

Simultaneous removal of organic contaminants and heavy metals from kaolin using an upward electrokinetic soil remediation process

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Received 8 August 2006; received in revised form 29 September 2006; accepted 7 October 2006

Available online 13 October 2006

Abstract

Kaolins contaminated with heavy metals, Cu and Pb, and organic compounds, *p*-xylene and phenanthrene, were treated with an upward electrokinetic soil remediation (UESR) process. The effects of current density, cathode chamber flushing fluid, treatment duration, reactor size, and the type of contaminants under the vertical non-uniform electric field of UESR on the simultaneous removal of the heavy metals and organic contaminants were studied. The removal efficiencies of *p*-xylene and phenanthrene were higher in the experiments with cells of smaller diameter or larger height, and with distilled water flow in the cathode chamber. The removal efficiency of Cu and Pb were higher in the experiments with smaller diameter or shorter height cells and 0.01 M HNO₃ solution as cathode chamber flow. In spite of different conditions for removal of heavy metals and organics, it is possible to use the upward electrokinetic soil remediation process for their simultaneous removal. Thus, in the experiments with duration of 6 days removal efficiencies of phenanthrene, *p*-xylene, Cu and Pb were 67%, 93%, 62% and 35%, respectively. The experiment demonstrated the feasibility of simultaneous removal of organic contaminants and heavy metals from kaolin using the upward electrokinetic soil remediation process.

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Keywords: Upward electrokinetic soil remediation (UESR); Phenanthrene; *p*-Xylene; Heavy metals; Soil remediation

1. Introduction

Soil polluted with heavy metals often contains also organic contaminants such as benzene, toluene, ethylbenzene, xylene (BTEX) and polycyclic aromatic hydrocarbons (PAHs) [1]. The removal of such mixed contaminants from clayey soils is an especially a concern. The electrokinetic soil remediation process was proposed as an effective *in situ* technology to remove heavy metals from contaminated soil with low hydraulic permeability [2–5]. Applicability of electrokinetic treatment for the removal from soil soluble organic contaminants, including phenol, benzene, toluene, and phenanthrene, was also demonstrated feasible [6–8]. In these studies, direct current (DC) electric field applied to contaminated soil was horizontal one with constant current density or constant electric potential gradient (uniform). Electromigration and electroosmosis are the main mechanisms for

removal of contaminants from porous media [9]. Electroosmosis is transportation of pore water through pore medium from anode to cathode, while electromigration is ion movement under a DC field. Electromigration plays an important role for the removal of metals from contaminated soil, and electroosmosis is a main way for removal of organics. Although electromigration of metals through soil required pH control at the cathode, removal of organic contaminants is not affected by pH.

Electrokinetic remediation of soil contaminated by either metals or organic pollutants has been conducted. There were few researches on electrokinetic remediation of soil polluted with heavy metals and organic contaminants by horizontal DC in low permeability soils [10]. DC electric field applied to contaminated soil is horizontal one, but there it was known also some attempts to apply vertical electric field for the treatment of contaminated soil [11–13]. There has been no reported study on simultaneous removal of organic contaminants and heavy metals by vertical electric fields.

An upward electrokinetic soil remediation (UESR) process using vertical non-uniform electric field generated by point-

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shaped electrodes was proposed for removal of heavy metals from contaminated kaolins [13]. A non-uniform upward electric field was created between an anode embedded in soil and a cathode placed on the soil surface. Unlike conventional electrokinetic treatment that uses boreholes or trenches for horizontal migration of heavy metals, the UESR process used vertical non-uniform electric field causing upward transportation of heavy metals to the top surface of the treated soil. 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 aim of the present study was the investigation of an upward electrokinetic soil remediation for simultaneous removal of organic contaminants and heavy metals from kaolin by transporting them upwards via a vertical non-uniform electric field.

