Removal of heavy metals from kaolin using an upward electrokinetic soil remedial (UESR) technology

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Abstract

An upward electrokinetic soil remedial (UESR) technology was proposed to remove heavy metals from contaminated kaolin. Unlike conventional electrokinetic treatment that uses boreholes or trenches for horizontal migration of heavy metals, the UESR technology, applying vertical non-uniform electric fields, caused upward transportation of heavy metals to the top surface of the treated soil. The effects of current density, treatment duration, cell diameter, and different cathode chamber influent (distilled water or 0.01 M nitric acid) were studied. The removal efficiencies of heavy metals positively correlated to current density and treatment duration. Higher heavy metals removal efficiency was observed for the reactor cell with smaller diameter. A substantial amount of heavy metals was accumulated in the nearest to cathode 2 cm layer of kaolin when distilled water was continuously supplied to the cathode chamber. Heavy metals accumulated in this layer of kaolin can be easily excavated and disposed off. The main part of the removed heavy metals was dissolved in cathode chamber influent and moved away with cathode chamber effluent when 0.01 M nitric acid was used, instead of distilled water. Energy saving treatment by UESR technology with highest metal removal efficiencies was provided by two regimes: (1) by application of 0.01 M nitric acid as cathode chamber influent, cell diameter of 100 mm, duration of 18 days, and constant voltage of 3.5 V (19.7 kWh/m^3 of kaolin) and (2) by application of 0.01 M nitric acid as cathode chamber influent, cell diameter of 100 cm, duration of 6 days, and constant current density of 0.191 mA/cm^2 (19.1 kWh/m^3 of kaolin).
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1. Introduction

Electrokinetic soil remediation is one of the promising in situ technologies to remove heavy metals from contaminated fine-grained soils with low hydraulic permeability [1–4]. A low-level direct current (DC) is applied across electrodes, inserted in the treated soil, to generate an electric field for removal of the contaminants [1,5–7]. These electric fields induce the transport of heavy metals ions in soil pore water due to electromigration, as well as electroosmosis and electrophoresis [8]. The process of contaminants electromigration is influenced by their diffusion coefficient, valence, and concentration. The affinity of the metal to the surface of soil particles also affects its mobility [9]. Positively charged ions of heavy metals migrate in electric fields towards cathode and can be further removed from the

contaminated soils by extraction, precipitation or ion exchange [4,6,8,10,11].

Usually, DC electric fields applied to contaminated soil are horizontal with constant current density or constant electric potential gradient (uniform). There were only a few attempts to apply vertical electric fields for treatment of contaminated soils. The Lasagna technology included either horizontal or vertical zones between electrodes to remove soluble organic compounds from contaminated soils with low permeability. To generate vertical electric fields, the horizontal electrodes were proposed to use for transportation of the contaminants upwards and/or downwards [9,10]. It was demonstrated that relatively uniform vertical electric potential gradient could be created between disk-shaped electrodes formed by hydraulic fracturing method in clay [12]. There has been no reported study on removal of heavy metals in vertical electric fields.

Most electrokinetic remediation technologies used one-dimensional uniform electric fields [13–15]. There were limited studies where non-uniform electric field was used [16,17]. For

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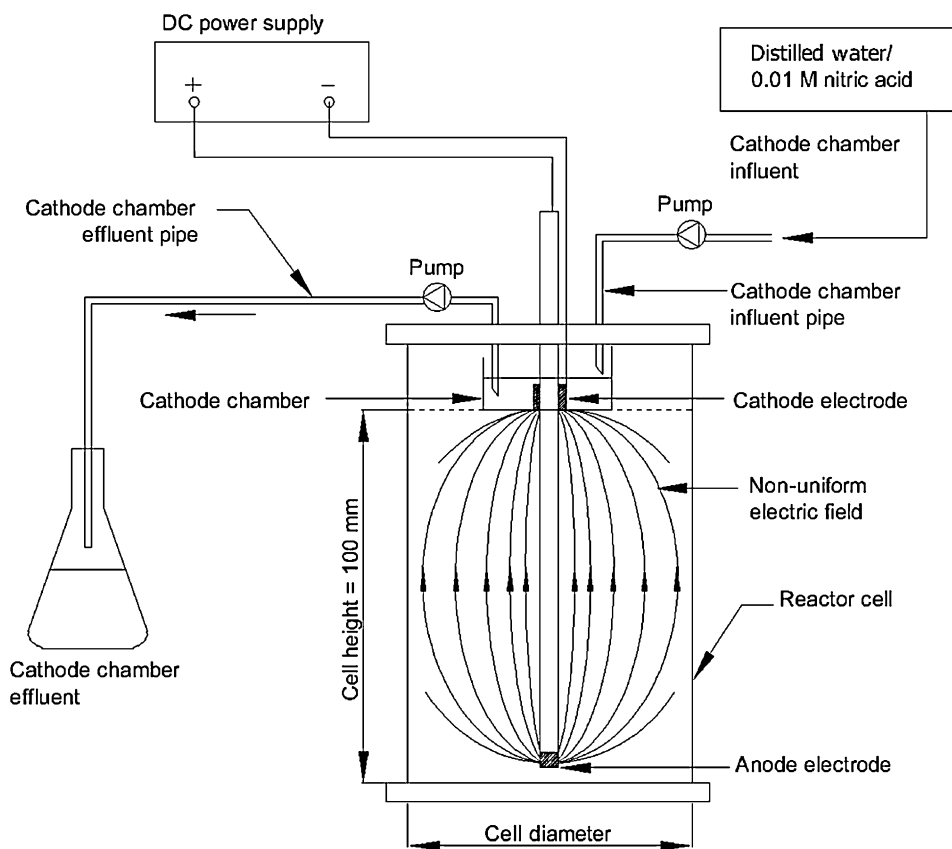 *E-mail address:* jywang@ntu.edu.sg (J.-Y. Wang).

