

Washing enhanced electrokinetic remediation for removal cadmium from real contaminated soil

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Abstract

The main objective of this study is to evaluate the combination of electrokinetic remediation and soil washing technology in order to remove cadmium from contaminated soil. This paper presents the results of an experimental research undertaken to evaluate different washing and purging solutions to enhance the removal of cadmium from a real contaminated soil during electrokinetic remediation. Two different experimental modules were applied in the laboratory. Soil was saturated with tap water, while acetic and hydrochloric acids, as well as ethylenediaminetetraacetic acid (EDTA) were used as purging solutions in the first module. Results show that there was a decrease of cadmium concentration near anode, but a significant increase in the middle of the cell, due to the increasing pH. Citric, nitric and acetic acids were used for soil washing and purging solutions in the second module. In this case, an 85% reduction of cadmium concentration was achieved. Therefore, results indicate that soil pH and washing solutions are the most important factors in governing the dissolution and/or desorption of Cd in a soil system under electrical fields.

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Keywords: Electrokinetic process; Soil washing; Cadmium; pH; Electroosmotic flow; Purging solutions

1. Introduction

The release of heavy metals in biologically available forms, as a result of human activity, may damage or alter both natural and man made ecosystems [1]. The chemical form (speciation) of heavy metals in soil solution is greatly dependent on the metal element concerned, pH and presence of other ions, etc. [2]. Cadmium is a non-essential heavy metal pollutant of the environment resulting from various agricultural, mining and industrial activities and also from the exhaust gases of automobiles [3]. It has been considered as an extremely significant pollutant due to its high toxicity and greater solubility in water which determines its wide distributions in aquatic ecosystems [4]. Cadmium has been suspected causing symptoms of hypertension, angiopathy, kidney and bone function decay [5].

Great efforts have been made to find ways to remove contaminated species from soil. In search of alternative techniques, there has been an increasing interest for in situ treatment, without excavation of the soil. The electrokinetic process is a great promise for remediation of polluted soils, as it has high removal efficiency and time effectiveness in low permeability soils [6]. Electrokinetic remediation can be used to treat soils contaminated with inorganic species [7–13], organic compounds [14–16] and radionuclides [17,18].

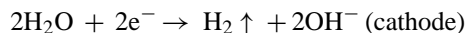
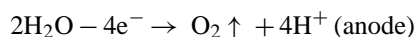
The main mechanisms of contaminants movement in the electrical field involved in electrokinetic technology are electromigration of ionic species and electroosmosis. Electromigration can be defined as the migration of ionic species present in the soil void fluid. Cations move towards the cathode, while anions move towards the anode. In some cases, electromigration probably contributes significantly to the removal of contaminants, especially at high concentrations of ionic contaminants and/or high hydraulic permeability of soil [19]. Electroosmosis in a

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pore occurs due to the drag interaction between the bulk of the liquid in the pore and a thin layer of charged fluid next to the pore wall that, like a single ion, is moved under the action of the electric field in a direction parallel to it. This phenomenon produces a rapid flow of water in low permeability soils and probably contributes significantly to the decontamination process in clay soils [13,20]. The removal of contaminants would have the advantage of these two concurrent movements of electromigration and electroosmosis. In the soil two other transport mechanisms, advection and diffusion, exist. Hence, when electrical current is applied to the soil, all four transport mechanisms have to be considered [21].

An important advantage of this electrochemical technique is the high degree of control of flow direction that can be achieved because the material move along electric field lines that are defined by the electrode placement [22].

When low dc current is applied to a porous medium, the electric current leads to electrolysis reactions at the electrodes, which generate an acidic medium at the anode and an alkaline medium at the cathode.



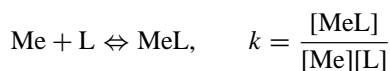
The H^+ generated at the anode moves through the soil towards the cathode by ion migration, pore fluid flow, pore fluid advection and diffusion. On the other hand, the reduction reaction at the cathode zone dissociates water to form H_2 and OH^- during electrolytic dissociation. Consequently, the pH value near the cathode increases. The H^+ and OH^- ions generated by the electrolytic dissociation move across the pore fluid within soil particles towards either the anode or the cathode [19,23]. Both soil pH and electrolysis reactions at the electrodes play a critical role in the electrokinetic process.

Acar et al. [24] demonstrated that the movement of this acid front together with migration and advection of the cations and anions under electrical gradients constitutes the mechanisms of removal contaminants from soils. The factors influencing the acid/base profile across the porous medium would significantly affect the flow, the flow efficiency and the extent of ion migration and removal in electrokinetic soil processing. The movement of the acid front would cause desorption of cations from the soil surfaces and facilitate their release into the pore fluid. This reaction, associated with the concurrent electroosmotic flow, reinforces metal removal from the soils. As a result, metals are deposited at the cathode and anions at the anode [25].

In low buffering soils, the pH of the soil decreases to 2–3 near the anode and increases to 8–12 near the cathode due to the electrolysis reaction at the electrodes. When heavy metals enter into basic conditions, they adsorb to soil particles or precipitate as hydroxides, oxyhydroxides, etc. and in acidic conditions, those ions desorb, solubilize and migrate [18]. In order to remove the heavy metals from

soils, different liquids, other than water, can be used near the electrodes. The cathode reaction should be depolarized to avoid the generation of hydroxides and their transport in the soil [25]. The selected liquids, also known as purging solutions, should induce favorable pH conditions in the soil, and/or interact with the heavy metals, so that the heavy metals are removed from the soil [26].

Recently, researchers have tried to develop soil washing techniques in which soil-bound contaminants are transferred to the liquid phase by desorption and solubilization. Several washing solutions have been investigated, such as water, acids, bases, chelating agents, alcohols and other additives [27,28]. In practice, acid washing and chelator soil washing are the two most prevalent removal methods [29,30]. The action of metal and washing solution (ligand) may be expressed by the following equation [31]:



where Me represents a metal cation, L represents a ligand anion and k is the formation constant.