2. Material and methods

2.1. Materials

Kaolin was chosen because of its low permeability, which ensures high electroosmotic water-transport efficiency [14]. Commercial kaolin I (Kaolin Sdn. Bhd., Malaysia) was used in experiments E1 through E5. It contained 45–50% of SiO_2 , 33–39% of Al_2O_3 , and trace amount of Fe_2O_3 and MgO . Approximately 68% of the kaolin particles had size smaller than $10\ \mu\text{m}$, mean particles size was $8.75\ \mu\text{m}$ and conductivity was

$293\ \mu\text{S}/\text{cm}$. The pH of the kaolin slurry, prepared by mixing of kaolin with distilled water in the ratio of 3:7 (w/w), was 4.7.

Commercial kaolin II (Hydrated Aluminium Silicate, Sigma Chemical, St. Louis, MO, USA) was used in experiment E6. Mean particles size was $8.25\ \mu\text{m}$, percentage of particles with size smaller than $10\ \mu\text{m}$ was 67.6% and conductivity was $160\ \mu\text{S}/\text{cm}$. The pH of the kaolin slurry, prepared by mixing of kaolin with distilled water in the ratio of 3:7 (w/w), was 4.9. Both samples of kaolins were sterilized by autoclaving at $120\ ^\circ\text{C}$ for 30 min prior to use to avoid anaerobic biodegradation of organics.

Phenanthrene, a three-ring polycyclic aromatic hydrocarbon, was selected as a representative of PAH compounds, and *p*-xylene, 1,4-dimethyl benzene, was selected as a representative of petroleum hydrocarbons contaminants.

Sample of kaolin I was artificially spiked with phenanthrene, *p*-xylene and nitrates of Cu(II) and Pb(II) in experiments E1 through E4. Samples of kaolins I and II were contaminated by phenanthrene and nitrate of Pb(II) in experiments E5 and E6. Phenanthrene (Sigma Chemical, St. Louis, MO, USA) was dissolved into 600 ml of dichloromethane (DCM). *p*-Xylene was dissolved in 30 ml of acetone. Nitrate salts of Cu(II) and Pb(II) were dissolved in 1 l of deionized water. Thousand grams of dry kaolin and 600 ml of phenanthrene solution were thoroughly mixed in a mixer (SP-800, RHINO, Taiwan) at 100 rpm for 5 min. The contaminated kaolin was placed under a ventilation hood at room temperature, $25\ ^\circ\text{C}$, for 1 week for DCM to evaporate. The kaolin contaminated with phenanthrene after 1 week,

