



Electrokinetic remediation of wood preservative contaminated soil containing copper, chromium, and arsenic

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ABSTRACT

As a result of wood treatment, and the recent banning of the copper, chromium, and arsenic (CCA) treated wood for residential use many CCA treatment facilities have been abandoned or being closed. Soil contamination resulting from CCA is common at these sites. In this study, the feasibility of electrokinetic technique to remove CCA from contaminated soil was investigated. To better understand the ionic mobility within the soil and to detect the generation and advancement of acid front, sampling ports were provided along the longitudinal axis of a test cell. To determine the effect of varying current, three tests were performed at different current densities of 5.9, 2.9, and 1.5 mA/cm² for a period of 15 days. The initial concentrations of copper, chromium, and arsenic in the soil were 4800, 3100, and 5200 mg/kg, respectively. Dilute nitric acid was used as an amendment to neutralize the hydroxyl ions produced at the cathode. Experiments resulted in removal efficiencies as high as 65% for copper, 72% for chromium, and 77% for arsenic. The results also indicated that the advancement of acid front favored desorption of metals from the soil and the metals were mobilized either as free cations or metal complexes. Chromium that was in its +6 valence state was transported as anion prior to its reduction. However, once the chromium was reduced to chromium(III) its transport direction reversed with transport being favored towards the cathode.

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1. Introduction

Historically soils have been contaminated with metals due to industrial, agricultural, and military activities. The presence of the metals in the soil poses potential environmental problems [1]. In the U.S. approximately 74% of the superfund sites for which records of decisions have been signed contain metals. Lead, Chromium, Arsenic, Zinc, Cadmium, Copper, and Mercury are the most common metals found at the contaminated sites [2]. Wood preservative industries have traditionally used Copper, Chromium, and Arsenic (CCA) salts to protect wood from damage caused by moisture, insects, and decay fungi. The CCA used in this process is a major source of pollution. One of the source of soil contamination results from storing the wood after treatment over exposed soil. Rain can leach the metals from the freshly treated timber and lumber stored at the treatment facility. Soils beneath these storage areas contain high concentrations of CCA. If these soils are left untreated the metals have a potential to subsequently leach from

the soil and contaminate the ground water. Hence, feasible cost-effective solutions to remediate CCA metal contaminated soils are needed.

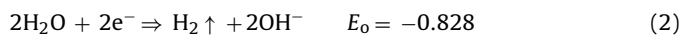
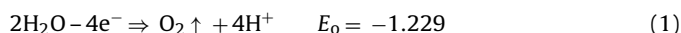
2. Background

Electrokinetic remediation is an in situ technique in which a low level direct current is applied across the soil medium to remove the contaminants. The major mechanisms by which the contaminant transport takes place are electroosmosis and electromigration. Electroosmosis is the movement of water from the anode to the cathode as a result of dipolar water molecules interacting with double diffuse layer when an electric potential is applied [1]. Electromigration is the movement of positively and negatively charged ionic species to the corresponding electrodes of opposite sign. Thus positive ions move towards the cathode and the negative ions move towards the anode.

Electrolysis reactions take place at the electrodes when a direct electric current is applied across the soil. The primary electrode reactions are given in Eqs. (1) and (2). Oxidation takes place at the anode producing hydrogen ions (H⁺) and liberating oxygen gas. Reduction takes place at the cathode producing hydroxyl ions

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(OH⁻) and liberating hydrogen gas.



The type of electrolysis reactions occurring at the electrodes depends on the availability of chemical species and the electrochemical potential of these reactions. Although, other secondary reactions might be favored at the cathode because of their low electrochemical potentials, the water reduction half-reaction (H₂O/H₂) is dominant during the early stages of the electrokinetic process [3]. The rates of acid and base production during electrolysis depend upon the current density. Based on Faradays law of equivalence of mass and charge, the rate at which ions are produced at the electrodes is given by Eq. (3).

$$J = \frac{I}{(Z) * (F)} \quad (3)$$

where J is the molar flux (mol/cm² s), I is the current density (A/cm²), Z is the ionic valence, and F is the Faradays constant (96,485 C/mol electrons).

3. Previous research

Numerous studies have been performed to evaluate the potential to treat heavy metal contaminated soils [3–38]. Although, most of the investigations were done on soils contaminated with single metallic species [4–9,11–21,26,38], limited tests have been done on soils contaminated with multiple metallic species [10,22–25,27–37]. Previous tests conducted on soils contaminated with multiple species have shown that, the presence of multiple metals had an impact on the removal efficiencies [34]. However, few studies were identified that evaluated the removal of copper, chromium, and arsenic from CCA contaminated soil [27,36,37]. Hence, the present study will evaluate the feasibility of electrokinetic technique to remove copper, chromium, and arsenic simultaneously from CCA contaminated soil from wood preservative industries.