Ethylenediaminetetraacetic acid (EDTA) is the most commonly used chelate because of its strong chelating ability for different heavy metals [27,30,32]. This chelating agent removes trace metals with less impact on soil properties than decontamination systems, using acids as flushing agents and being slowly degradable by microorganisms [33]. The ability to extract the metals without inducing a strong acidification of medium is a very desirable characteristic. The problems with EDTA are that it may complexes strongly with a variety of metals in soils including alkaline earth cations such as Al, Ca, Fe and Mn, may bind to the soil solid phase and no longer be available for the removal of contaminants [34]. It is also relatively expensive and given the tonnes of soils that need remediation, this often leads to an excessively costly remediation [32].

Citric acid forms mononuclear, binuclear or polynuclear and bi-, tri- and multidentate complexes, depending on the type of metallic ion. For example, metals, such as Fe and Ni, form bidentate, mononuclear complexes with two carboxyl acid groups of the citric acid molecule. Copper, Cd and Pb form tridentate, mononuclear complexes with citric acid involving two carboxyl acid groups and the hydroxyl group [35]. Because citric acid is relatively inexpensive, rather easy to handle, and has a comparatively low affinity for alkaline earth metals (Ca, K and Mg), it is a suitable candidate for soil washing [36].

A number of studies have also been conducted to determine the metal extraction efficiency of strong mineral acids, including HNO_3 and HCl [37]. These acids show a significant potential to extract metal ions from the soil. However, their use is associated with a number of disturbing physical, chemical and biological properties [36]. When HCl was used the final soil pH was 1, raising the concern an increase contaminant mobility, a decrease soil productivity and adverse changes in the soil's chemical and

physical structure due to mineral dissolution [38]. Another concern using HCl is its possible electrolysis and chlorine gas formation when it reaches the anode compartment [18].

Decontamination can be accomplished through in situ soil washing in which a soil solution is applied to the unexcavated contaminated zone by flooding or sprinkling it in order to extract pollutants from the soil. The migration of contaminants into the ground water must be prevented by using proper control measures specific to each location. The effectiveness of in situ washing is limited by the permeability of the soil in its undisturbed state. Soils with permeability of less than 10^{-4} cm/s are considered unsuitable for in situ washing, in which cases excavation of the contaminated soil followed by on-site clean-up by washing can provide a viable alternative [39].

The objective of this work was to examine the effectiveness of electrokinetic removal of cadmium using different washing and purging solutions. Two sets of experiments were conducted where soil was saturated by water and different acids were used as purging solutions. A third set of experiment where soil was washed by acids was also conducted. The distribution of cadmium in the soil during the experimental time is also examined. The optimum conditions of the above experiments will be used for in situ application of electrokinetic process.

2. Materials and methods

2.1. Description of soil

Real soil used was obtained from an abandoned military area, since it was polluted with numerous heavy metals. The composition of the soil used in the experiments is shown in Table 1.

Table 1
Mineralogical composition and properties of the remediated soils

Soil components and properties	Value
Mineralogy	Quartz Illite Muscovite
Particle size distribution (%) (ASTM D422)	
Gravel	1
Sand	19
Silt	70
Clay	10
Organic content (%) (ASTM D2974)	2.15
pH (ASTM D4972)	7.42
Metal concentration (mg/kg)	
Cd	55.0 ± 5
Ni	34.4 ± 6
Pb	81.1 ± 10
Zn	1238 ± 140
Cu	406 ± 60
Cr	39.3 ± 8

2.2. Experimental set-up

Two different electrokinetic cells were used in the experiments. The first instrument (Fig. 1a) consisted of a cylinder, two electrodes compartments, two tubes, two electrolyte solutions reservoirs and a power supply (Statron, 0–300 V, 0–1.2 A). The contaminated soil was placed into a plexiglass cylinder 50 cm in length and 5 cm in diameter approximately. The electrodes were graphite discs in order to avoid the appearance of corrosion products from the electrodes. Graphite discs were pierced to exchange liquids between the soil and electrode compartments. Paper filters (Schleicher & Schuell) were inserted between the electrodes and the contaminated soil. Reservoirs served as an electrolyte source for electrolysis. The electrolyte solutions were recirculated by a peristaltic pump (Watson–Marlow, 205S/CA8) from the electrodes compartment to the reservoirs. The tubes served both to gas vent (hydrogen and oxygen generated at the electrodes by electrolysis reaction) and to recycle liquid between the electrode compartments and the reservoirs. The second instrument (Fig. 1b) [40] included an electrokinetic cell, two electrode compartments, two rinsing reservoirs and a power supply. The cell was made of plexiglass 15 mm, 21 cm in electrode distance and 10 cm × 10 cm in cross-section. Graphite electrodes were placed at the end of the cell and the electrode compartments were separated from the soil by a paper filter (Schleicher & Schuell). Rinsing reservoirs were used for adding acid into the anode and cathode compartment.

2.3. Remediation experiments

Two different experimental techniques were used to evaluate the influence of washing and purging solutions on the enhancement of the removal of heavy metals. In the first method, Fig. 1a, the soil was saturated with tap water and three different acids were used as purging solutions in the electrode compartments. In the second method, Fig. 1b, the soil was saturated (washed) with the same acids like the electrode compartments. Tests I and II were carried out with the first method, while tests III were done with the second method. The experimental conditions for each test are shown in Table 2.

For tests I and II, a constant dc voltage gradient of 150 and 200 V was applied, while current was changed in time being stabilized after 3 days. For tests III, a constant current of 20 mA was applied and voltage changed in time at the beginning of the tests.

