

## Effects of Electric Current and Potential on the Electrokinetic Removal of Heavy Metals from an Abandoned Mine Tailings

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In the removal of heavy metals from the mine deposit using electrokinetic processes, the effects of operation under both constant current and constant potential conditions were estimated.

The results of soil pH distributions for DDW-20 V and DDW-100 mA cases after the electrokinetic remediation tests were observed. In the former case, soil pH was not much changed and kept to almost constant value just little higher than initial soil pH of 3.52, except near the cathode, which was about pH 5. While in the latter case, soil pHs of anode and the cathode regions were less than pH 3 and about 6, respectively.

The electroosmotic flow to the cathode increased rapidly till 10 hrs and decreased steadily and then maintained to constant rate until the end of operation at constant current condition. Electric potential gradient was continuously increased to as much as 34.375 V/cm. At the steady state, values of the apparent electric conductivity for DDW-20 V and DDW-100 mA were around 40  $\mu\text{S}/\text{cm}$  and 30  $\mu\text{S}/\text{cm}$ , respectively.

In the DDW-100mA test, Cu, Cd, and Zn except Pb showed the tendency of moving toward the cathode. While in the DDW-20 V case, it was observed that Cu, Zn, and Pb except Cd were not moved to any directions. The results of the tests demonstrated that the electrokinetic soil remediation process could be operated better under constant current condition than constant electric potential condition.

Key words : Electrokinetics, Electric current, Electric potential, Electroosmosis, Mine tailings, Heavy metal

### 1. Introduction

Electrokinetic phenomena are powerful bulk separation technologies for pollutant ions and molecules, plus very fine colloidal particles. Electrolytic processes are also compatible with separation and recovery of product 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>1)</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>1)</sup>

Up to now, most of the works 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>2-4)</sup> But those studies were short of consideration for real site soil contaminated by various metal and aged. The results obtained from the studies on spiked soils may actually be quite different from the aged soils since the strength of metal binding could be changed during weathering processes and various other reactions.

According to the these differences, changes of procedure conditions were expected in electrokinetic remediation at the real site. Therefore, the studies were carried out to estimate the applicability of electrokinetic technique in the

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metal mining deposit, same real contaminated soils which have been aged for longer periods of time. For those experiments, a mine deposit soil containing high concentration of heavy metals especially, Cu, Cd, Pb, and Zn were selected.

In the operations of electrokinetic processes for the remediation of contaminated soils, either constant current or constant potential condition has been adopted. Rodsand and Acar<sup>5)</sup> employed constant current conditions to keep the rate of charge input in the system. This provision keep the rate of production of the electrolysis constant at the boundaries and ease the evaluation of the experiments.

Jeong<sup>2)</sup> reported that the more current increased, the more removal rate increased. The lead in his report was removed as much as 95 % after 30 days reaction under the current of 50 mA, and was initial concentration of lead 5000 mg/kg. On the other hand, much research was conducted under constant electrical potential; 30 V DC<sup>6)</sup>, 25 V DC<sup>7)</sup>, and 25 V DC.<sup>4)</sup>

In order to estimate the effects of operation conditions of electrokinetic processes in the removal of heavy metals from the mine tailings, electrokinetic reactors just saturated with water in which any other electrolyte was not contained, were run under constant current and constant potential conditions. In the operation of the process, changes in pH, electric current, electric potential, osmotic flow, and contaminant distribution were investigated.

## 2. Materials and Methods

### 2.1. Soil samples

The soil specimen for the electrokinetic experiments were prepared with metal mine tailings, 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 (FeS<sub>2</sub>). "I" mine was opened in 1930, and closed in 1994. Samples were taken at the abandoned mine which contained the mining tailings of 160,000m<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 4cm×4cm. The gross weight of the compacter was 320g. Each layer was compacted by dropping a hammer 300 times on the top of the soil from 30cm 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%).

