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Diffusion of Municipal Waste Pollutants in Electrokinetic Lead-Remediated Compacted Lateritic Soil

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Abstract: This study investigates the spread of pollutants from municipal waste into the surrounding environment that could lead to environmental contamination, human health impacts, ecological damage, and economic consequences. Electrokinetically remediated lead-contaminated lateritic soil and leachate collected from an old municipal solid waste (MSW) dumpsite were used in the diffusion test to investigate the movement of certain inorganic species through the soil. The British Standard Heavy compactive effort was used to compact the diffusion setup, maintaining a 2% water content optimum. Water saturated the apparatus for thirty days, followed by the introduction of MSW leachate for an additional sixty days. The diffusion results indicate that in the natural soil, the diffusion coefficients for Pb^{2+}, Ca^{2+}, Mn^{2+}, SO_4^{2-}, and Cl^- were 1.09E-09, 2.16E-09, 2.17E-10, 6.43E-09, and 8.26E-10 m^2/s, respectively. In the remediated soil, the diffusion coefficients for Ca^{2+}, Mn^{2+}, and Cl^- decreased to 1.95E-09, 2.62E-09, and 1.144-07 m^2/s, respectively, whereas the diffusion coefficients of Pb^{2+} and SO_4^{2-} increase to 2.11E-09 and 1.14E-07 m^2/s, which could be due to the high concentration of this species in the leachate, and probably longer remediation time is required. Diffusion of pollutants is essential for addressing environmental challenges, protecting public health, and promoting sustainable development for present and future generations.

Keywords: containment barrier, lead, electrokinetic remediation, diffusion, leachate, lateritic

1. Introduction

A range of activities, including mining, industrial operations, manufacturing, illegal disposal, unintentional discharge, and agriculture [1, 2], generate pollutants. The pollutants mentioned include organic compounds, radionuclides, and heavy metals that have entered the soil, contaminating both the environment and groundwater [3, 4]. Groundwater plays a vital role in supplying drinking water and serving various household purposes. Groundwater pollution harms plant growth, ecological system, and human well-being [5]. In certain instances, it can even result in fatalities, as demonstrated by the incident of lead contamination in Zamfara State, northern Nigeria, in March 2010. This event led to approximately sixty-five deaths and numerous hospitalizations [6, 7]. Several procedures, such as soil washing, soil flushing, and electrokinetic remediation (EKR), can treat contaminated soil. EKR is a new technique used by environmentalists to remediate organic and inorganic species. Direct current passes through two electrodes, one acting as the anode and the other as the cathode in an electrolyte, to achieve the technique [8]. There are four major transport processes, which include electromigration (the movement of charged particles like ions or electrons within a conducting medium under the influence of an electric field), electroosmosis (the movement of liquid through a porous material under the influence of an electric field), diffusion (when ions move from a region of higher concentration to a region of lower concentration), and electrophoresis (the migration of charged particles through a liquid medium under the influence of an electric current) [9–11].

Inadequate landfilling techniques, the presence of open landfills in low-lying regions without protective barriers and safety measures, and the lack of organized waste disposal plans characterize Nigeria's waste management procedures. Nowadays, waste containment facilities contain waste and prevent leachate from polluting the ecological system, surrounding soil, and groundwater, which serves as the major source of drinking water and other domestic uses [12]. Liners and covers, made of compacted clay or geosynthetic, constitute the major components of a waste containment facility. Waste containment facilities commonly use compacted clay as a hydraulic barrier. This clay must meet certain requirements, such as having a hydraulic conductivity of less than or equal to 1 × 10 m/s, a volumetric shrinking strain of less than or equal to 4%, and an unconfined strength of 200 kN/m or more [13, 14]. At times, the available natural clay does not meet these criteria. In past studies, researchers have modified the quality of the clay by adding pozzolans like fly ash, bentonite, sand, biochar, marine clay, cement, and slag [15]. Researchers like Tiwari and Satyam [16] and Osinubi et al. [17] used more friendly technology, like the addition of bacteria, to produce calcite, which variably improved the properties of the compacted clay material. The research

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findings also indicated that the method proved effective in lowering the levels of potassium, chloride, lead, calcium, and chromium ions in municipal solid waste (MSW) containment systems.

Shu et al. [18] investigated the adsorption of contaminants usually present in leachate, focusing on their behavior under competitive adsorption settings. In addition, Boscov et al. [19] found a lack of studies conducted on lateritic red soil exposed to an acidic environment in pollutant containment. Laterite is abundant in extensive portions of tropical and subtropical locations and serves as a foundation and building material. Therefore, this study aims to determine the rate at which certain types of municipal species diffuse through lateritic soil treated with an EKR process.