For tests I, the initial concentrations of the acetic and hydrochloric acids, and EDTA were 10^{-3} M, so the pH was around 3 for both of the electrode reservoirs. Due to the electrolysis reactions at the electrodes, and the production of H^+ at the anode and OH^- at the cathode, the pH decreased to 2.5 at the anode compartment and increased to 11 at the cathode compartment. Similarly, for tests II, the initial concentration of acetic acid was 10^{-2} M, so the pH was about 2.5 for

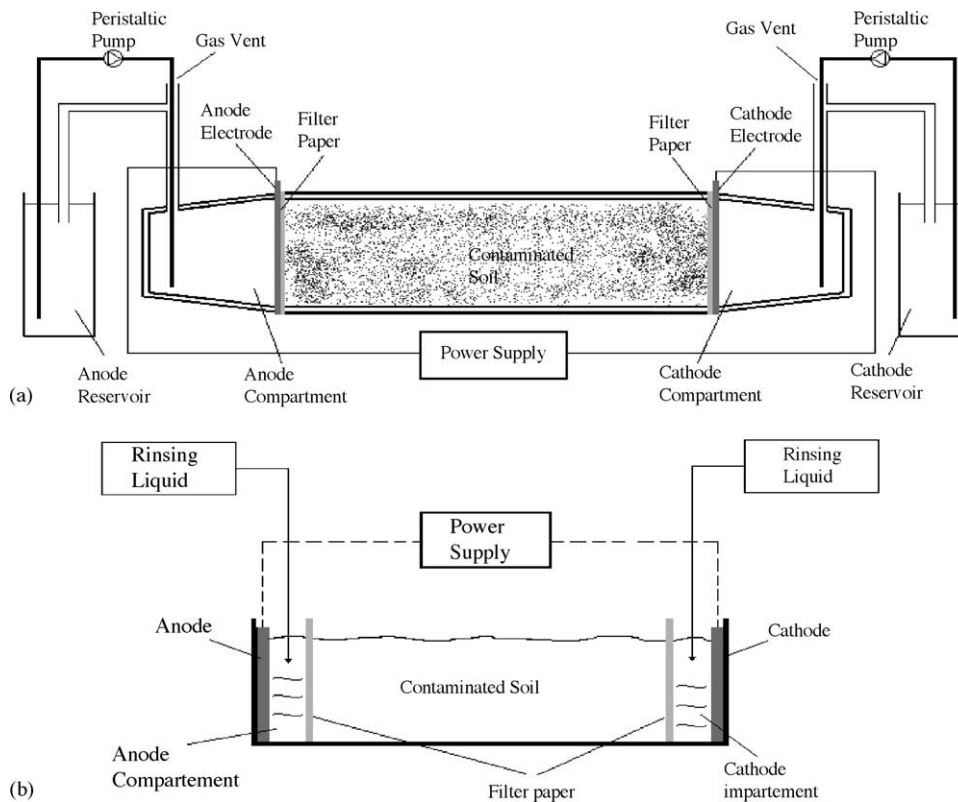


Fig. 1. Experimental instrument.

the anode and cathode reservoirs, respectively. After the end of the experiments, pH decreased at the anode compartment and increased to 4 at the cathode compartment. The raising of the liquid at the electrode compartments was kept at the same level to avoid the formation of a hydraulic gradient from forming across the specimen, and the pore liquid was transported along the cell by electroosmosis. For tests I and II, about 2 kg of soil saturated with water placed in the cylinder. The electric current across the soil sample, as well as the water flow, pH and redox potential in both the anode and cathode reservoirs were measured at different time periods throughout the duration of the experiments.

On the contrary, in tests III the soil was saturated (washed) with citric, nitric and acetic acids 10^{-2} M. Batch washing was conducted in the electrokinetic cell using 2700 g soil and

900 mL acid. The sample weight to the volume of the washing solution was 3 g:1 mL. At the beginning of the tests, the pH at the cathode compartment was controlled by adding continuously acid (pH 1) with a flow rate of 10 mL/day. When the pH in the cathode compartment was constantly lower than 4, the adding rate was reduced. When it was necessary, the loss of liquid due to evaporation was compensated with the addition of water in the anode or cathode compartment. Electric current and pH were measured daily at the electrode compartments. The pH of the soil was measured weekly at three different locations: 6, 11.5 and 17 cm from the anode.

After the tests, the treated soil of each cell was separated into 10 segments, for tests I and II, and 4 segments for tests III. Each segment was weighed and subsequently preserved

Table 2
Experimental conditions for each experiment

Experiment	Distance between electrodes (cm)	Voltage applied (V)	Current applied (mA)	Soil saturation	Acid at cathode compartment	pH At cathode compartment	Test period (days)
I(A)	50	150	4	Water	Acetic	3–10	25
I(B)	50	150	4	Water	HCl	3–12	25
I(C)	50	150	3	Water	EDTA	3–11	25
II(A)	50	200	9	Water	Acetic	2.5–4	11
II(B)	50	200	9	Water	Acetic	2.5–4	16
II(C)	50	200	9	Water	Acetic	2.5–4	22
III(A)	21	8	20	Citric	Citric	2–5	150
III(B)	21	5	20	Nitric	Nitric	2–7	120
III(C)	21	6	20	Acetic	Acetic	2–3	58

in plastic bottles. The mass of the soil was shaken thoroughly by hand for several minutes for homogeneity. To determine the pH distribution, 10 g of sample from each segment was mixed with 10 mL of distilled water. The pH of the resulting solution was the pH of each sample. pH Measurements were conducted using a WTW, digital pH meter (pH 525). Moisture content of each segment was also measured (ASTM D2974). A 0.5 g of a representative mixture of dry sample was analysed for heavy metal concentration using AAS (Perkin-Elmer 1100 B) following acid digestion with HCl (method 3051, U.S. EPA).