Fig. 1. Schematic design of UESR reactor.

example, two-dimensional electric field was proposed for transport across inhomogeneous charged porous media [18]. Two-dimensional electric field was used for removal of *m*-xylene from kaolin [19]. The characteristics and distribution of non-uniform electric fields were investigated for various configurations of line-shaped electrodes [20]. Application of two-dimensional electric field was studied for remediation of kaolin polluted by copper [21].

The present study proposed an upward electrokinetic soil remedial (UESR) technology based on the application of a vertical non-uniform three-dimensional electric field for the removal of heavy metals from contaminated kaolin.

2. Material and methods

2.1. Materials

Commercial kaolin with moisture content below 2.5% (Kaolin Sdn. Bhd., Malaysia) was used. It contained 45–50% of SiO_2, 33–39% of Al_2O_3, and trace amount of Fe_2O_3 and MgO. Approximately 67% of the kaolin particles had size smaller than 10 μm. The pH of the kaolin slurry, prepared from kaolin mixed with distilled water in the ratio of 3:7 (w/w), was 4.7. The kaolin was artificially contaminated by nitrates of As(III), Cr(III), Ni(II), Cu(II), Zn(II), Pb(II), and Cd(II). Nitrate salts of these heavy metals were dissolved in deionized water to produce solutions with the concentrations of individual metals from 175

to 1650 mg/l. One thousand grams of kaolin and 600 ml of heavy metals solution were thoroughly mixed in a mixer (SP-800, RHINO, Taiwan) at 100 rpm for 5 min. The contaminated kaolin was left at room temperature, 25 °C, for 24 h before it was packed into the reactor cell. Initial contents of heavy metals for experiments from T1 through T5 were as follows: As, 165 mg/kg; Ni, 107 mg/kg; Cu, 338 mg/kg; Zn, 363 mg/kg; Pb, 472 mg/kg; Cd, 288 mg/kg. Initial contents of heavy metals for experiments from T6 through T8 were as follows: As, 169 mg/kg; Ni, 180 mg/kg; Cu, 216 mg/kg; Zn, 210 mg/kg; Pb, 241 mg/kg; Cd, 188 mg/kg. Initial content of Cr for experiment T2 was 289 mg/kg.

2.2. UESR reactor design

The UESR reactor consisted of a cell, anode and cathode electrodes, a DC power supply, cathode chamber influent pipe, and cathode chamber effluent pipe (Fig. 1). Schematic design of UESR reactor shows directions of generated electric fields. Spreading of generated electric fields into kaolin will be limited by the position of anode and will not spread deeper in kaolin than the anode position. Therefore, for laboratory experiment a cell with bottom was used. In practice, electrodes will be introduced in treated soil directly without any mechanical restrictions.

The cell was transparent and equipped with a cap that had orifices, tubing, and wiring. The anode electrode consisted of rod-shape graphite (a diameter of 8.5 mm) sheathed in an acrylic

Table 1
Removal efficiencies of different heavy metals after UESR treatment

Test	Cathode chamber influent	Cell diameter (mm)	Current density (mA/cm^2)	Electric potential gradient (V/cm)	Duration (days)	Removal efficiencies (%)							Unit energy expenditure (kWh/m^3 of kaolin)
						As	Cr	Ni	Cu	Zn	Pb	Cd	
T1	Distilled water	100	0.191[a]		4	1.8	16.0	43.9	27.7	14.4	6.4	31.3	102
T2	Distilled water	100	0.191[a]		6	26.0	45.6	50.0	33.8	51.6	42.1	42.8	263
T3	Distilled water	100	0.191[a]		9	27.0	49.7	68.3	51.2	49.6	52.5	67.2	350
T4	Distilled water	70	0.390[a]		6	43.1	52.3	56.6	45.9	59.3	48.4	50.5	500
T2	Distilled water	100	0.191[a]		6	26.0	45.6	50.0	33.8	51.6	42.1	42.8	263
T5	Distilled water	140	0.097[a]		6	11.1	8.6	11.8	11.1	10.2	7.4	12.1	25
T6	0.01 M Nitric acid	100	0.140–0.204[b]	0.35[c]	6	15.4		32.8	32.2	30.6	25.9	32.0	9
T7	0.01 M Nitric acid	100	0.089–0.191[b]	0.35[c]	18	12.9		65.3	62.5	61.0	44.9	61.3	20
T2	Distilled water	100	0.191[a]		6	26.0	45.6	50.0	33.8	51.6	42.1	42.8	263
T8	0.01 M Nitric acid	100	0.191[a]		6	23.2		57.2	56.2	53.2	35.7	56.4	19

[a] Tests conducted with constant current of 15 mA.
[b] The range of current density measured during the tests.
[c] Tests conducted with constant voltage of 3.5 V.

insulating tube (with an internal diameter of 10.5 mm and an outer diameter of 12.5 mm). The insulating tube prevented direct contact between anode and cathode and ensured the anode was only exposed to the kaolin at the tip. The cathode electrode was a perforated stainless steel ring (with an internal diameter of 30 mm, an outer diameter of 60 mm, and thickness of 2 mm). The electrodes generated a non-uniform electric field that pointed upward in the treated soil. The DC power supply (Nemic Lambda; Model GEN300-2.5, USA) provided a maximum voltage of 300 V, or a current of 2.5 A. It had two operation modes, constant current or constant voltage. Peristaltic pumps were used to deliver cathode chamber influent to control the pH at cathode and to remove cathode chamber effluent at the same flow rate.

