Bench- and field-scale evaluation of chromium and cadmium extraction by electrokinetics

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Abstract

The results of bench-scale laboratory tests and in situ, pilot-scale demonstration of electrokinetic extraction of chromium and cadmium from contaminated soil are presented. The laboratory tests were conducted using 10 cm long samples under current density of $5 \, A/m^2$ for 1200 h. Tests were conducted with and without citric acid amendment at the cathode. The results showed that citric acid improved extraction, especially in the sections near the cathode. However, processing was not enough to result in complete cleanup. The field demo was conducted at the Naval Air Weapon Station (NAWS), Point Mugu, California. Three cathodes were centered between six anodes. The anode–cathode spacing was 4.45 m (15 ft). Constant voltage of 60 V ($\sim$13 V/m) was applied for 20 days and then was reduced to 45 V (10 V/m) for 6 months. Citric acid was used to maintain the cathode pH at 4. After 6 months of treatment, 78% of the soil volume has been cleared of chromium or treated to below natural background levels. The results also indicated that 70% of the soil between the electrodes had been cleared of cadmium contamination. A comparison between the bench-scale and field demo showed that the field process was more effective than the lab tests. This indicated that small sample size will induce a negative effect on the efficiency of the process due to an increased impact of the boundaries on the overall process.
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Keywords: Electrokinetics; Soil Remediation; Heavy metals; Electroosmosis; Ion migration

1. Introduction

Electrokinetic extraction of heavy metals from soils is based on application of direct electric current across electrodes in saturated soil resulting in transport by electroosmosis and ionic migration. Electroosmosis mobilizes the pore fluid to flush the soil system, usually toward the cathode, while ionic migration effectively separates the negative and positive ionic species by their transport to the anode and cathode, respectively. Application of electric current in a saturated medium results in electrolysis at the electrodes producing protons at the anode, dropping the pH to below 2, and hydroxyl ions at the cathode, increasing the pH to above 10 [1]. Unless transport of protons is retarded by the soil buffering capacity, the soil between the electrodes will be acidified due to (a) higher ionic mobility of the proton compared to hydroxyl ion and (b) retarded transport of hydroxyl

ions due to electroosmosis. This acidification results in solubilization of heavy metals by desorption and dissolution. Once contaminants are present in ionic form in soil pore fluid, they migrate to the electrode opposite in polarity, leading to their extraction. Extraction and removal are accomplished by electrodeposition, precipitation or ion exchange either at the electrodes or in an external extraction system.

In unenhanced electrokinetic remediation (without use of amendments or controls at the boundaries), protons that transport across the soil mass meet hydroxyl ions close to cathode. As a result, pH changes from about 2 to over 10 at a small zone within the vicinity of the cathode. It is necessary to consider the behavior of target species in an environment with such a widely varying pH values in assessment of transport. A rise in catholyte pH results in precipitation of metal hydroxides [2–4]. This precipitation decreases concentrations of ionic species in soil pore fluid, decreases electrolyte strength, and renders a zone of low electric conductivity. Formation of this zone causes significant increase in the voltage drop across the soil and increase in energy expenditure. Furthermore, some metals are amphoteric and can exist ei-

ther in positive or negative ion forms, e.g., $Pb^{2+}/[PbO_2H]^-$, $Cr^{3+}/[Cr(OH)_4]^-$, depending on local pH conditions. These ions when complexed into a negatively charged species at high pH, could be transported towards the anode under electric fields. Therefore, in unenhanced electrokinetic remediation, a rise in catholyte pH may result in complexation of heavy metals and their transport towards the anode. Such complexation should be considered and its effect on electrokinetic remediation should be evaluated.

Different schemes could be proposed to enhance transport and extraction of species under electric fields and to prevent formation of immobile precipitates. Some of these schemes are based on neutralizing the cathode water electrolysis reaction to avoid generation and transport of high concentrations of OH^- ions into soil and to enhance electrodeposition of metals [5,6]. Neutralization of cathode water electrolysis reaction will also assist in decreasing the electrical potential difference across the electrodes and consequently decrease energy expenditure. Neutralizing the cathodic electrolysis reaction is one of the feasible options. Weak organic acids could be used for electrode conditioning. Citric acid is used for pH control at the cathode. Other acids similar to citric acid, such as acetic or oxalic acids, may also be used.

The use of the technique (based on electroosmosis and ion migration) for extraction of heavy metals from soils was established in laboratory studies [1–3,7–11]. Most of the recent research (last 10 years) is focused on developing methods to enhance the process and improve its performance [5,6,12–18]. Practical aspects and scale-up engineering have also been discussed [19,20]. However, few pilot-scale and field demonstration/validation (Dem/Val) studies are reported. The Environmental Laboratory (EL) at the US Army Engineering Research and Development Center (ERDC) conducted a study on extraction of lead from soil excavated from an Army Firing Range. The study treated 1.5 t samples of clayey sandy soil contaminated with lead at concentrations in the range of 3500 mg/kg. Electrode spacings of 90 and 180 cm were used. Final analysis demonstrated lead reduction to less than 400 mg/kg. Other reported studies include removal of chromium(VI) from unsaturated soil at the Sandia National Laboratory, Albuquerque, New Mexico [21]; extraction of uranium from Oak Ridge K-25 Facility, Oak Ridge, Tennessee (Isotron Corporation). The Lasagna[TM] process [22] was used to treat an area of $14 m^2$ up to a depth of 5 m at the Paducah Gaseous Diffusion Plant (PGDP), Paducah, Kentucky. Lageman [23] reported successful demonstrations in Europe for in situ and ex situ electrokinetic extraction of metals and organics. The process reduced trichloroethylene (TCE) concentration in the soil (tight clay) from 100 to 500 ppm range to an average concentration of 1 ppm [22].