Major physicochemical properties of soil texture include, soil pH, cation exchange capacity (CEC), chemical composition of soil, and content of contaminant. The results of the characterization of "I" mine tailings are listed in Table 1. Through the XRD analysis, it was determined that the primary mineral was Quartz (SiO<sub>2</sub>) and secondary mineral was Illite. By USDA (U.S. Department of Agriculture) analytical procedures, the "I" mine soil was determined to sandy loam. The soil pH, it was determined to 3.52, which was seriously acidified.

Table 1. Characteristics of the metal mine tailings

Characteristic	Data
Soil minerals	
primary mineral	Quartz
secondly mineral	Illite
Soil texture (% by weight)	Sandy loam
Specific gravity	2.77
Cation exchange capacity (milliequivalents/100 g of dry soil)	2.32
Soil pH	3.52
Heavy metal concentration (mg/kg)	
Cu	1246.1
Pb	492.8
Cd	7.2
Zn	674.0

The acid digestion for the metal analysis in mine tailings resulted in the concentration of each heavy metals (Cu : 1246.1mg/kg, Pb : 492.8mg/kg, Cd : 1246.1mg/kg, and Zn : 1246.1mg/kg).

The pore volume of soil sample used in the electrokinetic test set was estimated to 750cm<sup>3</sup>.

### 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 removed quickly 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.

### 2.3. Experimental setup

At the end of each test, 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>8)</sup> Before the extraction, each soil sample was dried to reach constant weight in a dry oven (at 80°C, 12 hr), and then ground in a mortar to homogenize.

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

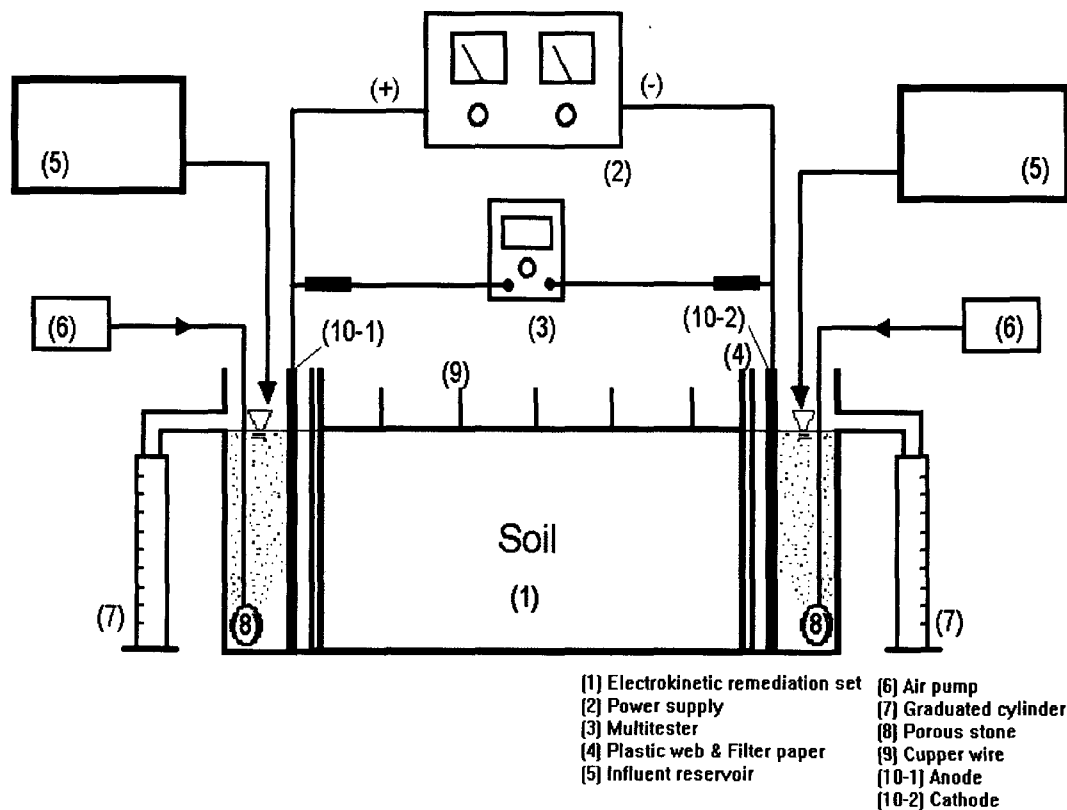


Fig. 1. Schematic diagram of electrokinetic process.

