

Modeling and Studying the Effect of Using Multi-Anode Electrodes on the Physical and Chemical Properties after Electro-Kinetic Remediation of the Contaminated Soil

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ABSTRACT

In this study, three laboratory experiments electro-kinetic experiments were implemented to investigate the effect of arranging three anode electrodes around the cathode electrode which is positioned in the center of the cell, on soil's physical and chemical properties. These experiments were conducted under unenhanced conditions for the contaminated soil without acidifying and with acidifying also enhanced conditions for the contaminated soil without acidifying: enhancement conditions used 1 M acetic acid in the cathode chamber as a catholyte solution with pH controlled (3–4) and distilled water as an anolyte solution. While unenhancement conditions used distilled water in the cathode chamber as a catholyte solution without pH controlled and distilled water as an anolyte solution and acidified the contaminated soil 600 ml of 3 M acetic acid per 1 kg of dry Cd-contaminated soil. This study's results parameters determined after the end of each experiment at each point of samples were soil pH, Cl^- , EC, CaCO_3 , and water content. Also, a two-dimensional numerical model has been used to simulate the electrokinetic remediation of soils contaminated with heavy metals. The results indicate that the parameters measured in this work differ according to the conditions used, as the pH and calcium carbonate values were lower in acidic conditions, especially at the anode region, where they reached 5.3 and 2.69%, respectively and Chloride ions accumulated and concentrated near the anode region in three experiments, while electrical conductivity was higher at the anode and cathode regions from in the central regions. The model results also showed agree with the laboratory results.

Keywords: cadmium, acidified soil, electro kinetic, remediation, anodes arrangement.

INTRODUCTION

The heavy metal cadmium (Cd) has long been recognized as a more dangerous pollutant for plants, animals, and humans than any other heavy metal. Because heavy metals do not break down and negatively impact the biota through the food chain, soil contamination with toxic heavy metals has been a global problem for food security and human health. As a result, the accumulation of heavy metals in soil can lead to a reduction in soil fertility, soil microbial activity, and biodiversity, which in turn causes crop losses. Furthermore, the accumulation of heavy metals in soil can have even more serious consequences for the health of animals and humans, as mentioned by [1]. The

heavy metals are present in soil in a variety of forms, including dissolved ions (e.g., Cu^{2+} , Cd^{2+} , CrO_4^{2-} , $\text{Cr}_2\text{O}_7^{2-}$, and MoO_4^{2-}) and organic complexes (e.g., Cu^{2+} , Pb^{2+} , and Hg^{2+} binding to dissolved organic matter) in soil solution, exchangeable ions (e.g., Cu^{2+} , Zn^{2+} , Cd^{2+} , Ni^{2+} , and Pb^{2+}) adsorbed on soil solid particles, and (co-)precipitates as part of soil solids (e.g., $\text{Cd}_3(\text{PO}_4)_2$, ZnS , PbCO_3 , and HgSO_4). These three broad forms maintain a thermodynamic equilibrium in activity and concentration between each other, with insoluble precipitates being the predominant species, as cited by [2]. One of the best techniques for in situ or ex situ soil decontamination over the last few decades has been shown to be electrokinetic (EK) remediation. Electrode reactions

occur on the surface during the EK remediation process, producing protons (H⁺) at the anode and hydroxyl (OH⁻) at the cathode, respectively. Due to the concentration of these ions close to the electrodes, which results in an acid front that transport from the anode to the cathode, whereas a basic front transport in the opposite direction. Concurrently, the cathode's production of OH⁻ ions causes the heavy metals to precipitate; this process is known as the "focusing effect", as reported by [3]. Therefore, in the process of electrokinetic remediation, soil pH plays a fundamental role in the remediation effect. In the EK process, an alkaline band forms at the cathode as a result of the electrolysis reaction, precipitating heavy metals that move to this location while also plugging soil pores, limiting removal effectiveness. Thus, controlling the pH of the cathode is crucial. Currently, most studies lower the pH of the cathode by adding an acidic material to it, as cited by [4]. To solve the problem of removing inefficient with conventional electrokinetic was suggested to use acidified soil through electrokinetic remediation technology. The findings demonstrated that the application of an acidizing pretreatment considerably increased the electrokinetic remediation's capacity to remove chromium from chromium-contaminated soil. Following acidification, the pH lowered in every sample group, and this lowering trend coincided with an increase in the acid concentration that was added [5]. Heavy metal contamination may influence on the physical and mechanical characteristics of developing soil, as reported by [6]. This study aims to investigate the effects of an anode electrode arranged in the triangle form, under unenhanced conditions for the contaminated soil without acidifying and

with acidifying also enhanced conditions for the contaminated soil without acidifying on the properties of the soil after electro-kinetic remediation such as pH, calcium carbonate, chloride ions, electrical conductivity, and water In order to obtain content. The experimental of electrokinetic used the acidification of the soil after spiking the soil with contaminant (cadmium) to enhance the migration of different metals that content in the soil towards the anode or the cathode electrodes.

MATERIALS AND METHODS

Preparation and characterization of soil

The soil of Iraq was used for the experiments described in this study specifically, an agricultural area in Babylon city as a porous media. It underwent thorough cleaning, drying, sorting, with an additional sieving to achieve satisfactory uniformity. Table 1 shows a breakdown of the physicochemical properties of utilized soil. In order to get Cadmium-contaminated soil with a concentration of roughly 655 mg/kg, a soil sample was artificially contaminated with Cd (NO₃)₂·4H₂O. For preparing the acidification soil after spiking the soil with the contaminant (cadmium), was add 600 ml of 3 M acetic acid per 1 kg of dry Cd-contaminated soil, as a practical method adopted by [7], and then kept in the container for some time to be ready to be placed in an electro-kinetic cell.