2.3. Experimental setup

Eight tests were conducted to study the effects of treatment duration, cell diameter, and nature of cathode chamber influent on electrokinetic removal of heavy metals (Table 1). To prevent kaolin acidification and taking into account that kaolin, used in the experiments, had initial pH of 4.7, distilled water was chosen as electrolyte in tests (T) for study the effects of treatment duration and cell diameter (from T1 to T5). However, application of the acids solutions such as 0.4 M acetic acid or 0.5N sulfuric acid [22], and 0.5N HCl [23] as the cathode electrolytes was shown more efficient for heavy metal removal than distilled water. Therefore, 0.01 M nitric acid was used, instead of distilled water, in tests (T6–T8). T1, T2, T3, T4, T5, and T8 were conducted with a constant current of 15 mA, while T6 and T7 were conducted with a constant voltage of 3.5 V.

The contaminated kaolin was packed into the reactor cell by layers with 2 cm high each and left for 12 h at room temperature (25 °C) to attain equilibrium before installation of the electrodes. Three samples were taken from different layers to determine the initial pH, moisture content, and contents of heavy metals.

The anode was inserted to the bottom of the contaminated kaolin. The cathode electrode was placed on the center of kaolin top. The tubing and electric wiring were then connected. The cell was capped and cathode chamber influent started to flow with the rate of 1.1 ml/min. After 1 h, the direct current or direct voltage supply was started. The cell, containing contaminated kaolin, stood vertically during the treatment. The liquid level in the cathode chamber was kept at level from 2 to 4 mm above the cathode surface. The cathode chamber effluent was continuously removed to maintain the constant liquid level. The voltage and current, as well as the pH and content of heavy metals in cathode effluent were measured twice a day.

The cell was disassembled and electrodes were removed from kaolin after the electrokinetic treatment. The cathode electrode was soaked in a 1 M nitric acid to remove the heavy metals deposited on the electrode surface. The treated kaolin was extruded out from the cell, sliced into layers of 2 cm and was analyzed for pH, moisture, and heavy metals contents. The heavy metal precipitate accumulated in the nearest to cathode 2 cm layer of kaolin (dark green in color) was collected. In the experiments, using the cells with diameters of 100 and 140 mm, the kaolin was divided into inner and outer zones (Fig. 8a) for further examination.

2.4. Chemical analysis

The pH value of the kaolin samples was measured in a suspension of 1 g of kaolin in 10 ml of distilled water using a pH meter (Model 710A, Orion, Boston, MA, USA). Kaolin was dried in an oven at 103 °C for 24 h to determine its moisture content. The content of heavy metals in kaolin was determined by acid digestion [26,27]. The oven-dried samples were ground into fine particles by a soil grinder mill (Fritsch, Canada). 0.1 g of sample was weighed with accuracy to 0.001 g and placed in a 15 ml quartz vessel and 3 ml of nitric acid with concentration of 69.9% was added. The mixture was ultrasonicated for 20 min (Branson, Model 1510, Switzerland) and subsequently digested under 300 °C and 90 bars in a High Pressure Asher (Anton Paar,

Model HPA-S, Craz, Austria) for 160 min. The digested mixture was diluted and then filtered using a 45 μm pore size Whatman membrane filter. The filtrate was analyzed for heavy metals using an inductively coupled plasma (ICP) emission spectrometry (Perkin-Elmer, Model Optima 2000DV). Two replicates were analyzed for each sample and the average value was reported.

2.5. Evaluation of heavy metals removal

The removal efficiency of heavy metal was calculated from the differences between metal amount removed from kaolin and its initial amount presented in kaolin using the following equation:

$$Q = \frac{C_0 - C_f}{C_0} \times 100\%, \tag{1}$$

where Q is removal efficiency of heavy metal (%) and C_0 and C_f are the initial and final amount of metal in kaolin (mg), respectively.

3. Results and discussion

3.1. Observations of kaolin during electrokinetic treatment

Visible deposition of heavy metals first formed on the bottom of cathode surface during 12 h of electrokinetic treatment and then propagated to all the cathode surfaces. Green precipitate of heavy metals was observed at the nearest to cathode 2 cm layer of kaolin in 24 h. The amount of this green precipitate at the end of the treatment varied depending on the types of cathode chamber influent used. There were usually large amount of precipitate when distilled water was used as cathode chamber influent; the cathode electrode was completely covered by it. The amount of precipitate was very small when 0.01 M nitric acid was used as cathode chamber influent.

Visible cracks developed in the treated kaolin after a few days of treatment and the cracks became wider and longer during the treatment. It was observed that the cracks appeared faster in the experiments with smaller cell diameter. The cracks probably resulted from unbalanced strains developed in kaolin when kaolin pore water was drawn off. The development of cracks in soils during electrokinetic treatment was also reported in the studies where horizontal eclectic fields were used [13].

3.2. Changes of electric potential gradient during electrokinetic treatment

In the tests with constant current (15 mA) and distilled water as cathode chamber influent (T1–T5), the electric potential gradient increased in 2–3 days to 9–11 V/cm and then steadily increased to 10–12 V/cm at the end of the process, probably due to the deposition of heavy metals on cathode and precipitation of metals in kaolin near cathode. The changes of electric potential gradient in kaolin for T2 and T4 are shown in Fig. 2. These data were in agreement with the observation that electric potential gradient increased rapidly in the first 4–5
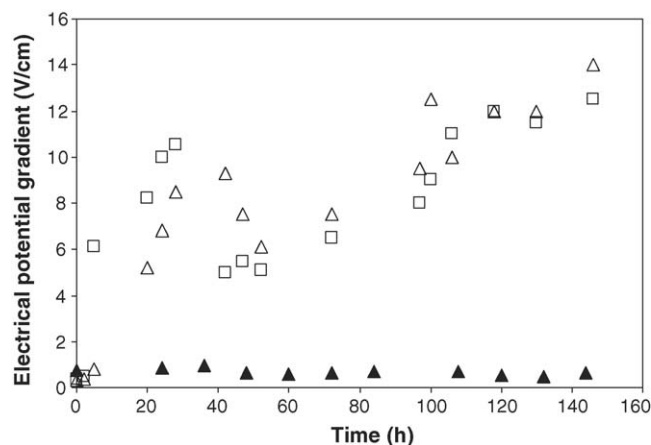