diagram of the experimental setup used in the electrokinetic remediation process. The reactor was made of acrylic material with 5 mm thickness for electrical insulation and also to resist the lateral compaction pressure. The dimension of the reactor was 10 cm in width, 15 cm in height, and 29 cm in length. The selected electrode spacing was about 16 cm. 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>9)</sup>

In order to supply electricity, a rod type of carbon electrodes with 0.5 cm diameter were purchased and cut to the length of 16.5 cm. At the cathode side, 10 cut carbon rods were fixed by specially designed electrode holder. For the anode, a titanium web was selected, because carbon can be decomposed by the oxidation reaction that is highly corrosive on electrodes. Also, filter paper fixed between plastic web was used to divide the soil specimen and electrode wells. A power supply was used to provide electro potential and current ranging of 0-600V DC and 0-200 mA. 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>10)</sup> Copper wires were 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 for 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.

#### 2.4. Experimental procedures

Various laboratory programs were run to investigate the feasibility of electrokinetic treatment

of mine tailings contaminated with heavy metals.

Two applicability tests (Code No. : DDW-100 mA and DDW-20 V) were conducted to estimate the applicability at different potential and current conditions.

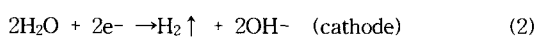
Constant voltage (20 V) and constant current (100 mA) were used to conduct the remediate mine deposits. The primary processing time for these tests was selected for 10 days. So far, there are no standardized experimental period. Han<sup>4)</sup> selected 12 days as the processing time. And Joung<sup>2)</sup> put his study through various processing times (5 day, 15 day, 30 day).

### 3. Results and Discussion

#### 3.1. Distribution of pH in catholyte, anolyte, and soil

It is necessary to know and understand the pH changes in the soil matrix since pH is a master variable in chemical equilibria and dissolution/precipitation, aqueous phase and sorption reactions in the fluid. Because variations in pH imply changes in concentration of H<sup>+</sup> ions, pH is also a strong indicator of the electrical conductivity which affects electrical conductances and species transport in the soil pore fluid under electrical fields.<sup>9)</sup>

Fig. 2 presents the plots of the pH at the catholyte and anolyte in the lapse of time. Electrolysis reactions at the electrodes, equation (1) and (2),<sup>5)</sup> caused oxidation at the anode which decreased the pH in the anolyte to less than 2 and reduction at the cathode which increased the pH in the catholyte to about 11~12 (in the DDW-20 V test, pH value was stabilized to about 11, and in DDW-100 mA, pH value was stabilized to about 12). Most of the changes in the catholyte and the anolyte pH were realized within the first 10~24 hours of processing.



The magnitude of the pH and its rate was predicted by Faraday's law of equivalence of mass and charge.<sup>10,11)</sup> If it is assumed that all charge is used in generation of the hydrogen and the

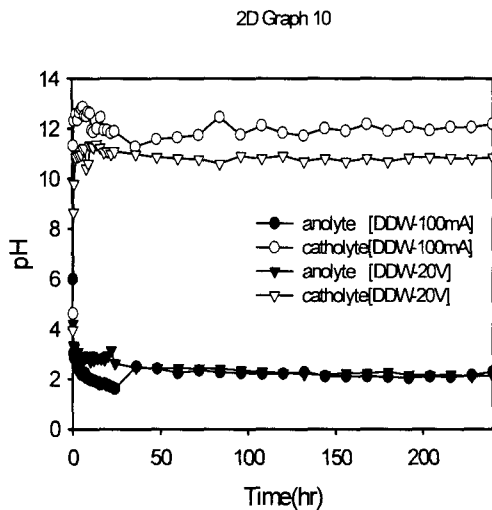


Fig. 2. Anolyte and catholyte pH in the lapsed of time.

