



## Study of the electrokinetic process on Cd and Pb spiked soils

J.G. Sah<sup>\*</sup>, J.Y. Chen

*Department of Environmental Protection, National Pingtung University of Science and Technology,  
Pingtung 91207, Taiwan*

---

### Abstract

This study examined three soil samples from different locations of Taiwan. According to those results, soil from Kaohsiung County (KH) is weak basic clay loam with the highest cation exchange capacity (CEC) among all samples. Soil from a Cd contaminated paddy field in Kuanyin village, Taoyuan County (TY) is neutral loamy sand. And, Latosol soil from National Pingtung University of Science and Technology campus in Pingtung County (PT) is acidic clay. Tested samples without heavy metal spiked have low total (aqua regia digested) Cd contents; the natural Pb contents are all lower than 50 mg/kg. All samples can adsorb more Pb than Cd. The order of soils adsorption capacity on Cd and Pb is as follows: KH clay loam > TY loamy sand > PT clay. In addition, electrokinetic experiments were performed on Cd and Pb spiked and 0.1 M HCl saturated TY soil, indicating it to be the optimum Cd and Pb removal efficiency, PT soil is the second and KH soil is the worst. In contrast with all samples saturated in water, dilute HCl soaking facilitated the Cd and Pb removal during the electrokinetic process. The process did not influence Cd and Pb in the spiked KH soil. In water saturated spiked TY soil, Cd and Pb exist in highly stable forms in soil near cathode during the experiment. Acid soaking not only reduced the formation of the high Cd concentration suspension, but also assisted quite effectively in concentrating the Cd and Pb in the zone near cathode in stable residual and carbonate forms. Cd spiked and water saturated PT soil sample clearly demonstrated that Cd is concentrated in soil near the cathode after electrokinetic process. When soaking with 0.1 M HCl during the process, even better results were obtained. However, the exchangeable Cd in the soil near cathode is extremely high, thereby requiring further treatments. The Pb spiked water saturated PT soil displayed no change in Pb forms after the electrokinetic process. When soaked with 0.1 M HCl, the electrokinetic process yielded excellent results. In addition, spiked PT soil in 0.1 M HCl also has lower Cd and Pb

---

<sup>\*</sup> Corresponding author. Tel: +886 8 774 0137; fax: +886 8 774 0256.

stabilities during electrokinetic process. Moreover, elongating the process time may enhance the removal efficiency. © 1998 Elsevier Science B.V.

*Keywords:* Cd and Pb spiked soil; Electrokinetic process

---

## 1. Introduction

Soil is a porous material having unique physical, chemical and biological characteristics. It contains minerals at different weathering stages, organic matter at different stages of decomposition, microorganisms at different life cycles and many intermediate and final products from biochemical reactions. Such compositions form a dynamic system having gaseous, liquid, solid and biological phases. In recent years, soil has always been seriously contaminated by improperly processed waste water and hazardous waste materials. The contaminants having entered the soil influence the normal functions and, ultimately, cause soil pollution [1]. Soil pollution surveys have been in Taiwan for many years. More than 50 000 ha of farmland have been heavy metals contaminated to the fourth level (high) in the temporary soil quality standard; more than 790 ha are listed as fifth level (highest). These contaminated lands represent 5.63% and 0.09%, respectively, of the farmlands in the survey area. This finding confirms that Taiwan's soil environment is gradually declining.

Heavy metals entering the soil in a salt form can be easily absorbed by the organism. Furthermore, these pollutants may be carried by the fluids in soil and cause secondary pollution [2]. When the heavy metal pollutants in soil solution are in ionic forms, these ions are attracted by the static electrical force of soil colloids, as soil colloids themselves have negative charges. The attraction of metal ions to the soil colloids depends primarily on the soil electronegativity and the dissociation energy of the ions. Through ion exchange processes, the metal pollutants may be attracted and reduce the effective concentration in soil, thereby decreasing the effect toward the organisms and the mobility of pollutant [3]. Soil colloids are also selective in attracting different ions. Ions that are difficult to be adsorbed can be substituted by the ions that are more easily adsorbed on the soil colloids' surface [4]. Pb, for example, is more easily adsorbed by soil than Cd. Generally, soil is more attracted to cation of a higher charge than a lower one [5].

Under alkaline condition, most heavy metal ions in the soil may become sediments of hydroxides ( $\text{Cd}(\text{OH})_2$ ,  $\text{Pb}(\text{OH})_2$ ) and carbonates ( $\text{CdCO}_3$ ,  $\text{PbCO}_3$ ). Soil pH value determines the concentration of hydroxide and carbonate in soil solution, which plays a critical role in the formation of heavy metals in soil.

The initial stage of electrokinetic technique is an electrolysis reaction [6–10], in which (1) electrons are released from the anode during the process and (2) the water is electrolytically dissociated into  $\text{O}_2$  and  $\text{H}^+$ , thereby lowering the pH value near the anode. On the other hand, reduction reaction continues around the cathode area, in which water forms  $\text{H}_2$  and  $\text{OH}^-$  during electrolytic dissociation. Consequently, the pH value near the cathode increases.