2. Theoretical Framework

Diffusion is the net impact of Brownian motion over a concentration gradient area. Diffusion in porous media is traditionally characterized using a modified version of Fick's law, which links diffusive flow to concentration gradient [20]. Fick's first law governs diffusion and describes one-dimensional transport, expressed as:

$$\overline{J_D} = -nD_0\tau\left(\frac{\partial C}{\partial x}\right) \tag{1}$$

where

$$\tau = (L/Le)^2 \tag{2}$$

where $\overline{J_D}$ is the diffusion flux ($ML^{-2}T^{-1}$), and D_0 is the diffusion coefficient of the solute (L^2T^{-1}). c refers to the amount of solute in solution (ML^{-1}), n stands for the total porosity of the soil (dimensionless), x is the space coordinate, L_e represents the actual effective distance of flow through the soil between two sites that define the flow path, and L represents the distance (in meters) between two points. The dimensionless tortuosity factor, denoted by τ, represents the actual microscopic or effective distance of flow through the soil between the same two sites that define the flow path [21].

The specific kind of diffusion influences the value of the free diffusion coefficient (D_0). They are inter-diffusion, self-diffusion, tracer diffusion, and salt diffusion [22].

In fully saturated soils, a modified form of Fick's first law is used to determine diffusion.

$$\overline{J_D} = -D_0\theta\frac{\partial C}{\partial x} \tag{3}$$

where

$$\theta = nSr \tag{4}$$

(θ) is defined as the volumetric water content.

The total soil porosity (n) is a dimensionless quantity representing the volume of pores per unit soil volume, and the soil degree of saturation (Sr) is expressed as a decimal.

Currently, it is not possible to quantify tortuosity factors independently [23]. Hence, the definition of the effective diffusion coefficient, denoted as D^*, may be easily established according to Rowe et al. [24].

$$D^* = Do^*\tau a \tag{5}$$

Experimental findings along with Equation (3) can be used to ascertain the value of the effective diffusion coefficient denoted as D^* of diffusing species in the soil. Equation (5) can be used to compute the apparent tortuosity factor once D^* is established and an acceptable value for the free solution diffusion coefficient is known. The literature documents commonly observed values for τa [25].

$$\frac{\partial C}{\partial t} = D^*\frac{\partial^2 C}{\partial x^2} \tag{6}$$

It is believed that the transient transport of nonreactive solutes through the soil is governed by Fick's second law. Nonreactive solutes do not undergo chemical or biological reactions, while reactive solutes undergo chemical or biological reactions. Simulations typically focus on adsorption, desorption, and radioactive decay, excluding complexation, precipitation, ion coupling, dissolution, and oxidation-reduction previous modifications by Bear [26]; Freeze and Cherry [27] have addressed this modification, allowing for the inclusion of reversible sorption processes during diffusive transport for nondecaying, reactive solutes in Equation (5).

$$\frac{\partial C}{\partial t} = D^*\frac{\partial^2 C}{\partial x^2} - \frac{\partial q'}{\partial t} \tag{7}$$

q' represents the sorbed concentration of chemical species measured as the mass of sorbed species per unit volume of vacancies.

$$q' = \frac{\rho d}{\theta}q \tag{8}$$

where q is the concentration of sorbed solute per unit mass of soil, and ρ_d represents the dry (bulk) density of the soil. One can derive Fick's second law for reversible sorption processes involving reactive solutes during diffusive transport in soil by taking the derivative of Equation (7) concerning time, substituting it into Equation (8), and rearranging the resulting equation yields a modified expression [26, 27].

$$\frac{\partial C}{\partial t} = \frac{D^*}{Rd}\frac{\partial^2 C}{\partial x^2} \tag{9}$$

The retardation factor, represented by Rd,

$$Rd = 1 + \frac{\rho_d}{\theta}k_P \tag{10}$$

and

$$k_p = \frac{dq}{dc} \tag{11}$$

The retardation factor is a dimensionless quantity, as described by Freeze and Cherry [27], that measures the correlation between the fluid's flow rate and the rate at which a reactive solute is transported; the partition coefficient is represented by K_p, K_p is used as the distribution coefficient when the relationship between q and c is linear.

The dependent variable K_p is determined by the equilibrium concentration in the pore water of the soil. For solutes that do not undergo a chemical reaction, the value of K_p is 0, while the value of R_d is 1.0. However, the value of R_d [1.0] indicates that solutes undergo a chemical reaction. The laboratory determines the values of Rd based on the results of either column tests or batch equilibrium testing. Various mathematical solutions to Equation (6) have been uncovered by researchers, and each of these solutions relies on specific initial and boundary conditions [28].