Fig. 2. Change of electric potential gradient during electrokinetic treatment of kaolin with constant current 15 mA for 6 days. (□) T4 (distilled water; cell diameter, 70 mm); (△) T2 (distilled water; cell diameter, 100 mm); (▲) T8 (0.01 M nitric acid; cell diameter, 100 mm).

days of electrokinetic treatment [5,8]. Similar results of electric potential gradient or apparent electric conductivity changes during electrokinetic treatment were reported in other studies [5,13,26–28].

In the tests with constant current and 0.01 M nitric acid as cathode chamber influent (T8), relatively stable electric potential gradient (0.5–0.9 V/cm) was observed during the electrokinetic treatment (Fig. 2). The increase of voltage was accompanied with the rise of pH at cathode indicating the precipitation of heavy metals (Fig. 3).

3.3. Changes in pH and concentrations of heavy metals in cathode chamber effluent during electrokinetic treatment

The pH values of cathode chamber effluent in the tests when distilled water was used as cathode chamber influent changed in
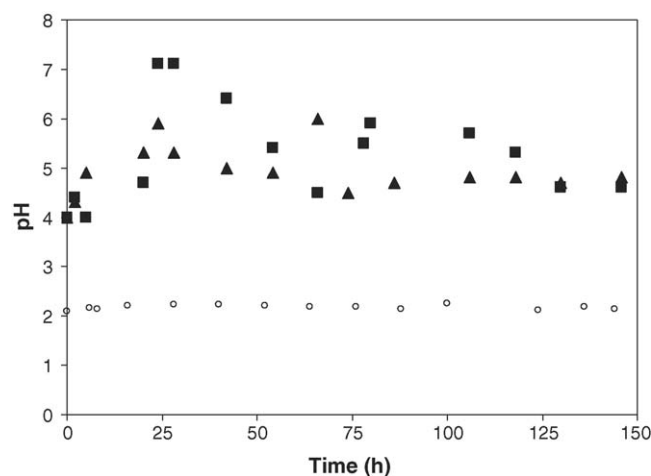

Fig. 3. Change of pH of cathode chamber effluent during the electrokinetic treatment with constant current 15 mA for 6 days. (▲) T4 (distilled water; cell diameter, 70 mm); (■) T2 (distilled water; cell diameter, 100 mm); (○) T8 (0.01 M nitric acid; cell diameter, 100 mm).

the range from 4 to 7 during electrokinetic treatment. The pH value was stable in a range from 1.9 to 2.3 when 0.01 M nitric acid was used as cathode chamber influent (Fig. 3).

The concentrations of heavy metals in cathode chamber effluent were near zero during all the electrokinetic treatments except the first 12 h when distilled water was used as cathode chamber influent. Cathode chamber effluent contained significant amount of heavy metals throughout the treatment when 0.01 M nitric acid was used (Fig. 4). Similar results were obtained when hydrochloric, nitric or acetic acids at low concentrations were used to control the pH in the cathode chamber [5,7,29].

3.4. Removal of heavy metals from contaminated kaolin by UESR technology

The removal efficiencies of heavy metals determined for eight tests are shown in Table 1. The influence of some factors on heavy metals removal efficiency was investigated.

It was shown that the removal efficiencies of heavy metals positively correlated with the duration of the electrokinetic treatment in the tests when either distilled water (Fig. 5a) or 0.01 M nitric acid were applied as cathode chamber influent (Fig. 5b).

Higher heavy metals removal efficiency was observed for the reactor cell with smaller diameter (70 mm) compared to those with bigger diameters, i.e. 100 and 140 mm, under the
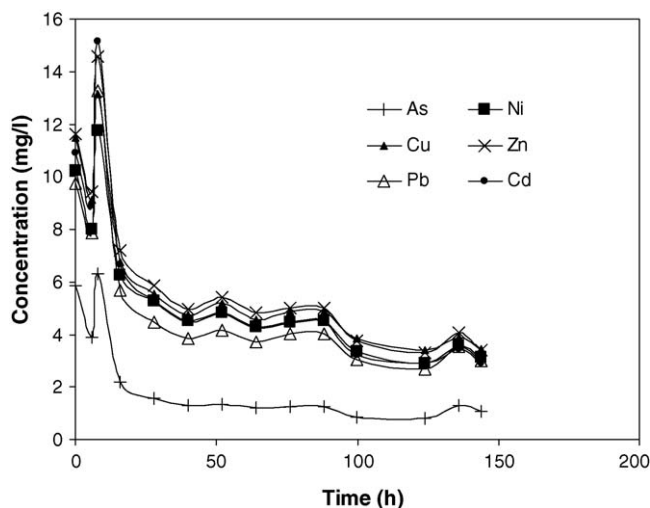

Fig. 4. Concentration of heavy metals in cathode chamber effluent in T6 (0.01 M nitric acid, 6 days, cell diameter 100 mm) with constant voltage of 3.5 V.

same conditions, i.e. distilled water was used as cathode chamber influent, duration of the treatment was 6 days, and constant current of 15 mA was applied (Fig. 6a). The application of the cell with bigger diameter at the same constant current caused the decrease of current density. The removal efficiency of heavy metals was higher when current density was increased (Fig. 6b).