Experimental work

Figure 1 and 2 shows the experimental setup and the schematic diagram of arrangement of anode electrodes around the cathode electrode was used in this study. The set-up experiment Figure 1 consist of the rectangular cell (15 cm depth ×

Table 1. The native soil's physical and chemical characteristics

Properties	Value
Distribution of particle size	
Silt (%)	50
Sand (%)	10
Clay (%)	40
pH	8.6
Water content (%)	30.57
CaCO ₃ (%)	11.847
Chloride ions, Cl ⁻¹ (mg/l)	1.124
Organic content (%)	0.57
Electric conductivity EC (ms/cm)	1.696
Cation exchange capacity (meq/100g)	8.25

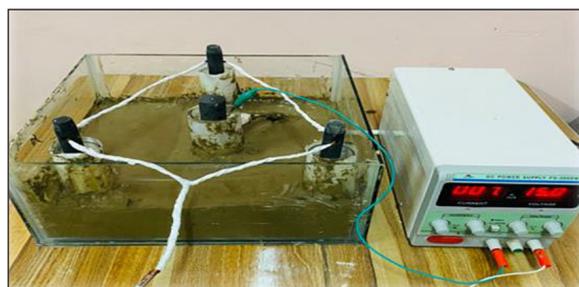


Figure 1. The electrokinetic cell experimental apparatus which arranged anode electrodes around the cathode electrode in a triangle form

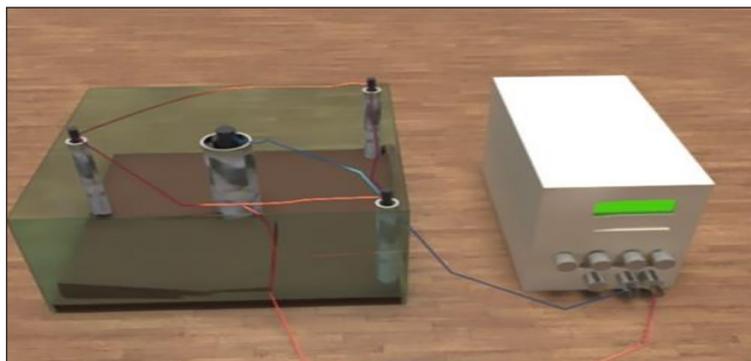


Figure 2. Schematic diagram of the electrokinetic experiment setup for arranged anode electrodes around cathode electrode in a triangle form

30 cm width \times 30 cm length), a power supply, and a multi-meter with 4 electrode compartments. The arrangement and particle methods in this study according to previous research by [8] using a self-made device test, which involves electrodes arranged in triangle, quadrangle, and hexagon designs, to perform electrochemical remediation of soil contaminated with cadmium. The cathode electrode used of cylindrical graphite material with a purity level of 99.9 percent, while the anode electrode is used from stainless steel. Both the cathode and anode have a diameter of 1 cm, and they are separated by a distance of 14.5 cm. The cathode electrode chamber was filled with a citric acid solution at a concentration of 0.1 mol/L, which served as the cathode electrolyte. The power-on hours are all set to 120 hours, the control voltage gradients are all set to $2 \text{ V} \cdot \text{cm}^{-1}$, and the cathode-anode distances in the three-electrode configuration are all 14.5 cm. In this present study also adopted forms of the arranged of three anode electrodes in form of triangle and the cathode electrode put in the center of the chamber. The experimental setup for this investigation consisted of plexiglass cylindrical tubes measuring 5 cm in diameter and 13 cm in height serving as the cathode chamber. A thin tube connects at the end of a cell through a valve; this valve controls the amount of purging solution that may enter the cell. In addition, anode chambers, made from plexiglass and measuring 3.5 cm in diameter and 13 cm in height, were arranged in a triangular configuration around the central cathode chamber. Both the anode and the cathode were made of cylindrical graphite electrodes with high purity, as used in the previous study by [9]. The electrodes)anode(had a diameter and length of 1.8 and 15 cm, respectively, while the cathode

electrode had a diameter and length of 2.5 and 15 cm, respectively. Similar to the methodology used by [10], the length of the soil specimen between anode and cathode electrodes in this particular cell is 10 cm. Following the experimental setup described by [11], the cathode compartment was positioned in the central cylinder to minimize the extent to which it generated a basic environment, while the anode compartment was placed in the outer cylinder to maximize the spread of the acidic environment. To facilitate electro-osmotic water flow as a result of an applied electric field, the surfaces of four plexiglass electrode chambers (cathode diameter 5 cm; 36 holes of 0.3 cm and anode diameter 3.5 cm; 42 holes of 0.3 cm) were perforated. Furthermore, filter paper was used to cover the chambers' surfaces to hinder soil from the passage to the electrode compartments, as described in practical methods by [12]. The contaminated soil is placed in the cell and exposed to direct currents by the anode and cathode electrodes linked to a continuous supply powered by direct current (DC), according to cite by [13]. In accordance with the methodology employed by [14], a voltage gradient of 1.5 V/cm was implemented in all experiments conducted in this investigation. In order to achieve the objectives of the present study, a rigorous methodology was employed to conduct three experiments [EK-1, EK-3 and EK-4] as illustrated in Table 2. The first Experiment was represented as that EK process is carried out as a reference (unenhanced) experiment as described by [15] when used distilled water as electrolyte in the anode and cathode chambers. Which was included the experiments: EK-1 (the arranged of three anode electrodes in form of triangle relative to cathode electrode put in the center of the chamber and EK-3 experiment use 600 ml of 3 M acetic