The  $H^+$  and  $OH^-$  ions generated from the electrolytic dissociation are moved across the solution within soil particles toward the electrodes [11]. A situation in which the attraction of the soil to  $H^+$  exceeds that of heavy metal ions causes the exchange of metal ions from the diffuse electrical double layer on soil particle surface to the solution. These ions can then moved to the cathode through migrational flux, electroosmosis flux or diffusive mass flux. Diffusive mass flux is attributed to a phenomenon in which the  $OH^-$  at cathode and  $H^+$  at anode diffuse toward opposite polarities during electrolytic dissociation. A circumstance in which metal ions are attracted to the solid surface implies that they possess the lowest potential energy. Diffusion starts to occur after a sufficient amount of metal ions have accumulated on the solid surface. This occurrence correlates with the entropy law in thermodynamics, which says that ions diffuse from a high concentration to a low one. Migration flux is that ionic movement affected by an electric field, i.e. the major mechanism of soil electrokinetic remediation technique.

The electrodes' irreversibility causes the polarization. In addition, the electrodes' surface attracts the gas generated from the electrolytic dissociation, subsequently increasing the resistance that retards the reaction, this is called activation polarization. In addition, if the concentration gradient is formed due to the localized concentration difference by the electrodes, the electrical voltage must be increased to overcome this gradient, this is called the concentration polarization. Moreover, the oxidant film or other impurities formed on the electrode surface also increases the resistance of the electrodes, this phenomenon is called resistance polarization. The existence of various polarizations partially accounts for the lessening of the efficiency of electrokinetic technique.

Hamed et al. [8] pointed out that soil resistance is lower in the earlier stage of electrokinetic process and therefore, the required input voltage is lower as well. When the electrokinetic process continues, either the soil conductivity decreases, or the resistance increases. The input voltage must be increased to maintain the same current, which also increases the voltage gradient. Non-conducting gaseous bubbles generated from electrolytic dissociation cover the cathode's surface, thereby increasing the resistance and possibly even forming an open circuit; a local maximum on the voltage gradient ultimately forms.  $OH^-$  also reacts with cations and forms sediment which plugs the spacing between soil particles, subsequently hindering the electrical current and decreasing the diffusive flow over time when a voltage is applied. This occurrence clearly indicates that the pH value near the electrodes heavily influences the electrolytic diffusion's efficiency. Acar and Alshwabkeh [6] and Lageman [10] pointed out that using  $Ca(OH)_2$  as a depolarizer at the anode can neutralize the excessive production of  $H^+$ . Similarly, using HCl or HOAc as a depolarizer at the cathode also neutralizes the production of excessive  $OH^-$ .

Electrokinetic technique was initially applied to soil dehydration or slop stabilization. In recent years, it has also been utilized to remediate contaminated soil in situ and off site. This technique has been applied in some countries and demonstrated to economically treat a wide range of contaminants [12]. European and American research institutes have begun to collaboratively develop this soil remediation technique [10,11]. In Taiwan, an effective and complete means to remediate a contaminated site has not yet been established. Although we are aware that a simulated contaminated soil has many

different performances from those real hazardous waste site soils while using electrokinetic technology, this study attempts to initially contribute to the application of this technique in Taiwan.

## 2. Material and methods

### 2.1. Pretreatment of the soil samples and basic property analysis

Three soil samples were tested in this study. Soil KH was taken from Kaohsiung County (Taiwan Clays with Lime Concretions), soil TY was obtained from Kuanyin village, Taoyuan County (Laterite Alluvial Soils) and soil PT was collected from Pingtung County (Diluvium Red Soils). The samples were air-dried, coarsely ground and sieved (20 mesh). Standard analysis methods [13] were used to obtain the soil's basic properties.

The soil pH measurement was based on a sample having a soil/water ratio of 1:1. A pH meter was used to measure the suspension's pH value; in addition, soil texture was obtained by using soil mechanical analysis [14]. Ammonia acetate method was used to obtain cation exchange capacity (CEC). Next, measured amounts of dried soil were placed in a bottle where  $\text{Ca}^+$  was exchanged by 0.1 M neutral ammonia acetate. By using  $\text{NH}_4\text{Cl}$ , soil was washed five times and isopropyl alcohol was used to wash the electrolytes. The measurement of overall quantity of  $\text{NH}_4^+$  can be converted into the soil's cation exchange capacity. The method for total heavy metal content in soil was that samples were digested with aqua regia (one part of  $\text{HNO}_3$  with three parts of  $\text{HCl}$ ), then diluted with distilled water. Finally, a Hitachi Z-8000 atomic spectrum analyzer was used to measure the metals' total concentrations.

### 2.2. Cd and Pb spiked soil preparation

Calculated concentrations of  $\text{CdCl}_2$  or  $\text{Pb}(\text{C}_2\text{H}_3\text{O}_2)_2$  solution were added to each of the three soil samples, in which the soils Cd or Pb concentration was converted to about 500 mg/kg. The soils were allowed to stand and dry in air for 7 days. These samples were then coarsely ground and sieved (20 mesh). Finally, aqua regia digestion was used to analyze the heavy metals' total concentration.

### 2.3. Preparation of electrokinetic reaction cell

Graphite rods obtained from Hg free batteries were used as the electrodes in this experiment (50 mm  $\times$  8 mm,  $L \times D$ ). These graphite rods were cleaned in an ultrasonic cleaner. To avert corrosion between the electric wire and graphite rod, the junctions were covered with water-resistant glue. As Fig. 1 depicts, these electrodes were finally installed into an acrylic cell (180 mm  $\times$  50 mm  $\times$  30 mm,  $L \times W \times H$ ).

### 2.4. Soil Cd and Pb adsorption capacity

To further understand the adsorption capacity of the three soil samples to Cd and Pb, solutions containing 200 mg/l to 2000 mg/l of Cd and 200 mg/l to 10 000 mg/l of Pb were prepared.