The effect of varying current densities on the contaminant removal efficiencies conducted suggested that, the remediation efficiencies increased with an increase in the amount of current applied [6]. This study will evaluate the effect of varying current densities on CCA removal. Also, the experimental setup was designed and fabricated such that the process performance during the experiment could be monitored. The process performance parameters like the voltage, pore fluid pH, and pore fluid metallic concentration variations along the soil specimen, with time were monitored.

4. Methods and materials

4.1. Soil spiking procedure

The soil used in these experiments was 80% sand and 20% silty clay loam obtained from a local source. This soil was mixed with 3% CCA solution obtained from a local wood preservative industry at a soil-to-liquid ratio of 1:10 by weight. The soil and CCA solution was allowed to mix for 24 h in a paddle mixer. Then the soil was allowed to settle, and the supernatant was decanted and appropriately discarded. This process was followed by washing the soil. The soil was washed by adding 10 l of clean tap water to the soil and mixing it for an additional 2 h. After washing, the sand was allowed to settle for an hour, and the supernatant was once again decanted and discarded. This washing procedure was repeated twice, which facilitated the removal of any ions remaining in the soil pores. The

Table 1
Copper, chromium, and arsenic spiked soil properties

Specific gravity	1.72
pH	6.2
Permeability (cm/s)	0.4 exp ⁻⁴
Particle size distribution	
Gravel (%)	0
Sand (%)	78
Silt (%)	14
Clay (%)	8
Organic content (%)	1
Cation exchange capacity (meq/100 g)	12
Carbonate content (%)	0.5
Copper concentration (mg/kg)	4800
Chromium concentration (mg/kg)	3100
Arsenic concentration (mg/kg)	5200

spiked soil from the mixer was removed and air-dried. The characteristics of spiked soil are presented in Table 1.

Tests were performed to evaluate free and bound heavy metals. One hundred (100) ml of distilled water was added to 5 g of spiked soil and allowed to equilibrate for 24 h. After the equilibration period the soil solution was filtered and analyzed for CCA. The amount of metals leached into the distilled water was contributed to the unbounded metals as reported below:

	Bound (%)	Free (%)
Copper	100	0
Chromium	66	34
Arsenic	98	2

4.2. Cell design

The cell was designed to monitor the performance of the remediation process. The test cell used in this study was divided into three sections. Anode and cathode half-cells that hold the electrodes and the middle section that hold the soil. The middle cell section was constructed of clear polyvinyl chloride 3 in. in diameter and 12 in. in length. Along the longitudinal axis of middle cell Section 3 pore fluid sampling ports were provided at equal distances. Adjacent to the sampling ports, secondary electrodes were provided to measure the voltage gradient. The middle section and the cathode and anode half-cells were separated using a 0.125 in. sintered polyethylene plate. Hewitt–Packard's DC power supplies were used to supply cell power. Resin impregnated carbon discs, 2.5 in. in diameter were used as the electrodes. The pH at the cathode was maintained at 3.0 by dosing it with 1 M nitric acid using a pH control system. Anode and cathode solutions were recirculated using a pump to avoid any complex boundary conditions occurring at the electrodes. To monitor the electroosmotic flow, cathode and anode overflow collection containers were used and the volume of fluid collected in the containers monitored. A schematic of the experimental set up is shown in Fig. 1. A detailed description of the cells is provided in [39].

4.3. Experimental procedures

A series of three tests were performed at different current densities, to evaluate the effect of varying current density on the rate of removal of CCA. All the experiments were performed in duplicate to evaluate test reproducibility. An experimental matrix for this study is provided in Table 2. Prior to the start of testing the test cells were conditioned after packing the cells with spiked soil by equilibrating the cells with tap water and a zero hydraulic head across the cells for 24 h. After the cells were conditioned the power supply

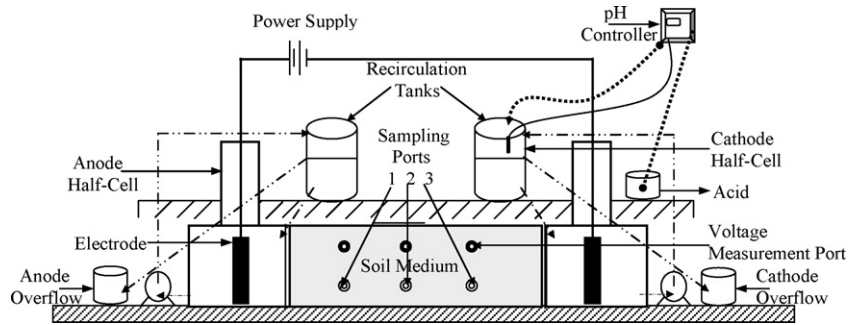


Fig. 1. Schematic of electrokinetic test cell.

energized and the cell was set to operate at a desired constant current mode as shown in Table 2.