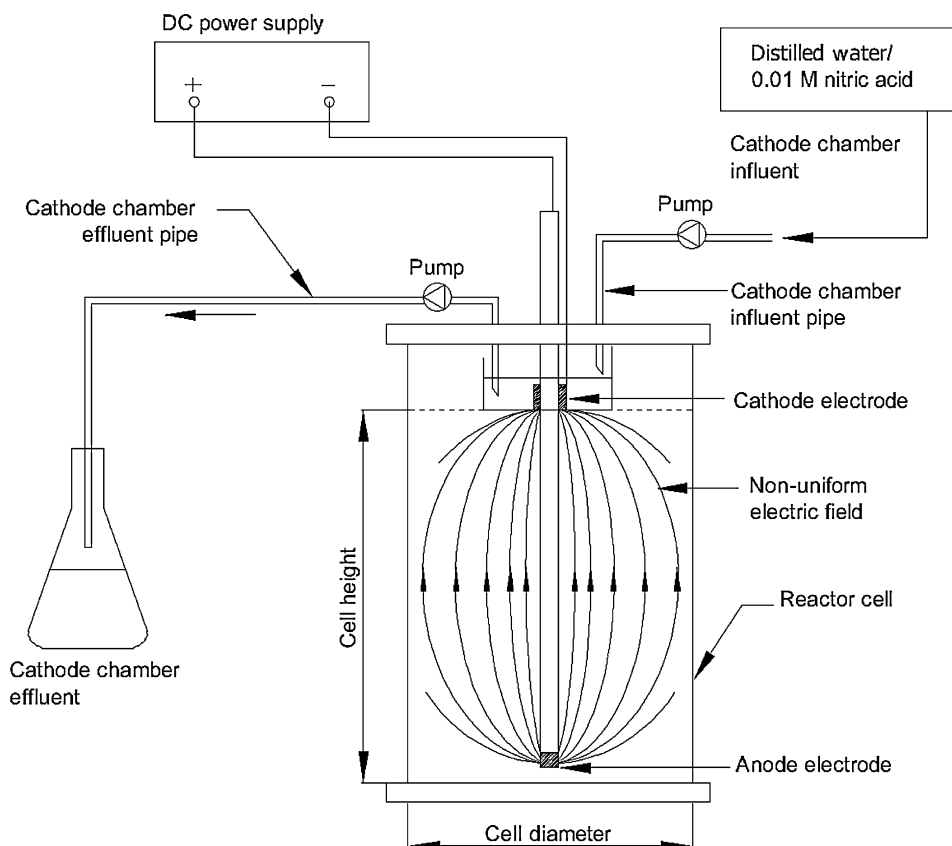


Fig. 1. Schematic of UESR reactor.

solutions of *p*-xylene and heavy metals were thoroughly mixed in a mixer at 100 rpm for 5 min. The contaminated kaolin was left at temperature 4 °C for 24 h before it was packed into the reactor cell. Initial content of phenanthrene was 895 mg/kg, *p*-xylene was 895 mg/kg, Cu was 740 mg/kg, and Pb was 820 mg/kg in kaolin I in experiments E1 through E4. The initial content of phenanthrene was 402 mg/kg and Pb was 226 mg/kg in kaolin I in experiment E5. Initial content of phenanthrene was 380 mg/kg and Pb was 201 mg/kg in kaolin II in experiment E6.

2.2. The 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 [13]. The cell was equipped with a cap that had orifices, tubing and wiring. The anode was rod-shape graphite (a diameter of 8.5 mm) sheathed in an acrylic 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 a 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) with operation mode of constant current or constant voltage was used in the experiments. 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. The schematic of the UESR reactor, used in the experiments, is shown in Fig. 1.

2.3. Experimental setup

The contaminated kaolin was packed into the reactor cell by layers with 2 cm high each and left for 12 h at temperature 4 °C to attain equilibrium before installation of the electrodes. The number of layers in the cell varied from 5 to 10, while the height of kaolin varied from 10 to 20 cm. Duration of the electrokinetic treatment was 6 days in experiments E1 through E4 and 30 days in experiments E5 and E6.

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 the cathode chamber influent started to flow with the rate of 1.1 ml/min. After 1 h, the direct current 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. Current and voltage, as well as the pH and content of phenanthrene, *p*-xylene and heavy metals in cathode effluent were measured twice a day.

Four experiments, from E1 through E4, were conducted under constant current of 15 mA for 6 days to study the effects of cell diameter, cell height and nature of cathode chamber influent

on electrokinetic removal of organic pollutants and heavy metals (Table 1). Kaolin was contaminated with phenanthrene and heavy metals, Cu, and Pd. Kaolin used in experiments E3 and E4 was additionally contaminated with *p*-xylene. 0.01 M nitric acid was used as the cathode electrolyte in all the experiments, except experiment E2 where distilled water was used instead of nitric acid. Experiments E5 and E6 were conducted under constant voltage of 20 V for 30 days. 0.01 M nitric acid was used as the cathode electrolyte. Diameters and heights of cells used are shown in Table 1.

After electrokinetic treatment, the kaolin was taken out and the cathode electrode was soaked in 1 M nitric acid to dissolve the deposited heavy metals. Precipitate of heavy metals, accumulated on the top of the kaolin, was collected. The kaolin was immediately sectioned into layers of 2 cm thick, and each layer of kaolin was divided into an inner part (inner zone) and an outer part (outer zone). The diameter of outer zone was equal to the diameter of cell. The diameter of inner zone was half of the diameter of outer zone. The inner and outer parts were analyzed separately as the inner part and outer part contain different amounts of contaminants [13]. Each sample of kaolin was separated into three parts; first part was used to measure pH and *p*-xylene content, the second part was used to determine the contents of water and heavy metals, and the third part was air dried and analyzed for phenanthrene content.

The removal efficiencies for organic contaminants were calculated by comparison of their content in the treated kaolin in the experimental cell and in the kaolin packed in the control cell with the same characteristics as experimental cell left for the duration of the experiment without treatment.