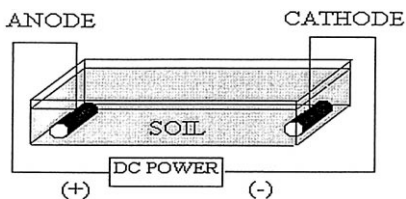


Fig. 1. Electrokinetic reaction cell.

Adsorption experiments adhered to the methodology by Liu [15]. Soil samples without Cd and Pb spiked were mixed with five times the amount of solutions prepared above, shaken horizontally (200 rpm for 4 h) and centrifugally separated. The supernatant were collected and inspected with an atomic spectrum analyzer (Fig. 2).

### 2.5. Formal transition of Cd and Pb in spiked water saturated soil samples before and after the electrokinetic process [16]

The Cd and Pb forms in the soil were obtained by the sequential chemical extraction procedure. Initially, spiked soil was oversaturated by distilled water for 7 days. A soil sample of 1 g was then placed in a tube with 12.5 ml of distilled water, shaken for 4 h and, then, separated centrifugally. These extracts were water soluble forms; 12.5 ml of 0.5 M  $\text{KNO}_3$  were then added, shaken for 16 h and separated centrifugally. These extracts were of exchangeable forms. The soil portion were again added with 12.5 ml 1.0 M NaOAc (pH = 5), shaken for 5 h and centrifugally separated. These extracts were of carbonate forms; 12.5 ml of 0.5 M NaOH were further added, shaken for 16 h and, then, centrifugally separated. These extracts were organic forms. The quantities of residual form were obtained by the sum of the four forms obtained in above procedures and subtracted by the total amount of aqua regia digested.

The formal transitions of Cd and Pb at the end of each experiment of electrokinetic process were obtained by placing Cd and Pb spiked soil in the reaction cell, with subsequent electrification for 7 days; samples were obtained every 4-cm interval

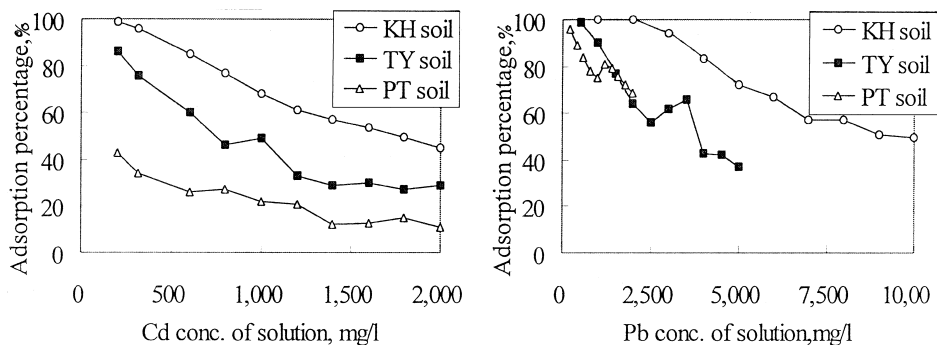


Fig. 2. Comparison of Cd and Pb adsorption abilities of three tested soils.

between the electrodes. The procedures mentioned earlier were used again on each sample.

### 2.6. *Electrokinetic experiments*

Cd and Pb (150 g) spiked soils were separately put in the reaction cell. Distilled water or 0.1 M HCl (100 ml of solution) were added and the cell was covered to prevent water vapor from escaping during the reaction. A constant 8 V DC was then applied and the current and the pH values were monitored at fixed time intervals. When the prescribed time period had expired, acrylic separators (50 mm × 530 mm × 51 mm) were used to separate the soil samples at prescribed intervals. Soil samples were then removed, oven dried and aqua regia digested.

## 3. Results and discussion

Table 1 lists the basic properties of the three soils selected herein. KH soil is a clay loam having a pH value of 7.9. Its cation exchange capacity (CEC) is 12.3 cmol/kg, i.e., the highest among all samples; TY soil is loamy sand with a pH value of 6.6. Its CEC is 5.3 cmol/kg, i.e., the lowest of all samples; PT soil is acid clay with a pH value of 4.4 in which the CEC is 5.8 cmol/kg. The original Cd concentrations from the three soils were found to be low from aqua regia digestion. The Pb contents in KH soil, TY soil and PT soil are 27 mg/kg, 48 mg/kg and 28 mg/kg, respectively. The CEC of the soil is one of the determining factors in the amount of soil colloids that can absorb the contaminating heavy metal ions. For a high CEC or a high pH value, the cations can easily be attracted by the soil. From this assumption, the adsorption capacity toward heavy metal contaminants should be KH soil > TY soil > PT soil.

The heavy metal contaminants in the soil and solution exist primarily in the form of salts or ions. The capability of electrokinetic remediation technique heavily relies on the quantity of these water-soluble materials. The soil adsorption analysis with Cd and Pb solutions of different concentrations can be used to preliminarily identify the heavy metals' removability by the electrokinetic process. The adsorption percentage is defined as follows: (added amount – residue amount)/added amount. Experimental results indicated that the order of adsorption capacity of the soil samples to Cd and Pb are as follows: KH soil > TY soil > PT soil, thereby corresponding to the above assumption. When contaminants such as Cd and Pb entered KH soil, they might be easily adsorbed by the soil, causing them to adversely impact the environment to a lesser extent. Restated, this type of contaminated soil is extremely difficult to be remediated by electrokinetic technique. If the metal contaminants entered PT soil, due to its low pH and low CEC, these contaminants diffuse very quickly with rain and make a greater impact on the environment. It, however, will also be more effective for electrokinetic technique.