hydroxyl ion under steady state conditions with neglect of all other chemical reactions, one Faraday of charge (96,500 C/mole) will generate two mole of  $H^+$  at the anode and one mole of  $OH^-$  at the cathode.<sup>10,11)</sup>

With the same quantity of electricity twice as many water molecules are electrolyzed at the cathode than at the anode, the production of  $H^+$  ions at the anode decrease the pH two units (eq(1) and eq(2)) than the increase pH at the cathode.<sup>12)</sup>

The current of 0.1 A across the specimen in the DDW-100 mA test will produce  $3.7 \times 10^{-3}$  moles of  $OH^-$  every hour in the cathode compartment. While, in the anode compartment, the  $H^+$  production will be twice as much as cathode compartment ( $7.4 \times 10^{-3}$  moles/hr). Considering a 0.65 l volume of liquid in each compartment, the rate of increase in  $OH^-$  and  $H^+$  concentrations will be approximately equal to  $5.7 \times 10^{-3}$  moles/l · hr and  $11.4 \times 10^{-3}$  moles/l · hr, respectively.

The  $H^+$  concentration estimated above shows the tendency of  $H^+$  increase steadily, but only within the first 1 hr. Subsequently, the concentration of  $H^+$  at the anode and the  $OH^-$  at the cathode were decreased and maintained to constant values. These were not the concentrations predicted by the electrolysis reactions.<sup>9)</sup>

The differences were due to prevailing secondary electrolysis, transport of hydrogen and

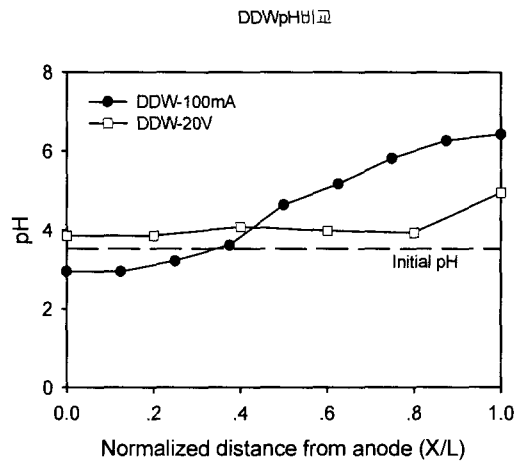


Fig. 3. Distribution of pH in soil over normalized distance.

hydroxyl ions across the specimen towards respective counter electrodes and the aqueous phase reactions associated with their transport,<sup>13)</sup> the dilution of the species to a larger volume due to transport, the water auto-ionization reaction, and electrodeposition reactions.<sup>9)</sup>

The acid front generated at anode by electrolysis will advance toward the cathode by transport mechanisms including migration caused by electrical gradients.<sup>14)</sup>

And Zeta potential of the soil and electroosmotic coefficient of permeability across the soil may be affected by the changes in pH.<sup>9)</sup> Also, the structure of the soil and engineering characteristics such as hydraulic conductivity may be influenced by pH.

Fig. 3 shows the pH distribution in soil over normalized distance from anode to cathode after the electrokinetic remediation test. In the DDW-20 V test, the pH through most of the section was not much changed except for just near the cathode, which was about 5. This phenomenon may be caused by the fact that at DDW-20 V electroosmotic flow and the movement of the acid front did not occur.

In the case of DDW-100 mA, anode showed a soil pH of less than 3, while the cathode region showed a final pH ranging from 4 to 6. The soil pH value changed at the normalized distance of

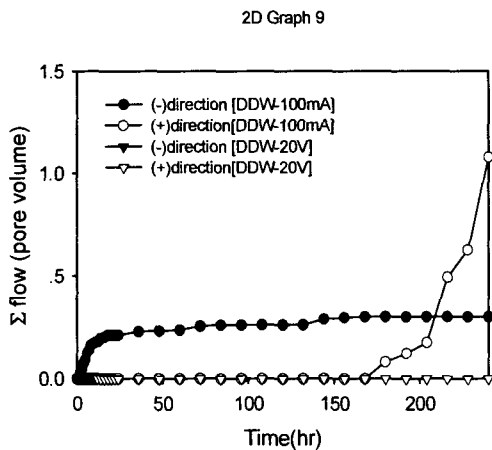


Fig. 4. Cumulative volume of effluent over time. pore volume = 750 ml.