Researchers determine the diffusion coefficient by fitting an analytical solution to Fick's second law of diffusion. For each chemical species needing identification, a comparison between pore water and depth profiles is conducted at the test's conclusion [29]. The selection of the analytical solution hinges on the existing flow pattern and boundary conditions [30].

$$\frac{(\mathrm{Cx} \geq 0, \mathrm{t})}{\mathrm{co}} = \frac{\alpha}{1+\alpha} \sum\nolimits_{\mathrm{m}=1}^{\infty} \frac{2\alpha}{1+\alpha+\alpha^2\mathrm{q}^2\mathrm{m}} \times \exp\left(\frac{-\mathrm{D}^*\mathrm{q}^2\mathrm{mt}}{\mathrm{R_d L^2}}\right) \cos\left[\frac{\mathrm{qm}\left[1-\left(\frac{\mathrm{x}}{\mathrm{l}}\right)\right]}{\cos(\mathrm{qm})}\right] \tag{12}$$

Crank [28] provides analytical solutions for Fick's second law, which deals with the one-dimensional diffusion of substances through fully saturated soils. These solutions consider a limited cell length and a decreasing source concentration.

C_o represents the solute's initial concentration in the source reservoir. The symbol D^* represents the effective diffusion coefficient. The symbol R_d represents the retardation factor for linear, instantaneous, and reversible sorption. L represents the length of the soil specimen, x represents the depth of the chemical species inside the soil specimen, and qm represents the non-zero positive roots of the function below.

$$\tan(\mathrm{qm}) = -\alpha \mathrm{qm} \tag{13}$$

α is a constant defined as follows

$$\alpha = \frac{\mathrm{HL}}{\mathrm{nR_d L}} \tag{14}$$

The variable n represents the overall porosity of the soil specimen, while H_L denotes the height of the liquid in the source reservoir.

3. Research Methodology

3.1. Materials

3.1.1. Lateritic soil

The disturbed sampling method was used to collect lateritic soil from a formation located in Shika, Zaria, Kaduna State (latitude 11°15' and longitude 7°45'E). From the depth between 1.5 m and 2.0 m, representing the B-horizon, which is usually characterized by the accumulation of material leached from the overlying A-horizon is where the soil sample was collected. The soil samples were air-dried and subsequently pulverized to acquire particles that pass through a sieve with a 4.75 mm aperture according to BS No. Standards.

3.1.2. Leachate

The leachate used for this study was obtained from a non-engineered, active MSW landfill. It is located behind the Local Government Authority primary school in Samaru, Zaria, Nigeria. The leachate was collected from a low-lying open point in the landfill, where waste from students, staff living off campus, and others was dumped.

3.1.3 Index properties

The lateritic soil is reddish brown, both the natural (0%) and the electrokinetic lead-remediated soil. Both soils fall under the A-7-6 soil group of the AASHTO [31]. For the Unified Soil Classification System [32], the natural soil (0%) falls under CH, while the remediated soil is categorized as CL.

The formation of new compounds could be attributed to the change in classification. The characteristics of natural and electrokinetically lead-remediated soil are shown in Table 1.

Table 2 displays the chemical composition utilized in the study.

Table 1
Index properties of natural and electrokinetic lead-remediated soil

Engineering properties	Natural soil 0%	0.2% EKR	0.4% EKR	0.6% EKR	0.8% EKR	1.0 EKR
In situ moisture content	22.70					
Liquid Limit, %	52.00	49.40	48.00	47.60	47.00	39.60
Plastic Limit, %	22.93	22.01	29.02	29.49	29.24	22.01
Plasticity Index, %	29.07	27.39	18.92	18.12	17.76	17.59
Linear Shrinkage, %	12.14	11.43	10.00	9.00	7.60	5.00
Percentage Passing BS No. 200 Sieve. (BSL)	82.15	7.68	8.50	9.75	4.60	5.85
Percentage Passing BS No. 200 Sieve. (WAS)	82.15	5.09	9.78	9.06	10.30	5.50
Percentage Passing BS No. 200 Sieve. (BSH)	82.15	10.4	14.8	7.73	10.30	5.60
AASHTO Classification	A-7-6	A-7-6	A-2-6	A-2-6	A-7-6	A-7-6
USCS Classification	CH	CL	CL	CL	CL	CL
Specific Gravity	2.67	2.63	2.54	2.58	2.43	2.39
MDD mg/m^3						
Standard Proctor	1.68	1.78	1.78	1.79	1.74	1.86
West African Standard	1.76	1.87	1.84	1.61	1.86	1.86
Modified Proctor	1.84	1.96	1.97	1.97	1.96	1.94
OMC%						
Standard Proctor	19.00	13.20	14.40	14.60	14.98	15.60
West African Standard	16.80	13.10	13.40	13.00	11.20	13.40
Modified Proctor	14.00	10.40	9.40	10.60	10.80	11.66
pH Value	4.20	5.83	6.0	7.03	5.6	4.28
Color	Brown					
Dominant Clay mineral	Muscovite					