Successful field studies at various conditions are needed to support the hypothesis and laboratory experiments that claim the potential of the processes. The objective of this study is to evaluate heavy metal (chromium and cadmium) removal from soil under laboratory and field conditions. This will provide an in depth assessment of the variation between field and lab conditions.

2. Site and laboratory electrokinetic (EK) testing systems

The field study was conducted at the Naval Air Weapons Station (NAWS), Point Mugu, Ventura County, California (approximately 50 miles northwest of Los Angeles). Established in 1944, the main base comprises approximately $18 km^2$ (4500 acres). Contamination exists in a large area where electroplating and metal finishing operations disposed of their effluent. The waste disposal locations are less than 1 acre in size. They are the result of lab and shop waste disposal practices in the Old Area 6 shops between 1947 and 1978. Samples were collected from the site for laboratory analysis and EK testing, while the pilot-scale demo was conducted in situ. Below is the description of laboratory and field testing conditions.

2.1. Laboratory bench-scale testing

Several 19-L (5-gal) buckets of Point Mugu soil were homogenized and screened to pass a 0.635 cm (1/4 in.) sieve. The sieved and homogenized soil was transferred directly from the 5-gal sample bucket to the test cell with a clean, plastic scoop. The cell was approximately one-quarter filled, placed on a vibrating table, and then agitated for approximately 10 min or until no air bubbles were visually observed. This procedure was continued until the entire cell was densified. The excess soil was removed, the surface of the cell cleaned, and the cell was assembled. Care was taken to be sure that the edge of the soil sample lied flush with the edge of the middle section in order to ensure proper fit of the pressure plate. A piece of 0.45-μm filter paper was placed on the soil sample interface; the pressure plates were inserted to hold the soil in place, and the end pieces containing the electrodes were attached to the soil cells. The assembled cell was plumbed and the electrical connections were attached.

Laboratory testing was conducted using an automated laboratory system outfitted with a data acquisition system that automatically recorded and calculated all power, pH, and flow readings. A schematic representing the automated system is presented in Fig. 1. Pumps and probes were used for the pH control/enhancement addition system. The pH control pumps were very sensitive in regard to pumping rate. After each run, all pumps were cleaned and re-calibrated so that accurate amendment addition could be achieved.

The cell used for the bench-scale tests is 10 cm diameter and is 10 cm in length. A current of 40 mA was used in these tests resulting in a current density of $5 A/m^2$. The tests were processed in the range of 1140–1230 h under constant current density. After completion of each experiment, the power supplies were turned off, and the electrode wires were disconnected. The cell was disassembled, and notes were
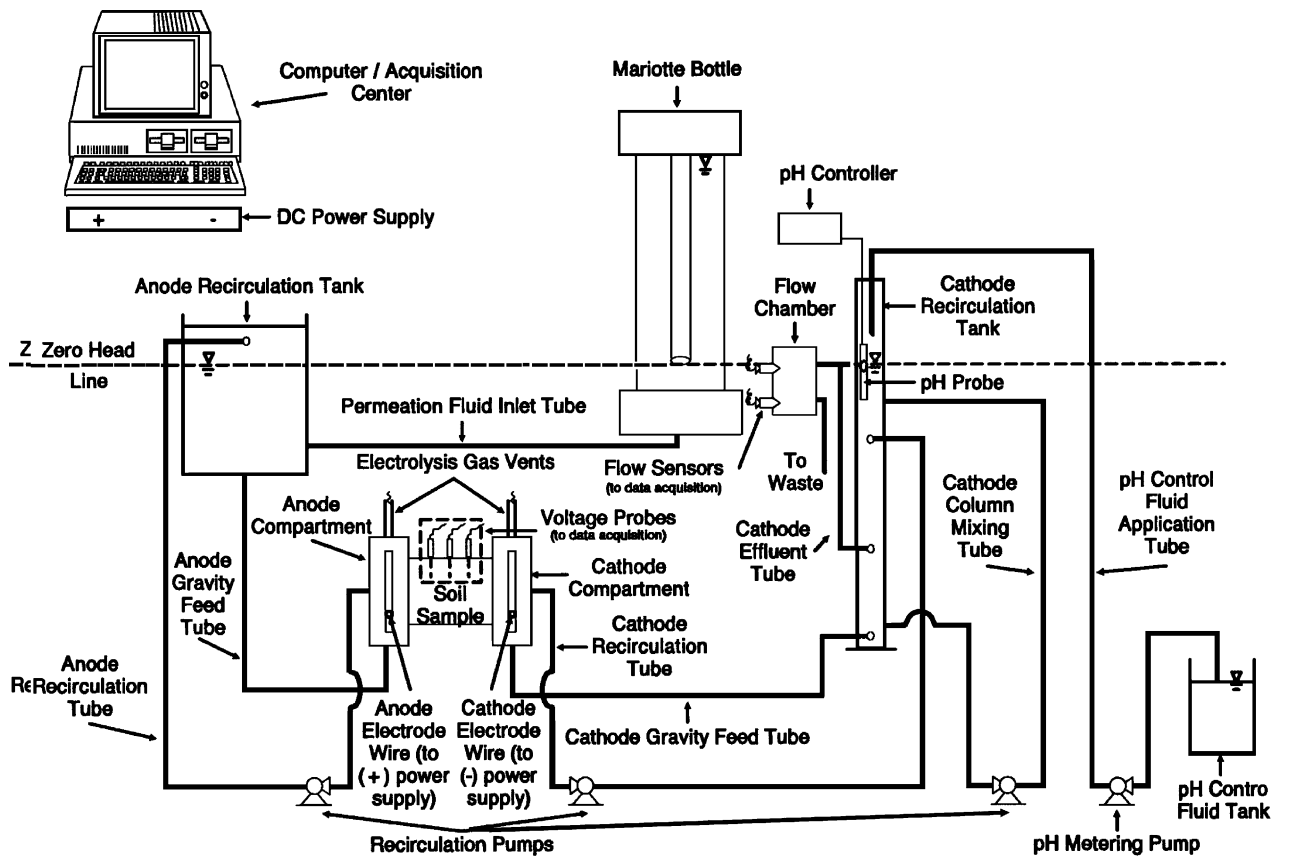
Fig. 1. 10-cm study schematic of electrokinetic remediation system.

