

## **Electrokinetic Removal and Removal Characteristics of Heavy Metals from Metal-Mining Deposit**

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(Manuscript received 16 December, 2002 ; accepted 17 February, 2003)

Electrokinetic remediation technique offers the opportunity to extract heavy metals from soils with high plasticity. The experiment demonstrated the applicability of electrokinetic remediation on metal-mining deposit and the decision of the enhancement method for four kinds of bench-scale studies. According to the sequential extraction of heavy metals in the "I" mining deposit, Pb and Cu were mostly associated with residual fraction and Zn and Cd were associated with water soluble and residual fraction. Therefore, removable fractions by electrokinetic technology was determined by the sum of the fraction of water soluble and exchangeable, which is Cu : 19.53 %, Pb : 1.42 %, Cd : 52.82 %, Zn : 57.28 %, respectively.

When considering electrical potential, volume of effluent, soil pH, and eliminated rate of contaminant, results determined by sum of each weight were Citric acid+SDS (13) > 0.1N HNO<sub>3</sub> (10) > HAc (8) > DDW (4). Therefore, citric acid and SDS mixed solution was determined the best enhancing agent for the remediation of metal mining deposit.

Key words : Electrokinetics, Metal-mining deposit, Sequential extraction

### 1. Introduction

Since 1980 when the Comprehensive Environmental Response, Compensation and Liability Act, (CERCLA) or Superfund, was enacted, many kinds of remediation technologies have been developed. Early remedial actions for contaminated soils consisted primarily of excavation and removal of the contaminated soil from the site and disposal at landfill site. More emphasis is now placed on in situ treatment of soil<sup>1)</sup>.

Among the soil remediation technologies, most methods such as soil flushing, vacuum vapor extraction, and bioventing applicable in the clean up of contaminants can only be suitable for high water permeable soils. Because of such restrictions for soils with low water permeability, there is a need for sound

alternatives to resolve the proposed problems.

According to the reports(1998) of MOCIE (Ministry of Commerce Industry and Energy), approximately 900 of closed metalliferous mines in Korea has been abandoned without appropriate post audit. MOE(Ministry of Environment) has been monitoring and surveying 158 metalliferous mines with high potential of the contamination of soils during 1997~2000. Most of these mines exceeded soil pollution levels, and water quality criteria in groundwater, mine and river water.

For the remediation of those abandoned metal mine, stabilization method or chemical extraction could be considered. However, stabilization is not removal technique but only the way of reducing the chemical mobility and possible hazard. Soil washing and chemical extraction require excavation of soil, so that they are applicable only small quantity of contaminated soil.

Electrokinetic remediation is one of the alternatives developed to fulfill the requirement. Electrokinetic phenomena provides powerful

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bulk separation technologies for pollutant ions and molecules, plus very fine colloidal particles. Electrolytic processes are also compatible with separation and recovery of produced materials. They are applicable to the treatment of mixed wastes containing organic and inorganic pollutants. Electrochemical methods can be applied to soils in place or the slurries of soils in water or electrolyte solutions<sup>2)</sup>.

Electrokinetic processes refer specifically to movement of materials by using electric fields. They can be used to move pollutants in soils to collection points for physical removal<sup>2)</sup>.

Up to now, most of the work about electrokinetic remediation have been done for spiked soil (e.g., kaolinite spiked lead) on the applicability studies, selection of enhancements methods and/or development of modeling for phenomena<sup>3-5)</sup>. But those studies were short of consideration for real site soil contaminated by various metals and aging. The results obtained from the studies on spiked soils may actually be quite different from the aged soils such as metal mining deposit since the strength of metal binding could be changed during weathering processes and various other reactions.

The applicability tests were needed as a means for obtaining basic information. Therefore, the studies were carried out to estimate the applicability of electrokinetic technique on the metal mining deposit as a real contaminated soils which have been aged for longer periods of time. Also, the enhancement study was performed to accomplish the remediation of heavy metals from target soils more effectively.

For those experiments, a mine deposit soil containing high concentration of heavy metals especially, Cu, Cd, Pb, and Zn were selected.