3. Results and discussion

3.1. Soil saturated by water

Fig. 2 shows the pH, electroosmotic flow and electroosmotic velocity variations for tests I that were performed under water saturation of soil, whereas acid was used in the anode and cathode reservoirs. Due to the electrolysis reactions, H^+ is produced at the anode, causing pH values around 2.5. The OH^- produced at the cathode results in a pH-increase to around 11. The cumulative electroosmotic flow was calculated by measuring the changes of volume in the electrode reservoir. The electroosmotic flow velocity was calculated by dividing the cumulative flow volume by the elapsed time and cross-sectional area of the soil. The electroosmotic velocity variations indicate the changes in the velocity of the pore fluid in time during the application of an electric potential [41]. The electroosmotic flow occurred towards the cathode from the beginning of the tests, and the cumulative electroosmotic flow, after 25 days, was about 500 mL for test I(A), 1000 mL for I(B) and 850 mL for I(C). The electroosmotic flow velocity increased in the first 2 days, and then started decreasing. The average electroosmotic flow

velocity was approximately 1.43×10^{-5} cm/s for test I(A), 2.35×10^{-5} cm/s for I(B) and 2.20×10^{-5} cm/s for I(C).

Fig. 3 shows the distribution of cadmium in the soil for tests I. The pH distribution is also shown to further explore the observed cadmium distribution. Due to the electrolysis of water, the pH near the anode area decreased to 4, and it was lower than the initial value of the soil 20 cm from the anode. For the next 25 cm, the pH value was the initial one and it only increased 5 cm from the cathode. After the completion of the tests, cadmium concentration was measured versus its section location within the electrokinetic cell. Generally, under low pH values cadmium exists in ionic form in solution and migrates towards the cathode due to its positive charge.

Comparing the three tests, it appears that the HCl acid as purging solution has the higher removal efficiency. Based on the mass distribution, there is a 24% cadmium removal from the soil when using HCl solution. When using acetic acid and EDTA the removal efficiency is 16 and 9%, respectively. Most of the cadmium is expected to be adsorbed on the soil surface, as cadmium is highly attracted by the clay surface. It is necessary to acidify the soil substantially to desorb and solubilize cadmium in the pore fluid of the soil. In all tests I, results show transport of cadmium through the column to the cathode region. There is a decrease of cadmium concentration (around 80%) in the areas near the anode (low pH values), but a significant increase in the middle of the cell, due to the increasing pH. At this point Cd starts to precipitate as hydroxides $[Cd(OH)_2]$ or to re-adsorb to the soil. These pH values were not low enough to achieve the complete desorption and dissolution of cadmium. Further acidification might be required. Because of the high value of Cd contamination 20 cm from the anode section, the soil analysis was repeated. In the same experiments, the concentration of nickel, zinc and copper, were also determined. The distribution of those metals after the electrokinetic treatment was similar to the distribution of cadmium.

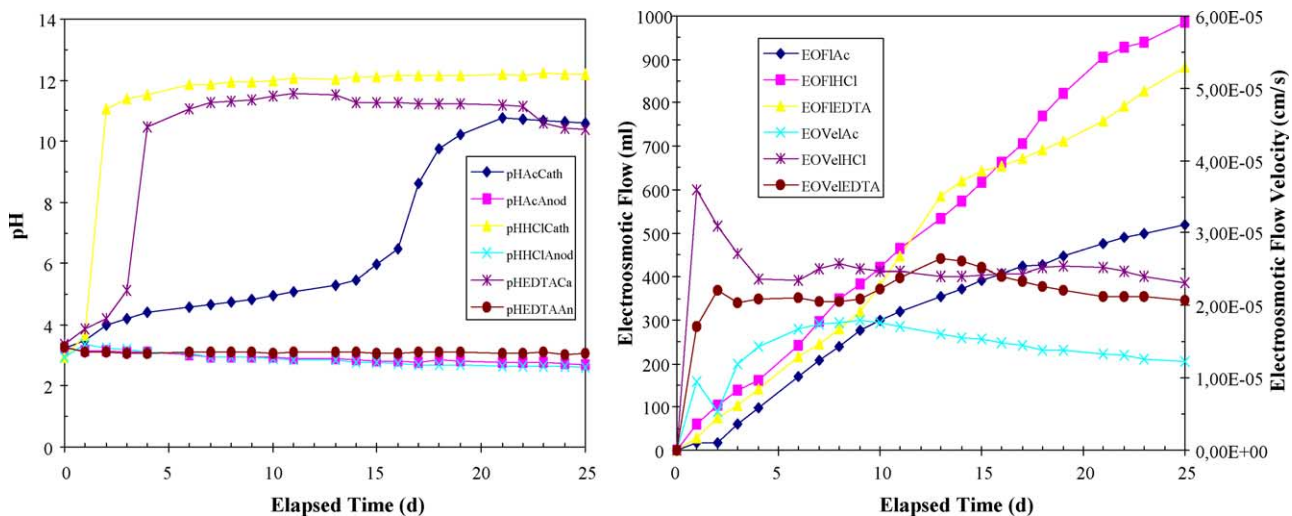


Fig. 2. The pH and electroosmotic flow variations at the electrode compartments for tests I.