taken to outline pertinent information, such as precipitation formed, post-run electrode color, filter degradation, etc. The EK post-run soil from the 10-cm cells were sliced into four, 2–1/2 cm sections with a stainless steel, serrated knife. Each section was then divided into three sections (top, middle, and bottom), corresponding to how the cell was positioned. Each sub-section was weighed and stored in Ziplock® disposable bags at 4 °C until further analysis could be conducted on the samples. Prior to analysis, each sub-section was thoroughly homogenized. Approximately 40–50 g of soil taken from each sub-section were weighed for moisture analysis and metals analysis. Sub-section soil pH was also determined via a soil-slurry and a Beckman® Φ45 pH meter. The sub-section soils were digested and analyzed for metals content using atomic absorption spectrophotometry (AAS). All sub-section results were averaged to obtain a total of four profiles across the cell with regard to soil; pH, moisture content, and metal contamination.

2.2. Field pilot study

The original Dem/Val plan was to address the heavy metals contamination in two lagoons. Approximately 18-ft deep high density polyethylene (HDPE) barrier wall was installed to contain the two waste lagoons. The HDPE barrier was in-

stalled to minimize the impacts of the tidal and groundwater flow into and out of the demonstration area, thus providing proper control during treatment. However, some difficulties were encountered during remediation of two lagoons. The major challenges occurred because of the brackish water and its impact on conductivity and ionic transport. The study was transitioned from a Dem/Val to a pilot-scale project and EL-ERDC restarted the EK system with a reduced number of electrodes. The results of chromium extraction in this pilot-scale study are compared to laboratory tests.

The main field components of the EK system are: a process control trailer, power supplies, electrode wells, chemical storage tanks and pH control and fluid distribution system. The electrokinetic remediation system consists of an array of electrodes, a power distribution and control system, automated process monitoring equipment, and process piping to distribute chemical amendments to the electrode wells and to extract contaminants from the electrode wells. Other equipment necessary to support system operations due to the site conditions at NAWS, Point Mugu, included off-gas extraction and treatment equipment for the gases that were generated in the electrode wells during system operation. A pH control system was used at the cathode wells by regulating the addition of citric acid to the cathode wells. The pH control system contains several pumps and solenoids

that are controlled and operated via the computer program. If there is a failure in the pH system, the system shuts itself down. Operation is suspended until a technician corrects the problem. Citric acid was selected because it is inexpensive and environmentally acceptable. The EK system operation required electricity (220 V, 100 A, 3-phase power), freshwater supply, and telephone lines to be installed at the site. The electrical supply was needed to provide power to energize the field of electrodes, pumps, and other control equipment. The fresh water was required for make up water for the electrode wells. The two telephone lines were for voice communication and system monitoring/remote control.

The distance between the anode and cathode wells was 4.6 m (15 ft). The anode and cathode wells were 3 m (10 ft) deep. The distance between like electrode wells was 1.5 m (5 ft). EL-ERDC operated the pilot-scale study at reduced electrode field in the north end of Pit 1. The anode, which operates under highly corrosive conditions, consisted of 0.9 m (3 ft) long, 2.54 cm diameter titanium hollow tubes (Eltech) with an iridium oxide coating. The cathode electrodes were constructed of 3.2 mm × 5.2 cm × 3 m long stainless steel mesh. The anode and cathode wells were capped with PVC couplings for easy removal. The anode wells were sealed with a system attached to vent the gases produced during system operation (e.g., chlorine and oxygen). Gas from the wells passed through a scrubber unit prior to release to the atmosphere. At first, the cathode wells were vented to the atmosphere, since only small volumes of hydrogen sulfide gas were expected to be produced. During treatment, hydrogen sulfide gas (H_2S) was detected in the cathode wells. Upon determination that H_2S was being produced during system operation, the cathode wells were sealed and the gases were vented to a scrubber unit prior to release to the atmosphere. The wells were installed using standard well drilling and casing installation practices. The only notable exception was the extra care required installing the cathode well ceramic casings. These casings are brittle and easily broken.