2.4. Chemical analysis

The pH 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 conductivity of kaolin was measured using a conductivity meter (Horiba ES-14, Horiba Ltd., Kyoto, Japan). Dry kaolin, 6 g, was mixed with 30 ml of deionized water, the mixture was shaken for 24 h at 25 °C at 250 rpm, and supernatant, separated from solid fraction by centrifugation at 2500 rpm for 30 min, was analyzed.

The content of heavy metals in kaolin was determined by acid digestion [15,16]. 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 bar 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 Optima 2000DV inductively coupled plasma (ICP) emission spectrometer (Perkin-Elmer, UK). Three replicates were analyzed for each sample and the average value was reported.

Table 1
Removal of organic pollutants and heavy metals after UESR process

Test	Cathode chamber influent	Cell diameter (mm)	Cell height (mm)	Constant current (mA)	Voltage (V)	Duration (days)	Removal of contaminants (%)			Unit energy expenditure (kWh/m ³ of kaolin)
							Phenanthrene	<i>p</i> -Xylene	Cu	
E1	0.01 M HNO ₃	100	100	15		6	38.5	82.8	51.8	15
E2	Distilled water	100	100	15		6	55.2	92.8	44.0	305
E3	0.01 M HNO ₃	70	100	15		6	40.0	85.4	71.5	32
E4	0.01 M HNO ₃	70	160	15		6	66.9	92.5	62.1	29
E5	0.01 M HNO ₃	140	200		20	30	48.5	N	N	263
E6	0.01 M HNO ₃	140	200		20	30	52.0	N	N	273

Notes: N, this contaminant was not added to kaolin. Kaolin I was used in E1–E5. Kaolin II was used in E6.

p-Xylene was extracted by dichloromethane from kaolin immediately after its sampling and extract was analyzed by a high performance liquid chromatograph (HPLC) Series 200 Norwalk (Perkin-Elmer, UK) equipped with Chromspher C18-PAH column (Chrompack, Middelburg, The Netherlands) and an ultraviolet detector set at a wavelength of 280 nm. A mixture of acetonitrile and deionized water at volume ratio of 70:30 was used as a mobile phase at a flow rate of 0.5 ml/min.

To measure phenanthrene, the air-dried kaolin was grounded into fine powder, phenanthrene was extracted from kaolin by acetonitrile, and extracts was analyzed by the HPLC.

3. Results and discussion

3.1. Moisture content in kaolin during electrokinetic treatment

The difference between the initial and final moisture contents in kaolin indicates the electroosmotic transportation of pore water through the sample [17–19]. The reduction of moisture content in all the experiments was in the range from 3% to 5%. Similar moisture content reduction in clayey soils treated electrokinetically was reported by Thevanayagam and Rishindran. However, much higher moisture content reduction, 13–20%, was found in clay material after electrokinetic treatment [17,18]. One of the reasons of low moisture content reduction in kaolin treated by the UESR process is the weak electroosmotic flow because the migration of pore water upward has to overcome gravitational force.

The pH across the kaolin samples after treatment in E5 and E6 was constant within a range from 2.8 to 3.1.

3.2. Current and voltage during kaolin electrokinetic treatment

Experiments E1 through E4 were conducted with a constant current of 15 mA. The voltage in these experiments varied in a range from 4 to 12 V decreasing as treatment proceeded (Fig. 2a). However, the voltage in experiment E2, with distilled water to control cathode pH, increased rapidly to 100 V and stayed in a range from 90 to 110 V (Fig. 2b). The voltage variations, shown in Fig. 2, suggest that smaller cell diameter and larger cell height give rise to higher voltage drops across the electrodes. The current was gradually decreased due to the accumulation of the precipitates on cathode electrodes (Fig. 3).