## 2. Material and Methods

### 2.1 Soil samples and chemicals

#### Soil samples

The soil specimen for the electrokinetic experiments were prepared with metal-mining deposit, which were collected from the "I" mine located at the North Eastern suburban area in Busan Metropolitan City. The main mining metals were gold, silver, copper, and

tungsten. Also, the mine contained pyrite( $\text{FeS}_2$ ). "I" mine was opened in 1930, and closed in 1994. Samples were taken at the abandoned mine which contained the mining deposit of 160,000 m<sup>3</sup>.

The collected samples were air dried at room temperature then sieved to separate and to homogenize the particles with mesh 2mm in size. The sieved soil samples were preserved in labeled plastic bags until needed.

In the preparation of electrokinetic experiments, soil was put in electrokinetic set (container) by compaction. In order to maintain constant compaction in the soil specimen, a square type of compacter was used. The compacter was made of a steel rod of 20 cm in length, welded steel plate with a contact area of 4 cm × 4 cm. The gross weight of the compacter was 320 g. Each layer was compacted by dropping a hammer 300 times on the top of the soil from 30 cm above the soil surface. The compaction energy applied by this procedure might be enough to bring the wet soil to 1.46 t/m<sup>3</sup> of optimum water content and bulk density with relatively high degree of saturation(approximately 95%).

#### Chemicals

The pore solutions used were double distilled water, ethanoic buffer, citric acid(50mM) + SDS(0.5%) and 0.1N  $\text{HNO}_3$ . In the preparation of all reagents used in this experiments, double distilled water was used. The ethanoic buffer was prepared by mixing the 0.1N  $\text{CH}_3\text{COOH}$  and 0.1N  $\text{CH}_3\text{COOK}$  solution with the same volume. It was used as an enhancement conditioner to fix the pH of the catholyte and the anolyte solution and soil pH near the cathode. The citric acid was prepared by dissolving citric acid in distilled water at the concentration of 50mM and dissolving a SDS in this solution at the concentration of 0.5%(W/V). It used the enhancement conditioner to decrease the pH of the catholyte and soil pH near the cathode and made the negative charged micell to precipitate near the cathode.

The initial normality of  $\text{HNO}_3$  solution that obtained commercially was about 13N. Therefore, 0.1N  $\text{HNO}_3$  was prepared by diluting the pure solution with distilled water. It used the enhancement conditioner to decrease the pH of

catholyte and soil pH near the cathode.

## 2.2 Analytical methods

During the experiments, solution pHs in the catholyte, anolyte, and effluent flow rate were measured. Also, the supplied electrical potential, current, and resistance at each section of soil specimen were monitored. These were monitored at a constant interval and a pre-determined time period. After a selected period of current application, the specimen was quickly removed from the reactor and sliced to sections of 2.0 cm in length. Each sliced section was analyzed for water content, pH, and contaminant content. At the end of each run of the reactor, metal concentrations in anolyte, catholyte, outflow, and filter paper were also analyzed. Soil pHs were recorded for each section before drying them in an oven for chemical analysis and water content evaluation. The pH distributions of anolyte, catholyte, and soil were determined with pH meter (Orion960 Autochemistry System) and electrical potential was determined with a multimeter.

The amount of heavy metals were determined with a AAS (Atomic Absorption Spectrophotometer; GBC 909PBT).

Metal extractions from the soil sample and filter paper were done by the total extraction method using the aqua regia solution<sup>6)</sup>. Before the extraction, each soil sample was dried to reach constant weight in a dry oven (at 80°C, 12hr), and then ground in a mortar to homogenize.

## 2.3 Sequential extraction of metal mining deposit

Sequential chemical extraction were used to

Table 1. Conditions for sequential chemicals extraction<sup>7)</sup>

Extraction order	Designated form extracted	Reagent/ Method	Extraction time	Solids : reagent volume ratio
1	Water soluble	Distilled water	16 h	1 : 5
2	Exchangeable	1.0M KNO <sub>3</sub>	16 h	1 : 5
3	Organically bound	0.1M Na <sub>4</sub> P <sub>2</sub> O <sub>7</sub>	16 h	1 : 5
4	Carbonate	0.1M EDTA	16 h	1 : 5
5	Sulfide	1.0M HNO <sub>3</sub>	16 h	1 : 5
6	Residual	HNO <sub>3</sub> +HCl(1:3)	-	-

the evaluate the forms of Cu, Cd, Zn and Pb in the metal mining deposit. Sequential chemical extraction procedure was as follows:

Samples of 4g dry soils were extracted directly in 35ml polypropylene centrifuge tubes. After 16h the mixtures were centrifuged at 15000rpm for 20min, the supernatants being a acidified contain 1% Nitric acid, and retained for metal analysis. The pellet was extracted using the next reagent in sequence. The last extraction for defined residual fraction, the pellet was extracted by total extraction method. Table 1 show the conditions for sequential chemical extraction.