0.4 from the anode. Soil pH before the distance of 0.4 was below the initial value, while after 0.4 the pH value was above the initial pH. It was due to the movement of base front from the cathode caused by the reverse electroosmotic flow (Fig. 4). There was an observation of a significant difference between the pH value in the soil and the catholyte. The decrease of the pH within the incoming pH within this zone relative to the catholyte value is directly related to the extent the consumption of the hydrogen/hydroxide ions in the transport.<sup>15)</sup>

### 3.2. Flow change of effluents

In the most part of spiked test, the direction of electroosmotic flow was from anode compartment toward cathode compartment.<sup>7,11,15)</sup>

Acar et al.<sup>16)</sup> noted that the interaction of the species in the pore fluid with negatively charged surface resulted in alignment of the ionic species as conceptualized. The excess negative charge in the soil results in attraction and cluster of excess cations close to the surface, while the neutrality of charge in the pore fluid is maintained by the equivalent concentration of anionic and cationic species elsewhere. When an electric field is established along the capillary, the excess cations close to the surface move towards the cathode. The movement of these species and any water molecules closely associated with these species imparts a net strain on the pore fluid surrounding

their hydration shell. This strain translates into a shear force through the viscosity of the pore fluid. Since there is usually an excess amount of cations close to the surface, the net force and momentum towards the cathode result in a pore fluid flux in the same direction.

The equivalent hydraulic head difference generated by the suction caused pore fluid to flow towards the section with the highest suction. In other words, pore fluid flow could have occurred from the cathode and the anode compartments towards the section with highest suction but the net flow was towards the cathode.<sup>9)</sup>

However, this experiment showed very different trends. Fig. 4 shows the direction of electroosmotic flow and the pore volume of effluents. In this test, pore volume was evaluated to 750 ml. In the DDW-100 mA test, effluent to the cathode rapidly increased till 10 hrs and decreased steadily and then maintained to constant rate until the end of operation. Meanwhile after 180 hr effluent to the anode was occurred and increased very rapidly until the end of the duration.

The flow reversion occurred here may be due to the net surface charge reversion of soil particles and pH plays a significant role in determining the charge on soil particles. Below  $pH_{zpc}$  (pH at zero point charge), the clay may have a positive zeta potential ( $\zeta$ ) and the electroosmotic flow can go toward the anode. While above the  $pH_{zpc}$ , the zeta potential is negative and the electroosmotic flow takes place in the direction of the cathode.<sup>7)</sup>

In the application of 20 V, any flows to the cathode and even anode were not observed. This result is quite different with that obtained from the use of spiked soil. According to the Helmholtz-Smoluchowski theory, electric potential was an important factor of electroosmotic pore fluid transport. Electroosmotic pore fluid flux is a function of the coefficient of electroosmotic permeability and the electric gradient; therefore, changes in the electroosmotic flow were expected to be either due to a change in the electric gradient or a change in the coefficient of electroosmotic permeability.

If electroosmotic permeability was very low in the specimen, low electric gradient was assumed

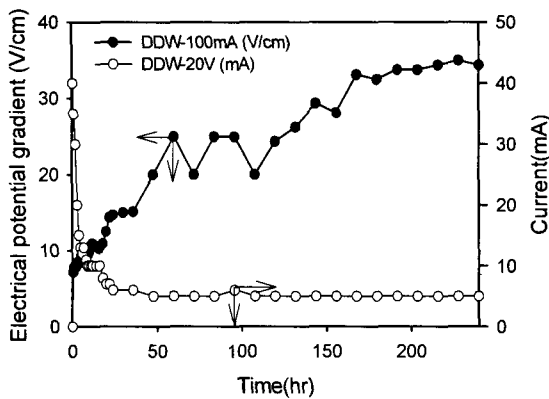


Fig. 5. Electric potential gradient and current changes over time.