3.3. Effluent pH and contaminants concentration

The pH of the effluents in experiments E1, E3 and E4 was constant around 2.2. The pH of effluent in experiment E2 increased rapidly from 4 to 9 in 12 h and remained on this level to the end of the treatment. The lowest concentrations and the smallest total amounts of both Cu and Pb in the effluent were observed in experiment E2 in comparison with experiments E1, E3 and E4 (Table 2). The amount of Cu in the effluents was found to be bigger than Pb despite the initial content of Pb in the kaolin was higher than that of Cu. The concentrations of *p*-xylene in

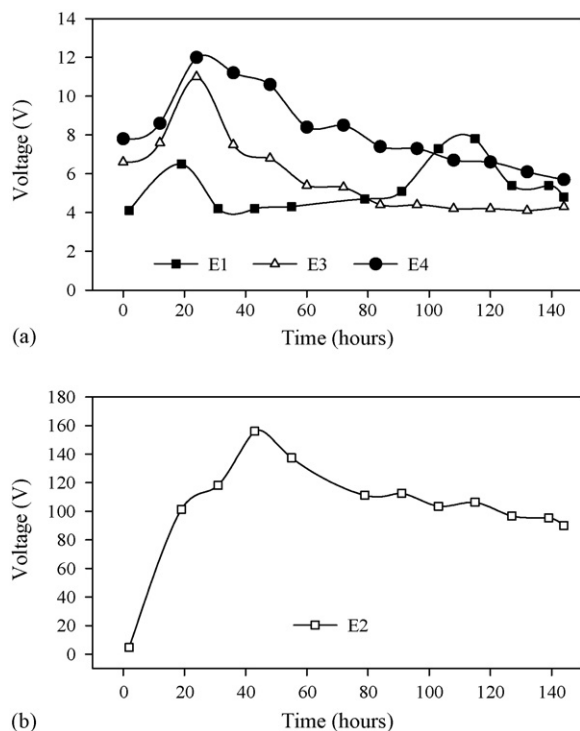


Fig. 2. Changes of voltage during electrokinetic treatment of kaolin with constant current of 15 mA for 6 days (a) with 0.01 M nitric acid and (b) with distilled water. (■) E1 (cell diameter, 100 mm; cell height, 100 mm); (□) E2 (cell diameter, 100 mm; cell height, 100 mm); (△) E3 (cell diameter, 70 mm; cell height, 100 mm); (●) E4 (cell diameter, 70 mm; cell height, 160 mm).

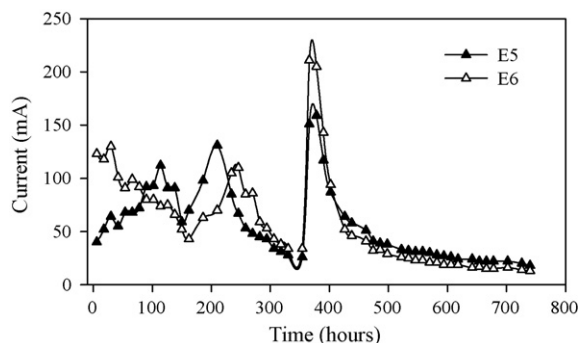


Fig. 3. Changes of current during electrokinetic treatment of kaolin with constant voltage of 20 V for 30 days with 0.01 M nitric acid; cell diameter, 140 mm; cell height, 200 mm. (▲) E5 (kaolin I); (△) E6 (kaolin II).

Table 2
Contents of Cu and Pb in the effluents

Experiment	Cu		Pb	
	Average concentration (mg/l)	Total quantity (mg)	Average concentration (mg/l)	Total quantity (mg)
E1	20.4	205.6	12.8	129.1
E2	5.0	50.7	3.1	30.8
E3	13.2	133.4	6.9	69.5
E4	16.8	169	9.1	91.6
E5	N	N	2.6	217.6
E6	N	N	2.7	263.6

Note: N, this contaminant was not added to kaolin.

