

# Enhancement of electrokinetic remediation of arsenic spiked soil by chemical reagents

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## Abstract

An enhanced electrokinetic remediation process for removal of arsenic, presented as As(V) form, from spiked soil has been investigated with groundwater (GW) and chemical reagents of cetylpyridinium chloride (CPC, a cationic surfactant), ethylenediaminetetraacetic acid (EDTA) and citric acid (CA) under potential gradient of 2.0–3.3 V/cm for 5 days treatment. The removal efficiency of As(V) in EK-EDTA system was better than that in other two EK systems. As potential gradient increased from 2.0 V/cm to 3.0 V/cm, the removal efficiency of As(V) was increased from 35.4% to 44.8% in EK-EDTA system. It showed that the arsenic removal could be enhanced by selecting suitable chemical reagent and increasing potential gradient. The intensive of electroosmotic flow towards the cathode caused a significant retardation of electromigration of arsenic towards the anode. The quantity of As(V) collected in anode reservoir was 1.4–2.5 times greater than that in cathode reservoir for all EK systems. It implied that As(V) removal was directly related to the electromigration rather than electroosmosis mechanism in EK systems. A further investigation need to be conducted to achieve higher removal efficiency of As(V).

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**Keywords:** Arsenic; Electrokinetic process; Processing fluid; Potential gradient; Soil remediation

## 1. Introduction

Arsenic is biologically toxic and a threat to human health and other living organisms, which has been classified as a Group A carcinogen by the United States Environmental Protection Agency. Arsenic in groundwater is mainly release from soil environments through natural process and as a consequence of anthropogenic activities. Soil deterioration by arsenic contamination may result in high exposure for human body through soil ingestion and the food chain. Nriagu and Pacyna [1] reported that 52,000–112,000 t of arsenic was released annually to soil from anthropogenic sources, which widely included such as mining, smelting agriculture, disposal of chemical warfare agent, preservation of wood and illegal dumping [2–4]. In natural environment, arsenic is present as As(V) (arsenate) in oxidizing environment, while As(III) (arsenite) is the dominant form in reducing environments [5]. Arsenic contaminated soils have been treated by capping [6], soil replacement and solid-

ification/stabilization, and acid washing [7]. By such off-site technology, it is cost prohibitive and labor consuming. Besides, most arsenic still remains in the environment and there is always a risk of leaching caused by changes in the environmental condition. Combination of high toxic and widespread occurrence of arsenic has created a pressing need to develop and improve existing remediation technology.

Electrokinetic (EK) process appears as a promising in-situ strategy for remediation of fine-grained soils. It has been demonstrated to be successful and cost-effective in removing wide variety of heavy metals in many bench- and field-scale studies [8–11]. However, research focused on electrokinetic removal of arsenic from soil was rare [12]. Basically, EK technique is upon the action of an electric field generated between inserted electrodes in the medium by applying a direct current or a constant voltage. The applied potential causes the migration of electrolyte solution and soluble contaminants toward the electrodes. Positive ions are attracted to the negatively charged cathode, and the negative ions move to the positively charged anode. Electromigration, electroosmosis, and electrophoresis are the principal mechanisms responsible for the electrokinetic removal of metals from soils for neutral and charged chemical reagents

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[9,13]. During electrokinetic process, the contaminants migration in the soil is simultaneously achieved by phenomena such as sorption/desorption, precipitation, and dissolution [13]. The resulting high pH in the cathode side in EK system causes precipitation of metal hydroxides and leads to decrease the permeability of soil. Various enhancement techniques have been proposed to improve EK effectiveness. Careful management of the pH and other electrolyte conditions within the electrode reservoir to enhance desorption and increase the electroosmotic flow rate is one of the critical factors in controlling EK system performance [14–16]. Addition of Hydroxyl ion membranes [17] and enhancing reagent [18,19] in the cathode reservoir were used to prevent precipitation or solubilize cationic metals. The other technology was to add or mix complexing agent such as EDTA into soil, which compete with soil for metals to form soluble complexes [20,21].