## 2.4 Electrokinetic experiments

### Experimental setup

The equipment for this study was composed of a electrokinetic remediation set, graduated cylinders, electric circuit, power supply, pH meter, and multimeter. Fig. 1 shows the schematic diagram of the experimental setup used in the electrokinetic remediation process. The reactor was made of acrylic material with 5mm thickness for electrical insulation and also to resist the lateral compaction pressure. The dimension of the reactor was 10cm in width, 15 cm in high, and 29cm in length. The selected electrode spacing was about 16cm. The dimension selected was in an attempt to minimize boundary effects and establish one-dimensional flow condition. The effect of electrode spacing to the efficiency of the process was not considered, which was also not studied well in other researches<sup>8)</sup>.

For the anode, a titanium electrode was selected, because carbon can be decomposed by

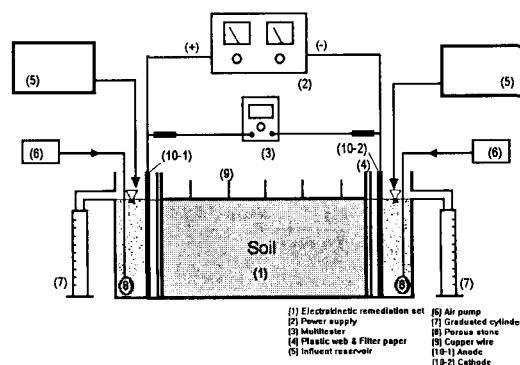


Fig. 1. Schematic diagram of electrokinetic process.

the oxidation reaction that is highly corrosive on electrodes. Along with the corrosive aspects the anode, releases carbon particles in to the anolyte during a period of time. Therefore, in this experiment, carbon and titanium were used as each the cathode and anode.

In order to supply electricity, a rod type of carbon electrodes with 0.5cm diameter were purchased and cut to the length of 16.5cm. At the cathode side, 10 cut carbon rods were fixed by specially designed electrode holder. Also, filter paper fixed between plastic web was used to divide the soil specimen and electrode wells. A power supply was used to provide electropotential and current ranging of 0-600V DC and 0-200mA. At the constant voltage mode, the output voltage was regulated to a selected value, while the output current was varied with the load requirements. At the constant current mode, the output current was regulated to the selected value, while output voltage was varied with the load requirements. Constant current mode was selected in this experiments to sustain a constant rate of production of electrolysis products at the electrodes and simplify analysis of the chemistry at the boundaries<sup>9)</sup>. Copper wires are used as voltage probes to measure the electric potential distribution of the soil specimen in a horizontal direction.

Open electrode arrangement is one that allows egress and ingress of species and pore fluid from the soil to the fluid well in the electrode compartment. In both anolyte and catholyte wells, air was supplied and bubbling was used in an air stone to make solutions mix completely.

#### Experimental procedures

Various laboratory programs were run to investigate the feasibility of electrokinetic treatment of metal-mining deposit contaminated with heavy metals.

Two applicability tests(Code No. : DDW-100 mA and DDW-20V) were conducted to estimate the applicability at different potential and current conditions. Also, three enhancement tests (Code No. : HAc, Citric acid+SDS, and 0.1N HNO<sub>3</sub>) were conducted for enhancing remediation efficiency using HAc, HNO<sub>3</sub>, and citric acid+SDS(sodium dodecyl sulfate)mixtures. Table

2 presents the processing parameters used in these tests.

In the absence of any enhancing agents, constant voltage(20V) and constant current(100 mA) were used to conduct the remediate mine deposits. The primary processing time for these tests was selected for 10days. So far, there are no standardized experimental period. Han<sup>5)</sup> selected 12days as the processing time. And Jeong<sup>3)</sup>put his study through various processing times(5day, 15day, 30day).