Table 2
Distribution of heavy metals after UESR treatment

Heavy metal	Test	Distribution (%)			
		Fraction 1, remained in kaolin	Fraction 2, precipitated on nearest to cathode 2 cm layer of kaolin	Fraction 3, deposited on cathode	Fraction 4, dissolved in cathode effluent
As	T2	70.1	26.3	3.6	<1
	T8	78.9	0.7	3.8	16.6
	T6	85.2	0.4	3.5	10.9
	T7	81.8	1.0	2.1	15.0
Ni	T2	52.8	26.4	20.8	<1
	T8	38.1	2.9	9.1	49.9
	T6	63.3	0.7	7.6	28.4
	T7	33.6	4.3	1.6	60.6
Cu	T2	61.8	17.9	20.4	<1
	T8	40.7	5.5	8.3	45.5
	T6	65.2	0.9	7.4	26.5
	T7	37.7	5.3	2.3	54.7
Zn	T2	49.8	32.8	17.4	<1
	T8	41.8	3.6	8.1	46.5
	T6	64.8	0.6	7.1	27.4
	T7	36.6	3.7	1.6	58.1
Pb	T2	51.9	36.8	11.3	<1
	T8	63.0	2.6	6.1	28.4
	T6	72.4	0.9	6.5	20.2
	T7	52.7	4.4	2.5	40.5
Cd	T2	58.4	21.5	20.1	<1
	T8	39.9	4.3	7.9	47.9
	T6	64.4	0.8	6.6	28.2
	T7	37.0	3.7	1.8	57.5

Note: T2 (distilled water, constant current 15 mA, 6 days, cell diameter 100 mm); T8 (0.01 M nitric acid, constant current 15 mA, 6 days, cell diameter 100 mm); T6 (0.01 M nitric acid, constant voltage 3.5 V, 6 days, cell diameter 100 mm); T7 (0.01 M nitric acid, constant voltage 3.5 V, 18 days, cell diameter 100 mm).
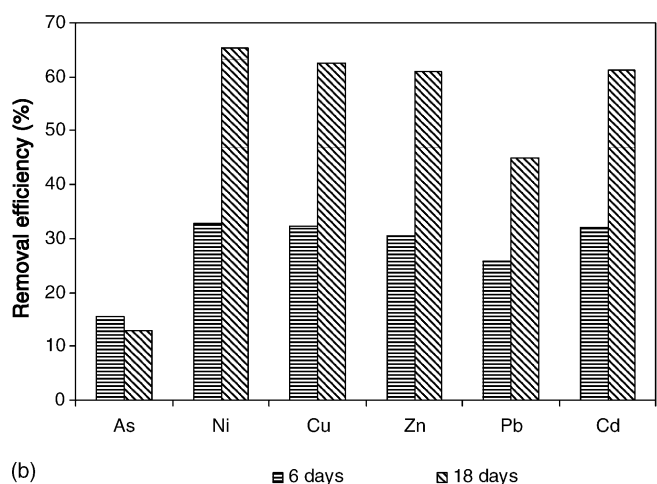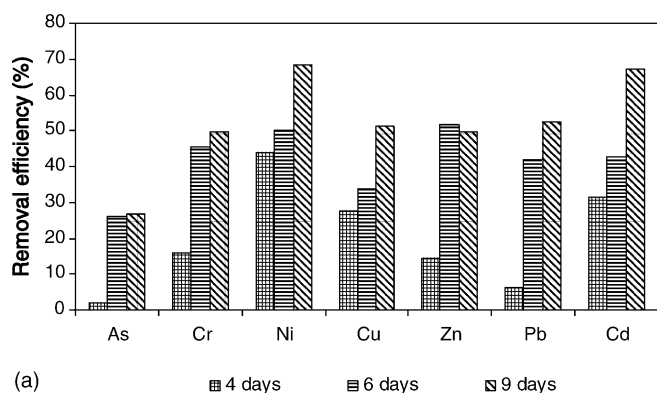
(a)

(b)

Fig. 5. Effect of duration on the removal efficiency of heavy metals: tests with distilled water and constant current 15 mA (a); tests with 0.01 M nitric acid and constant voltage gradient 3.5 V (b).

When current density changed from 0.1 to 0.2 mA/cm^2, the removal efficiencies increased in two to five times depending on the metals. However, removal efficiencies of heavy metals did not significantly change with further increase of current density to 0.4 mA/cm^2 (Fig. 6b). It could be due to the excess amount of OH$^-$ ions generated at the cathode for tests with higher current density when distilled water was used as cathode chamber influent.

The removal efficiencies obtained for different metals were as follows: Ni, 68.3%; Cd, 67.2%; Cu, 62.5%; Zn, 61%; Pb, 52.5%; Cr, 52.3%; and As, 43.1%. As was the least mobile metal and Ni was the most mobile metal. The other five metals showed similar mobility. There was no correlation of mobility with atomic weight. Other factors including diffusion constant, the radius of the hydrated metal ions, and affinity of metals to the kaolin particle surface probably played a more important role. The results of Cd, Pb, and Cr removal are in agreement with their reported effective mobility: Cd > Pb > Cr [7].