Table 2. Description of the electrokinetic remediation experiments carried out for this study

Tests	Experiment designation	Concentration mg/kg	Time hours	pH	
				Anode	Cathode
Unenhanced	EK-1	655	100	DW	DW
Acidified soil	EK-3	655	100	DW	DW
Enhanced	EK-4	650	100	DW	1M AA (~3)

Note: DW – distilled water; AA – acetic acid; M – molar.

acid add to 1 kg of dry Cd-contaminated soil to achieve acidified environment, as adopted by [7]. While the experiment EK-4 was implemented in the experiment (enhanced) for clean-up the soil contaminated with cadmium. These experiments were performed with 1M acetic acid. as a catholyte to buffer the hydroxide ions and keep a low pH [~3]. After each experiment, the soil specimen was extracted from the cell according to the sample sites' arrangement, As shown by [16], a line segment with an anode and cathode is the location of a type sampling indicating. Three sampling sites were established (A1, A2, and A3). The distance between the A1, A2, A3 type sampling point and the anode was 3.3 cm, 6.6 cm and 10 cm, respectively, to determine soil pH, electrical conductivity (EC), chloride ion (Cl⁻), calcium carbonate (CaCO₃) and water content in the soil. Following drying, 5 g of soil from each soil sampling point had been mixed with 12.5 milliliters of water that has been distilled. The solution was mixed manually for a few minutes and the solids were then left to settle for one hour. The pH of the supernatant was subsequently determined, indicating the pH of the soil, according to a practical method by [17].

Use of Comsol multi-physics

The properties of soil contaminated with heavy metals were simulated using a 2D

geometric mathematical model and electric fields. The model elucidates the concurrent movement of substances and electric charge in response to an electric field. The transport processes considered in this study include electro-osmosis, electrophoresis, pressure-driven convection, electro migration, and diffusion, as cited by [18].

RESULTS AND DISCUSSION

The results of tests on both native and contaminated soil

Scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS) images of natural soil and artificial soil polluted with cadmium ions are shown in Figure 3. In Figure 3 (a) SEM taken at a 10 μm magnification, which reveal the morphological features of the native soil (before its artificial contamination with cadmium ions). It was observed that the particles were separated and with different sizes with presented spacing between them. According to a previous study by [19] when the soil was contaminated with 100% saline industrial hazardous landfill leachate (SI-HLL), SEM images showed that the micropores reduced greatly in size, but when the natural soil, the images showed discrete aggregates with large pore spacing. The major cause of this reduce was

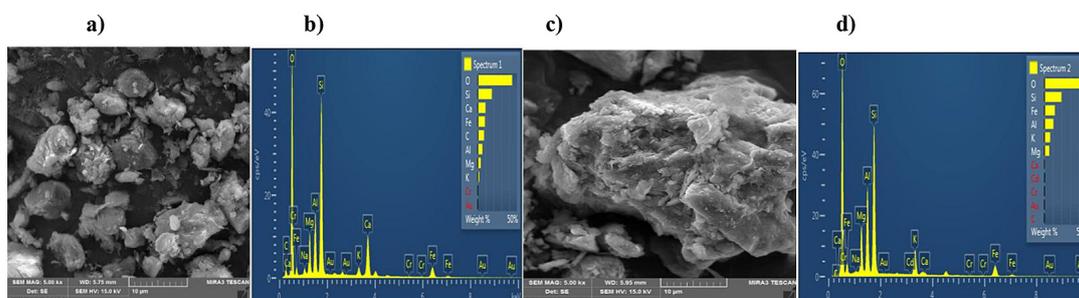


Figure 3. EDS spectra and SEM before applying the electro-kinetic remediation: (a) SEM of the native soil sample and (b) EDS spectra of the native soil sample; (c) SEM of the artificially contaminated soil with cadmium ion; and (d) EDS of the artificially contaminated soil with cadmium ion

due to the introduction of salts, which lowered the permeability. Figure 3 (c) SEM image for the artificially contaminated soil with cadmium ions before applying the electro-kinetic remediation. It appears that the discrete particles with a big size and are covered with a white surface which refers to accumulated cadmium salt on it. According to [20], displayed the morphologic properties of the chromium-contaminated soil particles was a heterogeneous soil, as well as tiny grumes attached to particles that large size, illustrating that the substance is a heterogeneous powder. The Figure 3 (b), elucidates that the sequenced the peak of spectrum for each ions found in the native soil are as follows: O, Si, Ca, Fe, C, Al, Mg, K, Cr and Au, while in the artificial contaminated soil Figure 3 (d) was the arrangement the spectrum for ions from highly peak to low as: O, Si, Fe, Al, K, Mg, Ca, Cd, Cr, Au and C. It was noticeable that the cadmium ion was found in the composition of the soil after artificial contaminated with cadmium ion.