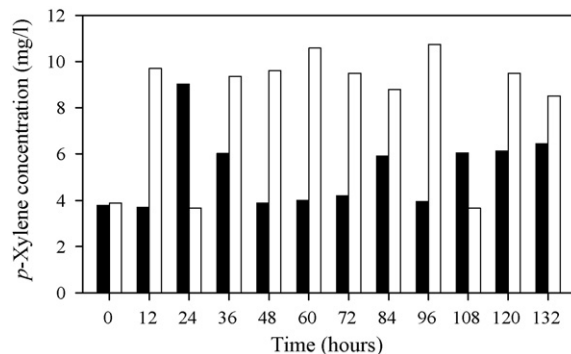


Fig. 4. Concentration of *p*-xylene in effluents during the electrokinetic treatment of kaolin with constant current of 15 mA for 6 days; cell diameter, 100 mm; cell height, 100 mm. (■) E1 (0.01 M nitric acid); (□) E2 (distilled water).

the effluents are presented in Fig. 4. The average concentrations of *p*-xylene in the effluent in experiments E1 and E2 were 5.4 and 8.1 mg/l, respectively. Higher concentrations of *p*-xylene were observed in the effluent of experiment E2, where distilled water was used as cathode chamber influent. The results suggest that the use of 0.01 M HNO₃ solution to control the pH at cathode impeded the transporting of *p*-xylene from contaminated kaolin into the cathode effluent. Zeta potential of kaolin can be increased toward zero when the pH approaches the point of zero potential [20,21]. The overall low pH condition presented in the kaolin in experiment E1 probably reduced the magnitude of zeta potential in the kaolin and, consequently, the amount of electroosmosis flow. It was observed that potential drop across the electrodes in E2 were much larger than in E1 due to the kaolin resistance buildup in the top 4–6 cm. The localized large potential gradient in E2 probably enhanced the electroosmotic flow since flow by electroosmosis is positively related to the potential gradient as well as the magnitude of the kaolin zeta potential.

The concentration of phenanthrene, detected in the most of the effluent samples, was near 1 mg/l, which is close to its solubility in water, 1.1 mg/l [22]. Therefore, phenanthrene was unlikely to be transported by effluent in the dissolved phase. The free phase phenanthrene if presented at the cathode chamber was most likely to be attached to cathode electrode surface or float on the surface of the flushing liquid due to its low density. The quantification of transported phenanthrene was impractical because its low solubility and the free phase phenanthrene particles could adhere to the tubing walls and containers.

3.4. Heavy metals and organic contaminants removal from kaolin

The removal efficiencies of contaminants are shown in Table 1. The average concentration as well as the total amount of heavy metal was affected by cell parameters, nature of the cathode electrolyte and the treated kaolin properties (Table 1). The removal efficiency of metals increased when cell diameter and height decreased, when nitric acid was used as cathode chamber influent instead of distilled water, and contaminated kaolin had lower conductivity. The removal efficiencies for Cu and Pb from kaolin I treated for 6 days in experiments E1 through E4 were in the ranges from 44% to 72% and from 25% to 44%, respectively. Cu and Pb have distinctive mobility because their diffusion constant in solution, hydrated ionic radius, and affinity to the kaolin particle surface are different [23]. The removal efficiencies of Cu and Pb in experiment E3 were higher than those obtained in experiment E1 (treatment using lower current density), which is in line with the observation of other authors [13,23]. Removal efficiency of Pb was higher for kaolin II in experiment E6 with lower conductivity than that for kaolin I with higher conductivity (Table 1) probably due to the smaller amount of dissolved salt in the pore water [23,24].

The removal efficiencies of *p*-xylene and phenanthrene ranged from 83% to 93% and from 39% to 55%, respectively, for experiments E1 and E2. It was reported that the organic contaminants with high water solubility and low distribution coefficient, like BTEX and trichloroethene (TCE), were easily removed from kaolin by electroosmosis [4,7]. However, the chemicals with low water solubility and high distribution coefficient, like phenanthrene, were transported at a slower rate. The larger particle size as well as the higher dissolved salt content in kaolin I probably decreased transport of phenanthrene. Higher removal efficiency of phenanthrene was observed in experiment E2 than that in experiment E1. Therefore, removal efficiencies for heavy metals, Cu and Pb, were higher, but for organic pollutants, *p*-xylene and phenanthrene, were lower, when 0.01 M HNO₃ solution was used as a cathode electrolyte instead of distilled water.