Table 2
Chemical characteristics of municipal solid waste leachate samples used

S/N	Parameter	Unit	Leachate A	Leachate B	Maximum permitted limit
1	pH	–	9.60	7.50	6.50–8.50
2	Odor	–			Unobjectionable
3	Color	TCU	138		15
4	Taste	–			Unobjectionable
5	Temperature	°C	28.10	27.80	Ambient
6	Turbidity	NTU	226.00	188.00	5.00
7	Conductivity	mS/cm	3.15	0.67	0.15–0.30
8	Total Dissolved Solids	mg/l	1451.00	490.00	500.00
9	Total Hardness	mg/l	183.00	120.00	150.00
10	Chloride	mg/l	138.00	248.30	<4.00
11	Iron	mg/l	7.02	2.72	0.30
12	Lead	mg/l	2.11	0.02	0.01
13	Nitrate	mg/l	133.00	52.20	45.00
14	Sulphate	mg/l	111.00	130.00	<10.00
15	Sodium	mg/l	27.60	1.01	<3.00
16	Zinc	mg/l	5.30	2.30	0.00
17	Chromium	μg/I	135.00	80.00	0.00
18	Calcium	mg/I	244.00	80.00	75.00
19	Potassium	mg/I	121.00	2.14	55.00
20	Magnesium	mg/I	2.60	0.35	20.00
21	Manganese	μg/I	20.14	15.52	0.20
22	Dissolved oxygen	mg/I	1.35	3.88	6.00
23	Biological Oxygen Demand	mg/I	23.43	3.46	3.00
24	Chemical Oxygen Demand	mg/I	1386.00	190.00	<20.00

3.2. Method

3.2.1. Preparation of sample

Soil contamination with P_b was carried out at 0%, 0.2%,0.4%, 0.6%, 0.8%, and 1% by dry weight, which corresponds to 2000 mg/kg, 4000 mg/kg, 6000 mg/kg, 8000 mg/kg, and 10 000 mg/kg, according to Udiba et al. [33]; Tirima et al. [34]

a) *Artificial contamination of soil samples*

Five separate plastic containers were filled with soil, weighing a total of 117 kg each. Each plastic container's soil sample was mixed with lead nitrate in a stepwise increment of 0.2%, ranging from 0% to 1.0% based on the sample's dry unit weight. Researchers Karkush et al. [35] and Resmi et al. [36] reported that the mixture achieved a homogeneous saturation of lead nitrate after being left in the laboratory for a month. After 30 days, the contaminated soil was stirred for 10 min in a mixer to evenly distribute the lead nitrate throughout the soil [37]. The soil was then air-dried in large trays at room temperature, pulverized, and stored in polyethylene bags after passing through a 2 mm sieve

b) *Set-up and calibration of electrokinetic cells*

The test equipment consists of an acrylic plastic EKR cell, a DC power supply, a peristaltic pump, an overflow collection system, and a data acquisition system. The electrokinetic cell had a dimension of 30 × 20 × 30 cm, with the electrolyte chamber having a dimension of 5 × 20 × 30 cm, and the soil compartment measuring 30 × 20 × 30 cm. The graphite electrode measured 8 mm in diameter and 30 cm in length. There were a total of six electrodes. Porous Plexiglas separated the soil compartment from the electrolyte compartment. On the porous plate, the holes were 5 mm in diameter and 2 mm apart. To prevent the inflow of soil particles into the electrolyte during the test, a 40-mm-diameter Whatman filter paper was placed between the porous plate and the soil. Two control valves were installed at the top and bottom of the electrolyte chamber. One valve collects the electromotive flow fluid, while the other pumps the electrolyte into the electrolyte chamber. Figure 1 depicts the schematic diagram of the setup.