Ethylenediamine tetraacetic acid (EDTA) is the most commonly used chelate because of its strong chelating ability for different heavy metals [22]. The ability to extract the metals without inducing a strong acidification of medium is a valuable characteristic, moreover it may complexes strongly with alkaline earth cations such as Al, Ca, Fe, Mn, which bind to soil surface [23]. Citric acid is a weak acid, which would acidify the soil, making the As(V) easy to desorb from soil and it can form mononuclear, binuclear or polynuclear and bi-, tri-, and multidentate complexes with metallic ions [24]. It is also relatively inexpensive, rather easy to handle, and has a comparatively low affinity for alkaline earth metals. Ionic surfactants have been applied in the process of micellar enhanced ultrafiltration (MEUF) for separation of ions and smaller organic molecules [25,26]. The separation efficiency depends upon the binding of pollutant onto surfactant micelles, which is influenced by valence of pollutants [27]. It might largely because of the electrostatic forces between ionic surfactants and counterions. As such, many researches were focused on the extract of metals (Pb, Cu, Cr, Zn, etc.) from aqueous phase by anionic surfactant [3,28] and extract anionic pollutants ( $\text{SO}_4^{2-}$ ,  $\text{CN}^-$ ,  $\text{CrO}_4^{2-}$ ,  $\text{NO}_3^-$ , etc.) by cationic surfactant [26,29]. Baek and Yang [27] found that the removal efficiency of  $\text{CN}^-$  and  $\text{CrO}_4^{2-}$  reached 90% in aqueous solution by cetylpyridinium chloride (CPC), a kind of cationic surfactant. Results were shown that CPC is potentially applied in anionic pollutants removal for soil remediation.

This study was aimed to investigate the enhancement of electrokinetic remediation of arsenic spiked soil by suitable chemical reagents (chelating agent, acid solution and cationic surfactant) under potential gradient of 2.0–3.3 V/cm for 5 days treatment. The electrokinetic behaviors and cost analysis was also evaluated for the tested EK systems.

## 2. Materials and methods

### 2.1. Soil selection and characteristics

Soil samples were collected from a depth of approximately 0.7–1.5 m below the surface within a farmland located in southern Taiwan. Table 1 shows the basic properties of the soil sample.

The texture of this soil was classified as silt loam. The bulk density of soil was  $2.5 \text{ g/cm}^3$ , which was determined according to the method of ASTM D854-92. The pH of zero point charge ( $\text{pH}_{\text{ZPC}}$ ) of soil samples determined by a zeta potential instrument ((Pen Kem-Laser Zee 3.0, USA) was about 2.4. The soil pH was 7.40 measured in water suspensions at 1:1 rate of soil to solution by volume. The soil had an average particle size of  $27.8 \mu\text{m}$  measured by a laser particle analyzer (Coulter Ls100, England). A soil organic matter content of 0.35% was observed by the combustion method [30]. The hydraulic conductivity for clay was  $8.73 \times 10^{-4} \text{ m/day}$  measured by a falling head permeameter. After removing the debris, the soil sample was treated with air-dry and pressure steam sterilization ( $1.2 \text{ kg/cm}^2$  for 5 min). The soil sample was then crushed and sieved to less than 2 mm in diameter. The arsenic contaminated soil was prepared by adding specific amount of sodium arsenate dibasic heptahydrate ( $\text{Na}_2\text{HAsO}_4 \cdot 7\text{H}_2\text{O}$ ), 280 mL of DI water, and 600 g of sieved soil into a 2 L polypropylene bottle. The mixture was then rotated at a speed of 50 rpm and rotating angle of  $360^\circ$  for 3 days to achieve a uniform concentration of arsenic in soil. The arsenic contaminated soil sample was then respectively digested with 20 mL of 30%  $\text{H}_2\text{O}_2$  and 30 mL of 9.6 M HCl and the arsenic in digested solution was determined by means of atomic emission spectrophotometer with inductively coupled plasma source (ICP, Perkin Elmer Optima 2000DV, USA) at a wavelength of 193.7 nm. Triplicate soil samples were analyzed for quantification. This arsenic spiked soil sample was then ready for EK experiments.

