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Enhanced electrokinetic (E/K) remediation on copper contaminated soil by CFW (carbonized foods waste)

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ABSTRACT

The E/K remediation method is presented to purify low permeable contaminated soils due to Cu^{2+}, and carbonized foods waste (CFW) was used as a permeable reactive barrier (PRB) material. For adsorption and precipitation of the Cu^{2+} in the PRB during its motion, PRB was installed in a zone of rapidly changing pH values. The adsorption efficiency of CFW used as PRB material was found to be 4–8 times more efficient than that of Zeolite. Throughout the experiment, a voltage slope of 1 V/cm was implemented and acetic acid was injected on the anode to increase the remediation efficiency. The electrode exchange was executed to more completely remove precipitated heavy metals in the vicinity of the cathode. The majority of Cu^{2+} was adsorbed or sedimented by CFW prior to the exchange of the electrode, and the remaining quantity of precipitated Cu^{2+} on the cathode had decreased with an increase in the operating time. Experiments of seven cases with different E/K operating times were performed, and the average removal ratios were 53.4–84.6%. The removal efficiencies for the majority of cases increased proportionally with an increase in the operating time. After the experiments were completed, the adsorbed Cu^{2+} on CFW was 75–150 mg. This means that the role of CFW as the material in PRB for remediating heavy metals was confirmed. The cost of energies needed to remove Cu^{2+}, CFW, and acetic acid are estimated at US$ 13.3–40/m^3.

1. Introduction

There has been an increasing awareness of the potential risks to the ecosystem and human health from contaminated soils due to heavy metal contamination caused by industrialization and expansion of social activities [1,2]. Contamination is caused by a variety of heavy metals, organic and inorganic compounds that are discharged from the activities of industry and society, and by the hydro-geological characteristics of the soil [3], whereby the balance of the ecosystem is destroyed. The E/K method is an in-site remediation method that could be useful for removing heavy metals and organics in contaminated low permeable soils and cohesion soils [4,5] by taking advantage of the electro-osmosis and ion transportation phenomena. E/K can have various applications and is effective in several situations including horizontal and vertical cutoffs installed in landfill sites, pollutant roundabouts in the ground, and repair of drilling points on geomembranes, etc. [6].

The E/K remediation method to remove contaminated soil from contaminants can be applied exclusive of a cation to elements such as Cu^{2+}, zinc, chrome, iron, cobalt, nickel, arsenic, cadmium, lead, mercury and uranium ions as well as exclusive of an anion to elements such as chlorine, cyanogens, nitrogen and sulfur. Also, this method can be applicable for the removal of organic materials such as polynuclear aromatic hydrocarbons (PAHs). Pamukcu and Wittle have indicated that metal ion could be desorbed by itself from the soil to the cathode due to the acid front created from the anode [7]. Acar et al. have reported that the implementation of E/K remediation of contaminated kaolinite by Cd^{2+} has about 90–95% cadmium removal [8]. Bruell et al. have successfully conducted their experiment in eliminating organic matters such as BETX (benzene, toluene, ethylbenzene, and xylenes) and TCE (trichloroethylene) from kaolinite using the E/K method [9]. Also using the same method, Shapiro and Probstein obtained 94% removal efficiency and higher elimination ratios from the contaminated soils by phenol and acetic acid [10].

These problems are discussed in more detail below. First, the E/K method discharges a cation and anion at each electrode due to the DC current, and a change of pH level occurs for the separation of elements. Electrolysis causes a decrease or increase in pH at the anode and cathode, respectively. The rising of pH due to hydroxide ions causes the precipitation of the heavy metals in the cathodes [11]. In general, the pH value can be as low as 2 at the anode and up to 14 at the cathode. The latter is created to solidify the sediment, impede the electric current and reduce electrical conductivity. Therefore, to prevent sedimentation, enhancers are often injected [4,12]. There are few chemicals used as enhancers in E/K methods; the solvent

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includes HCl, HNO_3, and acetic acid; the chelating agent includes EDTA and citric acid; the surfactant includes SDS. Acar et al. and Lageman have applied $Ca(OH)_2$ at an anodic area to excessively decrease H^+ ions, and in order to decrease the OH^- ion generated at the cathode they have applied HCl or HOAc [8,13]. The electrode exchange in E/K methods is known as the most traditional E/K improvement method. Chappell and Burton have used electric osmoses to obtain stable drainage work that has a significant influence on the drainage level and energy consumption [14]. Segall et al. have reported through electrode exchange that the increase of ion concentration and the dryness of the anode followed by electrolysis during the E/K remediation process are the main reasons behind the decrease of drainage speed and energy efficiency. Segall et al. have also provided solutions to this problem [15].