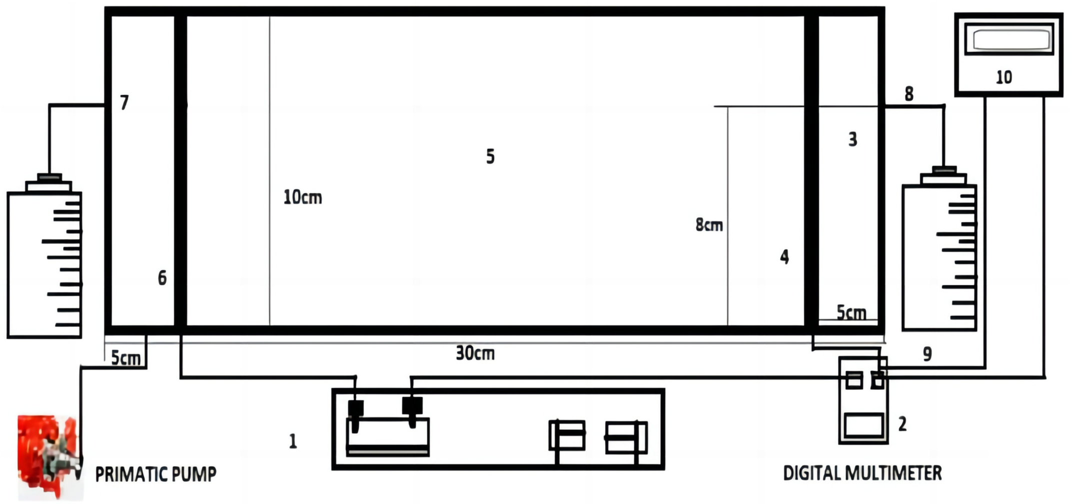
c) *Soil sample preparation for* EKR

A digital scale is used to measure three numbers of 15 kg of contaminated soil for each of the three cells that were constructed. The soils were mixed with the amount of water content of the liquid limit and were mixed properly for homogeneity, then compacted into electrokinetic cells with a plastic rod 50 mm long and 10 mm in diameter. A DC power supply was used to apply a voltage of 30 volts across the electrodes to achieve 1 volt per cm [38]. Both the anolyte and the catholyte consisted of 0.1 M acetic acid. After the test, four thin metal sheets were inserted with a 6 cm gap between them into the chamber containing the soil sample, and the soil was divided into five equal parts. Each soil part was carefully excavated with a spatula; the areas from the cathode to the anode were sequentially labeled S1–S5, and the soil was dried for testing.

3.2.2. Preparation of the sample for diffusion

The single reservoir decreasing source test method, as stipulated by Shackelford and Daniel [25], was followed for this test. The electrokinetically remediated soil at (0, 0.2, 0.4, 0.6, 0.8, and 1.0% concentration) was sieved through a BS standard of 4.75 mm aperture and then compacted at +2 optimum moisture content using the British Standard Heavy compactive effort into polyvinyl chloride pipes of 25 cm and 10 cm diameter. The diffusion cell was then sealed with perspex at the top with a narrow tube through which leachate was introduced, but before that, each of the diffusion cells was permeated with distilled

Figure 1
Schematic diagram of experimental setup. 1 – power supply; 2 – digital millimeter; 3 – cathode chamber; 4 – cathode; 5 – soil chamber; 6 – anode; 7 – anode chamber; 8 – overflow port; 9 – graduated bottle



water for 30 days. This was done to achieve soil saturation and minimize the mass transport of contaminants due to suction in the soil.

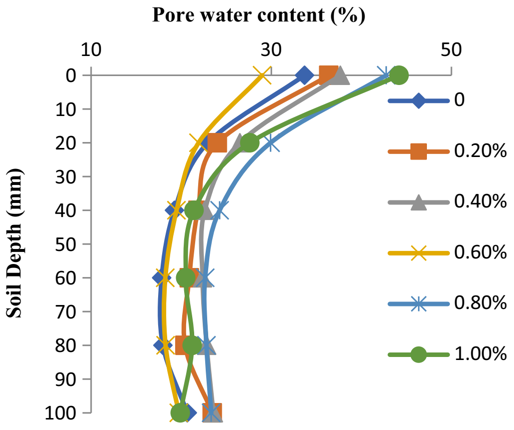
a) *Diffusion, sectioning, and extraction*

On the thirtieth day, the distilled water was poured out of the diffusion cells, and the leachate from the MSW was introduced via the pores in the perspex, ensuring no air bubbles were trapped on the surface of the solution. The diffusion studies were conducted over 90 days to allow for the movement of the contaminants under a hydraulic gradient. The chemical components in the leachate diffused into the saturated and densely packed soils for a duration of 90 days. After the end of the diffusion process, each cell containing soil with a diameter of 10 cm, a height of 20 cm, and a thickness of 12 cm of electrokinetically remediated lead soil was pushed out and cut into slices that were all 1.1 cm thick. Sectioning was conducted to determine the water contents present in the specimens using the process of oven drying, resulting in a variation of values. A concentration profile of the specified ions for use in determining the effective indicated ions is required to calculate the effective diffusion coefficients.