Electrical power is applied to the electrode array via three 10 kW power supplies (Electronic Measurement, Inc., part number ESS 30-333). Each of these power supplies is capable of delivering up to 30 V at up to 333 A. The power supplies were wired in series to deliver up to 90 V at up to 333 A. Application of the electric power to the electrode array was controlled by an on-site computer system with customized LabView 4.0 software. EL-ERDC operated the system with constant voltage beginning in January 1999. The applied current fluctuated with the varying resistivity of the soil in the treatment area. The total power supply current as well as each individual electrode current was logged by the computer system. The data were collected by computer data acquisition/control and manually recorded by hand. The data were stored in four separate file types in text from and are viewable with most spreadsheet software. The data from the field (electrode wells and other sensors) and the power supplies were collected approximately every 30 min to multiple computer files.

To conduct frequent monitoring of the electrokinetic remediation process, eighteen 5- cm diameter piezometer wells were installed in and around the test cells. Furthermore, a series of piezometer wells were installed to determine transport profiles and pH front (acid front) development. The wells were screened at various depths and located in positions where contaminant transport or electric field effects would most likely occur if the electrokinetic process control could not be maintained.

Sampling and chemical analysis were conducted by an independent certified laboratory. Soil cores were taken from 20 coring points to a depth of 3.6 m (12 ft) for baseline analysis. The sampling analysis results are presented in isopleths by depth. The baseline data presented in this section were extracted from the isopleths by creating a transparency grid overlay for the reduced treatment area at the north end of the pit. Metal analysis included Cr, Cd, Pb, Cu, and Zn. No significant concentrations of Pb, Cu, and Zn in the liquid or the soil were detected. The two major soil contaminants, chromium and cadmium, are presented here.

Processing conditions are summarized in Table 1. The volume of the treated soil is estimated about 64 m³. Initially, a total voltage of 60 V was applied, but it was reduced to 45 V after 20 days of processing. The reason was the difficulty in controlling the catholyte pH under 60 V application. After 118 days of processing, the electrodes were shortened to 1.2 m (4 ft) to facilitate extraction at shallow depths. Further discussion regarding the changes is provided in the following section.

3. Results and discussion

3.1. Laboratory experiments

Fig. 2 illustrates total chromium results obtained from EK laboratory treatment for unenhanced (no amendments) and

Table 1
Field testing conditions

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Athode–cathode spacing	4.57 m (15 ft)
Same electrode spacing	1.5 m (5 ft)
Electrode length	3 m (10 ft shortened to 4 ft after 118 days)
Soil volume	9.14 m × 4.57 m × 3 m = 125 m³ (30 ft × 15 ft × 10 ft)
Initial conditions	
Initial Cr (mg/kg)	180–1100
Initial Cd (mg/kg)	5–20
Initial pH	4–8
Electric energy (constant voltage, varying current)	
Day 1	60 V
Day 20	45 V
Day 118	45 V (electrode lengths were shortened to 1.2 m)
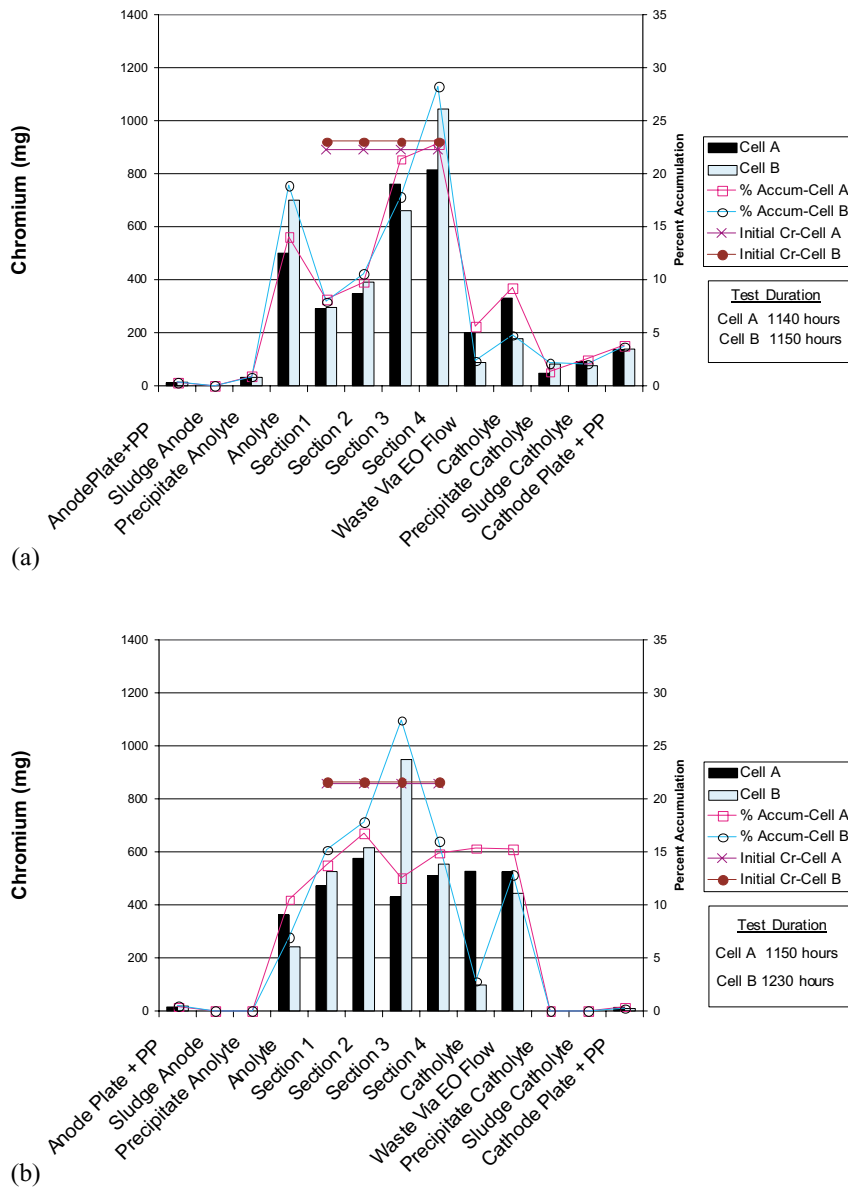
Fig. 2. 10-cm laboratory study: total chromium removal for (a) non-amended and (b) citric acid amended tests (PP = Pressure Plate).