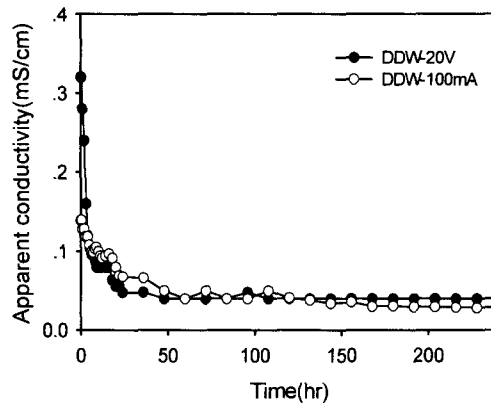


Fig. 6. Apparent electric conductivities of DDW-20V and DDW-100mA.

not enough to make the fore move. According to the result, high voltage was needed in remediation of metal mine tailings. Therefore, constant current (100 mA) condition was adopted in electrokinetic remediation for ongoing studies.

### 3.3. Distribution of electric potential and current

Fig. 5 shows the development of the average electric potential gradient and current across the cell electrodes. In DDW-100mA test, electric potential gradient was continuously increased. At end of duration, electric potential gradient was 34.375 (V/cm). Comparing the existing report,<sup>2,12)</sup> this value was 3~10 times larger than those reported.

In the DDW-20 V test, current was rapidly dropped first during reaction duration (till 4 hr) and then maintained to a constant value (5 mA) after 48 hrs. This current drop was caused by increased resistance in soil. As time goes by, resistance may be increased by the depletion of ions (by the discharge of ions by flow, precipitation and adsorption near the cathode). Because of maintaining the constant current condition, electric potential should also be increased.

Acar et al.<sup>9)</sup> have recommended the relation between electric conductivity and applied voltage as equation (3).

The total voltage applied across each specimen depended upon the chemistry developed across the medium, since the electric conductivity of the soil was the function of the ionic strength of the soil

pore fluid. Generally, the soil pore fluid was composed of a multicomponent solution of different species such as heavy metal, hydrogen, calcium, sodium, nitrate, chloride, and hydroxyl ions. However, multispecies transport under the applied electric gradient redefined the electric conductivity distribution across the soil. Electric conductivity changed significantly from one position to another depending upon the pH and ionic strength.

And then,  $\chi_a$  gave an equivalent conductivity value for the medium across the electrode that disregarded the discrete. The discrete changes in conductivity across the soil. In other words, the soil across the electrodes was assumed to behave as series of resistors and the apparent conductivity represented an equivalent value for all the resistors. The apparent electric conductivity of each sample was evaluated by,<sup>9)</sup>

$$\chi_a = \frac{I_t L}{EA} \quad (3)$$

where,  $\chi_a$  = the apparent conductivity of the soil (s/cm);  $E$  = the voltage applied (V);  $I_t$  = the total direct current (A);  $L$  = the specimen length (cm);  $A$  = the cross-sectional area of the specimen (cm<sup>2</sup>)

Fig. 6 shows that the apparent electric conductivities in DDW-20 V and DDW-100 mA specimens decreased and reached a constant value after 50 hours run. Similar findings were reported by Hamed et al.<sup>12)</sup> and Acar et al.<sup>9)</sup> The decrease in apparent electric conductivity occurred in the

first 24 hr of processing each tests. The sharp decrease after this stage may have been directly related to the precipitation of contaminant at its hydroxide solubility limit or due to the effect of the high pH environment developed near the cathode.<sup>9)</sup> The steady state values of the apparent electric conductivity were around 40  $\mu\text{S}/\text{cm}$  in DDW-20 V and around 30  $\mu\text{S}/\text{cm}$  in DDW-100 mA. Similar result were reported by Acar et al.<sup>9)</sup> According to the report, the steady state values of the apparent electric conductivity were around 30  $\mu\text{S}/\text{cm}$  in bench-scale tests and around 50~70  $\mu\text{S}/\text{cm}$  in pilot-scale tests.