After conditioning for 24 h, approximately 5 ml of pore fluid samples were collected from the anode and cathode half-cells and sampling ports provided along the cell every 12 h during the treatment process. The samples were collected in vials by gravity flow from the ports provided along the cell. The samples solution collected was replaced with an equal amount of water at the anode and cathode half-cells. Also, the voltage across the cell and the secondary ports were measured every 12 h. The pH of the samples collected was measured using an Oakton model 310 pH meter and the concentrations of the metals was measured using an Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES) by USEPA method 6010B [40].

4.4. Post run soil analysis

At the end of the test duration, soil was divided into 6 cylindrical sections of equal length along its longitudinal axis. The anode and cathode end solutions were collected and all liquid and solid samples were digested according to EPA method 3015 and 3051, respectively, and analyzed using ICP-OES for metals. The moisture content, pH, and metal concentration of the soil samples was also measured. Chromium speciation was also performed on soil samples by alkaline digestion according to EPA method 3060 [40].

5. Results and discussion

5.1. Effect of electroosmotic flow contaminant removal

Electroosmotic flow was monitored in this system by measuring the amount of water collected over time in the cathode and anode overflow compartments. However, there was no measurable amount of water deposited in the cathode and anode cells over the course of the experiment, which suggested that there was no electroosmotic flow. Hence, the effect of electroosmotic flow on the contaminant migration is not discussed as part of this study.

Table 2
Experimental matrix

Run number	Current density (mA/cm ²)	Time duration (h)	Cathode amendment
1	1.5	360	Nitric acid
1D	1.5	360	Nitric acid
2	2.9	360	Nitric acid
2D	2.9	360	Nitric acid
3	5.9	360	Nitric acid
3D	5.9	360	Nitric acid

5.2. Variation of pore fluid pH with time and current density

Fig. 2 presents typical results of the effect of varying current density on pH with time at the anode and port 2. The pH at the anode drops to 2.0 within the first 12 h of cell operation for the experiment with high current density. This drop in pH is due to the high production of H⁺ ions generated at the anode. The anodic pH follows similar trend for the runs with medium and low current densities but the decrease in pH to 2.0 is delayed, taking approximately 45 and 95 h, respectively. This suggests that the rate of H⁺ ion production at the anode is proportional to the amount of current applied as shown in Eq. (3). The pH variations at port 2 show that the pH values of 2.0 were achieved at approximately 108, 175, and 195 h for test with high, medium, and low current densities, respectively. Similar trend is observed for ports 1 and 3 as shown in Fig. 3. The H⁺ ions produced at the anode generate an acidic front, which moves through the soil medium toward the cathode. Hence, as well documented, the rate of movement of the acidic front is dependent on the amount of current applied to the system and H⁺ ion production.

The OH⁻ ions produced at the cathode were neutralized using nitric acid. This prevented the advancement of the basic front from the cathode into the soil. Hence, the pH at the cathode and the soil near the cathode never increased with time, thus, avoiding precipitation of the metallic species. The soil pH variation results were duplicated and there is a good agreement between each replicate indicating the repeatability of the results. Similar pore fluid pH trends were also observed and reported by Yang and Lin [8]. However, quantitatively the pH values were about 1 to 2 units lower in this experimental study.

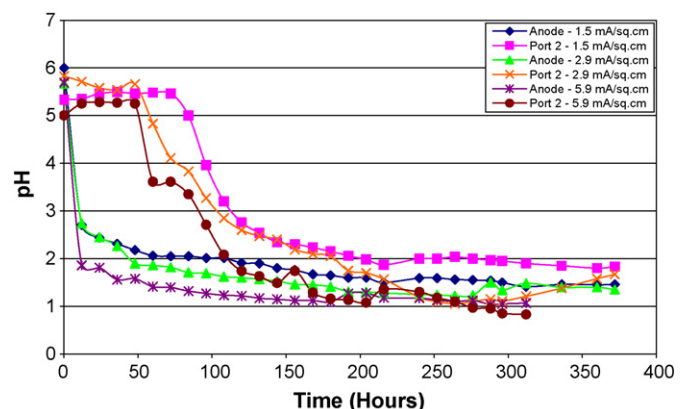


Fig. 2. In-situ variation of pH with time, at anode and port 2 for varying applied current densities.