Fig. 3 compares electric current density changes when the Cd and Pb spiked soil samples were soaked in 0.1 M HCl and water solutions while applying 8 V DC. HCl is a strong electrolyte that can provide better conductivity, capable of tremendously increas-

Table 1  
Basic properties of tested soil

Source of soils	Soil group	Org. matter, %	CEC, cmol /kg	pH	Texture				Metal content in soils		Metal content in spiked soil	
					Sand,%	Silt,%	Clay,%	Classification	Cd, mg/kg	Pb, mg/kg	Cd, mg/kg	Pb, mg/kg
KH	Taiwan clays with lime concretions	2.4	12.3	7.9	29	38	33	clay loam	< 5	27	536	551
TY	Laterite alluvial soils	3.0	5.3	6.6	80	5	13	loamy sand	< 5	48	502	522
PT	Diluvium red soils	0.7	5.8	4.4	24	26	50	clay	< 5	28	473	533

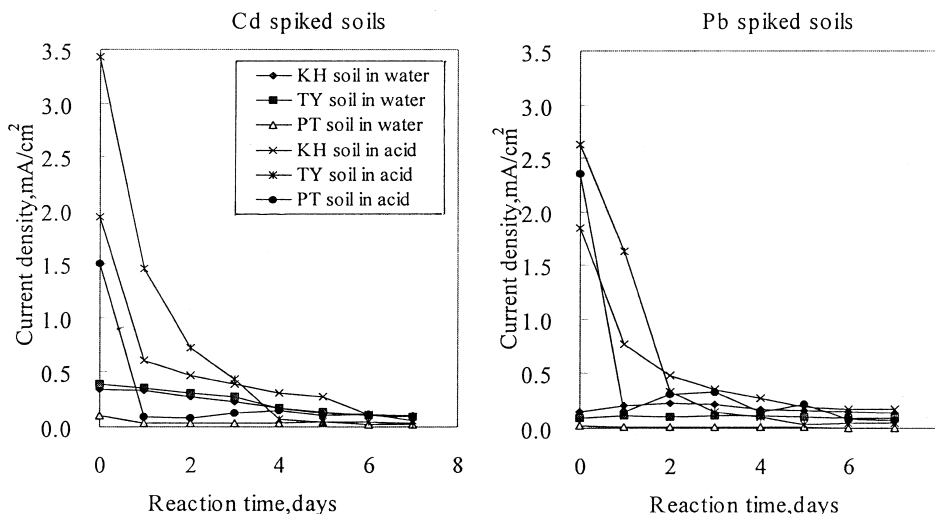


Fig. 3. Electric current change of Cd and Pb spiked soils saturated with water and 0.1 M HCl under 8 V electrokinetic process.

ing the electric current density. The initial current density from soil with HCl markedly exceeds that of soil with water solution; however, after 1–2 days, the current dropped sharply. After 3 days, the current density level stabilized to a level similar to that of soil in water solution. The reasons for the current density to drop are as follows: (1) activation polarization: visible gaseous bubbles ( $O_2$ ,  $H_2$ ) were formed around the electrodes during electrokinetic process. These bubbles are good insulator to reduce the electrical conductivity, subsequently reducing the current; (2) resistance polarization: after electrokinetic process, a white layer was discovered on the cathode surface. This thin film may be the insoluble salt and other impurities that were not only attracted to the cathode, but also inhibited the conductivity which causes the current to drop; (3) concentration polarization: the  $H^+$  generated at the anode are attracted to the cathode and the  $OH^-$  generated at cathode are attracted to the anode. If the acid and alkaline can not be quickly neutralized, the current also drops.

Above results clearly suggest that the solution's pH obviously influence the conductivity. To further understand the influence of heavy metal contaminants toward the current change, the contaminants were compared using TY soil sample with and without Cd spiked, soaked in water and 8 V of voltage were applied. The current changes were monitored during the electrokinetic process. Fig. 4 summarizes those results, indicating that the soil without Cd spiked showed a low and nearly constant current during the electrokinetic process. Although Cd spiked soil displayed a higher initial current, it started to drop as the process continued. Comparing the above findings obviously reveals that the spiked Cd positively influences the current. We can conclude that soil containing heavy metal contaminants influences the conductivity. Fig. 4 also contains the current changes in TY soil sample with Cd spiked due to different input voltages. The initial electrokinetic process current from 30 V exceeds that of 16 V, with 8 V the



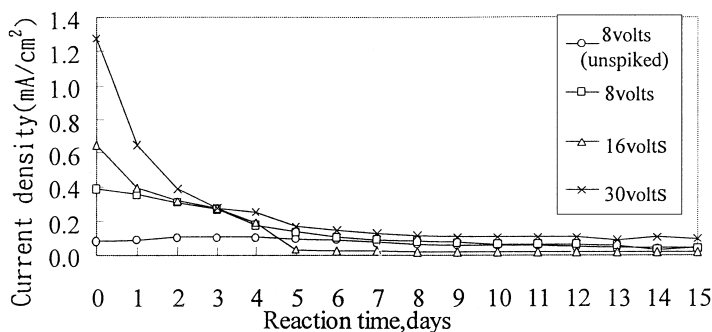


Fig. 4. Electric current density change during the electrokinetic process of Cd spiked Taoyuan (TY) water-saturated sandy loam.

lowest. This finding can also be realized from Ampere's Law ( $E = IR$ ). At the initial stage of the electrokinetic process, the resistance ( $R$ ) in the soil were identical, thus the current was proportional to the input voltage. The influence of Cd spike disappeared between the fifth to sixth day, whereas the influence from voltage disappeared on the third day.