In spite of different conditions for optimum removal of heavy metals and organics, it is possible to use the upward electrokinetic soil remediation process for their simultaneous removal. In experiment E4 with short duration of 6 days, removal efficiencies of phenanthrene, *p*-xylene, Cu and Pb were 66.9, 92.5, 62.1 and 35.2, respectively. These results could be further improved by increasing treatment time. Removal of phenanthrene probably was partially caused by mechanisms of being purged by water upward, while in the form of light non-aqueous phase liquid (LNAPL), and perhaps to limited extent dielectrophoresis besides electroosmosis.

3.5. Phenanthrene removal by the ‘up-lifting effect’ and dielectrophoresis

Solubility in water and affinity to the clay particle surface were the main factors in hydrocarbons removal from soil [7]. Probably, the high removal efficiency for *p*-xylene, 83% and

93%, observed in the present study, was mainly due to electroosmosis since *p*-xylene has relatively high solubility in water, 198 mg/l [22]. Meanwhile, electroosmosis was not the only mechanism for phenanthrene transport.

There are limited studies on removal of non-polar organic contaminants having very low water solubility, such as phenanthrene, from soils with low permeability. It was shown that during electrokinetic treatment of kaolin, phenanthrene migrated towards cathode and accumulated there [25]. Due to the upward movement of pore water flow, the UESR could provide an additional purging force to phenanthrene, which existed as light non-aqueous phase liquid (LNAPL) in the kaolin capillaries. As LNAPLs tend to rest on top of pore water surface due to its light density and low solubility in water, the upward traveling pore water could lift the LNAPLs in the same direction by pushing them upwards, or the ‘uplifting effect’. The transporting efficiency for the ‘uplifting effect’ is likely to be high if LNAPLs have low affinity to the soil particles and the capillaries exert small resisting forces to the pore water flow.

Besides the ‘upward lifting effect’, dielectrophoresis might also contribute to the removal of phenanthrene. Dielectrophoresis could induce neutral molecule to form an electric dipole in non-uniform electric field. As non-uniform electric field is stronger on one side of the dipole than on the other, movement of substance is observed [26–28]. Thus, both electroosmosis and dielectrophoresis could be the mechanisms of the treatment.

The distribution of heavy metals in kaolin after treatment showed that heavy metals were removed faster from the inner zone than from the outer zone (Fig. 5). Probably, it was due to

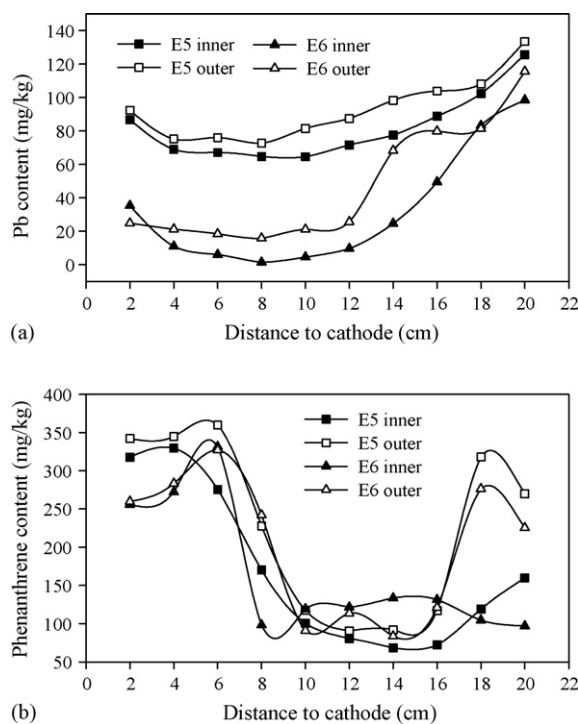


Fig. 5. Pb content (a) and phenanthrene content (b) in kaolin after treatment with constant voltage of 20 V for 30 days; 0.01 M nitric acid; cell diameter, 140 mm; cell height, 200 mm. (■) E5 inner zone (kaolin I); (□) E5 outer zone (kaolin I); (▲) E6 inner zone (kaolin II); (△) E6 outer zone (kaolin II).