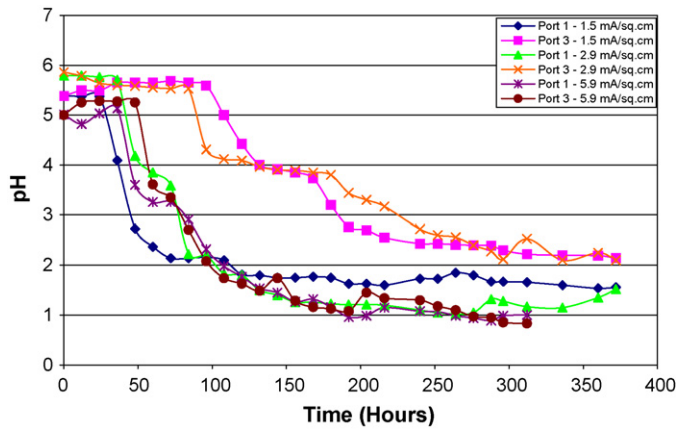


Fig. 3. In-situ variation of pH with time, at port 1 and port 3 for varying applied current densities of 1.5, 2.9 and 5.9 mA/cm².

5.3. Variation of power applied with time

The variation of power measured with time across the cell for the experiment run at a constant current operation of 2.9 mA/cm² is presented in Fig. 4. The power applied across the cell increases for the first 60 h and then starts decreasing with increasing time. For this experiment that was run at 2.9 mA/cm², the cell was set to operate at a constant current of 135 mA. However, the conductivity of the soil was not high enough at the beginning of the experiment to enable the cell to operate at the set current value. Hence, the cell operated at a maximum allowable voltage of 135 V until the constant current mode was reached, due to an increase in the conductivity of the cell with operating time. This increase in conductivity is attributed to the advancement of pH front across the cell. This phenomenon increased the concentration of ions in the pore fluid, thereby increasing the overall conductivity of the cell. Once the constant current mode was reached, which is represented by the peak in Fig. 4, the voltage dropped to maintain constant current conditions. This power drop continued until 288 h of testing. A bluish green precipitate was formed at the cathode, which increased with time. At approximately 288 h there was a substantial build up of this precipitate. This precipitate plugged the tubing that made the recirculation of the cathode fluid difficult. Hence, at 288 h the anode and cathode solutions were removed and filled with fresh tap water, which decreased the conductivity at the anode and cathode half-cells. This decrease corresponds to the increasing power after 288 h as shown in Fig. 4.

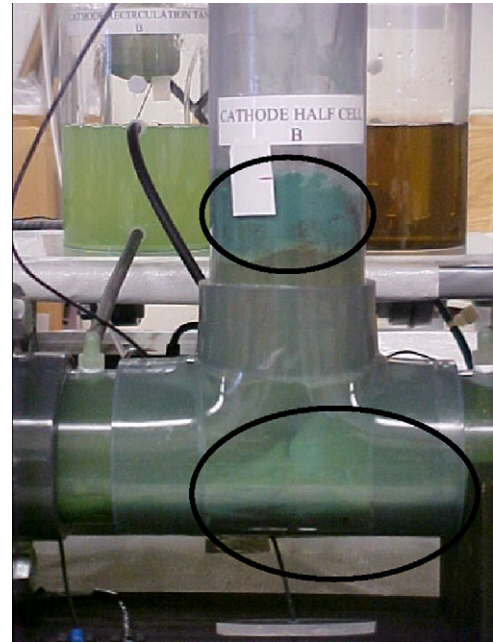


Photo 1. Bluish green precipitate at the end of 252 h of cell operation.

Fig. 4 also shows that there is significant difference between the amount of power measured at port 3 and the cathode, compared to anode–port 1, port 1–port 2, and port 2–port 3. Approximately 30–60% of the total resistance of the cell was across port 3 and cathode, which increased the energy expenditure. It is believed this can be attributed to the precipitation of metals visibly observed at the porous plate and the cathode half-cell. Although, the pH was maintained at 3.0, a substantial amount of bluish green precipitate was generated. If the precipitant was removed as it was produced it is believed that the energy expenditure could have been reduced substantially as illustrated by the decreasing trend for current after the anodic and cathodic solutions were changed at 288 h.

The bluish green precipitate that formed in the cathode half-cell by 252 h of cell operation is shown in Photo 1 for the experiments conducted at 2.9 mA/cm². As shown in the photo, there was a significant build of precipitate around the electrode. Analysis of this precipitate indicates that it is comprised of mostly copper and very little chromium and arsenic.