Effect of the arranged anode electrodes in triangle form on the chemical and physical characteristics for the soil treated after electro-kinetic technique

In this experiments to study effect of the arranging three anode electrodes put in the triangle form, while the cathode position was in the center of the chamber cell on the physical and chemical properties for the treated soil after electro-kinetic technique. According to Table 2 the experimental plan for included two electro-kinetic remediation tests, unenhanced experiment (EK-1), when used distilled water as anolyte and catholyte solutions. While enhanced experiment was represented by EK-4, which was conducted using DW as anolyte solution in the anode chamber and 1 M acetic acid (AA) as the purging solution (catholyte solution) with controlled pH in the cathode chamber within range (3–4). EK-3 was implemented for remediation of contaminated soil with cadmium ions by pre-acidifying the soil and enhance the electro-osmotic flow, therefor adding acetic acid (3 M) into the contaminated soils before the experiments started, as the same producer described in the study by [21]. Therefore, the acidified soil pH (6.9) was lower than its initial soil (8.8). Whereas, the electrical conductivity for acidified soil (6.13 mS/cm) was higher than its initial soil before treatment (5.43 mS/cm). the percentage of calcium carbonate for acidified soil (3.95%) was lower

than its initial value (4.32%). The operation conditions for EK-3 are the same as for EK-1, which used the DW as an anolyte and catholyte solution. In order to evaluate the effect of the arranged anode electrodes shapes on the performance of the soil through electrokinetic technique, were made comparison between enhanced and unenhanced conditions. A voltage gradient of 1.5 V/cm was applied to clean silty clay soil that had been contaminated with 655 mg/kg of cadmium (Cd (II)). Figure 4 illustrates the relationship between soil pH and distance from the anode compartment of the treated soil for experiment EK-1 (under unenhanced conditions), EK-4 (under enhanced conditions) and EK-3 (Acidified soil) following the completion of the 100-hour electrokinetic treatment period. Thus, the pH distribution in EK-1, EK-4, and EK-3 is as shown:

It was noticed that the pH for the treated soil at distances 3.3, 6.6, and 10 cm from the anode compartment, which was represented in symbols as A1 (close to the anode), A2 (center) and A3 (close to the cathode) for the EK-1(unenhanced conditions) as: 7.9, 8.3 and 9.01, respectively, was higher than these of the samples points (i.e., sample points: A1, A2, and A3) for treated soil in the EK-4 test (enhanced conditions) as following: 3.5, 4.6 and 5.4, respectively. The results presented were consistent with the findings of previous research. [22] noted that the soil pH in the vicinity of the anode electrode was consistently lower than that in the vicinity of the cathode electrode.

It was observed that the pH in the sample points A1 and A2 of the treated soil for test EK-1(unenhanced conditions) was lower than the pH of the initial contaminated soil (8.8). In contrast, the pH value for the sample point near the cathode region (A3) was higher than the initial contaminated soil (8.8). Whereas in the EK-3 experiment, the soil pH for each sample point A1, and A2 is below the background value after acidifying the contaminated soil (6.9). It has been observed that the soil pH for EK-3 at A1 A2, and A3 that are located at a distance 3.3, 6.6 and 10 cm from the anode, were 5.3, 6.2 and 7.3. The experiment EK-3 (acidified the contaminated soil) witnessed decreasing of the soil pH in all points of samples more than the experiment of EK-1 (without acidified contaminated soil), when the pH decreased to 5.3 near the anode (A1) and increased to 7.3 near the cathode (A3). Also, it's lower for each sample point from A1 to A3 in the EK-4, When using a 1 M AA solution as the

catholyte in the cathode chamber. The values of soil pH in EK-4 (enhanced experiment) for three points of samples (A1, A2, and A3) were lower than those in the EK-1 (unenanced experiment). In their study, [23] shown that the use of acetic acid with a concentration of 1 M as a purging solution (PS) in the cathode compartment, while maintaining a pH level of about 3, had a notable influence on the movement of contaminants. This is due to the ability of acetic acid to generate H⁺ ions, which lower the pH of the solution and dissolve metal precipitates. As a result, the presence of an enhancement allowed for a far greater removal and movement of lead towards the cathode, compared to the unenhanced condition, when distilled water was Suitable for use as the purging solution. Also, injecting purging solution (PS) into the soil-solution system via a well may lower the pH values of the soil. The reduction soil pH may enhance the solubility of metal species and/or salts, leading to a high ionic concentration. This, in turn, results in an increase in electrical current and a subsequent rise in the volume of electro-osmotic flow. Therefore, this reduction in the pH values in each sample point due to an increase in the number of the anode electrodes, produced more H⁺ by the anode as compared with the conventional technique of the electrokinetic then led quickly to transport toward the cathode chamber. In EK-4, the soil pH for points samples A1 to A3 ranged from 3.5 to 5.4 for this reason reduced the percentage of calcium carbonate in these points ranged between 1.86% in A1 to 2.76% in A3 from its initial value equal to 4.32%. In EK-1, the higher soil pH in these points of samples which ranged from 7.9 to 9.01 led to an increase in the amount of calcium carbonate which ranged from 4.2% in A1 to 9.03% in A3. The quantity of calcium carbonate in the soil specimen for EK-3 was decreased in sections A1 and A2 (2.69 and 3.14%, respectively), with a relative increase in section A3 (4.77%) as compared with the initial amount of calcium carbonate for native soil (4.32%). This is due to the presence relation between pH and the percentage of calcium carbonate, the soil pH for EK-3 was reduced and its values ranged from 5.3 to 7.3 in the case of acidified contaminated soil, as explained in Figure 5. There was a significant effect of soil pH When 1 M AA is used as a catholyte solution in the cathode chamber on the amount of calcium carbonate because acidification of soil under electrokinetic treatment from point A1 to A3 and

the amount of calcium carbonate decreased in all points of samples for EK-4. It may be interpreted that according to a study by [24] the unenhanced electrokinetic treatment, using deionized water as the processing fluid, did not exhibit significant mobilization and removal of heavy metals. This phenomenon may be ascribed to the restricted solubility of metals and their tendency to precipitate at elevated pH values encountered at the cathode. [25] proved that the use of injection wells is an effective method for enhancing the propagation of the acidic front towards the cathode. As a result, this will lead to a fall in soil pH. The acidic front propagated over the majority of the soil samples during experiments conducted with injection well enhancement. Decreasing the buffering capacity of the soil specimen will increase the removal of