The slices were divided into two portions; one set was used to determine the water content, while the second set was allowed to dry before extraction. The water content of the slices was determined through oven drying. The air-dried slices for concentration profiling underwent digestion by adding aqua regia (a mixture of HCl and HNO_3 in a 1:3 ratio, i.e., 5 ml of HCl to 15 ml of HNO_3) and adding 1 g of the electrokinetic remediated lead soil in a beaker. The substance in the beaker was heated and agitated for approximately 30 to 45 min until dry under a fume cupboard. After cooling, distilled water was added, and the mixture was filtered. The filtrate was collected in a 250-ml volumetric flask, adjusted to the 250 mark, and subjected to elemental analysis using the UNICAM 969 atomic absorption spectrometer.

For each sample, the effective diffusion coefficient was determined by using Equations (9–11), utilizing retardation factors (R_d) derived from the batch equilibrium results and reservoir concentration d at $x = 0$. The tortuosity factors were obtained by applying the self-diffusion coefficients for representative ions at infinite dilution in water and were documented by Chen et al. [39].

Figure 2
Moisture content changes at different depths following diffusion testing



4. Results and Discussion

4.1. Diffusion analysis

4.1.1. Influence of pore water content

After the 90-day diffusion tests, Figure 2 shows how the amount of water in each slice of soil changed with depth, while different concentrations of electrokinetic lead remediation were also taken into account. The water content in the soil column decreased with an increase in depth, as determined by using weighted averages.

The findings indicate that since the leachate must travel a longer and more intricate route at a deeper level in the compacted soil column, the hydraulic flow is reduced. Except for the top slice, the last slice had a somewhat greater water content than the other slices. The observed rise could have resulted from the bottom slice collecting all of the leachate that had diffused from the slices above it. Oluremi [40] reported a similar trend.

4.1.2. Effect of pore solution pH

The behavior of clay suspensions is significantly influenced by their pH values. A low pH promotes a negative surface contact, resulting in frequent flocculation of particles from the suspension. The pH conditions play a crucial role in maintaining the stability of clay particle suspensions or dispersions. The properties of the sediment fabric and the behavior of the suspended material are significantly impacted by the kind of action that is adsorbed. Clay suspensions have a higher tendency to clump together (flocculate) compared to monovalent cations, which encourage the opposite process of separating the particles (deflocculation).

Figure 3 illustrates the impact of pH on the viability of the soil slice. In the electrokinetically remediated soil, there is an observed pH increase from 0 to 100 mm. The initial rise in alkalinity in the remediated soil with depth can be attributed to the physiochemical reactions occurring in the soil during the electrokinetic processes. The decrease in pH values with depth in natural soil be attributed to the substitution of protons on clay surfaces with metallic cation from the leachate. The final pH values are in the Table 3. It indicates an acidic environment for the soil-leachate mixture.

Figure 3
pH changes at varying depths following diffusion testing

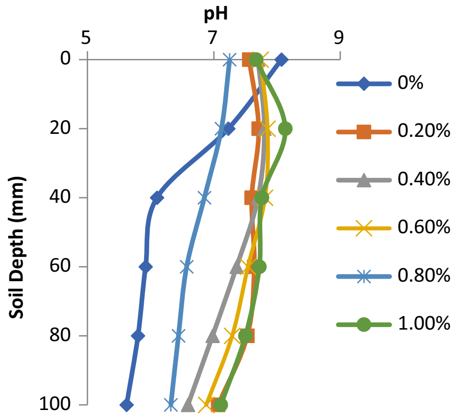


Table 3
Soil profile of pH with depth for the diffusion test

		pH					
Slice No.	Slice point (cm)	0%	0.2%	0.4%	0.6%	0.8%	1.0%
1	0	8.07	7.56	7.7	7.74	7.25	7.67
2	20	7.23	7.71	7.8	7.85	7.12	8.13
3	40	6.1	7.6	7.7	7.81	6.85	7.76
4	60	5.92	7.64	7.36	7.54	6.57	7.72
5	80	5.8	7.53	6.98	7.29	6.44	7.5
6	100	5.62	7.07	6.59	6.88	6.32	7.11

