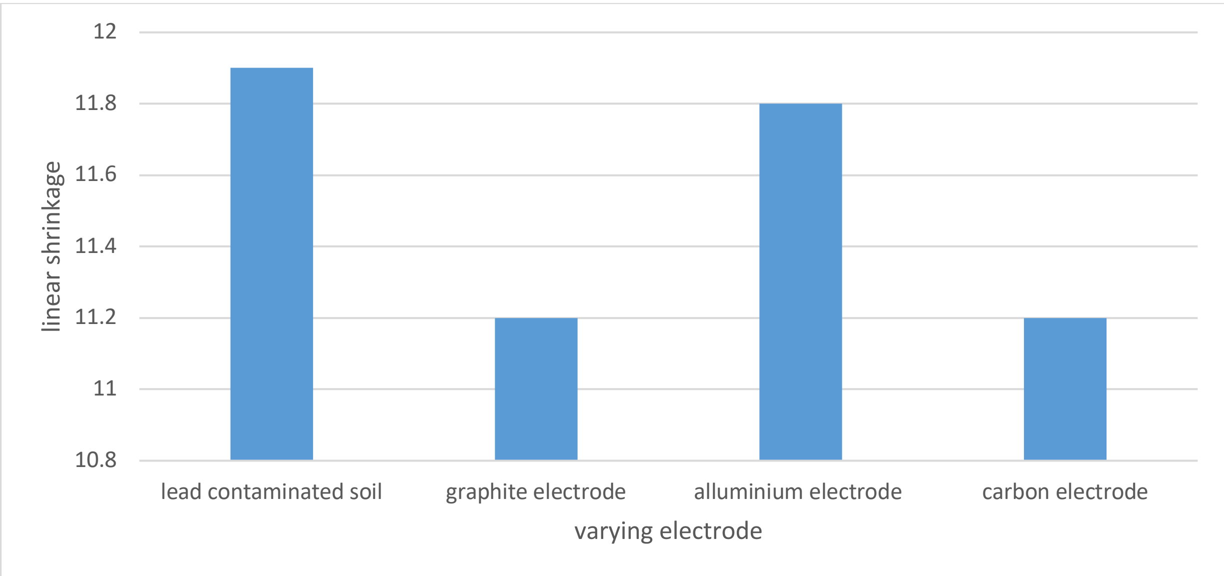

Figure 8: Shrinkage limit graph of varying EKR electrodes

3.4 Specific Gravity

The variation in the specific gravity of the lead-contaminated soil before and after electrokinetic remediation using aluminium, carbon, and graphite electrodes is presented in Figure 9. The untreated lead-contaminated soil recorded a specific gravity of 2.41, whereas the remediated soils recorded values of 2.57, 2.53, and 2.58 for the aluminium, carbon, and graphite electrodes, respectively. These results indicate that electrokinetic remediation enhanced the specific gravity of the contaminated soil regardless of the electrode material used. The increase in specific gravity following remediation suggests an improvement in the physical characteristics of the soil. Lead contamination can alter the mineralogical composition and particle interactions within the soil matrix, resulting in a reduction in specific gravity. The electrokinetic remediation process facilitated the migration and removal of lead and other contaminants, thereby restoring the soil's mineral composition and increasing its specific gravity. Similar observations were reported by Moses and Sani (2022), who found that electrokinetic remediation of contaminated lateritic soils improved specific gravity as a result of contaminant removal and the restoration of soil particle integrity. Among the electrode materials investigated, the graphite electrode produced the highest specific gravity (2.58), closely followed by the aluminium electrode (2.57), while the carbon electrode recorded the lowest value (2.53) among the remediated soils. The relatively higher specific gravity values obtained with the graphite and aluminium electrodes suggest that these electrode materials were more effective in enhancing contaminant removal and restoring the mineralogical characteristics of the soil.

From an engineering perspective, the increase in specific gravity is desirable because soils with higher specific gravity generally exhibit improved compaction characteristics, greater shear strength, and enhanced load-bearing capacity. Consequently, the improvement in specific gravity observed after electrokinetic remediation indicates enhanced engineering performance and increased suitability of the treated soil for geotechnical and pavement construction applications. This finding is consistent with the observations of Sani et al. (2023 a & b), who reported that improvements in specific gravity following electrokinetic treatment are associated with better engineering properties and improved suitability of contaminated soils for construction purposes.