### 2.2. Chemical reagents

Other than applied local groundwater as processing fluid, cetylpyridinium chloride (CPC), citric acid (CA), and ethylenediamine tetraacetic acid (EDTA) were selected as the target chemical reagents in this study to improve EK removal efficiency. The concentrations of above-mentioned chemical reagents were chosen as 0.1–0.5%, 0.0058 M, and 0.0058 M, respectively, for EK experiments, which was approximately 1.5 times of equivalents of metals involved. CPC ( $\text{C}_{21}\text{H}_{38}\text{ClN}$ ) is a cationic surfactant with critical micelle concentration of 0.12 mM, which purchased from ACROS, New Jersey, USA. CPC is biodegradable by soil and/or aquatic microorganisms [31] and its micellar surface is surrounded with positive charges. It has been friendly used for separation anionic pollutants from environmental matrix by micelle surface binding [27,29] via electrostatic attraction force. EDTA ( $\text{C}_{10}\text{H}_{14}\text{N}_2\text{Na}_2\text{O}_8 \cdot 2\text{H}_2\text{O}$ ) are selected based on its effective metal complexing ability. Citric acid ( $\text{C}_6\text{H}_8\text{O}_7 \cdot \text{H}_2\text{O}$ ) is a good pH conditioner to inhibit precipitation of metal hydroxide and consequently dissolution reaction is become dominant in the system. The other processing fluid was groundwater mainly consisted of anions of  $\text{SO}_4^{2-}$  and  $\text{Cl}^-$  and cations of  $\text{Mg}^{2+}$  and  $\text{Ca}^{2+}$ , other than the common geological ion of  $\text{Na}^+$  and  $\text{HCO}_3^-$ . The equivalent of anions and cations in tap water were 5.31 meq, respectively. The properties of processing fluids are summarized in Table 1.

Table 1  
Characteristics of experimental materials

Characteristics	Values	Characteristics	Values
<b>I. Soil</b>			
Texture	Silt loam	Density	2.50 g/cm <sup>3</sup>
Organics content	0.35%	BET areas	29.6 m <sup>2</sup> /g
pH	7.40	Average particle size	27.8 μm
pH <sub>ZPC</sub>	2.40	Hydraulic conductivity	8.73 × 10 <sup>-4</sup> m/day
<b>II. Groundwater</b>			
SO <sub>4</sub> <sup>2-</sup>	3.39 meq.	Mg <sup>2+</sup>	2.23 meq.
Cl <sup>-</sup>	1.65 meq.	Ca <sup>2+</sup>	1.75 meq.
NO <sub>3</sub> <sup>-</sup>	0.27 meq.	K <sup>+</sup>	1.33 meq.
pH	7.85		

Table 2  
Summary experimental results of EK systems

Test no.	System	Processing fluid	As(V) (mg/kg)	Electrode area (cm <sup>2</sup> )	Potential gradient (V/cm)	Q <sub>e</sub> (mL/day)	K <sub>e</sub> (cm <sup>2</sup> /V s)	As(V) removal efficiency (%)	Power consumption (kWh/m <sup>3</sup> )
1	EK-GW	Groundwater	966	4.0	2.0	15.6	6.5 × 10 <sup>-6</sup>	26.9	256
2		CPC (0.48 cmc)	966	4.0	2.0	30.2	12.6 × 10 <sup>-6</sup>	31.1	225
3	EK-CPC	CPC (2.41 cmc)	966	4.0	2.0	28.4	11.9 × 10 <sup>-6</sup>	31.7	237
4			966	4.0	2.0	21.1	8.8 × 10 <sup>-6</sup>	35.4	249
5	EK-EDTA	EDTA (0.0058 M)	966	4.0	2.7	21.8	6.8 × 10 <sup>-6</sup>	41.0	343
6			966	4.0	3.3	24.0	6.1 × 10 <sup>-6</sup>	44.8	465
7			966	4.0	2.0	21.2	8.9 × 10 <sup>-6</sup>	33.6	198
8	EK-CA	Citric acid (0.0058 M)	966	4.0	2.7	21.5	6.7 × 10 <sup>-6</sup>	32.2	292
9			966	4.0	3.3	21.1	5.3 × 10 <sup>-6</sup>	32.7	453

The treatment time for all EK systems was 5 days. The critical micelle concentration (cmc) of CPC is 1.2 × 10<sup>-4</sup> M. K<sub>e</sub>: electroosmosis permeability; Q<sub>e</sub>: electroosmotic flow rate.