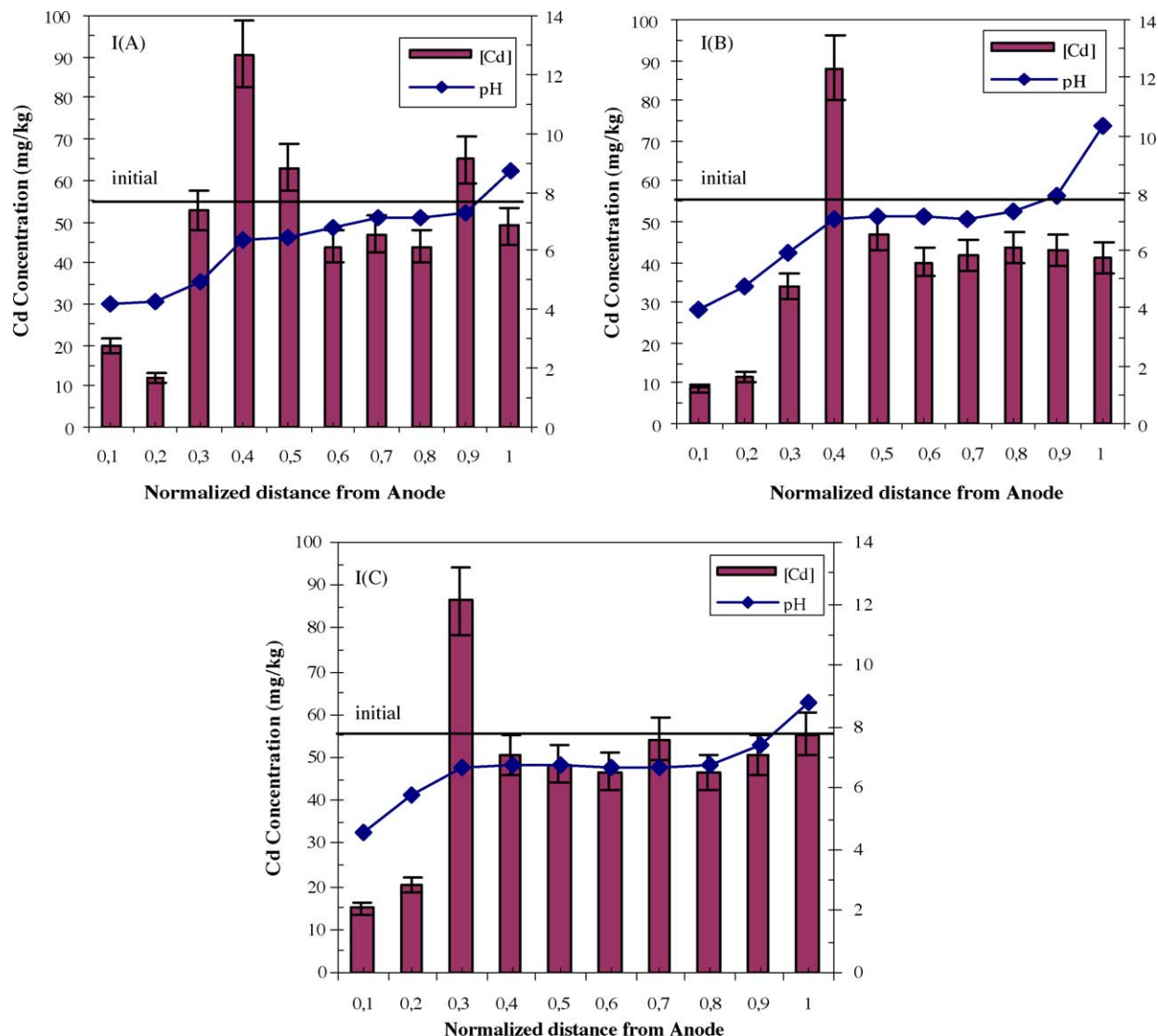


Fig. 3. Cadmium distribution vs. distance for tests I.

3.2. Distribution of cadmium when soil is saturated with water

In the next tests II, three different experiments, at the same conditions, were conducted to examine the distribution of cadmium into the column during the experimental time. Test II(A) lasted 11 days, test II(B) 16 days and test II(C) 22 days. Acetic acid at a concentration of 10^{-2} M was used as purging solution to keep pH at the cathode reservoirs below 4, compared to 11 in test I(A). Fig. 4 shows that pH decreased at the anode reservoir and increased at the cathode reservoir, due to electrolysis reactions. As seen in this figure, pH variation at electrode reservoirs was similar for all the tests. The cumulative electroosmotic flow was also similar for all of the tests. At the beginning of the tests electroosmotic flow was high enough and after 5 days was stabilised at few milliliter per day. The electroosmotic flow velocity increased rapidly

to 5.9×10^{-5} cm/s during the first day, and then it decreased to approximately 1.35 cm/s after 10 days.

Fig. 5 shows the distribution of cadmium concentration during the experiments at different times of the electrokinetic process. As can be seen, there is a continuously removal of cadmium towards the cathode area, where it accumulates as hydroxide due to the high pH of the soil. Based on the mass distribution, there is a 14% cadmium removal out of the soil during the first 11 days, a 21% removal after 16 days and 26% removal at the end of the experiment. But due to the high pH near the cathode area most of the cadmium stayed into the soil. When comparing with test I(A), to decrease the pH of the catholyte to 4 was not enough to prevent cadmium hydroxide precipitation. Soil could have been resistant to pH drop due to its high cation exchange capacity of the illite mineral. Therefore, a significant amount of acid is necessary to desorb cadmium and other metals from the soil surface. Also,