The second issue to address is the disposal of the discharged heavy metals from the soil using the E/K method. To stabilize the extracted contaminant as required, a secondary process is needed; however, the imperfect handling of the process can cause further contamination. When using the E/K method with the PRB as a countermeasure, various filling materials, such as zero-valent iron (ZIV), have been used in the installation of the PRB between the two electrodes. Weng's study presented successful results on contaminated soil by Cr^{6+} [16,17].

Recently, researchers in Korea studying PRB filling material have been examining an economical perspective and the recycling of unusable resources. Furthermore, treatment problems related to food waste are increasing and include environmental contamination and wastefulness of resources. The anticipated social cost per annum is about 15 billion dollars [18,19]. Many studies are therefore being carried out to solve this social issue.

In this study, the E/K method was applied using a PRB filled with CFW on low permeable soil contaminated by Cu^{2+}. Because the heavy metal was extracted and settled around the cathode during the experiment, PRB was installed at the rapidly increasing point of pH to remove adsorption through the current flow. In addition, the heavy metals within the soil which could not be removed with the PRB could be removed by the electrode exchange and remediation of a heavy metal in the near soil of the cathode through this method. For this purpose, a batch test and an experimental test have been executed.

2. Materials and methods

2.1. Material

2.1.1. Test devices

The testing devices used for the experiment are shown in Fig. 1 and are composed of three parts: power supply, mariotte-bottle, and soil compartment, where the soil compartment and mariotte-bottle are made of acrylic. An electrode water tank is installed at each end of the soil compartment, which provides an unrestricted outflow of electro-osmosis during the experiments, and the soil compartment also consists of a bubble tube and cylinder to measure the outflow amount. The testers were designed to conduct five experiments simultaneously, and an O-ring was installed between the soil compartments to prevent inflow of the outflows from each sample during the experiment and to prevent partial damage of the samples. The O-ring was designed to assemble the soil compartments through the upper valve, where a pH gauge port was attached to measure the electric potential inside the sample bottles and to measure the pH level based on time inside the anode and cathode tank.

2.1.2. Soil sample

The material properties and the results of the chemical analysis on the kaolinite made in USA (Southeastern Clay Company) are described in Table 1. The sample's liquid limit was 61.2%, the plastic limit was 31.8%, the specific gravity was 2.65, and the passing rate of 0.745 μm was 100%, resulting in a CL classification according to USCS (Unified Soil Classification System). To artificially create the contaminated soil, Cu^{2+} from de-ionized water was 180 mg. The Cu^{2+} was then mixed with the kaolinite in a stirrer to create 60% water content.

2.1.3. Filling material of PRB

Table 1 describes the chemical components of the CFW (carbonized foods waste) used in the PRB, which is composed of over 85% oxygen, calcium and carbon. The size of the CFW ranges from 75 to 150 μm (100–200 mesh) within porous structures. The CFW's pore distribution result, according to the BJH (Barrett–Joyner–Halenda) model, shows that the CFW's surface area was 14.16 m^2/g, the total pore volume was 0.0469 cm^3/g, and the average pore diameter was 132.4 Å. Micromeritics ASAP2010 was used as the analytic instrument, and KS L ISO 18757 was implemented as the measuring method.

2.2. Experimental conditions

2.2.1. Batch test of PRB material

To compare the relative strength of CFW's adsorption against Cu^{2+}, a batch test was executed using Zeolite. The conditions of the batch test are shown in Table 2. First, after filling 0.8 g of CFW and Zeolite into one 100 ml glass vessel each, 40 ml of concentrated Cu^{2+} solution was poured into 50–800 μg/ml, and the contents were shaken for 80 min at 200 rpm. After shaking, the best grade water was extracted by centrifuge and filtered to 0.24 μg by a membrane filter. The filtered contents were then examined through an ICP (Inductively Coupled Plasma Spectrometer, JY-Ultima-2, Jobin Yvon, France).