Figure 4
Changes in calcium pore water content at various depths

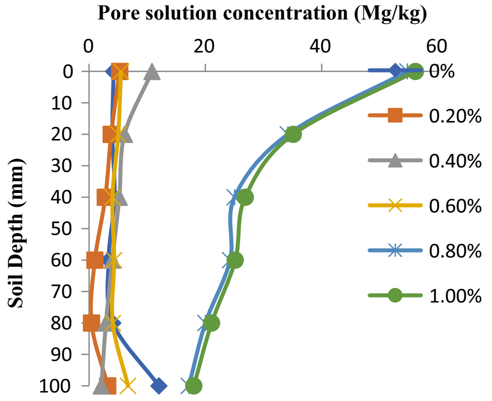


Figure 5
Changes in manganese pore water content at various depths

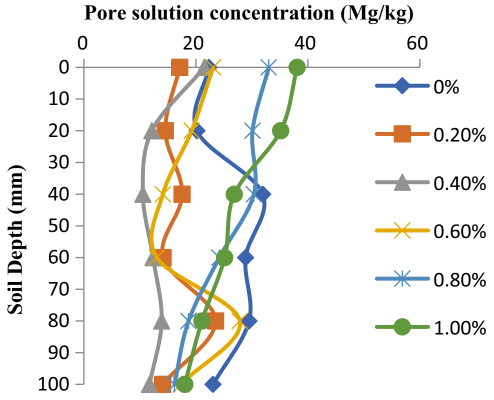


Figure 6
Changes in lead pore water content at various depths

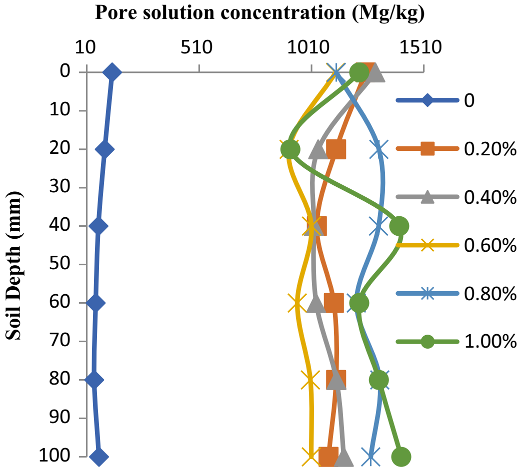


Figure 7
Changes in chlorine pore water content at various depths

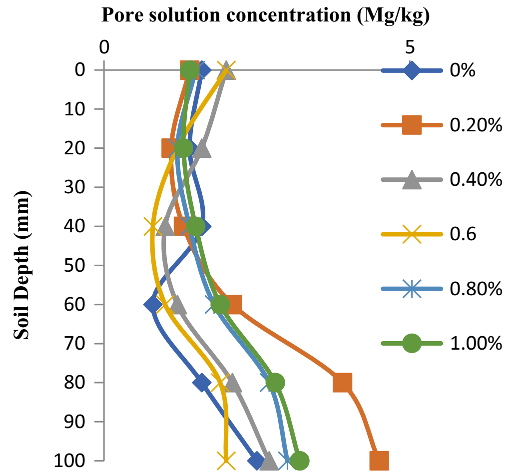
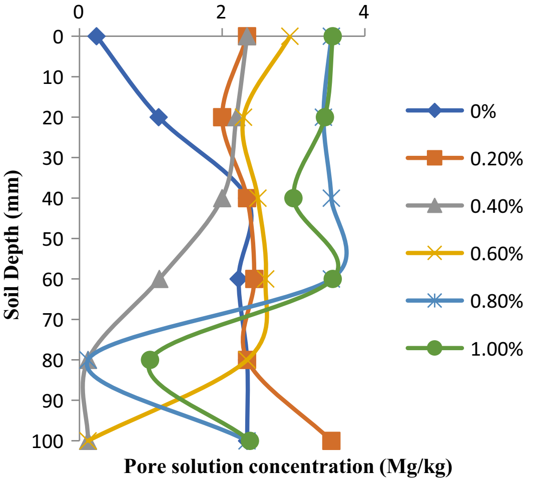


Figure 8
Changes in sulfate pore water content at various depths



The observation aligns with Mitchell [41] and highlights pH as a key factor governing cation adsorption in soil within the engineering system, Abollino et al. [42] and Sani [43] also noted a decrease in metal adsorption with rising soil pH.

4.1.3. Effect of pore solution concentration

The determination of the effective diffusion coefficient, D^*, involved was analyzing the pore water concentration profiles at different depths for various ionic species as illustrated in Figures 4, 5, 6, 7, and 8; subsequently, the data were combined using Equation (11) and results presented in Table 4.

The soil profile tortuosity factors as depicted in Table 5 were derived by employing self-diffusion coefficients of typical ions in water at infinite dilution, as reported by Rowe et al. [24]. Furthermore, the effective diffusion coefficient from Table 4 was used in conjunction with Equation (4).