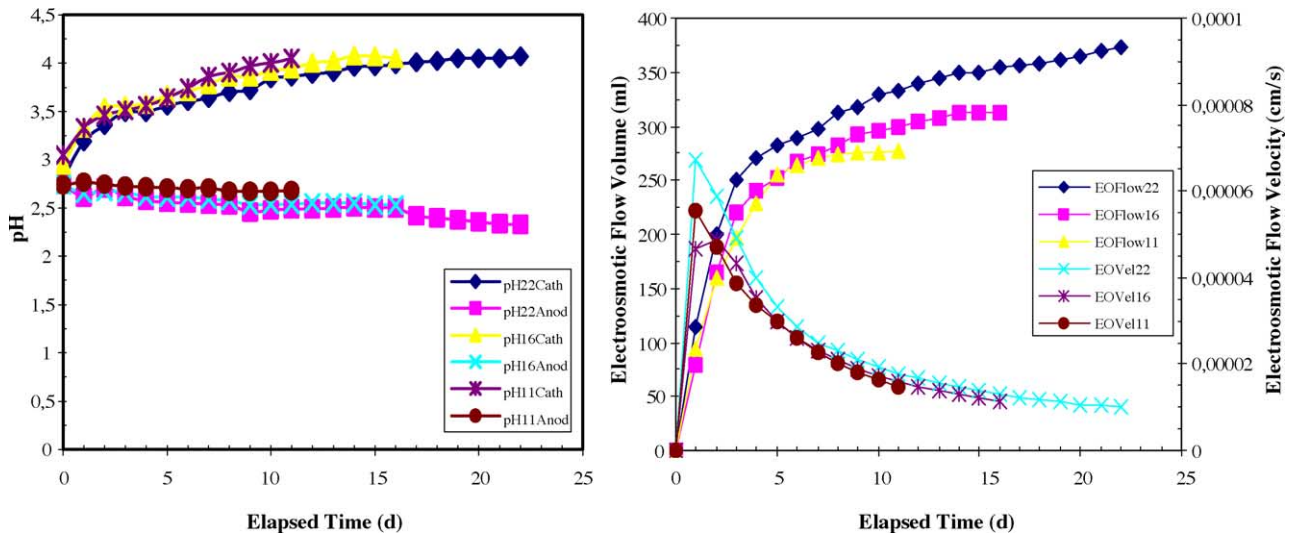


Fig. 4. The pH and electroosmotic flow variations at the electrode compartments for tests II.

time plays a critical roll in treating such soils, not only for the transport of species but also for the desorption and solubilization. Furthermore, illitic soils have high amounts of relatively free potassium ions that would complete with cadmium transport, and may hinder the electrokinetic extraction process [42]. Higher current might be necessary for this sort of treatment, but this would increase the energy expenditure and consequently cost of the process.

For tests II, it should be noted that, despite approximately constant moisture content in the soil (21%) at the beginning of the experiments, the moisture content at the end of the experiments was quite lower due to electroosmotic dewatering process. As seen in Fig. 6, the moisture content was reduced to 13% after 11 days of remediation. Then, moisture content was gradually reduced 15 cm from the cathode compartment. Due to high pH, metal ions sorbed or formed precipitates, such as hydroxides, blocking the soil pores. This fact produced a higher electroosmotic flow near the cathode than in sections near the anode, and as a result moisture content was reduced to 5.7%, 15 cm from the cathode compartment. Thus, electroosmotic flow ceased towards the end of the experiment (Fig. 4).

3.3. Soil saturated (washed) by acids

For tests III, the pH at the electrode reservoirs was controlled by adding acid, as mentioned before. Unlike tests I, the pH in the soil could be measured at tests III, because of the open cell. The pH was measured at three locations: 6, 11.5 and 17 cm distance from the anode. Fig. 7 shows the pH developed in the soil. Due to acid washing, the soil was acidic (pH between 2 and 6), apart from the cathode compartment where it increased.

When nitric acid was used as washing solution, pH decreased to approximately 1 by the end of the experiment. The low pH of the soil during nitric washing solution is of concern because, (1) there is a possibility that metals remaining on the soil, as well as metals that may be added to the soil, are highly mobile giving the low pH of the soil, (2) the ability of the soil to sustain microbial life is negligible unless pH adjustment occurs (e.g. liming the soil) and (3) soil's chemical and physical structure has been dramatically altered due to mineral dissolution. The final pH of the soil for citric and acetic washing solutions was between 3 and 4. Thus,

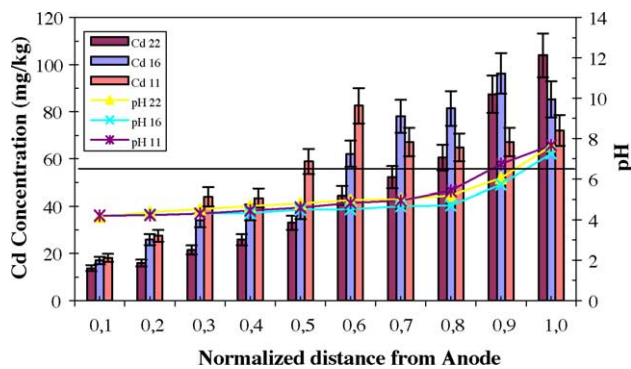


Fig. 5. Cd distribution vs. experimental time.

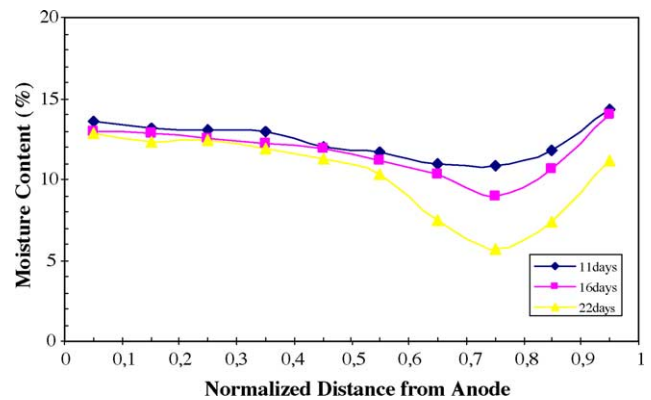


Fig. 6. Moisture content into the soil.