Table 1
Characteristics of experimental materials.

I. Physical characteristics of kaolinite

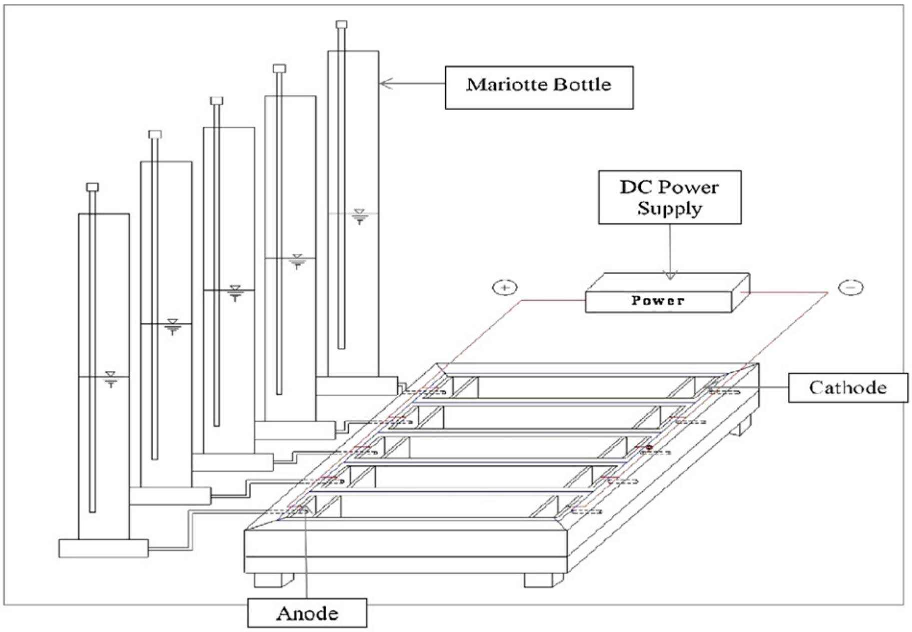
Liquid limit (%)	Plastic limit (%)	Plastic index (%)	Specific gravity	Passing 0.745 μm (%)	pH at $w = 400\%$	USCS	CEC (Cmol/kg)
61.21	31.82	20.39	2.65	100	4.5–5.5	CL	7.24

II. Chemical composition of kaolinite (%)

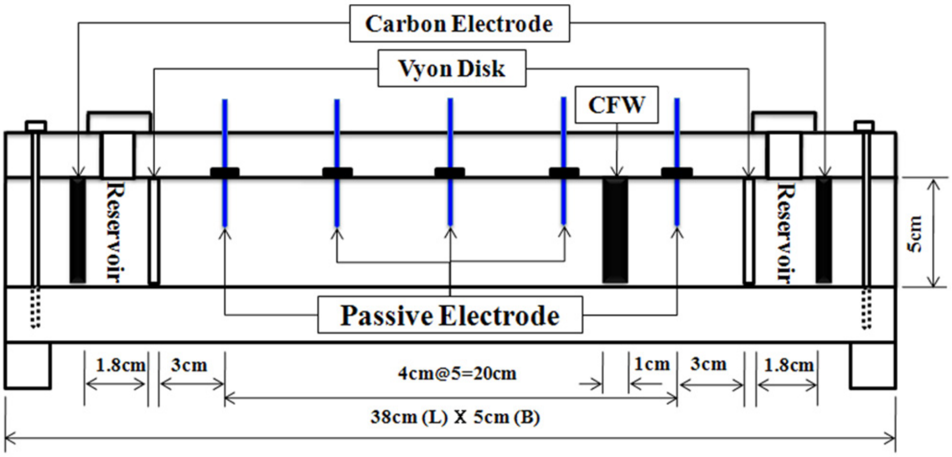
SiO_2	Al_2O_3	Fe_4O_3	TiO_2	CaO	MgO	K_2O	Na_2O
44.3	37.9	1.20	1.60	0.09	0.13	0.15	0.04

III. Chemical composition of CFW (%)

O	Ca	C	K	Cl	Na	P	Fe	Si	Mg	S	Al	Other	Total
38.39	25.51	21.73	3.2	3.05	2.64	1.5	1.29	0.97	0.71	0.51	0.27	0.23	100



(a) Diagram of E/K system



(b) Profile diagram of E/K system

Fig. 1. Schematic diagram and dimensions of test device. (a) Diagram of E/K system and (b) profile diagram of E/K system.