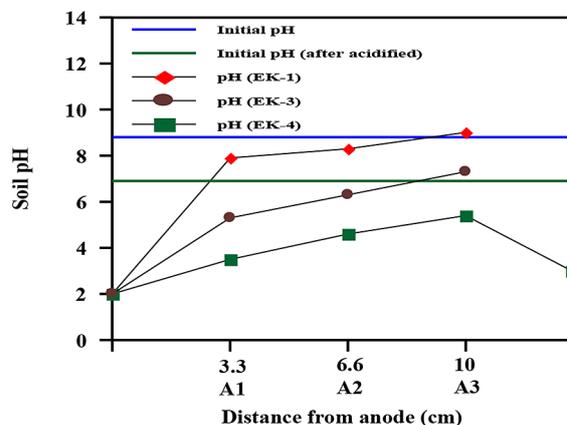


Figure 4. The values of the treated soil pH throughout the electro-kinetic process for EK-1, EK-3, and EK-4

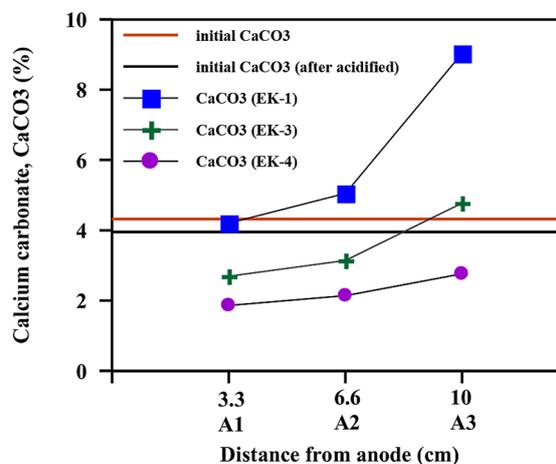


Figure 5. Changes in the amount of calcium carbonate along the specimen of the treated soil for EK-1, EK-3, and EK-4

contaminants, resulting in a reduction in calcite and carbonate content in the soil.

According to reported by [26] that the cadmium (Cd) fraction charges become more positive when lowering the soil pH. Therefore, net positive charges for Cd will accelerate migration towards the cathode electrode. Figure 6 (a and b) compares the amounts of salts that accumulated on the cathode electrode surface as a result of reduced residue carbonate across the soil specimen or increased metal solubility between the EK-1 test (unenhanced conditions) and EK-4 test (enhanced conditions). The low soil pH for the points of samples in the EK-4 test. It resulted in increased removal of salts from the sample soil can be distinguished by acceptable amounts of these salts that accumulated on the surface of the cathode electrode (Figure 6, b) as compared with a low amount of salt accumulated in the surface of cathode for EK-1 (Figure 6, a). The huge quantities of these salts that accumulated on the internal and external surface the of cathode chamber for EK-3 test (Figure 6, c and d).

Table 3 illustrates the amount of chloride ions in soil at three points of samples (A1, A2, and A3) at a distance from the anode: 3.3, 6.6, and 10 cm after the electrokinetic treatment for EK-1, EK-3 and EK-4 (100 h). It was noticeable that the amount of chloride ion in section A1 (near the anode) for EK-1, EK-3 and EK-4 was equal to 39.98, 37.99 and 40.89 mg/l, respectively, were

higher than in section A3 (near the cathode) for the same tests which equivalent to 19.99, 21.99 and 21.98 mg/l, respectively. Therefore, the direction of chloride ions movement for these tests (EK-1, EK-3 and EK-4) from the cathode region towards the anode region and accumulated in here. These results conformed to the previous study by [27] demonstrated that chloride ions were moved towards the anode area in all layers by electromigration.

Figure 7 Shows the distribution electrical conductivity profile for the EK-1 test and the EK-4 test as a function of distance from section A1 to A3 through soil specimen after the end of treatment time equal to 100 hrs. Electrical conductivity for the initial contaminated soil (without acidification) (5.43 mS/cm) was lower than it was in the acidified contaminated soil (6.13 mS/cm). It was determined that the EC for the EK-1 test (unenhanced condition) was the larger values at the two ends of sections A1 and A3 (6.52 and 6.32 mS/cm, respectively) (the anode and cathode region) as compared with the section A2 (central region) (3.76 mS/cm), which was lower value. Whereas, the amount of the EC for the EK-4 in each point of samples: A1, A2, and A3 were 7.14, 4.22, and 7.09 mS/cm, respectively. Whereas, the amount of EC at point samples A1, A2, and A3 (7.1, 4.33, and 6.94 mS/cm, respectively) for EK-3 was higher than at the same point for EK-1. The electrical conductivity for EK-3 was approximately