3.5. Distribution of heavy metals after UESR treatment between remained and removed from kaolin fractions

The heavy metals after UESR treatment were distributed in four fractions, i.e. remained in treated kaolin (fraction 1), pre-
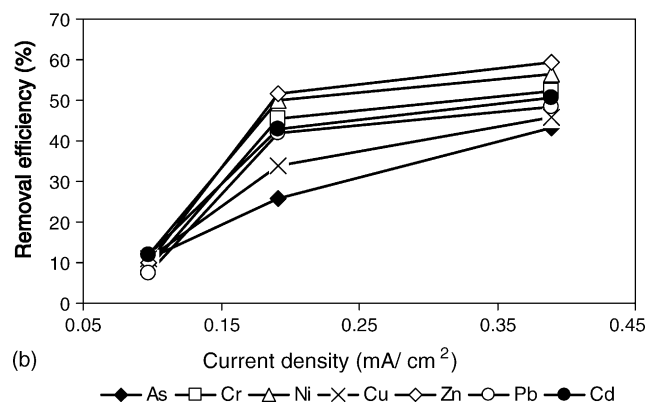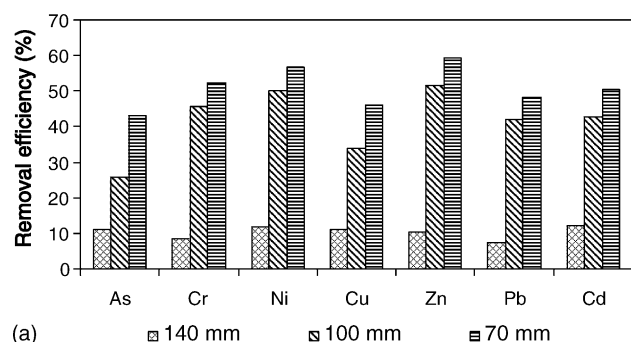

(a)

(b)

Fig. 6. Effect of cell diameter (a) and current density (b) on heavy metal removal efficiency (distilled water, 6 days, constant current 15 mA).

cipitated in the nearest to cathode 2 cm layer of kaolin (fraction 2), deposited on cathode (fraction 3) and dissolved in cathode chamber effluent (fraction 4) (Table 2). The metals which precipitated in the nearest to cathode 2 cm layer of kaolin, deposited on cathode, and dissolved in cathode effluent were considered as metals removed from treated kaolin. Most of removed heavy metals were in fractions 2 and 3, while only less than 1% of metals was found to be present in cathode chamber effluent when distilled water was used as cathode chamber influent (T2). The amount of metals in cathode chamber effluent significantly increased, while the other three fractions decreased for the tests with 0.01 M nitric acid as cathode chamber influent (T8). The higher removal of heavy metals with cathode chamber effluent and lower percentage of heavy metals remained in kaolin were observed when constant current density was applied (T8) in comparison with constant electric potential gradient (T6). The extension of duration from 6 days in T6 to 18 days in T7 improved the process of heavy metals removal with cathode chamber effluent and diminished the amount of heavy metals remained in kaolin.

3.6. Distribution of heavy metals in kaolin after UESR treatment

Content ratios, defined as ratios of final contents of heavy metals, i.e. As, Ni, Cu, Zn, Pb, and Cd, to their initial contents, were determined after UESR treatment at different distance to cathode (Fig. 7a and b).
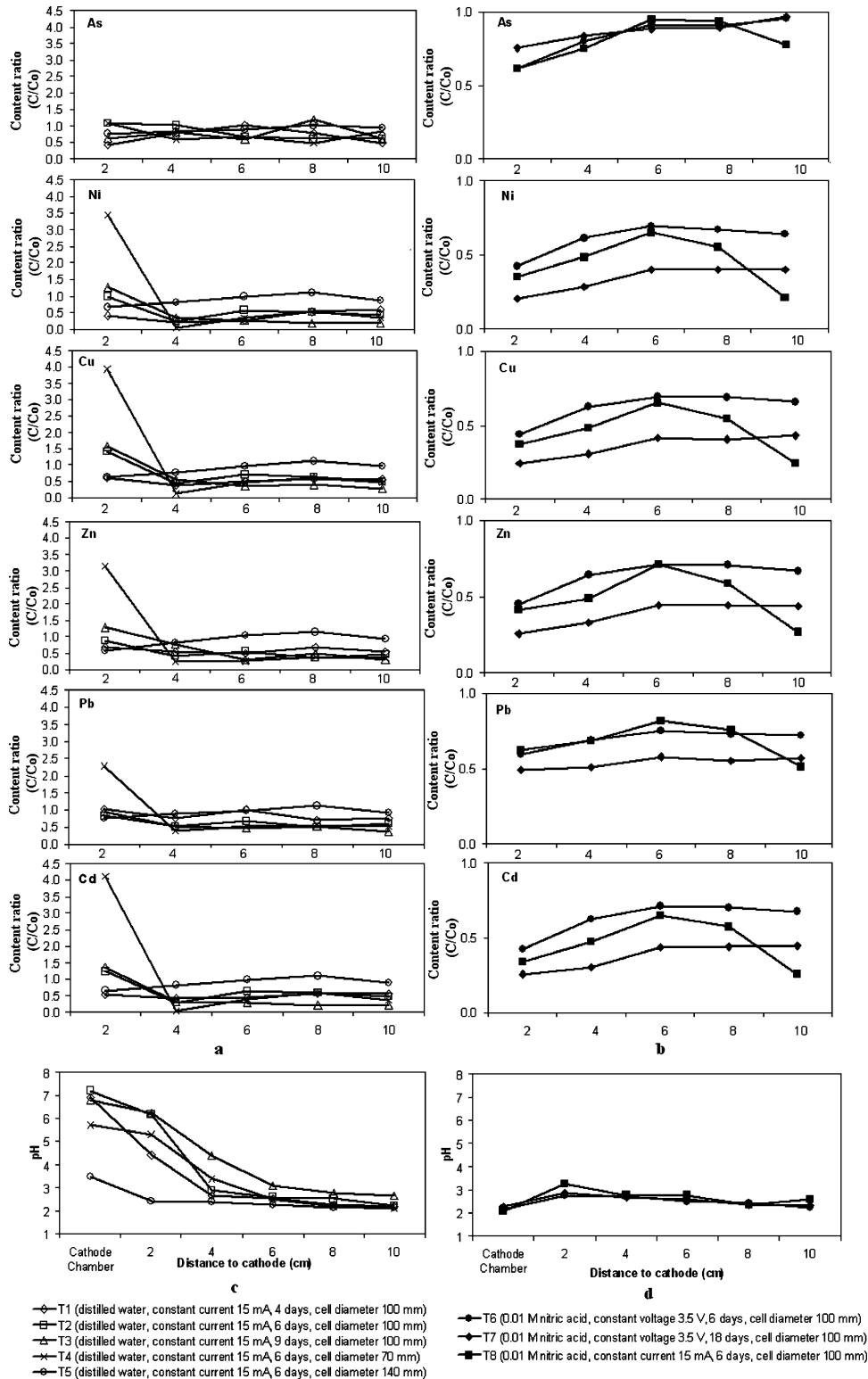
Fig. 7. Distribution of heavy metals in kaolin in tests 1–5 (a) and 6–8 (b); and change in pH profile of kaolin in tests 1–5 (c) and 6–8 (d).