Constant-current conditions were adopted in the enhancement tests. This was to keep the net rate of the electrolysis reactions stable and to minimize complicated current-boundary conditions, and ease the evaluation of experiments. To determine the appropriate enhancement methods. First we used the ethanolic buffer, then used the 0.1N HNO<sub>3</sub>, followed by the 50mM citric acid and then the SDS (0.5%W/V)mixture was employed.

### 3. Results and Discussion

#### 3.1 Metal fractionation by sequential chemical extraction

The removal rate of heavy metals present in mining deposit treated with electrokinetic remediation is determined by their mobility and physiochemical forms of the metals in the soil. In order to evaluate the chemical forms of the metals in soil, the sequential extraction method

Table 2. Experimental conditions for electrokinetic reactions

Kind of experiment	Cord No.	Run time (day)	Voltage (V)	Constant current (mA)	Enhancement method (pore solution)
Applicability test	DDW-20V	10	20	-	-
	DDW-100mA	10	-	100	-
Enhancement test	DDW	10	-	100	-
	HAc	10	-	100	Ethanolic Buffer
	0.1N HNO <sub>3</sub>	10	-	100	0.1N HNO <sub>3</sub>
	Citric acid + SDS	10	-	100	Citric acid+SDS

was adopted. The sequential extraction methods resulted in the distribution of metal forms in metal deposit shown in Fig. 2 and the ranking of each metal fraction was as follow:

- Cu : Residual(66.06%) >> Water soluble (12.16%) > Sulfide(8.55%) > Exchangeable(7.37%) > Organic(3.06%) ≥ Carbonate(2.79%).
- Cd : Water soluble(41.85%) > Residual (30.58%) >> Sulfide(11.15%) ≈ Exchangeable(10.97%) > Carbonate(2.79%) > Organic(1.61%).
- Pb : Residual(78.21%) >> Carbonate(10.17%) > Sulfide(8.99%) > Organic(1.22%) > Exchangeable(0.89%) > Water soluble(0.53%).
- Zn : Water soluble(47.56%) > Residual(32.70%) >> Sulfide(6.98%) ≈ Exchangeable(9.72%) > Carbonate(1.77%) ≈ Organic(1.27%).

Based on sequential chemical extractions, the residual fraction was found to be the most abundant chemical in the soil. Very small amounts of Pb were found in the water soluble and exchangeable fraction. Most of Pb fraction was residual form. This metal fraction is generally considered within the lattice of silicate minerals and can become available only after

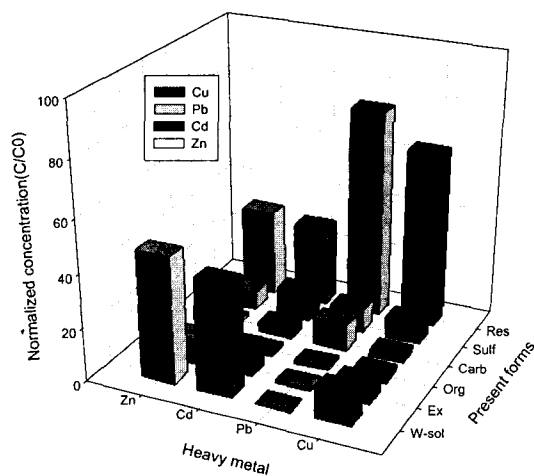


Fig. 2. The distribution of chemical forms of heavy metals in specimen after treatment by sequential chemical extraction.

W-sol : Water soluble fraction,  
 Ex : Exchangeable fraction,  
 Org : Organic fraction,  
 Carb : Carbonate fraction,  
 Sulf : Sulfide fraction,  
 Res : Residual fraction

digestion with strong acids at elevated temperatures<sup>10)</sup>. Therefore, this result indicated the reason why Pb was not removed by common extraction methods such as 0.1N HNO<sub>3</sub>, citric acid+SDS, ethanoic buffer<sup>11)</sup> and Pb and Cu were expected to be a very small part of the metals but could only be removed by electrokinetic remediation.