### 2.3. EK experiments

Nine EK experiments (as shown in Table 2) were conducted in an acrylic cell of 4.2 cm (Ø) × 22 cm (L), consisting of three compartments: cathode reservoir with 5 cm in length, anode reservoir with 5 cm in length, and soil specimen chamber with 12 cm in length (Fig. 1). The detail procedures for set up were shown in the previous paper [32]. The processing fluid was initially placed into both anode and cathode reservoirs and

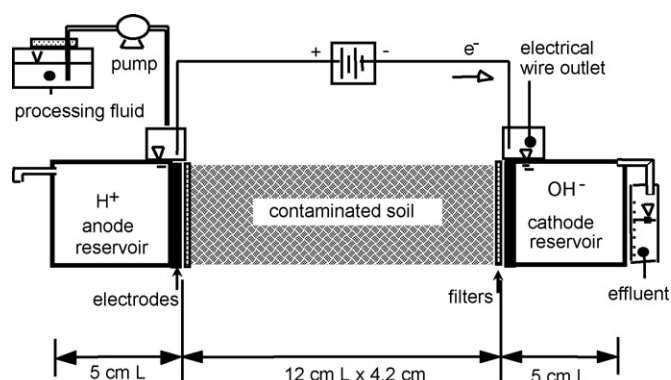


Fig. 1. Schematic setup of electrokinetic apparatus.

replenished in the anode reservoir every half day. The EK experiments were conducted under potential gradient of 2.0–3.3 V/cm for 5 days. The electric current, reservoir pH, concentrations of As(V) and total arsenic, and the quantity of electroosmotic flow were monitored during the test periods. After EK treatment, the soil specimen was removed from the cell and equally sectioned into six segments. Soil pH and residual arsenic profiles along the soil specimen were determined at the end of each test. The As(V) and total As were analyzed by means of ionic chromatography (IC, Dionex DX-120, USA) and atomic emission spectrophotometer with inductively coupled plasma source (ICP, Perkin Elmer Optima 2000DV, USA), respectively.

## 3. Results and discussions

### 3.1. Variation of soil pH and current density

Under an electrical field, the electrolysis of water occurs in the reservoirs. The hydrogen ions produced decreased the pH near the anode. At the mean time, an increase in the hydroxide ion concentration causes an increase in the pH near the cathode. Acar and Alshawabkeh [9] found that the H<sup>+</sup> ion dominates the electrokinetic system chemistry because the mobility of H<sup>+</sup>

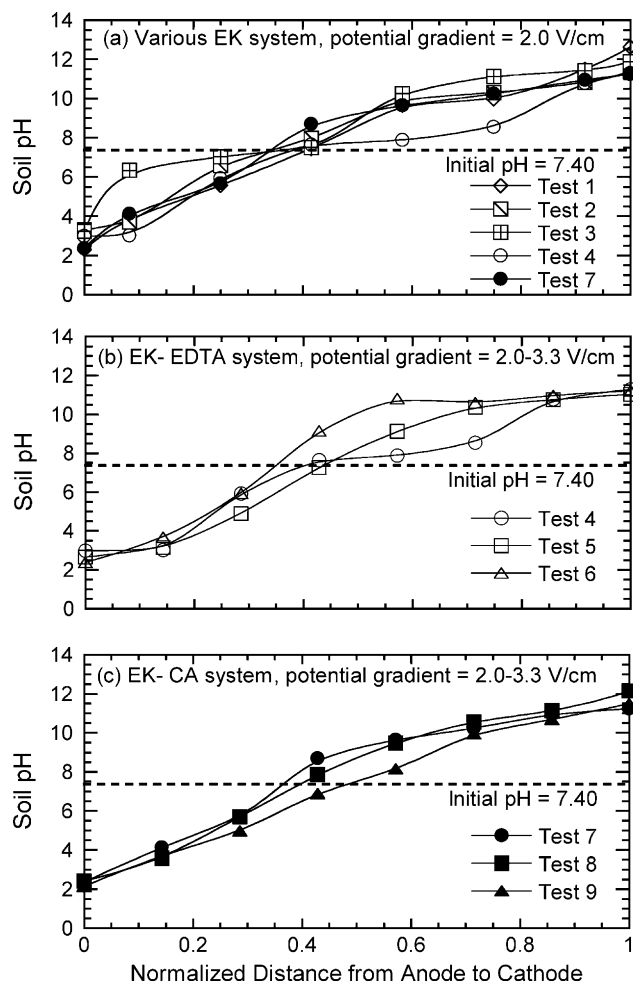


Fig. 2. Soil pH profiles in EK systems.