citric acid enhancement. The figure shows that similar results were observed between the duplicate specimens. Fig. 2 shows that citric acid enhanced chromium from the soil, particularly in sections 3 and 4 near the cathode. Over 50% of the total chromium contained in the two sections nearest the anode was removed in the citric acid amended tests. Chromium accumulation at the cathode is noted in the citric tests. There were significant amounts of chromium found in the anolyte throughout the tests. A high concentration of chromium is shown in section 3 of the citric acid test, replicate B. This is believed to be the result of non-uniform baseline concentration since no increase in voltage was observed in this test. It is very likely that negative chromium complexes were formed which accounted for some move-

ment towards the anode because of the high concentration of organic material in Point Mugu.

Cadmium results are presented in Fig. 3. As in the case of Cr removal, citric acid exhibited higher Cd removal characteristics than the unamended tests. The non-amended specimens failed to produce effective cadmium removal. The citric acid amended test results showed that the flux of cadmium was towards the cathode, but the removal was not as significant with chromium. While the results show removal rates (more than 50% in some locations), it still show relative resistance to cadmium extraction. It is believed that the relative concentration of ions in the pore fluid is critical. Factors, such as buffering capacity and indigenous species concentration (Ca, Na, etc.), come into
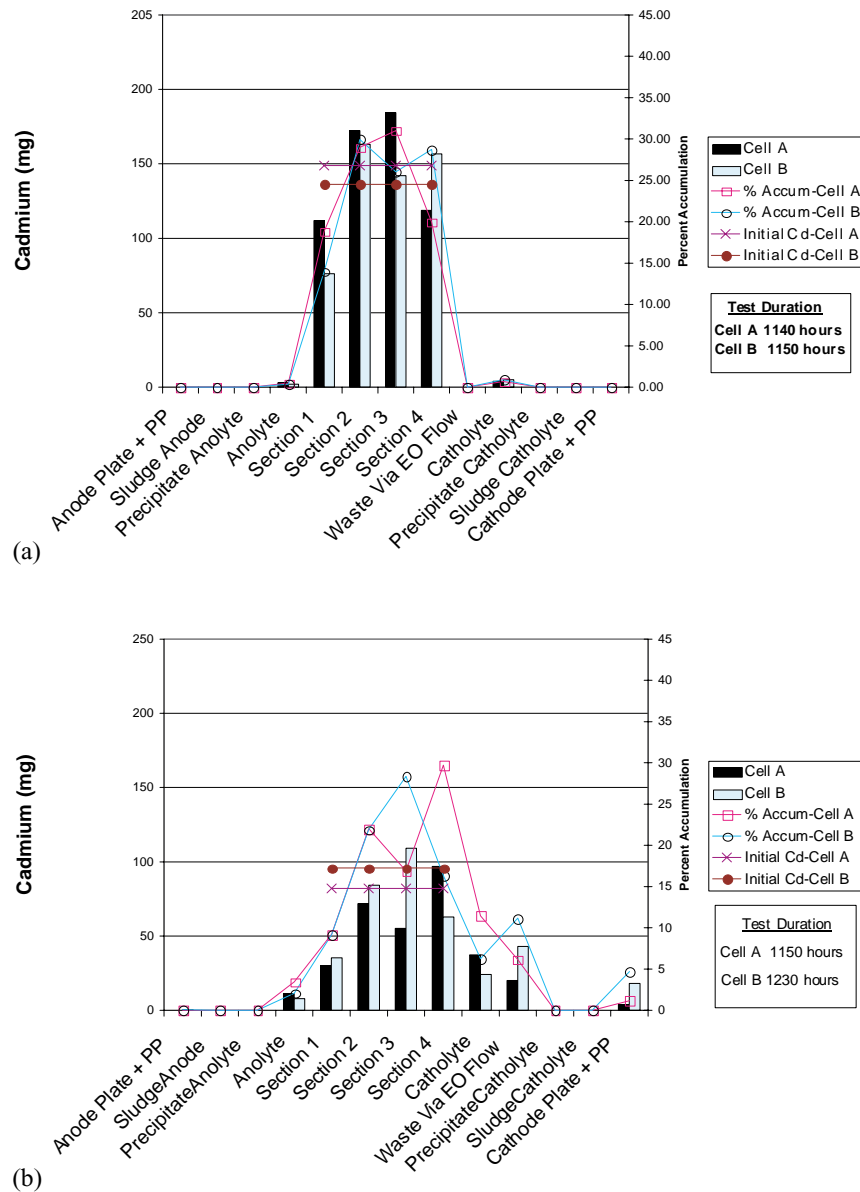
Fig. 3. 10-cm study: cadmium removal for (a) non-amended and (b) citric acid amended tests (PP = Pressure Plate).

play with respect to process application. Based on these findings, it is stressed that success of the process should not be based solely on batch test results. Extensive bench-scale investigations with conditioning agent incorporation is necessary to understand and evaluate electrochemical heavy metal removal from real world contaminated soils due to the complexity of reactions taking place in the soil matrix.