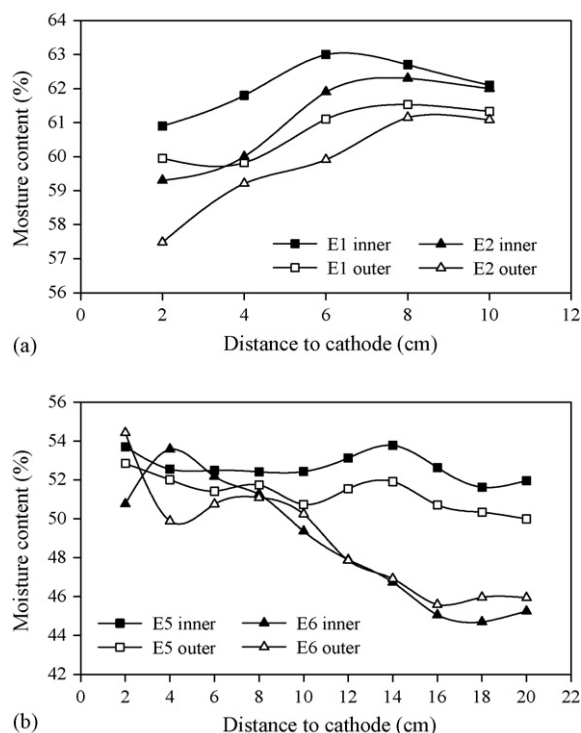


Fig. 6. Moisture content in kaolin after electrokinetic treatment (a) with constant current of 15 mA for 6 days; cell diameter, 100 mm; cell height, 100 mm. (■) E1 inner zone (0.01 M nitric acid); (□) E1 outer zone (0.01 M nitric acid); (▲) E2 inner zone (distilled water); (△) E2 outer zone (distilled water). Moisture content in kaolin after electrokinetic treatment (b) with constant voltage of 20 V for 30 days using 0.01 M nitric acid; cell diameter, 140 mm; cell height, 200 mm. (■) E5 inner zone (kaolin I); (□) E5 outer zone (kaolin I); (▲) E6 inner zone (kaolin II); (△) E6 outer zone (kaolin II).

the larger current densities in the inner part of the reactor. The final phenanthrene concentrations in the inner part were smaller than those in the outer part of the same layer (Fig. 5). However, the final moisture contents in the inner part of the treated soils were higher than in the outer part of the same layer (Fig. 6). Therefore, it could be suggested that a mechanism of the pore water transport was not the same that transportation of phenanthrene. It is very likely that dielectrophoresis transported certain amount of pore water as well as dissolved phenanthrene. As the pore water in kaolin has the higher dielectric constant (around 79) and phenanthrene has the much lower dielectric constant (around 2.8), the dielectrophoretic migrations of pore water and phenanthrene in the kaolin were probably in different scale, or even in opposite directions. Having a higher dielectric constant than the surrounding kaolin, the pore water moved towards the places of higher electric field in the inner part. Phenanthrene, however, hardly moved or even moved towards outer part in comparison with pore water. Nevertheless, dielectrophoresis is not likely to be the main mechanism that removed phenanthrene from the soils as the effect of dielectrophoresis was reported to be much less than electroosmosis when conducting electrodes were used [29,30].

Energy expenditures for the contaminated kaolin treatment are shown in Table 1. According to the literature, energy expenditure ranged from 18 kWh/m³ to more than 700 kWh/m³

for contaminated kaolinite [6,18,24,31]. The low energy expenditures in present study were mainly to cathode control of pH with solution of nitric acid, short duration of treatment, relatively low current density, and significant voltage gradient during the treatment.

4. Conclusions

The following conclusions can be drawn from the study:

- (1) The removal efficiencies of *p*-xylene and phenanthrene were higher in the experiments with smaller diameter or larger height cells, and with distilled water flow in the cathode chamber.
- (2) The removal efficiencies of Cu and Pb were higher in the experiments with smaller diameter or shorter height cells and 0.01 M HNO₃ solution as cathode chamber flow.
- (3) In spite of different conditions for removal of heavy metals and organics, it is possible to use the upward electrokinetic soil remediation process to remove them simultaneously. To increase effect of electrokinetic treatment, combination of parameters optimal for higher removal efficiency for different contaminants could be used.

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