Fig. 5 presents the concentration changes on three Cd spiked soil samples in 0.1 M HCl, with 8 V DC applied for 1 to 7 days, as well as the comparisons with those water saturated samples. Regardless of whether solution is water or HCl, KH soil sample did not show promising removal results. Soaked in 0.1 M HCl, TY soil sample revealed that the Cd concentration ranged from 3300 mg/kg to 4400 mg/kg in soil near the cathode after 1 to 7 days of electrokinetic process. The removal efficiency became more obvious over time. If saturated in water and after 7 days of electrokinetic process, a high Cd concentration green suspension would form at 4 cm from the cathode. Therefore, Cd would accumulate at this location, rather than at the zone near the cathode. With 0.1 M HCl, PT soil sample produced 1300 mg/kg to 4400 mg/kg Cd in soil near the cathode after 1 to 7 days of electrokinetic process. Cd clearing concentrated in soil near the cathode. When water saturated instead, the Cd concentration was 2200 mg/kg after 7 days of electrokinetic process, i.e. worse than the fourth day's results with HCl solution.

Fig. 5 also displays the electrokinetic process results of the three Pb spiked and water or 0.1 M HCl saturated samples. Regardless of whether it was water or HCl soaked, KH soil sample with Pb spiked did not offer satisfactory results on Pb removal. TY soil sample with 0.1 M HCl saturated showed excellent results after just 1 day of electrokinetic process, the Pb concentration in soil near the cathode was 2000 mg/kg. Apparently, Pb is condensed towards the cathode and the soil sample soaked with HCl yield a better result than with water. After 4 days of electrokinetic process, the Pb concentration at 2 cm from the cathode was 2500 mg/kg; a reasonable cause for such an occurrence is still being investigated. When the PT soil sample was soaked in 0.1 M HCl, 880 mg/kg to 1700 mg/kg Pb were found in soil near the cathode after 1 to 7 days of electrokinetic process. Again, the removal efficiency in HCl was better than that in water.

Heavy metal formal analysis can be used to understand the transition of Pb and Cd concentration differences between electrified vs. un-electrified soil samples under differ-

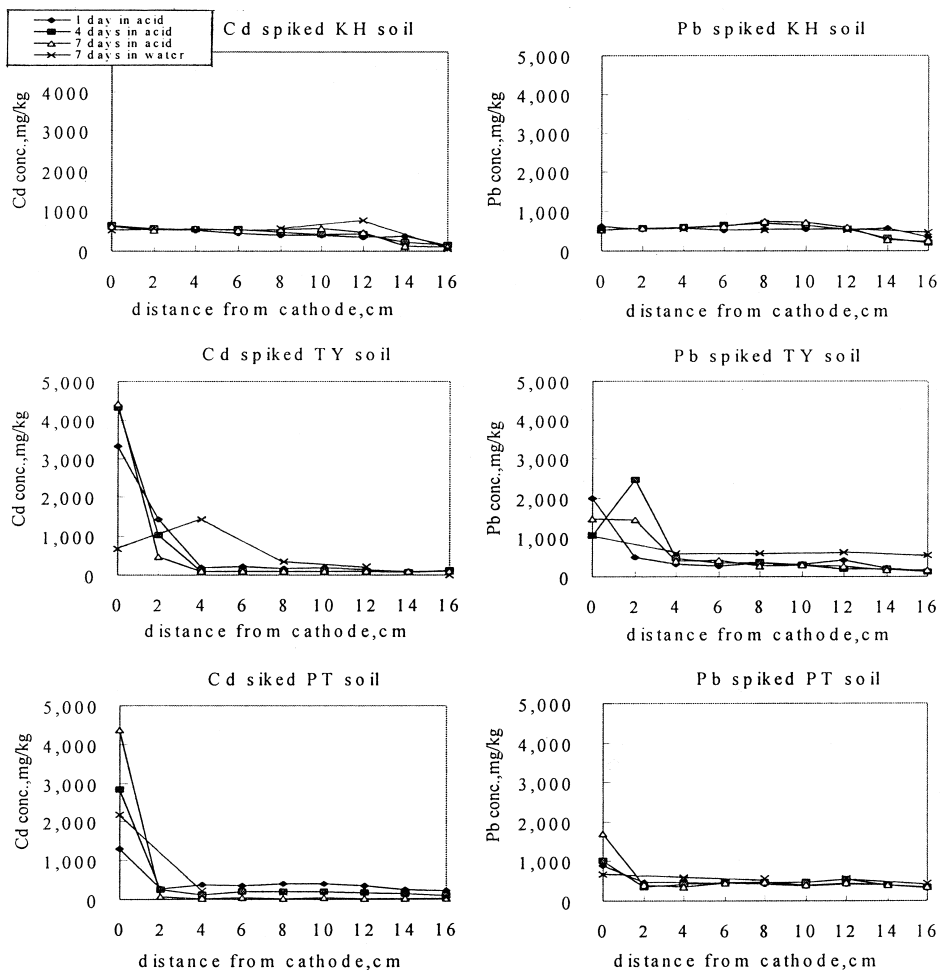


Fig. 5. Distribution of Cd and Pb in water-saturated soils and 0.1 M HCl saturated soils under 8 V electric pressure after 7 days.