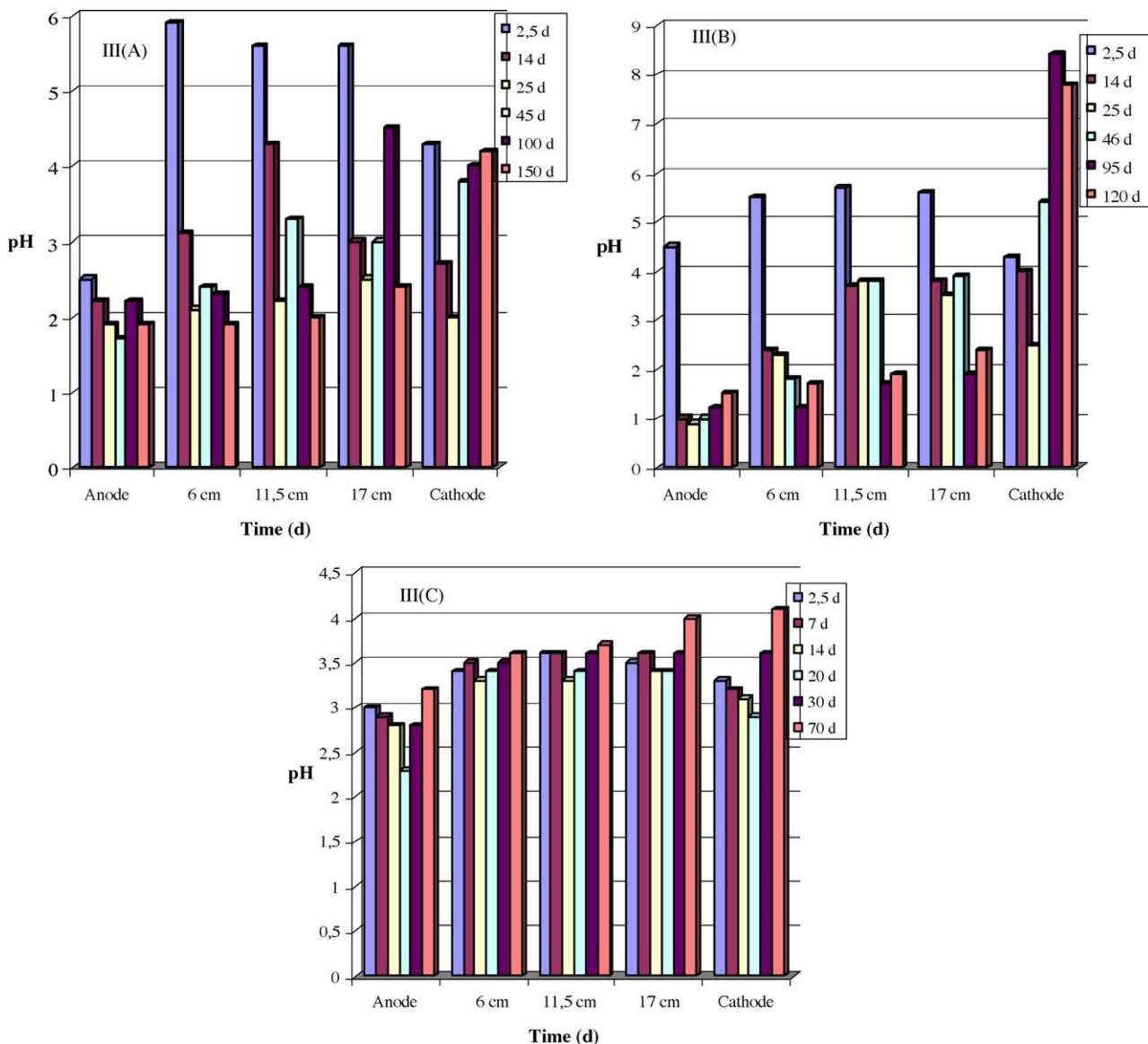


Fig. 7. pH variations for tests III.

the post-remediation problems associated with nitric washing solution should not be such an important issue if citric and acetic washing solutions are used.

The normalized concentration of cadmium in the soil cell, during and after the completion of tests III is shown in Fig. 8. These washing acids dissolve cadmium was presented on the particles surface and concomitantly solubilize it to the soil solution. Organic acids, such as citric and acetic can easily form soluble complexes with Cd^{2+} , reducing the quantity of metals retained by soil particles and thereby increasing the mobility of the heavy metals. The desorption of cadmium, using nitric acid as washing solution, was most likely due to the dissolution of the soil structure resulting from the too low pH values the soil was subjected to. Cadmium release could have been partially due to the selectivity of the soil surface groups for H^+ over the Cd^{2+} bound. From an electrostatic

point of view, negatively charged surface sites have a greater affinity for trivalent and divalent ions than for monovalent ions. However, H^+ ions are attracted more strongly than any other cation [43]. Speciation calculations using equilibria from Table 3 reveal the form of cadmium compounds. Based on the data from Table 3, pH and the use of complexing ligands were the most important factors affecting the reduction of Cd levels in the soil studied. The effect of lowering the pH between 1 and 4 resulted in the release of Cd^{2+} .

A significant decrease on the concentration of cadmium with citric and nitric acids as washing solutions was observed in the first sample after 29 days, while the opposite was observed in the soil with acetic acid. An increase of contamination could be due to an unequal distribution of cadmium concentration in the soil. The second sampling took place after a period of 58 days. It tends to show a further decrease