5.4. Pore fluid copper profile

The changes in the pore fluid concentrations of copper with time for the experimental run 2 (current density = 2.9 mA/cm²) are presented in Fig. 5. Since, copper was strongly held by the soil, copper was not detected in the pore fluid at the start of the experiment. After approximately 24 h of cell operation, copper began to desorb from the soil and was observed in the pore fluid at port 1. The pH profile for this experiment suggested that, desorption of copper began at a pH value of approximately 4.0. Similar pH values were reported for desorption of copper by Ottosen et al. [25]. As time advanced the low pH front in the soil advanced resulting in desorption of copper across the soil medium. The desorbed/solubilized copper species migrated towards the electrodes by electromigration. As shown in Fig. 5 the presence of copper in both anode and cathode compartments suggest that copper ions migrated in two directions, both towards the anode and cathode.

Desorption/dissolution/solubilization and transport of copper continued up until 240h of operation for port number 1. At

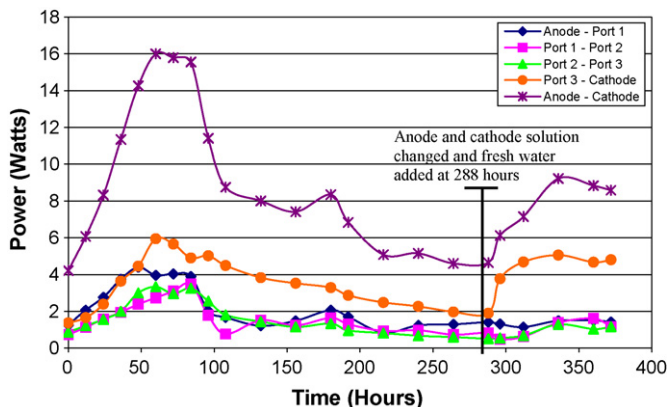


Fig. 4. Power variation with time across the cell for experimental run 2 (current density = 2.9 mA/cm²).

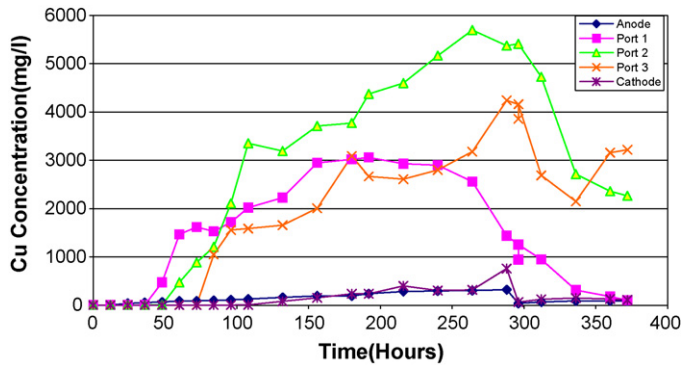


Fig. 5. Pore fluid concentration profile of copper across the cell for experimental run 2 (Current density = 2.9 mA/cm²).

approximately 240 h the copper pore fluid concentration starts to decrease, which suggests that the desorbed/solubilized copper species were being transported from the soil. Also, the pore fluid concentration of copper at port 1, dropped to 105 mg/l after 372 h of operation. This implies that most of the copper has been removed from the soil close to the anode, which is later supported by the post run soil analysis discussion. Similar profiles were observed for the other experimental runs.

5.5. Pore fluid chromium profile

The variation of pore fluid chromium concentration along the cell with time for the experiment performed at a current density of 2.9 mA/cm² is presented in Fig. 6. The initial pore fluid chromium concentration after conditioning the (pore fluid concentration is different from the in the initial soil concentrations) electrokinetic cell was approximately 4000 mg/l, which suggests that all chromium was not adsorbed during the soil spiking procedure. This is supported by the fact that approximately 10% of the chromium was measured in the anode and cathode half-cells at time zero. Although, the spiked soil was washed with water some unbound chromium was not removed. Also, Chromium +6, is more soluble and adsorbs less strongly to soil in alkaline conditions [35]. This unbound chromium was quickly transported at the start of the experiment by electromigration, as shown in Fig. 6. As shown in the figure within the first 24 h there was a rapid drop in the chromium pore fluid concentrations at ports 1, 2, and 3 and a corresponding increase at the anode.