As the electric current was passing through a unit area, the time was constant as well as space. The change in the electric conductivity of the medium was accompanied by the change in the electric gradient and current density, which were maintained to a constant value. Accordingly, the total applied voltage increased and applied current decreased with time until it reached a steady state value.<sup>9)</sup>

Acar et al.<sup>9)</sup> recommended the variation of electric conductivity during the electrokinetic remediation test and reason of these variation as follow.

In naturally contaminated samples, significant amounts of contaminants were expected to be present as salt precipitation in the soil. When the chemical species were present in the form of salts and the ionic conductivity of the pore fluid was low, the resistance to charge flux was high leading to high voltage gradients. Transport of the acid generated at the anode across the specimen resulted in dissolution of the salts and increase of the ionic conductivity in the pore fluid. However, if the process was continued to unenhanced state until the species in the pore fluid were removed from the soil, the ionic conductivity would decrease and push the voltage gradient up again. If enhancement techniques were used, then introduction of chemicals at the cathode or anode compartments would have resulted in species transport into the soil, affecting the electric conductivity of the pore fluid.

During the electrokinetic remediation process, electrical potential in the soil was changed by

various processes. Change in the electric conductivity across the soil and the corresponding variations in electric voltage distribution were directly proportionate to the electrochemical changes in the soil pore fluid; mainly the ionic strength and pH. The effect of pH on the electric conductivity was quite significant in electrokinetic soil remediation.<sup>9)</sup> During the operation, two voltage drops were observed in the soil. The first drop was near the anode and the second drop was near the cathode. These results were differenced with those of Acar et al.<sup>9)</sup> Acar et al.<sup>9)</sup> reported that most of the voltage drop was developed in the soil near the cathode and only a small decrease in the voltage was observed within the anode region. In this study, it may be caused by low electric conductivity occurring by low concentration of electrolyte in pore fluid. Therefore, the pore fluid did not contain any electrolyte in the beginning and ions in the soil pore were consumed by the migration of the cathode. By these reasons, electrolyte ions could be depleted in the pore space, which resulted in not enough driving force for the desorption of heavy metals.

### 3.4 Removal characteristics of contaminants

Fig. 7 presents the results of relative concentration of contaminants over the normalized distance from anode to cathode for each test. Final concentration distributions of the contaminant demonstrated that the DDW-100 mA test resulted in a higher degree of removal than the DDW-20 V test. However, it was found that in the DDW-100 mA test significant masses of contaminant were precipitated close to the cathodes.

In the DDW-100 mA test, Cu, Cd, and Zn except Pb tend to move toward the cathode. In the case of DDW-20V (Fig. 7(b)), it was observed that Cu, Zn, and Pb except Cd were not moved to any direction. According to the eq (4),<sup>17)</sup> mass flux of ion migration was the function of the effective ionic mobility of species, concentration of species, and electrical gradient. Actually, each species has a different mobility in the soil, which is caused by different ability of adsorption/desorption with soil.

$$J_j^m = u_j^* c_j i_e \quad (4)$$



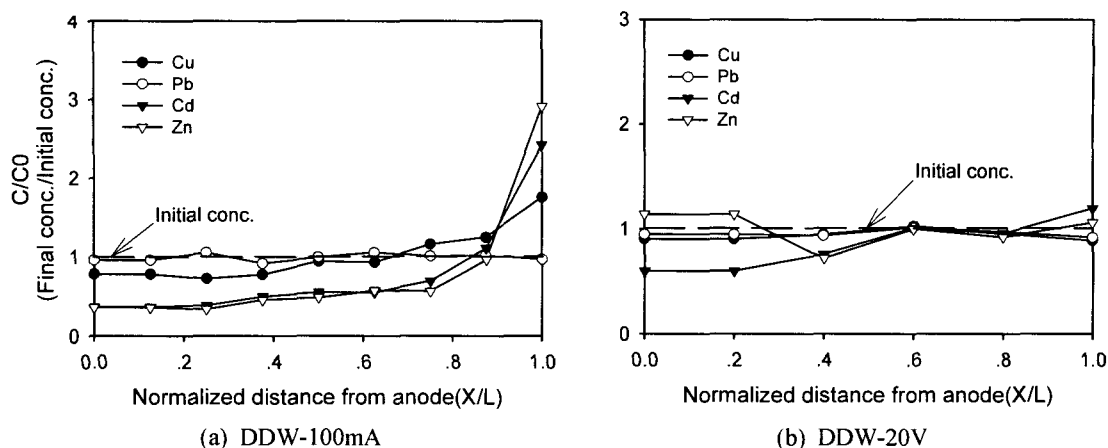


Fig. 7. Residual relative concentration of heavy metals as a function of normalized distance from anode.