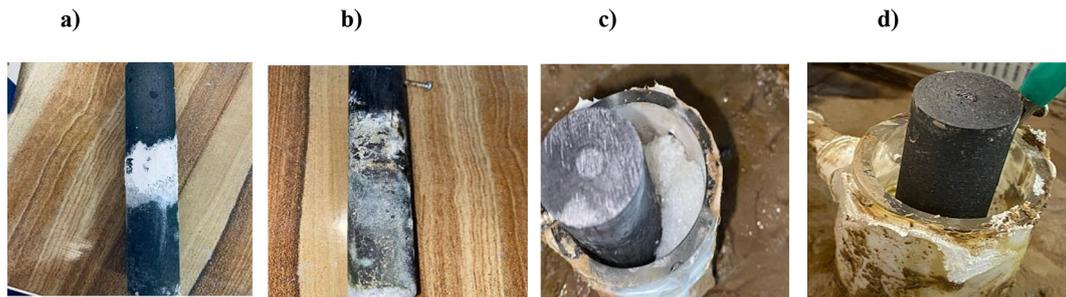


Figure 6. Salts that accumulate on the surface of the cathode electrode following the electrokinetic process: (a) in the EK-1 test; (b) in the EK-4 test; (c) on the internal surface of the cathode chamber for the KE-3 test; and (d) on the exterior surface of the cathode chamber for the EK-3 test

Table 3. Concentration of chloride after the end treatment period for the EK-1, EK-3, and EK-4 tests

Tests	Chloride ions (mg/l)		
	A1	A2	A3
EK-1	39.98	35.98	19.99
EK-3	37.99	32.98	21.99
EK-4	40.89	38.99	21.98

the same for each section points in the EK-4. It was noticed that the trend of the profile of the EC for the EK-4 test was the same as the EK-1 and EK-3, it was higher in the two points A1 and A3, and lower in the point A2. Also, it found that the amount of EC in EK-4 (when using acetic acid as a catholyte solution) and EK-3 (acidified soil), was higher than it was in EK-1 when distilled water as an anolyte and catholyte solution. In their study, [28] reported that when a DC electric field applied, Na^+ ions migrate towards the cathode, whereas Cl^- ions migrate towards the anode side of the specimen. Moreover, the ingress of the acidic and alkaline front is greater at the edges of the specimen. As a result, the electric conductivity (EC) is higher at the edges, which are located near the anode and cathode, while it is lower in the middle of the sample. It was noted that in three experiments EK-1 (unenhanced conditions), EK-3 (acidified soil) and EK-4 (enhanced condition), the values of EC in the A1 (6.52, 7.1 and 7.14 m S/cm, respectively) and A3 (6.32, 6.94 and 7.09 mS/cm, respectively) were higher than its initial value of soil (5.43 mS/cm), according to a study by [29] found that the electrical conductivity (EC) value for the soil near the cathode and anode electrodes was higher than those in the middle of the sample, because of the higher concentration of H^+ and OH^- generation at the anode and cathode electrodes respectively, then led to increase EC of the soil.

To investigate the effect of remediation using electro-kinetic technique on water content of the soil contaminated with cadmium ions by taking three samples A1, A2, and A3 at a distance 3.3, 6.6, and 10 cm from the anode electrode surface and operating under enhancing conditions (using 1 M acetic acid in the cathode chamber and distilled water in three anode chambers) and unenhancing conditions (using distilled water in the cathode chamber and distilled water in all anode chambers). Figure 8 illustrates the water content in (EK-1 and EK-4) as a function of distance from section A1 to A3. In the EK-4 experiment (enhanced conditions), it was observed that the percentage of water content in the A1 sample was equal to 27.91%, which is relatively higher than the initial value of water content before treatment, which was equal to 27.77%. Whereas the amount of water content in A2 and A3 was equal to 31.73% and 34.16%, respectively, which is higher than the initial value (27.77 %). In the EK-1 experiment (unenhanced conditions) the ratio of water content in three

samples (A1, A2, and A3) was equal to 23.12%, 25.64%, and 26.93%, respectively. It was observed that the water content in the region near the cathode was higher than the region near the anode for EK-1 and EK-4. The drainage sequence of each cross section from the anode to the cathode can be summarized as follows in relation to time: The water discharge from the cathode was primarily sourced from the soil near the anode during the initial phase, with a minor quantity from the soil near the cathode, as noted by [30]. Also, [31] reported that water transport from the region near the anode towards the region near the cathode, thus the water content at the cathode area ($x/L = 1$) was higher than at the anode area ($x/L = 0$).

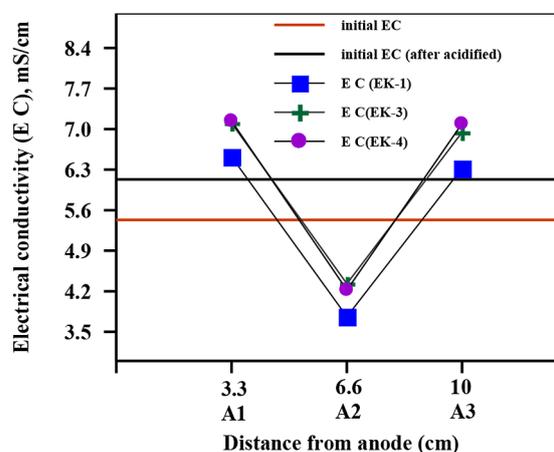


Figure 7. Electrical conductivity (EC) profile during the electro-kinetic process for EK-1, EK-3 and EK-4 tests