The chromium that was adsorbed to the soil started to desorb slowly as shown by a steady increase in the measured pore

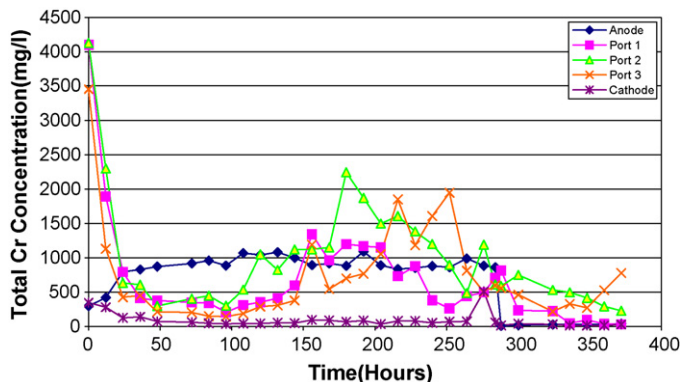


Fig. 6. Pore fluid concentration profile of chromium across the cell for experimental run 3 (Current density = 5.9 mA/cm²).

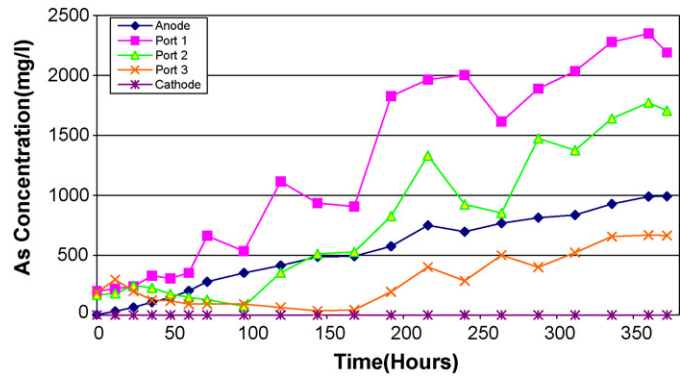


Fig. 7. Pore fluid concentration profile of arsenic across the cell for experimental run 1 (Current density = 1.5 mA/cm²).

fluid chromium concentration. Also, a decrease in the measured chromium concentration of port 1 was observed at the end of the experiment. This tends to indicate that most of the chromium was removed from the soil at this soil location which is later supported by the post run soil analysis results in this paper.

5.6. Pore fluid arsenic profile

Pore fluid concentration variations of arsenic, with time, along the cell for the experiment performed at 2.9 mA/cm² are shown in Fig. 7. Arsenic concentrations of approximately 100 mg/l were present throughout the soil prior to the application of power. After the application of power the arsenic ions in the pore fluid migrated towards the anode. This is shown by an increase in the arsenic concentration at the anode. Comparison of the pH profile for this experiment suggested that arsenic species were desorbed/solubilized at low pH values. The process of solubilization continued throughout the experiment as shown by an increase in the profiles of ports 1, 2, and 3 with time. The solubilized arsenic species were then migrated towards the anode, which is represented by an increase in the arsenic concentration at the anode. After approximately 300 h of cell operation there is a decreasing trend in the concentration of arsenic at port 1, which suggests that arsenic at that location was being removed, which is later supported by the post run soil analysis results. However, at ports 2 and 3 there an increasing trend was noticed, which suggested that not all the arsenic was removed from the soil during the experiment, hence, more treatment time would be required for complete arsenic removal.

5.7. Post run soil distribution of metallic species

The distribution of metals (initial/final concentration, M/M_0) in the soil versus normalized distance (X/L) at the test completion (372 h) is presented in Figs. 8–10. Maximum removal of copper occurred in the soil closest to the anode for all the three current conditions (Fig. 8) with a decrease in the copper concentration from the anode to the cathode. This supports the theory that H⁺ ions generated at the anode aided in the desorption/dissolution of copper as explained previously. The rate of acid front movement was the fastest with the high current density run; hence, the amount copper removed was the highest. Mass balance show approximate removal of greater than 32, 54, and 65% of copper for runs 1, 2, and 3, respectively.

Fig. 9 is a similar figure for total chromium at the end of testing period for different current densities. Chromium speciation for hexavalent chromium for the post run soil samples was performed for this study and these results are presented in Fig. 10. As observed

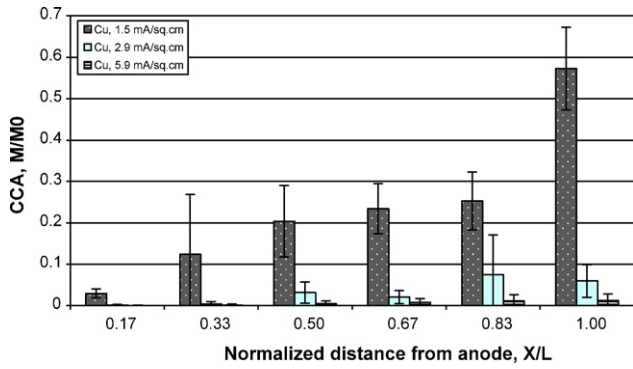


Fig. 8. Post run soil distribution of copper across the cell for varying applied current densities.