ent times, locations and solution types. Consequently, the heavy metal stability can be understood where electrokinetic process time period can be determined. The forms of Cd and Pb differ with the soil type they exist in. A critical factor is the soil's pH value. Electrokinetic process is intended to remove the ionic material, which carries an electrical charge. Therefore, the quantity of soluble material becomes a decisive factor in achieving a successful electrokinetic remediation. Fig. 6 compare the metal formal transitions between the three Cd spiked samples in water and 0.1 M HCl, with and without being electrified for 7 days. KH soil sample in water, if not electrified, contains primarily carbonate and residual forms. TY soil contains mostly carbonate, exchangeable and residual forms. PT soil sample contains chiefly residual, exchangeable and water soluble forms. Cd spiked has the highest stability in KH soil sample and the worst

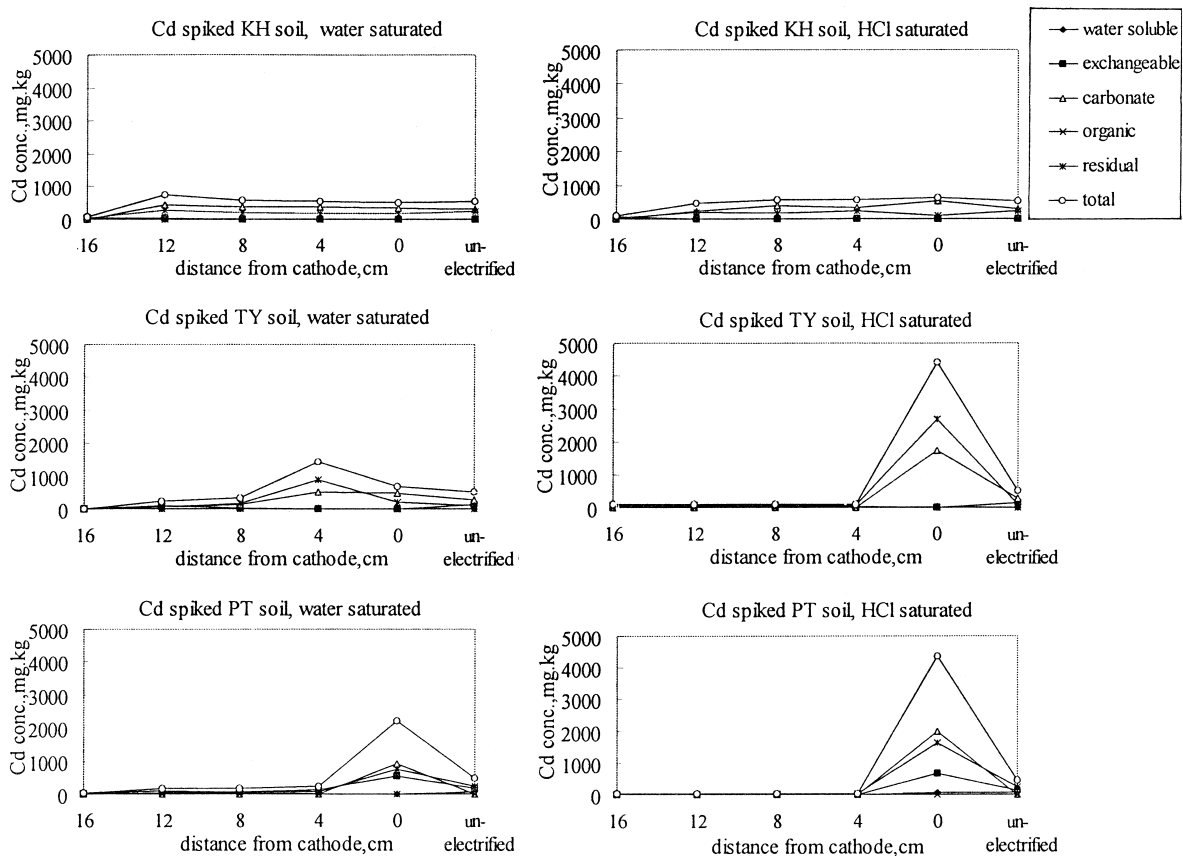


Fig. 6. Cd forms change in spiked soils saturated with water and 0.1 M HCl under 8 V electrokinetic process for 7 days.

in PT soil sample. Consequently if contaminated, KH soil sample might be the most difficult to be remediated. Moreover, the experiment has confirmed that the electrokinetic process removal efficiency on KH soil sample was insignificant. After 7 days of electrokinetic process, the Cd in KH soil sample from 0 to 16 cm from the cathode can be effectively removed; nevertheless, no change was detected at 12 cm from the cathode. For TY soil sample in water and 7 days of electrokinetic process, it contained a high Cd in carbonate and residual forms at 4 cm from the cathode. This is attributed to that high Cd concentration green suspension formed at this location. With TY soil sample in 0.1 M HCl, due to that acid may inhibit the production of suspension, Cd can therefore be moved and concentrated to the cathode. The Cd in residual and carbonate forms were 2700 mg/kg and 1700 mg/kg, respectively. The Cd has been reduced to highly stable forms and, subsequently, markedly reduced the environmental impact. After 7 days of electrokinetic process, PT soil sample in water had residual, carbonate and exchangeable forms Cd of 740 mg/kg, 900 mg/kg and 550 mg/kg each, Cd clearly was removed and concentrated in soil near the cathode. With PT soil sample in 0.1 M HCl, the Cd within 4 to 16 cm from the cathode was nearly completely removed after 7 days of electrokinetic process. The residual, carbonate and exchangeable forms Cd were 1600 mg/kg, 2000 mg/kg and 690 mg/kg, respectively.