Higher content ratio of metals (except for As) was observed in the nearest to cathode 2 cm layer of kaolin and lower content ratio was found in the rest of kaolin (2–10 cm to cathode) after UESR treatment when distilled water was used as cathode chamber influent (Fig. 7a). The curves of heavy metal dis-

tribution in kaolin after UESR treatment when 0.01 M nitric acid was used showed a different shape (Fig. 7b). The results of T6 and T7 demonstrated that the lowest content ratio of heavy metals was observed in part of the kaolin near cathode (1–4 cm to cathode), meanwhile content ratio of heavy
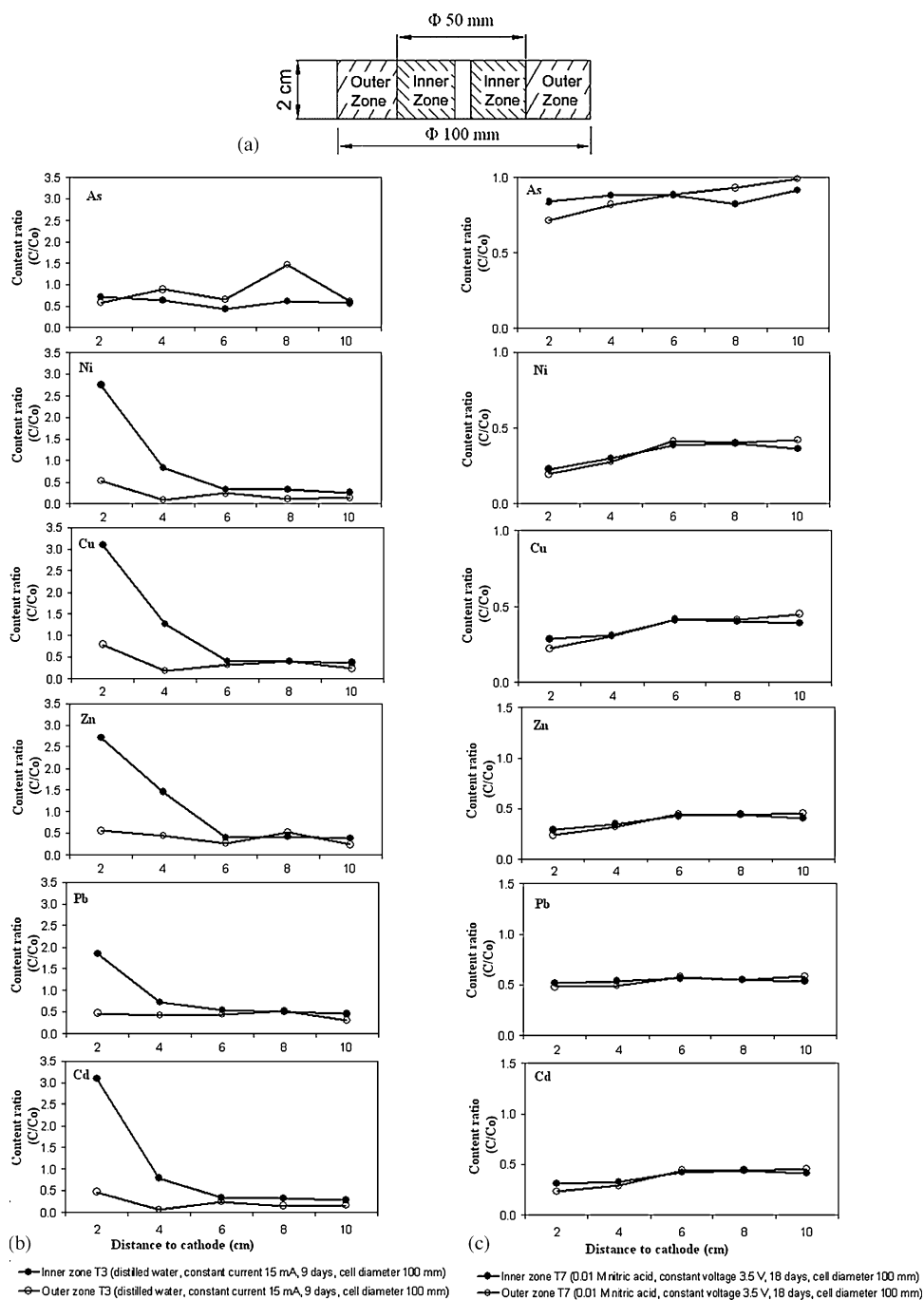
Fig. 8. Distribution of heavy metals in the inner and the outer zones (a) of kaolin in T3 (b) and T7 (c).

metals slowly increased and remained at constant level in the rest of kaolin (6–10 cm to cathode). The results of T8 deviated from those of T6 and T7 by registering the lowest content ratio in part of kaolin near anode (8–10 cm). The distribution of heavy metals across kaolin strongly correlated with the pH profile (Fig. 7c and d). No significant changes were found in the migration of As for both distilled water and 0.01 M nitric acid scenarios.