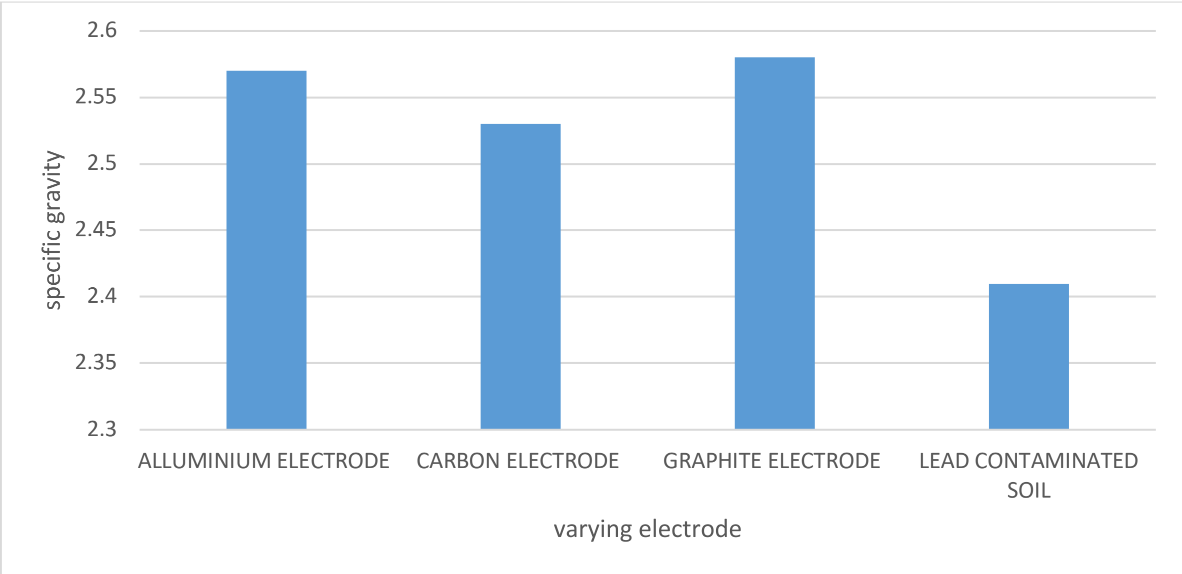

Figure 9: Specific Gravity of lead contaminated soil and varying electrode remediated soil with EKR

CONCLUSION

The results of this study demonstrated that electrokinetic remediation (EKR) was effective in removing contaminants from the lead-contaminated soil. For the primary contaminant (PbO), removal efficiencies of 84.20%, 82.60%, and 68.80% were achieved using aluminium, carbon, and graphite electrodes, respectively, indicating significant reductions in lead contamination. The remediation process also achieved high removal efficiencies for other contaminants, including Fe_2O_3 (80.14%), Cr_2O_3 (79.50%), SO_3 (72.60%), and K_2O (70.30%), further demonstrating the effectiveness of EKR in improving soil quality. Among the electrode materials investigated, the aluminium electrode exhibited the highest PbO removal efficiency, making it the most effective electrode for the remediation of lead-contaminated soil. Electrokinetic remediation also resulted in significant improvements in the engineering properties of the contaminated soil. The liquid limit decreased from 48.0% in the untreated soil to 45.3%, 46.2%, and 41.4% following remediation with aluminium, carbon, and graphite electrodes, respectively. Similarly, the plasticity index decreased from 19.8% to 18.8%, 16.7%, and 15.6%, indicating a reduction in soil plasticity and shrink–swell potential. In addition, the specific gravity increased from 2.41 in the untreated soil to 2.57, 2.53, and 2.58 for aluminium-, carbon-, and graphite-treated soils, respectively, reflecting an overall improvement in the physical and engineering characteristics of the soil following contaminant removal. These findings demonstrate that electrokinetic remediation not only enhances contaminant removal but also improves the geotechnical properties of lead-contaminated soil, thereby increasing its suitability for engineering applications. Overall, the aluminium electrode is recommended where maximum lead removal is the primary objective, while the graphite electrode offers the greatest improvement in the consistency and volume-stability properties of the remediated soil; the choice of electrode material should therefore be guided by the specific remediation objective and the intended geotechnical application of the treated soil.

Based on these findings, it is recommended that field-scale trials be conducted to validate the laboratory-derived removal efficiencies and geotechnical improvements under in-situ conditions, and that the long-term durability and leachability of residual contaminants in remediated soils be further investigated before their adoption in road subgrade and embankment construction. Future studies should also explore the economic and energy implications of each electrode material to support the selection of a cost-effective option for large-scale field application.

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