In comparison between the results of sequential extractions and total extractions in this study, the minimal extractable metals by electrokinetic remediation soil sample were expected as follow:

Cu : 19.53%, Pb : 1.42%,  
 Cd : 52.82%, Zn : 57.28%

The minimal extractable metals was estimated by summing up the fraction of water soluble and of the exchangeable.

### 3.2 Removal characteristics of contaminants

Figures from Fig. 3 shows the concentration profiles of contaminant in the soil matrix by each enhancement method. It was found that the contaminants were redistributed across the specimen because desorption from the mineral surface in the zone close to the anode compartment and precipitation close to the cathode might be occurred to the metal solubility limit. The removal rate of Cd and Zn were 55% and 81% of initial metal concentration in soil, respectively. It was observed that the removal rate in anode region was higher than that in cathode region, which might be caused by electroosmosis and ion migration.

On the other hand, at all section Pb could not be removed by any enhancement methods used. It may be related with the characteristic of each metal adsorption.

Also, based on the sequential chemical extraction, removable fraction of Pb was very little and most of Pb in soil matrix was strongly bound or in the soil structure. Therefore, these fractions can not be removed or extracted by ever enhancing methods be cause there are presented in very stable state.

Compared with most other contaminants, lead has a tendency of long residence time in soils. Detrimental effects associated with lead have been recognized for a long time<sup>12)</sup>. Lead was highly retarded and adsorbed in clay

minerals and low removal rate of Pb was caused by low rate of moveable fraction (like the water soluble fraction and exchangeable fraction) in metal mining deposit. According to the sequential extraction result, only 1.42% of Pb which was contained in soil sample was possible fraction of desorption. Main mechanism of metal removal in electrokinetic remediation was ion migration which was only for soluble ion in pore solutions.

On the other hand, removal rate of Cd and Zn which had more than 50% of possible fraction of desorption was over 50%. If this removal rate was converted about moveable fraction, removal rate was more than 100%. However, there have been few studies of the specificity and selectivity of different reagents, and, as a consequence, the precise nature of the metal forms obtained by many extraction techniques is uncertain<sup>13</sup>. Therefore, total metal extracted concentration was used to explain the

results obtained in this study.

Comparing the results of electrokinetic remediation and sequential chemical extraction, the fraction of metals moved by electrokinetic technique was much higher than that obtained the sequential extraction. This phenomena might be due to the electrophoresis effect of clay particles containing high concentration of metal.

Therefore, the results of sequential chemical extraction indicated that the application of electrokinetic technique was very efficient method in the remediation of heavy metals from metal mining deposit.

In this experiment, the interesting result was observed with 0.1N HNO<sub>3</sub>. Although effluent headed toward the direction of the anode and the quantity of effluent was discharged over 3 l, ion migration of contaminants were heading toward the cathode. It can be explained by the removal rate, which was very high at most of soil specimen except for the cathode compart-