( $3.625 \times 10^{-7} \text{ m}^2/\text{V s}$  in free solution) is 1.75 times greater than that of  $\text{OH}^-$  ion. Therefore, the migration of  $\text{H}^+$  and  $\text{OH}^-$  producing acid and basic fronts, respectively, significantly changes the soil pH during the EK process. The soil pH profiles along the EK cell are shown in Fig. 2. A general trend of low pH near the anode and high pH near the cathode was found for all EK experiments. A lower soil pH found in EK-CA system was resulted from citric acid. The acceleration of electrochemical reactions during a field increase leads to faster pH change in the near-electrode areas. Hence, as potential gradient increased, it resulted in a higher pH gradient along the EK cell (Fig. 3b and c).

The variations of current density as a function of time in four EK systems (EK-GW, EK-CPC, EK-EDTA, and EK-CA) were shown in Fig. 3. When the reservoir pH was not conditioned with any chemical reagents (Test 1), the electric current was relatively small. The electric current across soil cell is highly related to the concentration of mobile ions in soil cell [9]. The mobile ions might include two kinds of species [12]: (1)  $\text{H}^+$  and  $\text{OH}^-$  generated by water electrolysis; and (2) the species extracted from the original soil specimen due to mobilization mechanism such as ion exchange, desorption, dissolution, etc. When no external ions are added in the electrolytes, the electric current is

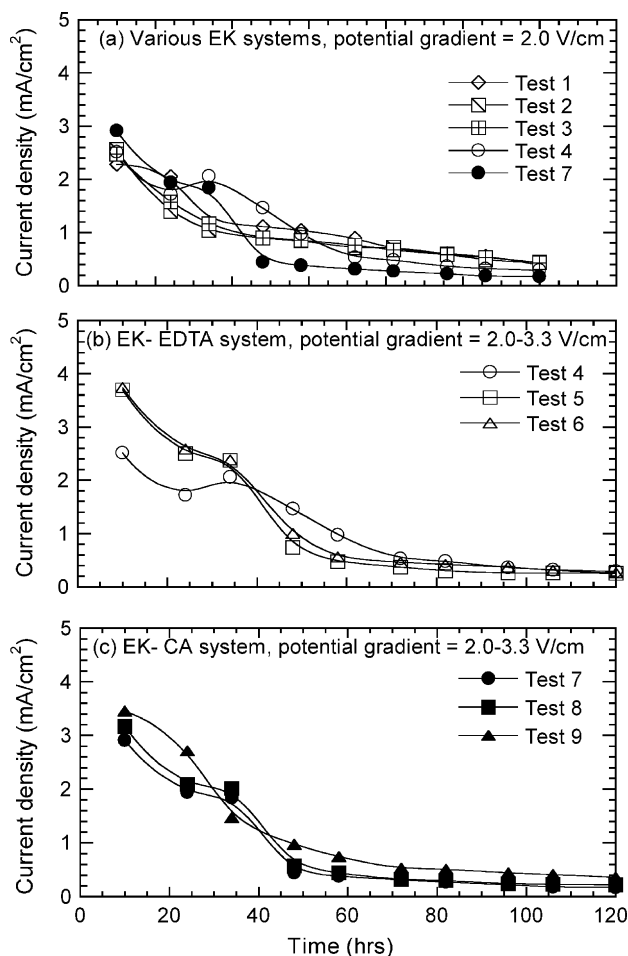


Fig. 3. Variations of current density as a function of treatment time in EK systems.

expected to be a low level. In Fig. 3a, the initial current density of EK-GW system (Test 1) was  $2.28 \text{ mA}/\text{cm}^2$ , then decreased to  $0.71 \text{ mA}/\text{cm}^2$  within 72 h, and reached to  $0.38 \text{ mA}/\text{cm}^2$  finally. Similar phenomenon was found in other three EK systems. The highest initial current density of  $2.91 \text{ mA}/\text{cm}^2$  was found in EK-CA system, then sharply decreased to  $0.44 \text{ mA}/\text{cm}^2$  within 48 h and gradually reached to  $0.17 \text{ mA}/\text{cm}^2$ . A similar trend of gradual decrease in current density to a stable value among Tests 1–4 and Test 7 suggests that the soil itself contained amounts of free ion, which was removed from soil matrix at early stages [16]. The soil pH variation (as shown Fig. 2) and clogging of complexing compounds in the soil pore resulted in a low current density at final. As shown in Fig. 3b and c, the current density in EK-EDTA and EK-CA systems were increased as applied potential gradient increased. This might largely because of permeability variation by soil pH and potential gradient.