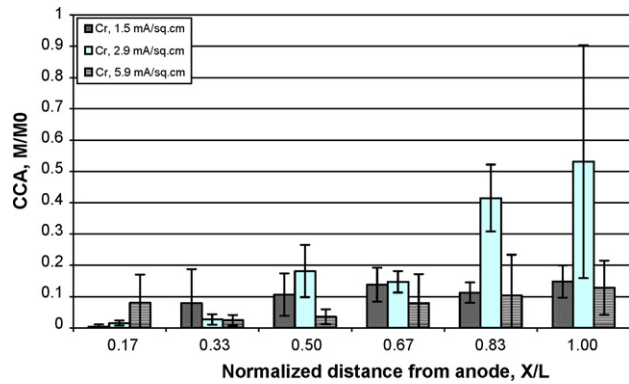


Fig. 9. Post run soil distribution of total chromium across the cell for varying applied current densities.

for the copper contaminant, section closest to the anode had the lowest chromium concentrations (0.5, 1.5, and 8% for runs with 1.5, 2.9, 5.9 mA/cm², respectively). Hexavalent chromium was used in the soil spiking procedure thus, chromium was in a +6 state aiding in its removal. The application of electric current aided in the migration of chromium +6 to the anode before the pH was reduced. With increasing time, the pH of the soil decreased, which favors the adsorption of chromium +6 species. Low pH environment favors the adsorption of chromium 6+ by the soil medium [35]. Since the rate of advancement of pH front through the soil was less for run number 1, most of chromium 6+ migrated to the electrodes before it got adsorbed to the soil.

Chromium speciation shows that more than 90% of chromium 6+ was reduced to chromium 3+ during cell operation, which is evident from the comparison of Figs. 9 and 10. Less than 10% of

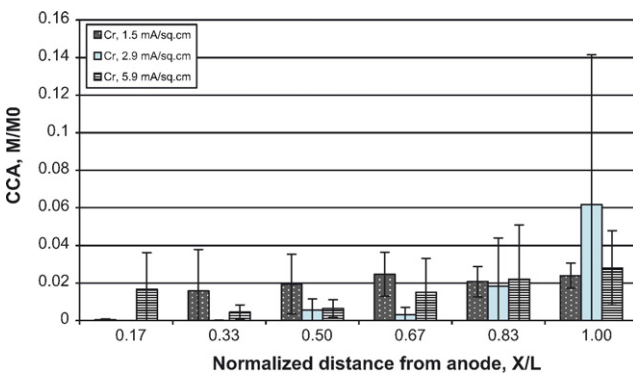


Fig. 10. Post run soil distribution of chromium +6 across the cell for varying applied current densities.

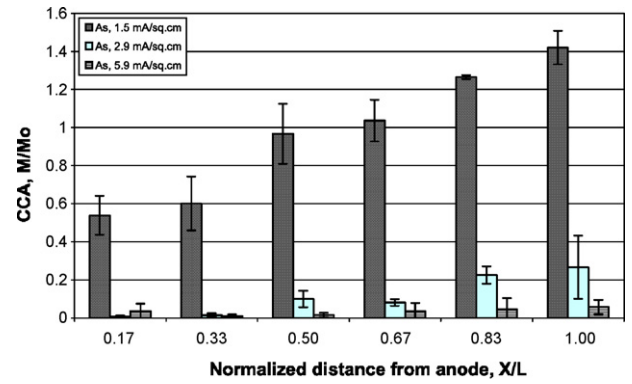


Fig. 11. Post run soil distribution of arsenic across the cell for varying applied current densities.

the chromium in the post run soil samples was in the +6 state, and greater than 90% of total chromium in the +3 state. All the experiments showed similar hexavalent chromium profiles. Similar trends were noticed with experiments conducted on glacial till soils by Reddy and Chintamreddy [41]. The reduced pH conditions of the soil may have transformed chromium 6+ to chromium 3+. The reduced chromium 3+ species were then desorbed from the soil due to a decrease in the pH and transported to the electrodes, preferably to the cathode. The percentages of chromium transported to the cathode and anode are presented in the next section.