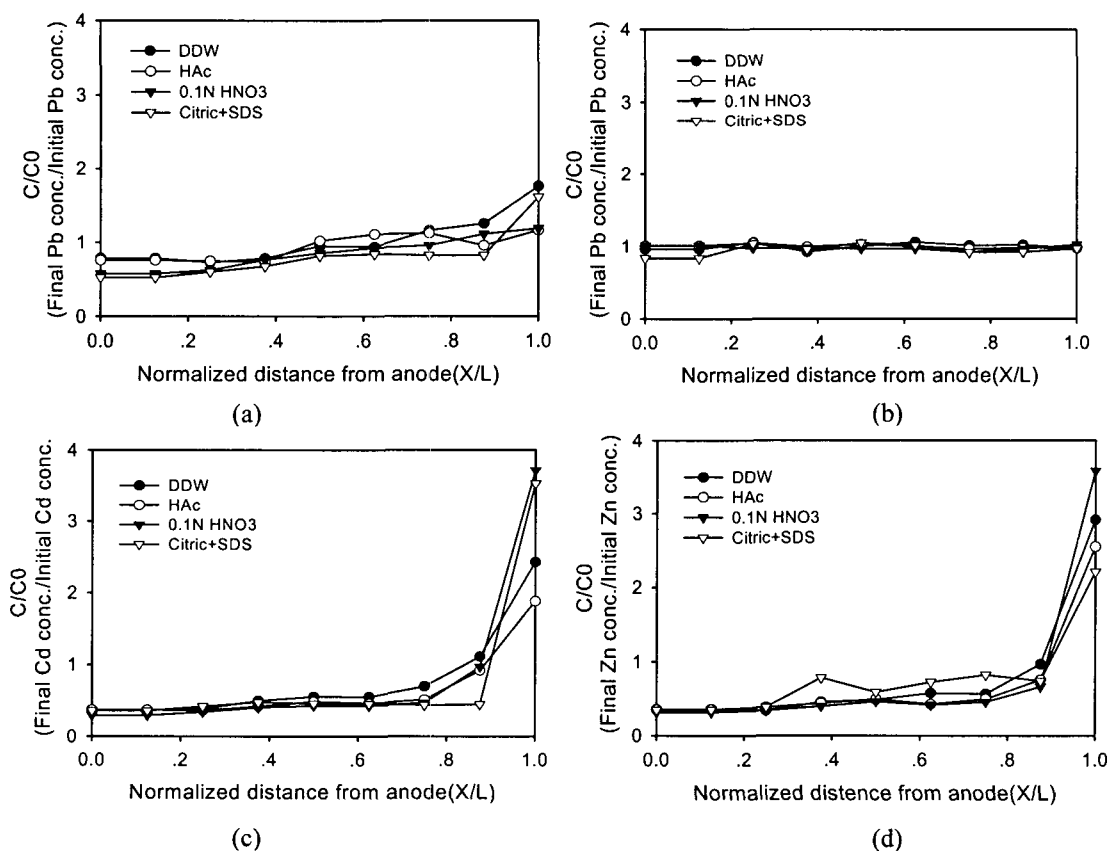


Fig. 3. Residual concentration of metals as a function of normalized distance from anode. (a) Cu, (b) Pb, (c) Cd, (d) Zn

ment.

Acar and Gale<sup>14)</sup> demonstrated that the efficient removal of cadmium was accomplished even when there was no electroosmotic flow and validate the hypothesis that electrical migration was a significant transport mechanism of species as much as electrokinetic remediation by electroosmosis.

Figures from Fig. 4 shows the distribution of contaminant in the end of the run for the electrokinetic remediation. Although four tests were carried out under different enhancement methods, metals were enriched in the cathode regions except for Pb. It may be caused by the rise of soil pH in the cathode region. The increase of soil pH could cause the adsorption and precipitation of contaminant at the cathode regions. Metals were not detected at the catholyte but detected at the anolyte. Also, Cd and Zn were detected at the filter of the cathode and the precipitation which might be caused by contaminant adsorption to the electrode

and filter paper and/or hydroxide precipitation in the catholyte.

The effects of injected chemical conditioners at the anode and the cathode were investigated by Electrokinetics Inc. in collaboration with the US Army Waterways Experiment Station at Vicksburg, Mississippi<sup>15)</sup>. These conditioners can modify the chemical reactions that take place at the electrodes and enhance the effectiveness of the system. For example, acetic acid depolarizes the reaction at the cathode<sup>16)</sup>.

3.3 Decision of the enhancement method

Table 3 shows the results of electrical potential, volume of effluents, soil pH, and elimination rate of contaminant by each enhancement method employed here.

Soil pH was measured and compared in 7 selected sections, except for section 8 which was near the cathode. The elimination of contaminant was summed as the mass(%) of the 8 section districtly sliced (section just near