### 3.2. The effect of chemical reagents on As(V) removal

In EK process, the principle mechanisms leading to the removal of metals from the soil are electroosmosis and electromigration [9,33]. The electroosmosis is a water flow causing by potential difference of the electrode and contaminants are carried

toward the electrodes. The electromigration is the charged ions in the water flow moved to the counter-electrode by the application of electrical current. The movement of electrolyte solution, i.e., electroosmotic flow,  $Q_e$  (mL/day), for a cylindrical soil core is directly proportional to the applied electric potential gradient ( $i_e$ , V/cm):

$$Q_e = K_e i_e A \quad (1)$$

where  $A$  (cm<sup>2</sup>) is cross-section area of soil core and  $K_e$  (cm<sup>2</sup>/V s) is electroosmosis permeability. The results of EK experiments are summarized in Table 2. As applied potential gradient of 2.0 V/cm (Tests 1–4 and 7), results showed that a higher cumulative electroosmotic flow rate of 28.4–30.2 mL was found in EK-CPC systems (Tests 2 and 3), which was nearly two times greater than that in EK-GW system (15.6 mL, Test 1). Consequently, it resulted in a highest  $K_e$  values of  $11.9 \times 10^{-6}$  to  $12.6 \times 10^{-6}$  cm<sup>2</sup>/V s for EK-CPC systems. It might largely because of the characteristic of mobility enhancement of surfactant, such as CPC. However, huge size of CPC micelles might adversely affect the permeability; hence the  $K_e$  value slightly decreased as applied higher concentration of CPC in EK system (Test 3). For EK-EDTA and EK-CA systems, the free ions contained in the soil were removed from soil matrix at early stages by EDTA and citric acid (as shown in Fig. 3) and resulted in a higher  $K_e$  and  $Q$  than those in EK-GW systems. As applied potential gradient of 2 V/cm for 5-day EK treatment, the removal efficiency of As(V) was in the range of 31.1–35.4% for EK-CPC (Tests 2–3), EK-EDTA (Test 4), and EK-CA (Test 7) systems, which was 1.2–1.3 times greater than that in EK-GW system (26.9%). The chemical reagents of EDTA showed a better EK performance for As(V) removal than other two chemical reagents. It implied that the binding capacity of  $\text{HAsO}_4^{2-}$  on CPC micelle surface was low and acid environment would not mobilize arsenic species from As–Fe associates in the soil. It was inferred that choosing suitable chemical reagents would enhance removal efficiency in EK systems.

### 3.3. The effect of potential gradient on As(V) removal

The potential gradient represents the potential difference across the electrode. It dominates the electroosmosis flow, which

carries the contaminants out from soil. As shown in Table 2, the  $K_e$  values were decreased as potential gradient increased from 2.0 V/cm to 3.3 V/cm in both EK-EDTA and EK-CA systems. It may largely because more  $\text{OH}^-$  produced by water electrolysis in EK system with high potential gradient, which could be confirmed by results of soil pH in Fig. 3b and c, and resulted in the clog of soil pore by precipitates of arsenic oxide. As potential gradient increased from 2.0 V/cm to 3.3 V/cm, the removal efficiency of As(V) increased from 35.4% to 44.8% (Tests 4–6) in EK-EDTA system. It may result from the high electroosmosis flow which carried more As(V) out off the EK cell. In EK-CA system (Tests 7–9), no significant improvement of removal efficiency of As(V) was found as potential gradient increased, which was stably maintained in a range of 32.7–33.6%. It was inferred that the releasing of  $\text{HAsO}_4^{2-}$  to aqueous could not be enhanced in low-pH environment.