Arsenic distribution in soil from anode to cathode at different current densities applied is presented in Fig. 11. As shown in the figure there was an increase in the concentration of arsenic in the soil from anode to the cathode. Also, the removal of arsenic increased with an increase in the amount of power applied. Arsenic, which exists as arsenate may have been, removed as anionic species before they were reduced to arsenite. It is believed that the rate of reduction of arsenate to arsenite and the pH of the soil medium governed the removal of arsenic species. Once, these species were reduced, the arsenite species which are more mobile [42] migrated preferentially to the anode, which explains a decrease in the arsenic concentration from the cathode to the anode for all 3 experimental runs.

5.8. Percentage removal efficiencies and energy expenditure

Table 3 presents the overall removal efficiencies of copper, chromium, and arsenic for different experiments conducted. The overall removal efficiencies for copper shows that the amount of copper removed from the soil increased with the increase in the current density. The reduction of the soil pH due to the increase in the current density, favored the desorption/dissolution followed by electromigration of copper towards the electrodes. Typically, copper exists in its +2 oxidation state; hence copper was expected to migrate to the cathode electrode. However, the results showed that copper migrated towards both anode and cathode. As shown in Table 3 the percentage of copper that migrated towards the anode and cathode varied with the amount of current applied. The percentage of copper transported to the anode decreased with an increase in the current density. No definite explanation is offered for the large amounts of copper measured at the anode, but one possible explanation is that copper ions might have formed complexes with arsenic or chromium, which migrated to the anode. Further investigation needs to be done to determine the effect of complex formation on the applied current.

As with copper Table 3 shows the percentage of chromium transported to the anode decreased with an increase in the amount of current applied. Almost all the chromium removed migrated

Table 3
Contaminant removal efficiencies and total energy consumption

Run no.	Removal efficiency (%)			Cathode removal (%)			Anode removal (%)			Energy usage (kWh)
	Cu	Cr	As	Cu	Cr	As	Cu	Cr	As	
1	32	58	35	35	0.7	0.3	65	99.3	99.7	0.00145
1D	32	57	36	47	0.2	0.5	53	99.8	99.5	0.00165
2	54	68	56	86	22	39	14	78	61	0.00302
2D	49	70	48	66	32	13	34	68	87	0.00324
3	65	98	77	93	58	51	7	42	49	0.00731
3D	62	72	68	85	24	44	15	76	56	0.00691

towards the anode for the experiment with low current. However, the tests run with medium and high current showed an increase in the transportation of chromium species towards the cathode with increasing current. This could be due to the reduction of chromium 6+ species to chromium 3+ as previously discussed in Section 5.7. Chromium 3+ was desorbed from the soil due to a decrease in the soil pH and with time and moved towards the cathode by electro-migration.

The removal efficiencies of arsenic increased with an increase in the amount of current applied. Also, the percentage of arsenic species transported to the cathode increased with the amount of current applied. For the run with the low current most of the arsenic migrated to the anode compartment. With increasing current density, the amount of arsenic transported towards the cathode increased. No definite explanation can be given for this behavior. However, one possible explanation could be the formation of arsenic complexes with chromium and/or copper that might have had an influence on the variation of the percentage anode or cathode removal.

A mass balance for the copper, chromium, and arsenic was performed for all the experiments. The mass balance included samples collected at the pore fluid sampling ports as well as anode and cathode compartments. The recovery of copper, chromium, and arsenic for all the experiments performed was between 85–95%, 71–88%, and 65–98%, respectively.

6. Conclusions

An electrokinetic cell was designed that could monitor the process performance. Experiments were conducted to determine the feasibility of electrokinetic technology to treat soil contaminated with copper, chromium, and arsenic. The effect of varying current densities on the metals removal was also evaluated. Based on the results obtained the following conclusions could be drawn.

- (1) Electrokinetic's is a feasible method to remove copper, chromium, and arsenic from CCA contaminated soils.
- (2) The use of nitric acid as a neutralizing agent prevented the migration of OH⁻ ions into the soil, thus preventing the precipitation of metals. This is necessary because the precipitation of metals will reduce the soil's permeability limiting the rate of electromigration (ionic transport).
- (3) The amount of current applied, which in turn affected the pH of the soil medium dominated the removal efficiency. Copper was desorbed from the soil and mobilized at pH values of approximately 4.0.
- (4) The amount of current applied effected the reduction, speciation of chromium in the soil. The processes involved with chromium desorption and transport appeared to be complicated. Chromium while effectively removed from the soil was transported both as anionic and cationic species as reflected the large amount of chromium extracted at both the cathode and anode. As evidenced by the total and hexavalent chromium

analysis, some of chromium was reduced to the trivalent states and removed from the soil.

- (5) The amount of energy required per ton of soil to achieve removal efficiencies as high as 65, 72, and 68% for copper, chromium, and arsenic is approximately 2.5 kWh/ton for the 372 h duration for this study.

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