The EK results obtained in this study are comparable to those obtained by other researchers in related studies. Electrokinetics, Inc. [24] reported that the addition of Cadex[TM] as an enhancement agent at the cathode removed 98% of the total cadmium, 40% of the total lead, and 35% of the total chromium from Point Mugu soil. However, they reported

that the energy expenditure to achieve these levels of removal was approximately 3500 kW h/m^3 of soil for nearly 1200 h of treatment. When compared to approximately 350 kW h/m^3 of soil found in this study, it is apparent that the type of enhancement agent utilized in the cathode is one of the controlling factors with respect to energy consumption by the process. While the results show removal of chromium and cadmium, it is clear that energy applied was not enough for complete remediation. This can be improved by increasing current density (as used in Ref. [24]) or process for longer periods. Process optimization will be necessary to select best methods for improving performance. It was recommended to use a higher current density in the field (10 A/m^2) to achieve better removal rates.

3.2. Field pilot-scale demo

3.2.1. pH profile and control

The piezometers were sampled before treatment and every month during treatment. The results show the development and advance of the acid front from the anode towards the cathode (Fig. 4). Acidification seems to occur at lower depths (below 1.75 m) and moves towards the cathode. The first few inches close to the cathode were acidified because of citric acid injection to control the cathode pH at 4. The upper middle section in the cathode side showed a relatively high pH (6.5–7.5).

In the first 20 days, the pH in the cathode wells was difficult to maintain below 4.0 with electric power applied at 60 V and 50 A. The current level at this applied power resulted in the citric acid cathode amendment being consumed faster than it could be physically pumped into the cathode wells. To maintain a pH of 4.0 in the cathode well, the applied voltage was lowered to 45 V. Occasional pH spikes (pH 12) occurred when the computer failed to respond to the software or when the software is turned off. This action trips the fail-safe relay circuit that allows a power supply to maintain 9 V in the test area. Since no citric acid is being pumped into the cathode wells, the well pH increases. Maintaining electrical energy to the field was considered a safety precaution to prevent soluble chromium from migrating outside the confined test area.

3.3. Chromium extraction

The results from the baseline soil characterization indicate that the majority of the chromium contaminant is located in the top sections of soil nearest the cathode where concentrations where up to 1100 mg/kg. The lowest chromium concentration (180 mg/kg) was located near the anode at a depth of 1.5 m. This analysis shows that the entire soil volume in pilot treatment area was completely contaminated with chromium from the surface to a depth of 3 m. The initial average contaminant mass of chromium in the treatment area was estimated to be 2319 g.

The soil sampling results after treatment indicate that most of the chromium contamination has moved upward toward the cathode (Fig. 5). The chromium movement in the direction of the cathode was expected because positively charged trivalent chromium is attracted to the cathode. Fig. 5 reveals that the chromium contaminant was not detected or was below the natural Point Mugu background levels (109 mg/kg) in the sections closest to the anode to over 8 ft toward the cathode. The total mass of chromium remaining in the soil was estimated to be 1621 g.

Extracted chromium was measured in the effluent storage tank and in the electrode wells. At the end of the treatment, the effluent storage tank held approximately 3000 L (800 gal) of liquid collected from the anode wells and a small amount of rinse water from the NAWS water distribution system. NAWS water was used to rinse out the well fluid from the field pumps, pipes, and valves. The effluent liquid contained 12 mg/L of chromium. This corresponds to a total of 33 g of chromium removed from the site.

These anode and cathode wells were sampled monthly. Cumulative total chromium concentration from the cathode and the anode wells indicated that the highest concentrations of chromium were in the anode wells not in the cathode wells. This indicates that a fraction chromium may have existed as negatively charged Cr(VI) oxyanions. A total mass of 126 g of chromium was moved from the soil into the electrode well liquid.

After 4 weeks of treatment, the soil sampling analysis along the piezometer profile between the anodes and cathodes indicated that most of the chromium contamination had risen to shallower depths near the cathode. The chromium movement can be detected when comparing the pretreatment and post-treatment profiles. The upward movement can be attributed to the electrode modifications. The field data results reveal that approximately 5% of the chromium mass had been removed from the soil to the electrode wells. The soil sampling results indicate that 78% of the soil volume has been cleared of the chromium contaminant or treated below the Point Mugu natural background levels. The mass balance error or chromium removal was 24.7%.

3.3.1. Cadmium extraction

The baseline characterization indicates that the majority of the cadmium contaminant (concentration of 20 mg/kg) was located in the top sections of soil evenly distributed between the anode and the cathode. The minimum cadmium concentrations were 5 mg/kg, located at 1.5 and 3 m depths. The maximum cadmium concentration was approximately 20 mg/kg, near the surface. This analysis illustrates that the entire soil volume was contaminated with cadmium. The initial average cadmium mass in the treatment area was estimated to be 70.9 g. Soil sampling results after treatment indicates that most of the cadmium contamination has moved upward and toward the cathode. Fig. 6 reveals that cadmium was not detected in most of the sections closest to the anode to over 2 m toward the cathode. The total calculated mass of cadmium remaining in the treatment area was estimated to be 36.8 g. These results follow the same pattern as the chromium analysis. EK treatment is effective in removing the cadmium contaminant from the soil. However, additional treatment is required to achieve the study goals of removing all the cadmium contaminant from the soil at the site.