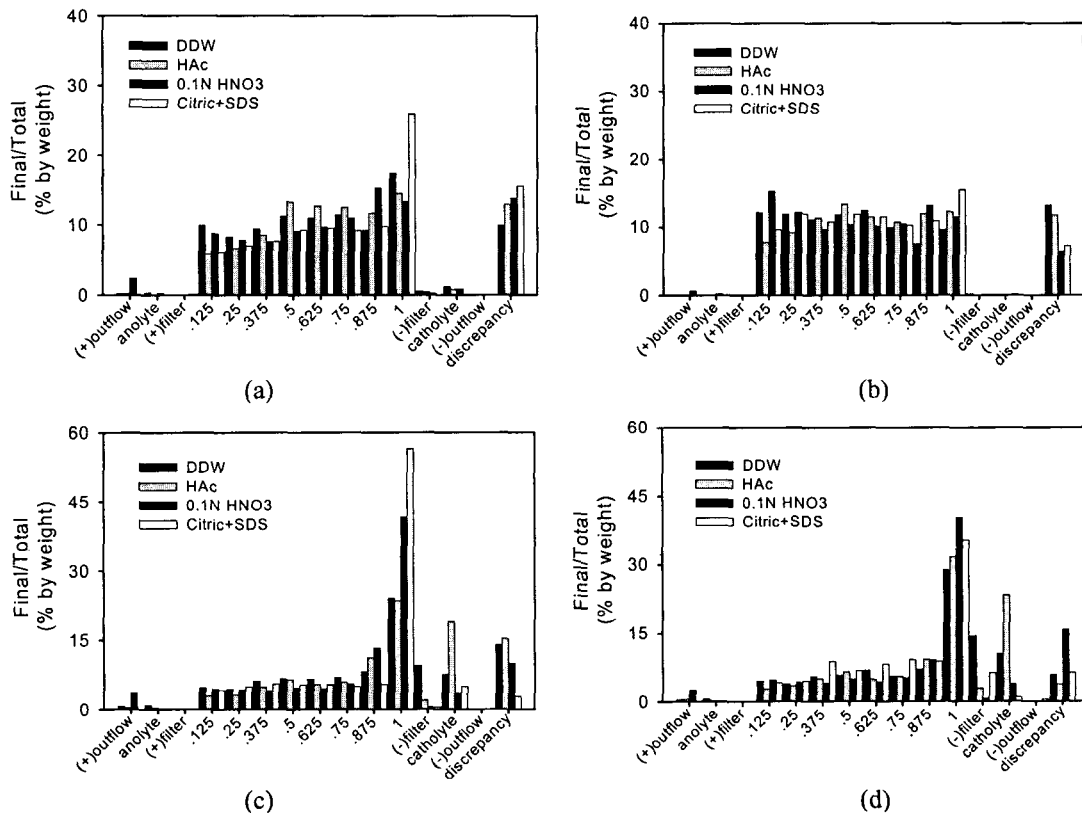


Fig. 4. Total concentration distribution of metals in soil, reservoir, and effluent. (a) Cu, (b) Pb, (c) Cd, (d) Zn

Table 3. Results of the each enhancement method

	DDW	HAc	Citric aic+SDS	0.1N HNO <sub>3</sub>	
Electrical potential [Initial(0.5hr)/Final(240hr)]	115V/550V	22V/195V	15V/215V	20V/78V [but, maximum Voltage was 175V in 120hr]	
Energy expenditure (kWh/m <sup>3</sup> )	6075.859	1701.891	1747.078	1131.056	
Volume of effluent [(-)direction/(+)direction]	341mℓ/810mℓ	97mℓ/456mℓ	787mℓ/0mℓ	165mℓ/3214mℓ	
Soil pH (pH average of section1 ~7 /pH of section8)	4.95/6.43	4.62/9.20	3.21/4.95	4.25/9.93	
Elimination and Precipitation of contaminant (Mass %)	Cu	19.21%	15.72%	26.02%	14.49%
	Cd	41.12%	44.47%	62.03%	45.78%
	Zn	53.83%	58.01%	43.30%	52.21%
	Pb	9.86%	12.38%	15.81%	11.68%

the cathode), (-)filter papers, catholyte, and effluents of (-)direction.

According to the Table 4 which lists the evaluation of enhancement methods for selection, the solution of citric acid(50mM) +SDS (0.5%) was determined to the best of methods. Although 0.1N HNO<sub>3</sub> pore solution was more effective than citric acid and SDS mixed solution for electrical potential, energy expenditure, and eliminated rate of contaminant, the direction of electroosmotic flow of citric acid + SDS mixture was only proceeded to the cathode compartments. It was very important for electrokinetic remediation. In electrokinetic remediation, the main mechanism that contaminant was removed was desorption, which was caused by the movement of the acid front heading to the cathode. Soil pH was decreased by increasing of the acid front and contaminant was desorbed form soil surface.