### 3.4. The mass distribution of arsenic

Mass distribution of arsenic in EK systems was shown in Table 3. Results showed that no reduction product of As(III) was found in EK systems hence toxicity suspicion was not needed to be considered. Arsenate was existed either in the soil phase, which represented the portion that can not be removed by EK process, or in the reservoir solution, which was the portion of effectively removed by EK process. The recovery rate of arsenic in these two phases was in the range of 95.9–97.3% for all experiments. As shown in Table 3, the portions collected in anode and cathode reservoir solution was 58.3% and 41.7%, respectively, which represented the quantity of As(V) collected in anode solution was 1.4 times greater than that in cathode solution. For other three EK systems, the difference of As(V) collected from two electrode reservoir became more significant. The quantity of As(V) collected in anode solution (61.7–71.6%) was 1.6–2.5 times greater than that in cathode solution (28.4–38.3%) for Tests 2–9. This was inferred that most of As(V) was existed as anionic form of  $\text{HAsO}_4^{2-}$  in the EK system and, consequently,  $\text{HAsO}_4^{2-}$  migrated to the anode by electrical force. Moreover, the electromigration of As(V) was related to chemical reagent. Less amount of As(V) was collected in anode solution in EK-CPC system than EK-EDTA and EK-CA systems. This might

Table 3  
Mass distribution of arsenic in EK systems

Test no.	(1) Initial As(V) (mg)	(2) Residual As(V) in soil (mg)	As(V) in reservoir			(6) Mass balance of As(V) (%)
			(3) Anode (mg)	(4) Cathode (mg)	(5) Total As (mg)	
1	193.2	141.2	27.0	19.3	46.3	96.9
2	193.2	133.2	34.2	19.2	53.4	96.6
3	193.2	132.1	33.5	20.7	54.2	96.4
4	193.2	124.9	43.5	18.0	61.5	96.5
5	193.2	114.0	51.4	22.3	73.7	97.1
6	193.2	106.7	55.7	22.9	78.6	95.9
7	193.2	128.3	40.5	18.5	59.0	96.9
8	193.2	131.0	40.8	16.2	57.0	97.3
9	193.2	130.0	40.1	16.2	56.3	96.4

No As(III) was detected in all EK experiments: (5) = (3) + (4); (6) = [(2) + (5)]/(1).

largely because of the large size of CPC micelles. Other than electromigration, electroosmosis flow caused by potential gradient is another electrokinetical mechanism to remove As(V) from soil, which is flow from anode to cathode. The intensive of electroosmotic flow towards the cathode caused a significant retardation of electromigration of arsenic towards the anode. As found in Table 3, it was found that the contribution of electromigration for As(V) removal in EK systems was higher than electroosmosis flow. This was consistent with results of Kim et al. [34].

### 3.5. The residual As(V) profile in EK systems

After EK treatment, the residual concentration of As(V) in soil specimen was quantitatively determined as equally sectioned into six segments. Results of residual profile of As(V) along the EK cell are shown in Fig. 4. The residual arsenic concentrations were globally lower than their initial concentrations. A general trend was found that higher As residual near anode end was found for all EK systems. This might largely because arsenic was formed as anionic type in solution and the concentration front was shifted from cathode to anode. Although, the

electroosmosis flow is from anode to cathode, Table 3 was shown that more arsenic was collected in the anode reservoir.

As shown in Fig. 4a, the residual concentration of As(V) tremendously decreased near the anode side as using chemical reagents under 2.0 V/cm of potential gradient, whereas it was not significant near the cathode side. It was implied that the concentration front of As(V) was shifted from anode to cathode by EDTA and citric acid and potential gradient of 2.0 V/cm was not high enough to shift the concentration front all throughout the EK cell. The effects of potential gradient on residual concentration of As(V) were shown in Fig. 4b and c. In EK-EDTA system, the As(V) removal was more significant near the anode side than the cathode side as applied potential gradient increasing from 2.0 V/cm to 3.3 V/cm. Furthermore, concentration peaks were found in the 2nd, and 3rd soil sections from the anode for EK-EDTA systems with potential gradient of 2.7 V/cm and 3.3 V/cm, respectively. It was clearly shown that the concentration front was shifted toward to cathode as potential gradient increasing. Hence, the applied potential gradient was a key factor to force As(V) removal from the soil matrix. Similar trend was also found in EK-CA system (Fig. 4c).