In comparing the pretreated cadmium analysis in to post-treatment cadmium analysis in Fig. 6, the results show that most of the cadmium contamination had moved toward the cathode and was rising to shallower depths. The analysis revealed that beginning from Anode to over 2 m toward cathode the soil was cleaned of cadmium contamination or treated below the natural background level. The data analysis from the 6-month sampling revealed that approximately 2% of the cadmium mass had been moved from the soil to the electrode well liquid. The mass balance error
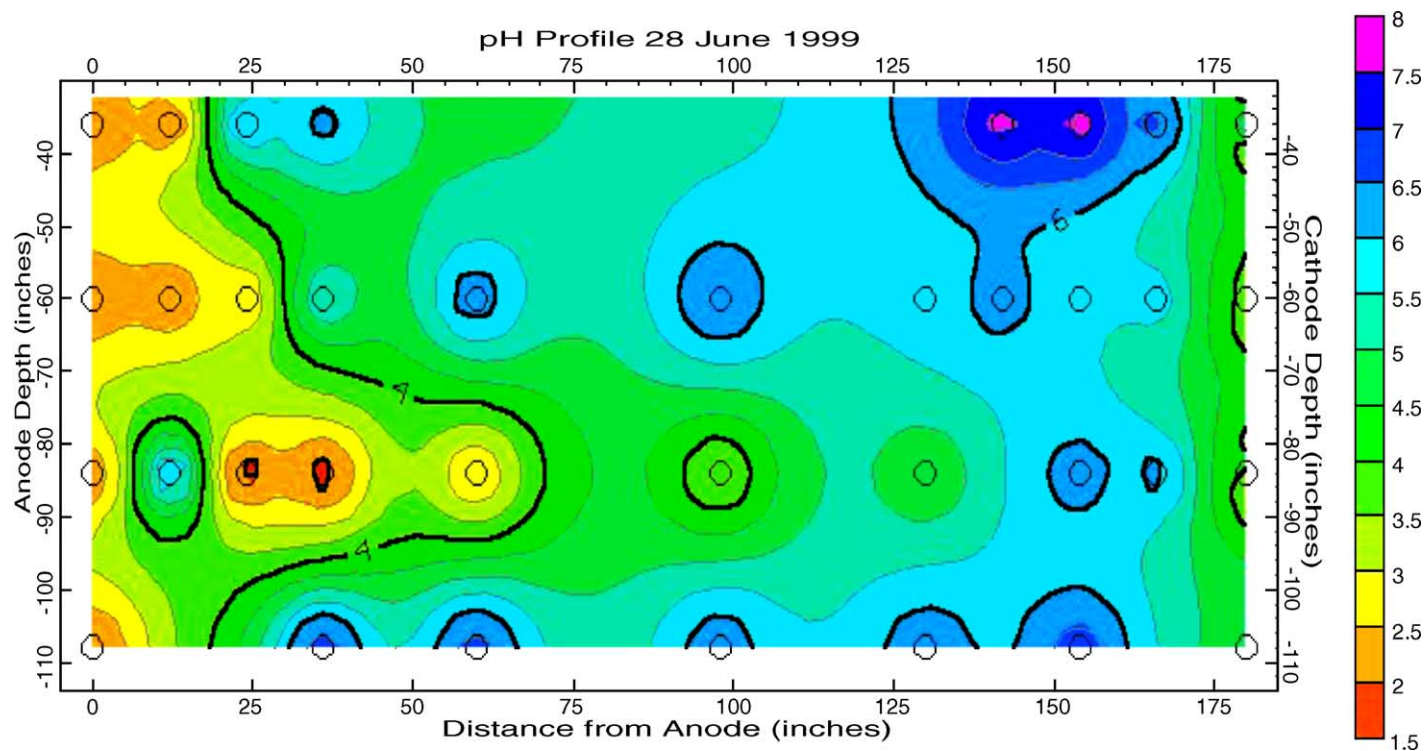
Fig. 4. Field pH distribution in depth between the electrodes after 6 months of processing.
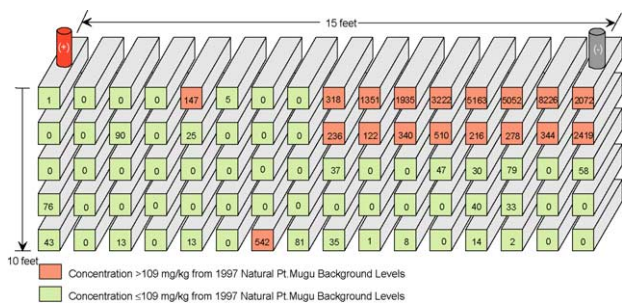
Fig. 5. Field demo: final chromium concentration profile (in depth) between the anode and cathode.

for cadmium removal was 46.3%. The analysis indicates that 70% of the soil between anode and cathode had been cleared of cadmium contamination. The bulk of the remaining chromium and cadmium contaminants are located in the upper soil sections closest to the cathode wells. These data conclusively verify the effectiveness of electrokinetic treatment at NAWS, Point Mugu, site.