Fig. 7 illustrates the Pb formal transition between electrified for 7 days vs. un-electrified samples with Pb spiked soil in water and 0.1 M HCl. The Pb in KH soil sample, with water saturated and un-electrified, contains mostly carbonate and residual forms; Pb in TY soil sample were chiefly residual and carbonate forms; PT soil sample contains Pb of mostly residual, exchangeable and carbonate forms. Pb, as a contaminant, is in an extremely stable form for all samples; hence, the Pb contaminated soil is usually quite difficult to be remediated. With KH soil sample in water and 0.1 M HCl and electrified, the Pb removal rate was poor and did not show formal change; TY soil sample with water saturated and electrokinetic process showed no observable Pb formal change either. When 0.1 M HCl was used, the Pb concentrations from 0 to 16 cm from the cathode were from 1500 mg/kg to 60 mg/kg after 7 days of electrokinetic process. The Pb concentration transition was clearly visible. The carbonate, residual and organic Pb contents in soil near the cathode were 910 mg/kg, 510 mg/kg and 44 mg/kg, respectively. Water soluble and exchangeable Pb were nearly completely removed. Owing to the existence of Pb in very stable forms, the environmental impact is limited even though the total Pb concentration in soil near the cathode is rather high. The Pb of water soluble and exchangeable at 4 to 16 cm from the cathode are still high, the process time should be lengthened, or be assisted with water drawing to remove the Pb of lower stability forms. With PT soil sample in water, the concentration and form of Pb is only slightly changed. Due to the current level being very low during the process, the efficiency becomes quite low also and did not show a positive effect in removing of Pb. When soaked in 0.1 M HCl, PT soil sample indicated that Pb concentration 0 to 16 cm from the cathode were 1700 mg/kg to 340 mg/kg after 7 days of electrokinetic process, which is remarkable. Pb might change into metallic form owing to that reduction at the cathode. Thus the Pb in residual form was high (1200 mg/kg); meanwhile, water-soluble contains only 2 mg/kg. The highly stable Pb forms in soil near the cathode are therefore unlikely to pose any impact to the environment, regardless

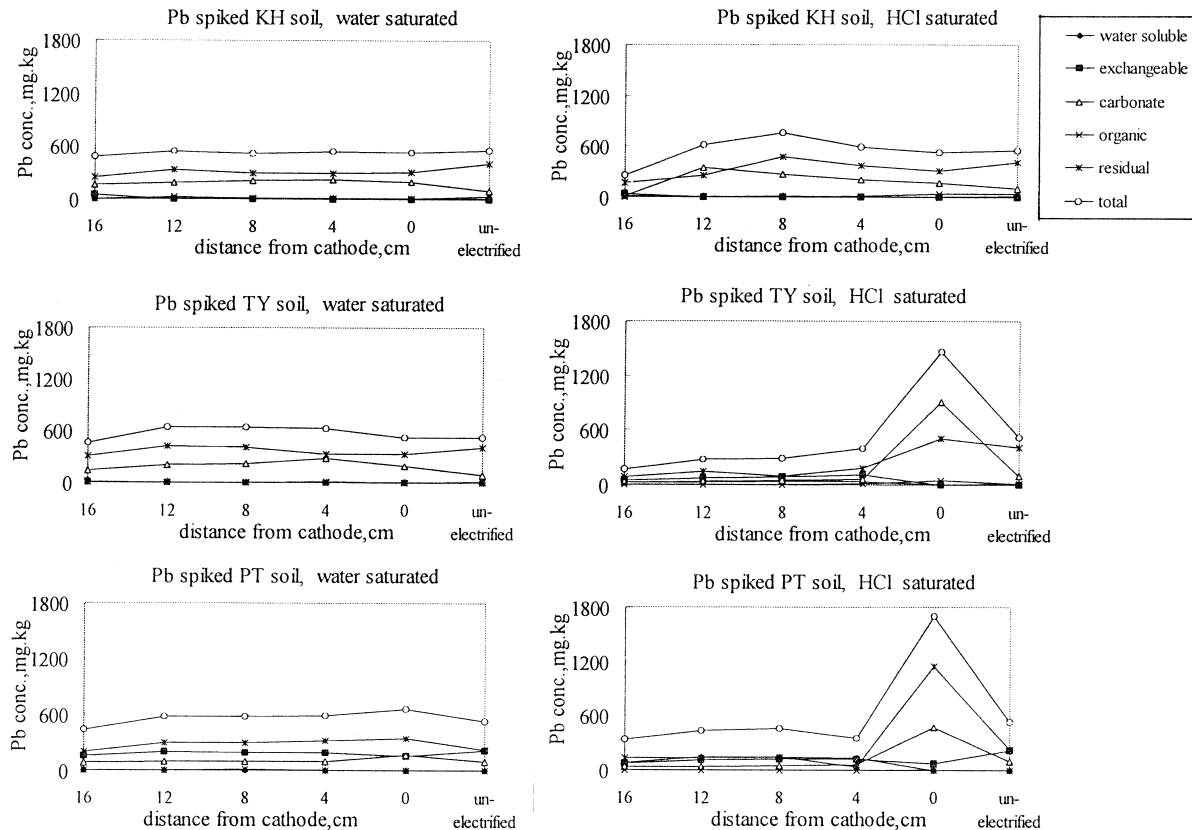


Fig. 7. Pb forms change in spiked soils saturated with water and 0.1 M HCl under 8 V electrokinetic process for 7 days.

of the high concentration. However, the residual form Pb at 4 to 16 cm from the cathode ranged from 32 mg/kg to 140 mg/kg, which has a tendency to increase. Also, Pb of exchangeable ranged from 120 mg/kg to 78 mg/kg, carbonate ranged from 64 mg/kg to 84 mg/kg and water-soluble form ranged from 130 mg/kg to 86 mg/kg, obviously decreased. Comparing the results with using water solution and un-electrified parts reveal that a highly stable Pb will transform to a lower stability form under acid condition, hereby allowing it to be more easily moved to the cathode and be condensed. We recommend a longer electrokinetic process time to improve the Pb removal efficiency.