where,  $J_j^m = u_j^m c_j$  mass flux of ion migration ( $g/cm^2/sec$ ),  $u_j^m$  = the effective ionic mobility of a species ( $cm^2/V/sec$ );  $c_j$  = the concentration of species ( $g/cm^3$ );  $j_e$  = the electrical gradient ( $V/cm$ )

In the result of Fig 7 (a), 50% of Cd and Zn was removed from the anode region and cumulated at cathodic section. That might be due to the increase of pH at the cathode boundary. The heavy metal ions were moved by electroosmosis, ion migration, and precipitated or adsorbed into the soil. Generally, at high pH conditions heavy metal ions could form hydroxide precipitation and/or re-adsorbed onto soil.

The DDW-100 mA test demonstrates significant contaminant transport and removal across the specimen except for Pb, while the DDW-20 V test does not cause contaminant transport and removal. It is also interesting to note that the lead concentration profiles are in conformity with the pH profiles presented in Fig. 3. The absolute initial rates of sorption decreased in the order of  $Pb > Cu > Cd > Zn > Ca$  on humic substances<sup>18)</sup> and  $Fe > Pb > Cu > Cd$  on silica.<sup>19)</sup> Although metal adsorption and desorption was different in each of these substances, mine tailings used in this test contain  $SiO_2$  as the main composition and primary minerals. Generally, Pb can be adsorbed into the soil strongly and not desorbed well.

Soil type, pore fluid chemistry, and pH were the major factors that affected lead sorption and retardation. Pb was highly retarded and adsorbed

in clay minerals. Kaolinite which was used by spiked soil in electrokinetic remediation test had a low sorption capacity compared to other minerals (such as montmorillonite or illite). Therefore, kaolinite was not expected to show significant retardation to lead transport. The presence of illite and montmorillonite in natural deposit was expected to cause a more significant retardation of contaminant transport.<sup>9)</sup>

However, even though the adsorption plays a major role of metal mobility in soil, other reasons might have influenced the result of Fig. 7(a). One of the reasons might be the speciation of metals existing in soil matrix.

The results of the applicability tests conducted demonstrate the feasibility of electrokinetic soil remediation.

#### 4. Conclusions

The effects of operation conditions of electrokinetic processes in the removal of heavy metals from the mine deposit were evaluated under constant current and constant potential conditions.

The pH distribution through most of the section after the electrokinetic remediation tests for DDW-20V test showed nearly steady value just near the cathode, which was about 5 due to the fact that at DDW-20V electroosmotic flow and the movement of the acid front did not occur. In the case of DDW-100mA, anode showed a soil pH of less than 3, while the cathode region showed a final pH ranging from 4 to 6.

In the DDW-100mA test, electroosmotic flow to the cathode rapidly increased till 10 hrs and decreased steadily and then maintained to a constant value until the end of operation. Meanwhile after 180 hr effluent to the anode was occurred and increased very rapidly until the end of the test duration.

In DDW-100mA test, electric potential gradient was continuously increased. At end of duration, electric potential gradient was 34.375 V/cm. The steady state values of the apparent electric conductivity were around 40  $\mu\text{s}/\text{cm}$  in DDW-20V and around 30  $\mu\text{s}/\text{cm}$  in DDW-100mA.

In the DDW-100mA test, Cu, Cd, and Zn except Pb tend to move toward the cathode. In the case of DDW-20V, it was observed that Cu, Zn, and Pb except Cd were not moved to any direction. The results of the tests conducted demonstrate that the electrokinetic soil remediation process may be operating better under constant current condition than constant electric potential condition.

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