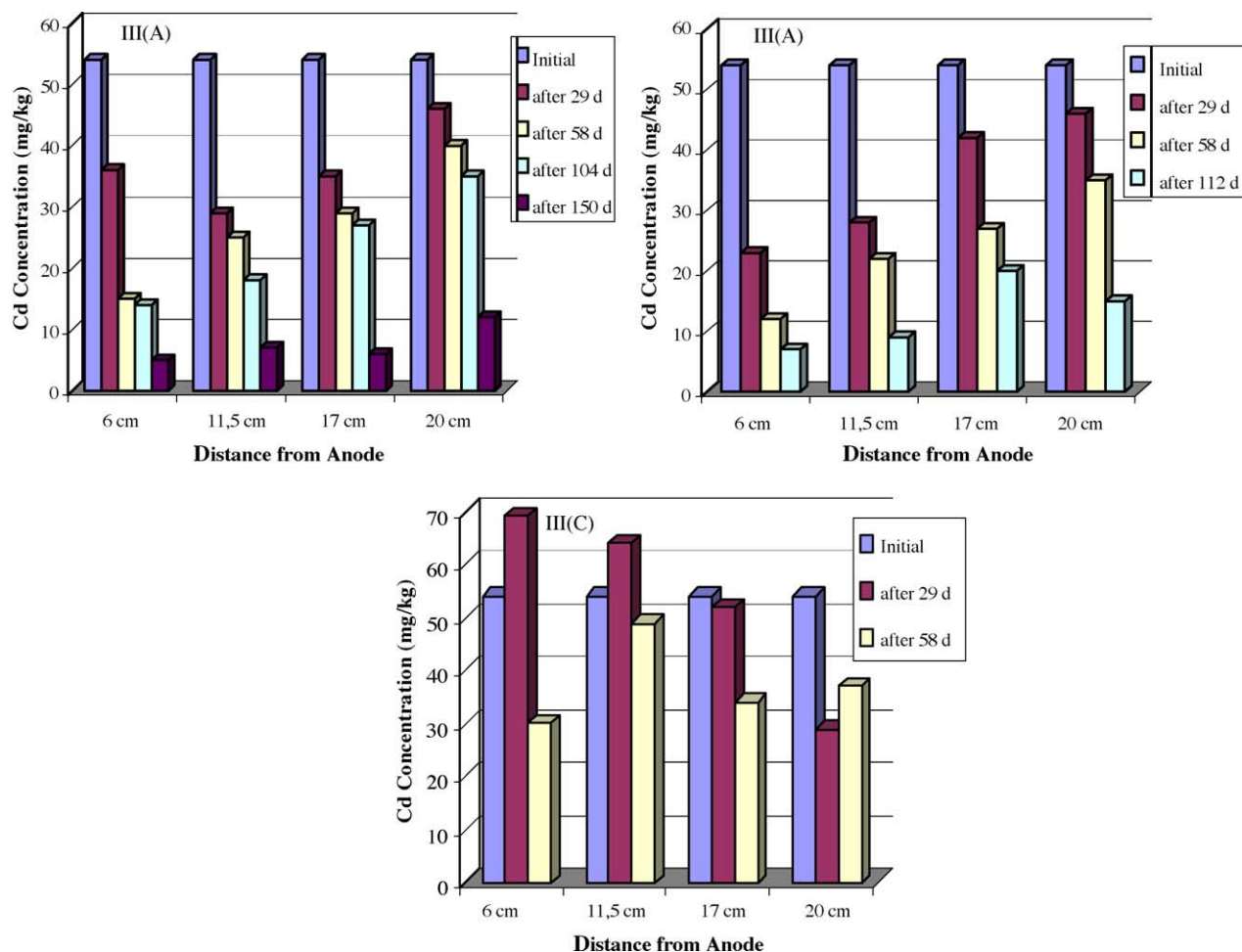


Fig. 8. Normalized concentration of Cd during tests III.

of cadmium concentration in those tests with citric and nitric acids. Cadmium moves towards the cathode and accumulates near the compartment. Even for the test with acetic acid, the second sample shows a small reduction of cadmium concentration in the cell compared to the first sample. However, when compared with the results obtained using citric and nitric acids, it was less effective. That was the reason to stop the experiment so early. The third sampling shows the expected results of a significant movement of cadmium from the anode to the cathode. After this sampling, the test with nitric acid

finished because all the analyses showed no concentration of cadmium higher than 20 mg/kg. After this sampling, current density was increased from 0.2 to 0.5 mA/cm². The last sampling took place after 150 days of experiment, and it showed a significant decrease for the test with citric acid. All samples, except the one near the cathode, showed a cadmium concentration less than 10 mg/kg. The reduction of the concentration of cadmium was specially high near the anode, around 93%. The mass balance shows a reduction of the concentration of cadmium around 85, 70 and 25% for the tests with citric, nitric and acetic acid, respectively. Thus, citric acid is well suited for removing metals bound to soils.

Table 3
Stability constants of cadmium complexes

Complex	Stability constant
Citrate	
H ₃ L	5.75
H ₂ L	4.30
HL	3.05
CdL	3.10
Acetate	
HL	4.76
CdL	1.9
CdL ₂	3.2

4. Conclusions

Based on the experiments conducted in this study, the following conclusions can be drawn:

- (1) The main results for tests I are identical. There is no significant removal of Cd from the soil (<24%) during the electrokinetic process. After 25 days of treatment, there is a high decrease of Cd concentration in the area

near the anode and a significant increase in the middle of the cell.

- (2) There is a continuously removal of Cd towards the cathode area during the experimental time, where it accumulates as hydroxide due to its reaction with the OH^- produced by the electrolysis of the water.
- (3) When acids were used for soil washing, there was not a remarkable difference on the extraction efficiencies for citric and nitric acids, but there was quite a difference for the acetic acid. The removal efficiency of cadmium reached 85%. Due to low pH values Cd exists in the ionic form in the soil solution and migrates towards the cathode.
- (4) Salts of weak organic acids (citrate and acetate) were environmentally friendly for the remediation of soils polluted by heavy metals because they enhanced soil aggregation and leached only small amounts of macronutrients from the soil.
- (5) Comparing the two methods, it can be observed that washing a soil with acid involves a higher Cd removal efficiency. It is believed that after a proper laboratory study, more than 95% removal of Cd could be achieved.

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