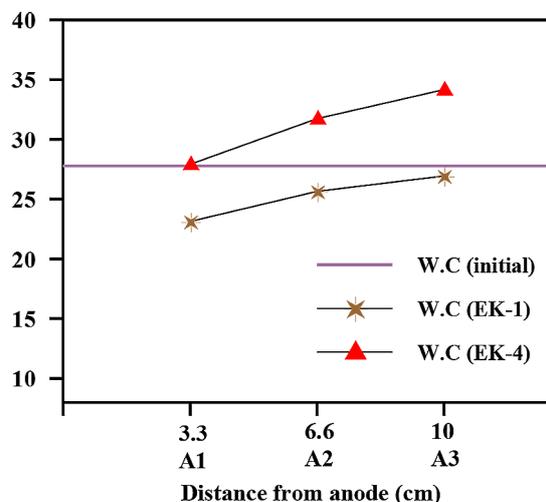


Figure 8. The percentage of water content (W.C) profile during the electro-kinetic process for EK-1 and EK-4 tests

Modeling results

Pressure and velocity distributions

Figure 9 (a, b, and c) display pressure and velocity distributions for unenhanced conditions, enhanced conditions, and acidified soil conditions for triangle arranged anode electrodes. In the left plot a flow distribution in the structure with pores when only the electric field acts as driving force.

In the right side, it is instead the pressure gradient that drives the flow. In all cases, the velocity is large around the cathode towards the anodes, where the field strength is large and the effect of the decrease in the geometries cross section is most pronounced. A comparison of the maximum flow-velocity values shows that the pressure gradient is the dominating driving force. The importance of the program or model lies in estimating

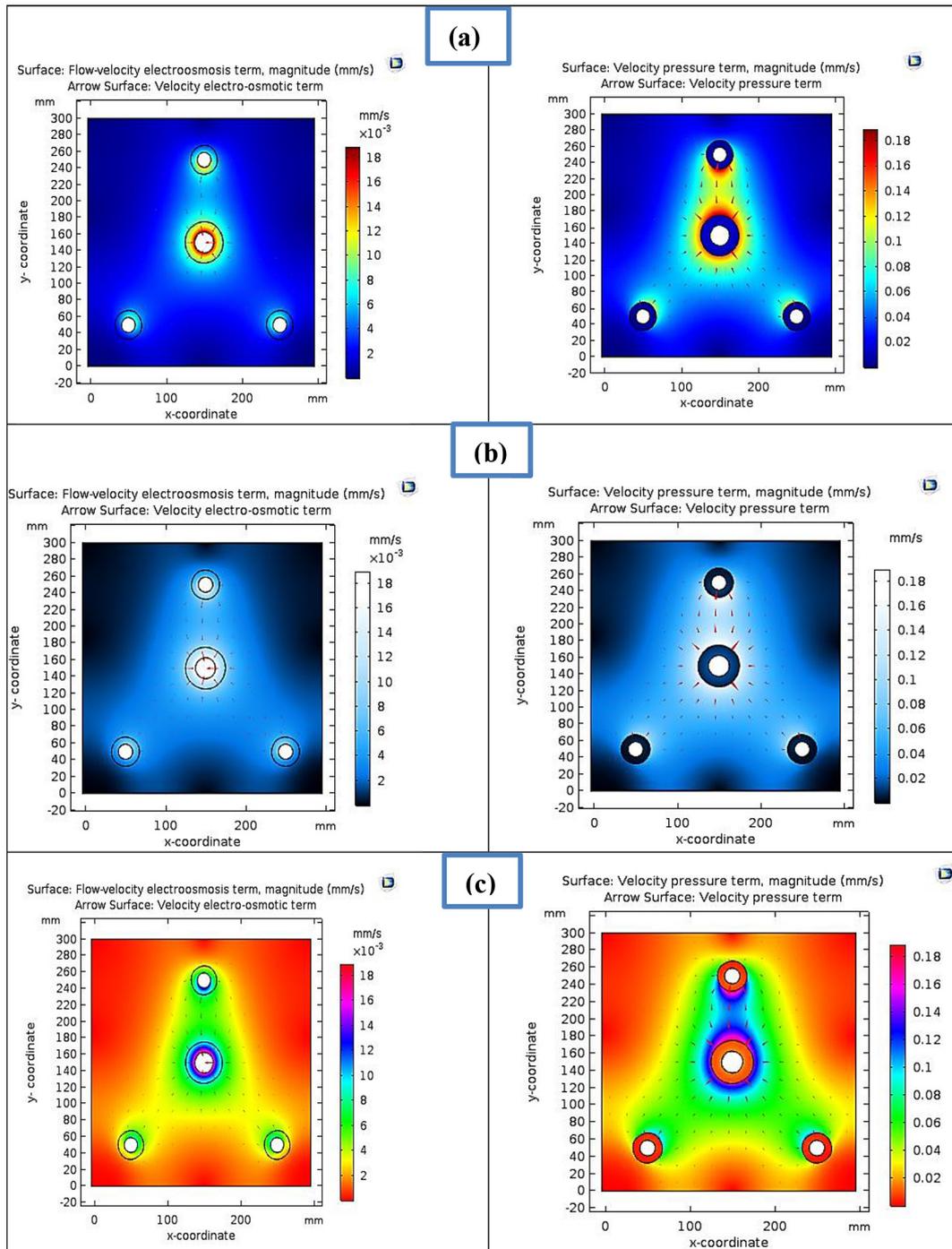


Figure 9. Pressure and velocity distributions in the cell in triangular shape: (a) unenhanced, (b) enhanced, and (c) acidified soil