If electroosmotic flow is proceeded to anode compartments, base front will be increased to anode compartments in long duration. It cause the increase of soil pH, and then the read-sorption and precipitation of contaminant. And then, It was conferred weight on each symbol, and results that was comparison about sum of weight in Table 4 were as follow:

Citric aic+SDS (13) > 0.1N HNO<sub>3</sub> (10) > HAc (8) > DDW (4)

Consequently, citric acid and SDS mixed

solution was determined as the best enhancing agents in this study.

Table 4. Evaluation for decision of the enhancement method

	DDW	HAc	Citric aic+SDS	0.1N HNO <sub>3</sub>	
Electrical Potential (V)	×(0)	○(2)	△(1)	◎(3)	
Energy Expenditure (kWh/m <sup>3</sup> )	×(0)	○(2)	△(1)	◎(3)	
Volume of Effluent (ml)	×(0)	×(0)	○(2)	×(0)	
Soil pH	×(0)	×(0)	○(2)	×(0)	
Eliminated rate of Contaminant	Cu	×(0)	○(2)	×(0)	
	Cd	○(2)	○(2)	◎(3)	○(2)
	Zn	○(2)	○(2)	○(2)	○(2)
	Pb	×(0)	×(0)	×(0)	×(0)
Sum of weight	4	8	13	10	

- Electrical potential(at 240hr)

◎: less than 100 V ; ○: 100~200V ;  
△: 200~300 V ; ×: more than 300 V

- Eliminated amount of Contaminant

◎: more than 60% ; ○: 40~60% ;  
△: 20~40% ; ×: less than 20%

- Weight of symbol

◎ = 3 ; ○ = 2 ; △ = 1 ; × = 0



#### 4. Conclusions

Electrokinetic remediation technique offers the opportunity to extract heavy metals from soils with high plasticity. The experiment demonstrated the applicability of electrokinetic remediation on metal-mining deposit and the decision of the enhancement method for four kinds of bench-scale studies.

The main conclusions obtained in this study were as follows :

- 1) The results of sequential extraction of metal mining deposit tended to show great variation at each species. According to heavy metals in the "I" mining deposit, Pb and Cu were mostly associated with residual fraction and Zn and Cd were associated with water soluble and residual fraction. And, in this study, removable fractions, determined by the sum of the fraction of water soluble and exchangeable, metal in soil sample were followed:

Cu : 19.53 %, Pb : 1.42 %, Cd : 52.82 %, Zn : 57.28 %

Therefore, Pb and Cu were expected to be a very small part of the metals but could only be removed by electrokinetic remediation.

- 2) In the enhanced electrokinetic test, although four tests were carried out under different enhancement methods, metals enriched in cathode regions and efficiency of Pb removal was very low. It was caused by the low rate of removable metal fraction and high pH in the cathode region. Also, based on the sequential chemical extraction, recoverable fraction of Pb was very small and most of Pb in soil matrix was strongly bound in the soil structure. Therefore, these fractions can not be removed or extracted by enhancing methods because there are presented in a very stable state. However, electrical potentials in enhanced electrokinetic tests were lower than unenhanced test. Also, it was observed that only the flow taken placed by electroosmosis with citric acid and SDS mixtures headed toward the cathode.
- 3) Although 0.1N HNO<sub>3</sub> pore solution was more effective than citric acid and SDS mixed solution in various results(like electrical

potential, energy expenditure and eliminated rate of contaminant), direction of electroosmotic flow of citric acid + SDS was only proceeded to cathode compartments. Electroosmotic flow was proceeded to anode compartments, the base front moved to anode compartments in long duration. It cause the increase of soil pH, the re-adsorption, and precipitation of contaminant. And then, It was conferred weight on each results(e. g., Electrical potential, Volume of effluent, Soil pH, and Eliminated rate of contaminant)and results that was comparison about sum of weight were as follow:

Citric aic+SDS (13) > 0.1N HNO<sub>3</sub> (10) > HAc (8) > DDW (4)

Therefore, citric acid and SDS mixed solution was determined the best enhancing agent for the remediation of metal mining deposit.

#### Acknowledgements

This work was supported by the research fund of Kyungsoong University in 2002.

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