3.3.2. Electric current and energy expended

The current density reached a peak of 17.9 A/m^2 on the 17th day of operation. At 60 V, the current in one of the anodes went to a high of 45 A. This current level consumed the citric acid cathode amendment faster than it could be physically pumped into the wells. When the voltage was dropped to 45 V, the total current density was 9.7 A/m^2. Assuming a linear voltage gradient of 9.8 V/m, the apparent electric conductivity of the soil between the electrodes is about 1 S/m. This is a very high electric conductivity, which is reflective of the site's saline water.

The total cumulative energy expended was collected from two different sources, the electric energy meter to the site and the calculated energy expended at the electrodes. The readings from the electric meter represent the total energy supplied to the site while the calculated energy represents the energy expended at the electrodes to treat the contam-

inated soil. The cumulative energy from the electric power meter was 25,798 kW h (208 kW h/m^3), and the reading from the data acquisition system was 24,978 kW h (200 kW h/m^3). The difference between the meter and the data acquisition was 820 kW h. The energy applied to the electrode field was not as high as the total energy supplied to the site. The computer controlled hardware (pumps, sensors, solenoids, lights, and refrigerator) consumed energy that contributes to the total energy supplied to the site. To provide a conservative cost estimate of the energy expended, the higher cumulative energy number was employed. At a cost rate of $0.08/kW h, the total energy expended from in 6 months was $2064 ($16.5/m^3). For comparison, the difference in cost between the two cumulative energy calculations was $66.

3.4. Comparison of laboratory and field results

Both laboratory and field tests showed that electrokinetic remediation with citric acid enhancement at the cathode was effective (with variable success rates) in extraction of chromium and cadmium. The field pilot-scale demo resulted in a better removal efficiency of chromium and cadmium than laboratory results. The extraction rates are controlled by energy expenditure for both cases and the effect of boundaries and sample length on the process. Energy expenditure was about 350 kW h/m^3 for bench-scale tests and around 200 kW h/m^3 for field demo. The fact that energy expenditure was higher in lab tests does not necessarily reflect that all energy was utilized in contaminant transport. The current density in lab test was 5 A/m^2 compared to 10–17 A/m^2 in the field. The results show that current densities are higher in the field than lab tests even though more energy was consumed in lab tests. This indicates that there was less electrical resistance in the field compared to lab tests. The major reason for the difference is the impact of voltage drop at the electrolytes versus the drop across the electrodes. There is always a significant drop in the voltage in the electrolytes. The significance of the voltage drop in the electrolytes on the
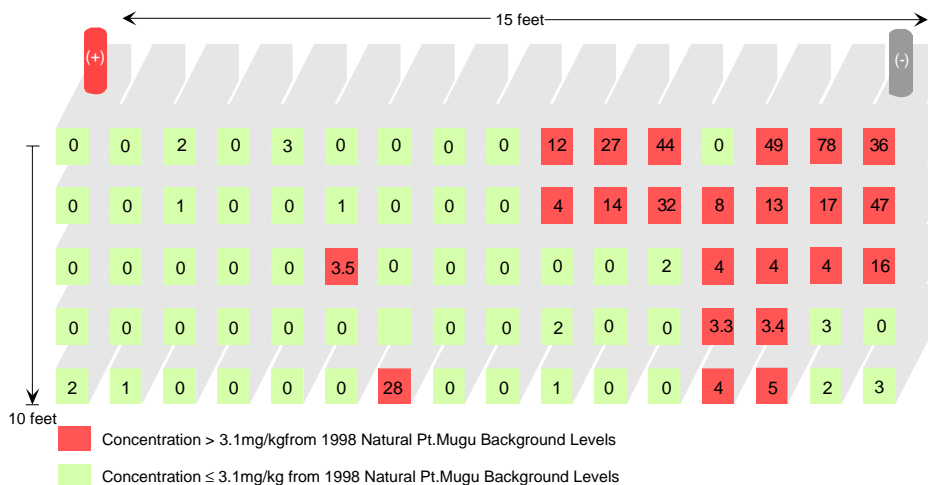

Fig. 6. Field demo: final cadmium concentration profile (in depth) between the anode and cathode.

overall voltage drop is dependent upon the electrode spacing. Accordingly, it is recommended that further tests should evaluate the role of sample spacing in assessing electrokinetic remediation for field applications. When calculating energy consumptions, it is necessary to assess the fraction of energy that is applied across the soil and the other fraction that is consumed at the electrode compartment.

4. Conclusions

The paper compares bench- and pilot-scale field tests for electrokinetic extraction of chromium from contaminated soils with brackish pore water. The results showed that better performance was achieved in the field compared to laboratory tests. The total volume treated in the field demo is $64 \, \mathrm{m}^3$, by placing three cathodes between six anodes with anode–cathode spacing of 4.45 m up to a depth of 3 m. A current density of $10–17 \, \mathrm{A/m}^2$, resulting in a voltage gradient of 13 V/m, was applied for a period of 4 months After treatment, 78% of the soil volume has been cleared of the chromium (initial concentration is 180–1100 mg/kg) contaminant or treated below the natural background levels. The results also indicated that 70% of the soil between the electrodes had been cleared of cadmium (initial concentration is 5–20 mg/kg) contamination. The brackish water caused a relatively very high apparent electric conductivity (reached 1 S/m). The contaminant removal was possible in brackish condition, because high current density ($10–17 \, \mathrm{A/m}^2$) was used. Energy expenditure was about $200 \, \mathrm{kW \, h/m}^3$. The process is more efficient in the field since higher extraction rates were achieved at lower energy levels. The sample size (especially length) in laboratory tests is critical and the boundaries impact may limit the success rate.

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