Distribution of heavy metals between inner and outer zones of kaolin (Fig. 8a) after UESR treatment with distilled water used as cathode chamber influent (T3) demonstrated the higher content ratio for all heavy metals (except As) in inner zone of kaolin, especially near cathode (Fig. 8b). It was due to non-uniform electric field generated by UESR. The electric field strength in the inner zone was higher than that in the outer zone; therefore, the transport of heavy metals in the inner zone was faster. For another point of view, electric fields in the outer zone delivered heavy metals to the nearest to cathode 2 cm layer of kaolin (Fig. 1). However, there was no significant difference in the content ratio of heavy metals in the inner and the out zones in T7 when 0.01 M nitric acid was used as cathode chamber influent (Fig. 8c).

Table 3
Comparison of the present study and the literature results

Heavy metals	Initial content (mg/kg)	Current density (mA/cm^2)	Electric potential gradient (V/cm)	Duration (days)	Removal efficiency (%)	Energy expenditure (kWh/m^3)	Reference
Pb	100–1064	0.037		17–54	75–95	29–60	[7]
	856–5322	0.133		54–123	80–90	60–700	[15]
	141–143	0.47		20–35	26–51	NA	[24]
	110–1000	0.022–0.111		23–31	70	NA	[25]
	472	0.191		9	53	250	Present study
	241		0.35	18	45	20	Present study
Cd	100–140	0.037		20–67	92–100	50–120	[14]
	288	0.191		9	67	349.7	Present study
	188		0.35	18	61	20	Present study
Cr	100–140	0.037		20–67	65–70	50–120	[14]
	233	0.191		9	50	350	Present study
	233	0.39		6	52	500	Present study
Zn	200		1	9	2–10	NA	[3]
	200		1	9	98	NA	[3]
	363	0.191		6	52	263	Present study
	210		0.35	18	61	20	Present study

NA: not available.

3.7. Energy expenditure

Energy expenditure for all tests was determined and shown in Table 1. Tests used 0.01 M nitric acid as cathode chamber influent consumed significantly less amount of energy than the tests that used distilled water. Higher energy consumption was observed for tests having smaller cell diameter or longer treatment duration. The energy expenditure reported in other studies ranged from 18 to >700 kWh/m^3 for kaolinite [8,13,30,31]. The energy expenditure for total removal of metals from contaminated soils was estimated as 500 kWh/m^3 [13]. The highest energy consumption for the tests conducted in the present study was 500 kWh/m^3 of kaolin and the lowest energy consumption was 9 kWh/m^3 of kaolin. More energy saving treatment by UESR technology with highest metal removal efficiencies was provided by application of 0.01 M nitric acid as cathode chamber influent, cell diameter 100 mm, duration 18 days, constant voltage of 3.5 V (T7), and by application of 0.01 M nitric acid as cathode chamber influent, cell diameter 100 cm, duration 6 days, constant current density 0.191 mA/cm^2 (T8) (Table 1).

3.8. Comparison between removal efficiencies of heavy metals in UESR technology and the related literature

The removal efficiencies and energy expenditure for heavy metals from contaminated kaolinite by electrokinetic treatment are given in Table 3. The removal efficiencies of Pb, Cd, Cr, and Zn obtained by UESR technology were comparable with literature data. High removal efficiencies up to 95% were reported for the removal of single heavy metal, e.g. Pb, but the treatment duration was from 54 to 123 days and energy expenditure was from 60 to 700 kWh/m^3 [4,8,30]. The ongoing research has demonstrated the UESR technology was effective in the simul-

taneous removal of heavy metals and organic contaminates from soils.

4. Conclusions

The upward electrokinetic soil remedial technology was proposed to remove heavy metals from contaminated kaolin. Unlike conventional electrokinetic treatment that uses boreholes or trenches for horizontal migration of heavy metals, the UESR technology applying vertical non-uniform electric fields caused upward transportation of heavy metals to the top surface of the treated soil. The removal efficiencies for heavy metals positively correlated to current density and treatment duration. A substantial amount of heavy metals accumulated in the nearest to cathode 2 cm layer of contaminated kaolin when distilled water was continuously supplied to the cathode chamber. Heavy metals accumulated in the upper layer of kaolin could be easily excavated and disposed off. The UESR technology had the beneficial features such as minimization of site disturbance as well as the reduction of the treatment costs because a cleanup of contaminated site takes place on the soil surface.

The main part of the removed heavy metals was dissolved in the cathode chamber influent and moved away with the cathode chamber effluent when 0.01 M nitric acid was used, instead of distilled water. Field application of UESR technology with 0.01 M nitric acid could remove heavy metals from the treated matter without excavation.

Energy saving treatment by UESR technology with highest metal removal efficiencies was provided by two regimes: (1) by application of 0.01 M nitric acid as cathode chamber influent, cell diameter of 100 mm, duration of 18 days, and constant voltage of 3.5 V (19.7 kWh/m^3 of kaolin) and (2) by application of 0.01 M nitric acid as cathode chamber influent, cell diameter

of 100 cm, duration of 6 days, and constant current density of 0.191 mA/cm^2 (19.1 kWh/m^3 of kaolin).

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