#### **4. Conclusions and recommendations**

(1) The soil adsorption experiments have revealed that soil can adsorb more Pb than Cd. Among the three samples, the order of soils adsorption capacity on Cd and Pb is as follows: KH clay loam > TY loamy sand > PT clay.

(2) The Cd spiked samples have a higher current density during electrokinetic process than those of Pb spiked samples. Due to the white oxidant layer found on the cathode during electrokinetic process, the conductivity is reduced, thereby lowering the removal efficiency. We recommend that depolarizer be added at the electrodes, or to clean or replace the graphite electrodes regularly during the electrokinetic process to avert resistance polarization.

(3) When soaked in 0.1 M HCl, TY soil sample has the optimum removal results, PT soil sample is second and KH soil sample is the worst. Using acid solution in the soil can enhance the effectiveness of electrokinetic remediation of Cd and Pb in the contaminated soil.

(4) The metal forms in KH soil sample with Cd and Pb spiked remains unchanged during the process. In addition, TY spiked soil in water has formed a highly stable Cd and Pb forms in soil near the cathode after the electrokinetic process. Suspension can be eliminated by using 0.1 M HCl instead; it can also effectively move and concentrate Cd and Pb to the cathode to form stable residual and carbonate, thereby having less of an environmental impact. Cd in PT soil with Cd spiked and water saturated has clearly been removed and concentrated to the cathode. However, the content of exchangeable Cd is higher than desired and, therefore, requires further treatments; Pb in PT soil samples with Pb spiked and water saturated shows no change after electrokinetic process. With 0.1 M HCl instead, this process yields an optimum result in Pb removal. When 0.1 M HCl is being added to PT soil, the electrokinetic process reduces the stability of Cd and Pb in the soil. These low stability Cd and Pb can be more effectively removed from the soil if proper treatment is later used along with electrokinetic process.

#### **References**

- [1] F.A.M. de Haan, P.J. Zwerman, Pollution of soil, in: G.H. Bolt, M.G.M. Bruggenwert (Eds.), *Soil Chemistry*, Elsevier, New York, 1976, pp. 192–271.

- [2] E.H. Wang, T.H. Chen, D.Y. Lee, *Soil Pollution*, National Konchung Univ., Taipei, 1995, pp. 145–219.
- [3] Y.C. Lee, Influences on plant growing affected by Cu and Pb pollution of different soil groups, Master thesis, Nation Chungshing Univ., Taichung, 1989.
- [4] T.F. Hsu, Estimation on the Cd and Cu allowance amount in soil and modification of Cd and Cu movement in soil by using LEACHM model, Master thesis, National Taiwan Univ., Taipei, 1993.
- [5] B.J. Alloway, Cadmium, in: B.J. Alloway (Eds.), *Heavy Metals in Soils*, Wiley, New York, 1990, pp. 110–124.
- [6] Y.B. Acar, A.N. Alshahwabkeh, Principles of electrokinetic remediation, *Environ. Sci. Technol.* 27 (13) (1993) 2638–2647.
- [7] Y.B. Acar, R.J. Gale, J.T. Hamed, Removal of inorganic contaminants from soils by electrokinetics, The Seminar on Environmental Planning and the Technology of Identification of Polluting Source and Site, Remediation-site Remediation for Soil Treatment Technologies, Taiwan Business Service Foundation, Taipei, 1994, pp. B4.287–B4.302.
- [8] J. Hamed, Y.B. Acar, R.J. Gale, Pb (II) removal from kaolinite by electrokinetics, *J. Geotech. Eng.* 117 (2) (1991) 241–271.
- [9] L.I. Khan, M.S. Alam, Heavy metal removal from soil by coupled electric hydraulic gradient, *J. Environ. Eng.* 120 (6) (1994) 1524–1543.
- [10] R. Lageman, Electroreclamation—applications in the Netherlands, *Environ. Sci. Technol.* 27 (13) (1993) 2648–2650.
- [11] B.E. Reed, T.B. Mitchell, J.C. Thompson, J.H. Hatfield, Chemical conditioning of electrode reservoirs during electrokinetic soil flushing of Pb-contaminated silt loam, *J. Environ. Eng.* 121 (11) (1995) 805–815.
- [12] J. Trombly, Electrochemical remediation takes to the field, *Environ. Sci. Technol.* 28 (6) (1994) 289A–291A.
- [13] Taiwan EPA, *Collection of Methods of Environmental Analysis*, Taipei, 1994.
- [14] K.S. Kou, *Soil Experiment*, 4th edn., China Bookstore, 1987, pp. 9–18.
- [15] Y.H. Liu, A study on the sorption and chemical forms of heavy metals in Taiwan soils, Master thesis, National Pingtung Polytechnic Institute, Pingtung, 1995.
- [16] C.M. Lai, Study on the dynamic existence of heavy metals in Taiwan soils—Cd and Pb pollutants existence and the forms change after enter soils, Report of EPA Taiwan Province, Taichung, 1992.