In the case of Ca^{2+}, the effective diffusion coefficient (D^*) value exhibited a decline with the increasing concentration of electrokinetically remediated lead soil. This trend was accompanied by a corresponding reduction in tortuosity as evidenced in Tables 4 and 5. The tortuosity factor ranged from 0.1 to 0.59 for natural soil [29]. Higher concentration may lead to increased competition for available pore spaces, impacting the diffusion of calcium. Additionally, the changes in soil structure and EKR efficiency could affect the transport of calcium ions, showing consistency with Amadi and Eberemu [44] in their work indicating an increase in diffusion values from 2.39×10^{-10} to 3.59×10^{-10} m^2/s for lateritic soil where kaolinite was the dominant clay m^2/s for lateritic soil with kaolinite as the dominant clay mineral.

For Pb^{2+}, no distinct pattern in diffusion value emerged clear trend with increment with electrokinetically remediated lead content, D^* ranged from 3.24×10^{-9} to 1.95×10^{-10} m^2/s while τa fluctuated between 0.05 and 0.22 between 0 and 1% at a stepwise of 0.2%. The increasing and decreasing trend in diffusion coefficient may be attributed to factors such as concentration-dependent interaction between lead and the remediation process; this reflects those of Ochepo [45] who also found no distinct pattern in Pb^{2+} diffusion value. Similarly, sulfate had a D^* of the range 6.43×10^{-9} to 5.37×10^{-11} m^2/s with the tortuosity factor ranging between 0.05 and 6.06. The value does not follow a straightforward linear trend indicating potential non-linear behavior in the diffusion process with changing concentration this result is similar to the finding of Moses [46] and Osim [47]. For Cl^- it had a D^* of values between 1.08×10^{-7} and 8.26×10^{-10} m^2/s with a tortuosity factor ranging between −349 and 56.10. There was a clear increasing trend in diffusion coefficient as the concentration of electrokinetically remediated soil increased. This suggests that higher concentrations are associated with higher rates of chlorine diffusion. It was also observed that the diffusion coefficient spanned several orders of magnitude indicating substantial variation in the movement of chlorine through the soil under electrokinetic conditions.

Table 4
Soil profile diffusion coefficient (m^2/s)

	Apparent diffusion coefficient					
	0	0.2	0.4	0.6	0.8	1.0
Lead	1.09E-09	5.35E-10	4.25E-10	2.07E-09	2.16E-09	2.11E-09
calcium	2.16E-09	2.60E-09	2.15E-09	2.80E-09	3.24E-09	1.95E-09
Manganese	2.71E-10	7.40E-10	9.32E-10	7.24E-10	2.46E-09	2.62E-09
Sulphate	6.43E-09	2.30E-10	3.64E-10	5.37E-11	2.98E-09	4.81E-11
Chloride	8.26E-10	7.09E-09	9.23E-08	9.01E-08	1.08E-07	1.14E-07

Table 5
Soil profile tortuosity factor

	Tortuosity factor					
	0	0.2	0.4	0.6	0.8	1.0
Lead	0.12	0.06	0.05	0.22	0.23	0.228
Calcium	0.27	0.33	0.27	0.35	0.41	0.25
Manganese	0.34	0.93	1.18	3.11	0.91	3.31
Sulphate	6.06	0.22	0.34	0.05	2.81	0.07
Chloride	−349.00	40.70	45.50	44.40	53.00	56.10

As for Mn^{2+}, D^* increases from 0 to 0.4% of the electrokinetic remediated lead content and then decreases at 0.6% of the electrokinetic remediated soil and then increases at 0.8% before decreasing again at 1.0% of the electrokinetic remediated soil, these coefficients indicate the ability of manganese to move through the soil matrix under the influence of an electric field might be linked to the physiochemical characteristic of the pollutant/leachate and the physiochemical properties of lateritic soil [48].

5. Conclusion

Examinations of diffusion under varied concentrations in electrokinetically remediated lead soil demonstrate that diffusion remains an active method of transport for chemical species, even at very low flow rates. The efficacy of lead removal directly influences the diffusion coefficient. Testing across different chemical species highlights that the concentration profile of pore fluid suggests the ability of compacted electrokinetically remediated lead soil to absorb and reduce concentrations of Pb^{2+}, Ca^{2+}, Mn^{2+}, SO_4^{2-}, and Cl^- ions present in the leachate.

Recommendations

The studies showed that soil contaminants can cause environmental contamination that harms humans and ecosystems. Therefore, pollution prevention and mitigation are crucial, and more efficient cleanup technologies should be studied. This research also helps policymakers create effective pollution control and environmental monitoring techniques.

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Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

Data Availability Statement

Data available on request from the corresponding author upon reasonable request.

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