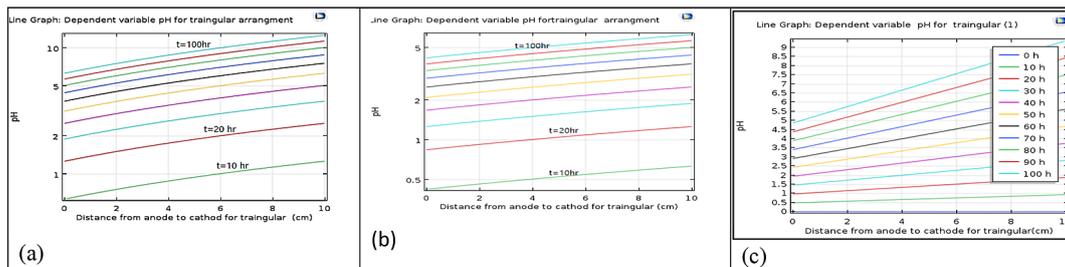


Figure 10. Estimation of pH from anode to cathode for time (0 to 100) h., (a) Unenhanced, (b) enhanced, and (c) Acidified soil, for triangle arranged anode electrodes

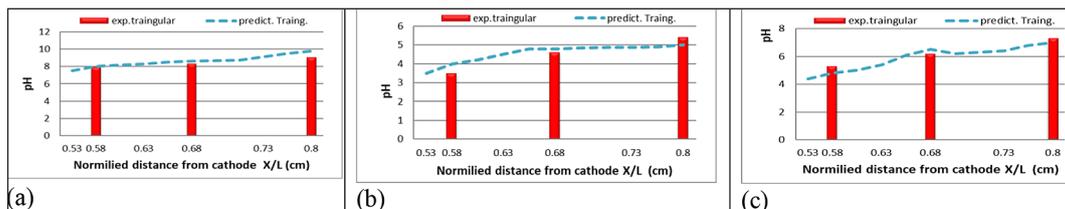


Figure 11. Comparison between numerical and experimental data for pH profile in soil specimen at time 100 h. for (a) unenhanced, (b) enhanced, and (c) acidified soil, for triangle arranged anode electrodes

the distribution of speeds and pressures for the surface area of the model or specimen that are not measured or difficult to measure in the laboratory.

pH distribution

Figure 10 (a, b, and c) shows pH for unenhanced conditions, enhanced conditions, and acidified soil conditions, for triangle arranged anode electrodes. In the electrode cells (unenhanced condition) that were predicted by the model for pH. The pH after 100 hours reached around 6 in the anode cell and reached around 10.2 in the cathode cell for Figure 10 (a) and a same principal for other cases (acidified soil conditions and enhanced conditions).

Proton and hydroxide ions are made by the electrolysis process at the electrodes. Ionic migration and electro-osmotic flow bring proton ions into the soil sample. The direction of electro-osmotic flow is from the anode to the cathode. Ionic migration also brings hydroxide ions into the soil. The transfer of protons and hydroxide into the soil results in the movement of acid and base fronts, which changes the pH of soil. A comparison between numerical and experimental investigations is illustrated in Figure 11. The results near the anode are satisfactory, as illustrated in the figure. However, the numerical model and the experimental data diverged as a consequence of the self-ionization reaction of water near the cathode. The prognosis is more significantly influenced by the self-ionization reaction of water

in the vicinity of the cathode, where the acid and base fronts intersect.

The coefficient of determination (R^2) was calculated between the simulation results and the experimental measurements in order to show the accuracy of the model for (Unenhanced, enhanced, Acidified) soil, for triangle arranged anode electrodes (0.983, 0.943, 0.874), respectively. Which indicate that our model was capable of simulating the pH profile in the soil.

CONCLUSIONS

The most important conclusions that can be reached from the experimental work are the following. The values of soil pH in the EK-1 (unenhanced conditions) were higher than those at the corresponding points of samples in EK-4 (enhanced conditions). Due to reduce soil pH in EK-4 this is reason for the reducing the percentage of calcium carbonate in these points ranged between 1.86% in A1 to 2.76 % in A3 from its initial value equal to 4.32%. In Ek-1 the higher soil pH in these points of samples led to an increase in the amount of calcium carbonate which ranged from 4.71% in A1 to 9.89% in A3. The amount of chloride ion in section A1 (near the anode) for EK-1 and EK-4, were higher than in section A3 (near the cathode) for the same tests. The higher amount of chloride ions was concentrated and accumulated in the region near the anode. The percentage of water content for the EK-4 test in

the A1 sample is relatively higher than the initial value of water content before treatment (27.77%). Whereas the amount of water content in A2 and A3 is higher than the initial value (27.77%). In the EK-1 experiment (unenanced conditions) the ratio of water content in three samples (A1, A2, and A3) was lower than the initial value (27.77%). The model predicts significantly different responses for cases with and without the acid/base chemistry of the soil. This suggests that the system buffer capacity, relative to the expected acid/base generation at the electrodes, is a crucial parameter to consider when evaluating the remediation of a site using electric fields. The test cases' findings and the satisfactory interpretation of the experimental data, in relation to the modeled transport and chemical processes, validate the theoretical justifications supporting the model, especially in predication of pH and give more explanation about velocity and pressure distribution. The coefficient of determination (R^2) was obtained to assess the accuracy of the model in predicting pH values for different types of soil (unenanced, enhanced, acidified) using triangle arranged anode electrodes. The estimated coefficients were 0.983, 0.943, and 0.874, respectively.

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