### 3.6. Power consumption

Energy expenditure in EK systems is calculated as follows:

$$E_u = \frac{P}{W} = \frac{1}{W} \int VI dt \quad (2)$$

where  $E_u$  = energy expenditure per unit weight of soil ( $\text{kWh}/\text{m}^3$ );  $P$  = energy expenditure ( $\text{kWh}$ );  $V_s$  = volume of soil ( $\text{m}^3$ );  $V$  = voltage (V);  $I$  = current (A);  $t$  = time (h). In the tests of constant-voltage condition, the energy expenditure is directly related to the time integral of the current across the cell. The calculated energy consumption is 256, 225–237, 249–465, and 198–453  $\text{kWh}/\text{m}^3$  in EK-GW, EK-CPC, EK-EDTA, and EK-CA systems, respectively (Table 2). It is apparent that the chemical reagents and potential gradient applied are the controlling factors with respect to energy consumption in EK systems.

## 4. Conclusions

An enhanced electrokinetic remediation technology for As spiked soil was investigated in this study. It was concluded that the arsenic removal could be enhanced by selecting suitable chemical reagents and increasing potential gradient. After 5-day EK treatment under potential gradient of 2.0 V/cm, the removal efficiency of As(V) in enhanced EK systems was 1.2–1.3 times greater than that in EK-GW system (26.9%). The enhanced removal of As(V) was resulted from the characteristics of chemical reagents, included counterion binding, chelating and solubility enhancement in acid environment. A better EK removal of 44.8% for As(V) was found in EK-EDTA system with higher potential gradient. The quantity of As(V) collected in anode reservoir was 1.4, 1.6–1.8, 2.3–2.4, and 2.2–2.5 times greater than that in cathode reservoir in EK-GW, EK-CPC, EK-EDTA, and EK-CA system, which was reasonably inferred that most of As(V) was existed as anionic form of  $\text{HAsO}_4^{2-}$  and,

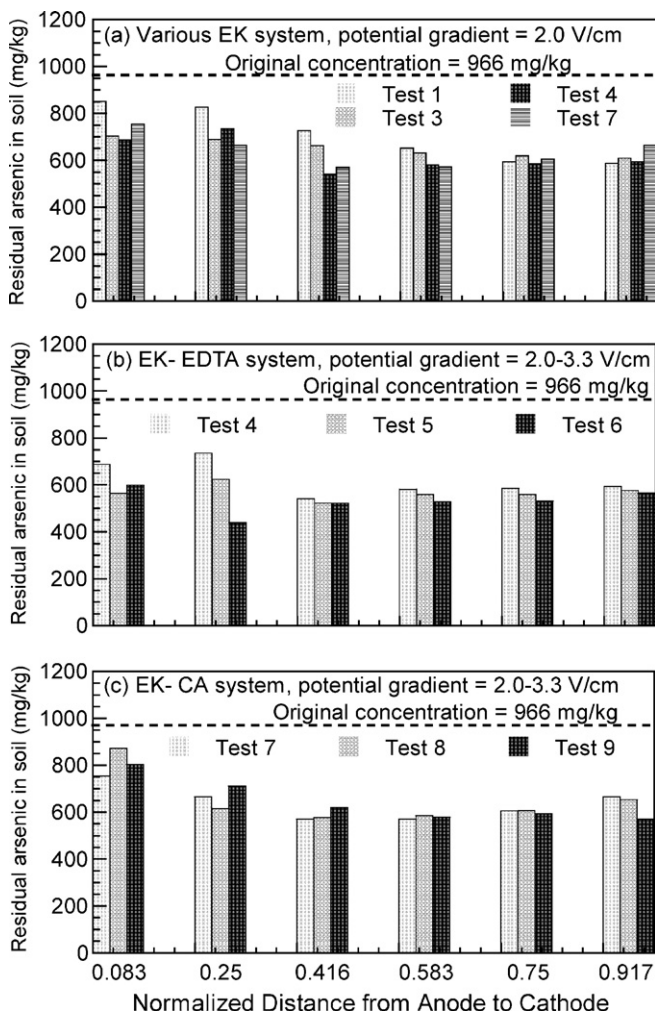


Fig. 4. Residual arsenic profiles in EK systems.

consequently, it migrated to the anode by electrical force. It indicated that As(V) removal was directly related to the electromigration rather than electroosmosis mechanism in EK systems. However, a further investigation need to be conducted to achieve higher removal performance of As(V), such as applying more suitable chemical reagent and prolonging treatment time.

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