2.2.2. Selection of enhanced solution

HCl, acetic acid, citric acid, EDTA (ethylene diaminetetraacetic acid), and SDS (sodium dodecyl sulfate) were used in the experiment to determine the E/K enhancer. HCl and acetic acid are solvents that prevent hydration sedimentation caused by electrical current. Citric acid and EDTA can prevent and restrain the hydration sedimentation of metal ions, made possible by the chelating of chelate-zero metal ions and by the surfactant. Additionally, the surfactants of the anion and cation are widely used in purification experiments on contaminated soil [20,21]. It is effective as a chelating agent when injected into the anode to move simultaneously with water flow in the soil [22].

In this study, SDS, the anion surfactant, was used and the concentration of all enhancers was set at 0.05 mol. The enhancers were injected into the anode side of the tank using a level control device to control the neutralization by electrolysis and the reverse osmosis caused by zeta potential reverse allowing an excessive inflow of H^+ ions into the samples.

Table 2 describes the conditions of the enhancer used in the experiment. The contaminated soil was made up according to Section 2.1.2, and the experimental conditions and method are as follows. Typical pH jump points were between $(x/L) = 0.6–0.9$, depending on the E/K operating period [23]. In this study, the installing position of PRB was considered to be at the maximum E/K operation of 240 h prior to the electrode exchange, which was installed at $(x/L) = 0.75$ points from the anode. The electric potential was around 1 V/cm, and the E/K operating time was a maximum of 20 days. The exchange period of the electrode and operating time after exchange was a maximum of 10 days.

The thickness of PRB was derived from the following equation with consideration of the CFW's possible adsorption quantity at per unit gram,

$$T_{\mathrm{CFW}} = \frac{C_i/Q_e}{\gamma A} \tag{1}$$

Table 2
Tests condition.

I. Batch test

Materials	Concentration (mg/l)	Contact time (min)	Shaking speed (rpm)	Mixture rate
CFW	50,	5	200	50:1
	100,	10		
Zeolite	200,	20		
	400,	40		
	800	80		

II. Test condition for the determination of enhanced solution

Solutions	HCl	Acetic	Citric	EDTA	SDS
Initial conc. (M)	0.05	0.05	0.05	0.05	0.05
Initial pH	2.16	3.42	2.56	4.78	6.89

III. E/K test

Fixed factor				Variable factor							
C_o (ppm)	Electric gradient (V/cm)	Solution (mM)	PRB location (x/L)	Polarity reversal (day)	8			10			
500	1	50	0.75	Process after polarity reversal (Day)	6	8	10	4	6	8	10
				Test no.	Exp. 1	Exp. 2	Exp. 3	Exp. 4	Exp. 5	Exp. 6	Exp. 7

where C_i is the contaminated Cu^{2+} amounts in the soil (mg); Q_e is the maximum amount adsorbed of the CFW (mg/g); γ is the density of CFW (g/cm^3); A is the cross-section area of the experimental cell. Q_e was applied to 30 mg/g as the result of the batch test shown in Fig. 2, and γ was given a loose state of 0.4 g/cm^3, which does not effect the permeability. Hence, the thickness of CFW (T_{CFW}) becomes about 1.0 cm.

The samples were equally extracted from the 5 locations (Fig. 1), and were dried at 105 °C according to the KSTM (Korea standard testing method) and then mixed with 50 ml of 0.1 M HCl [24]. After shaking at 100 rpm and 30 °C for 1 h, the residual concentrations were measured according to Section 2.2.1.

First, the extracted 5 g and 25 ml of distilled water were placed in a 50 ml beaker and poured and shaken. After 1 h, the pH was recorded and set at a pH of a standard solution.

2.2.3. *E/K experimental*

Table 2 shows the test results for the best time for the electrode exchange to extract the heavy metals from the contaminated soils. To enhance the purification, enhancers were inserted using the same test method, electric potential, location of PRB, and extracting method as described in Section 2.2.2.

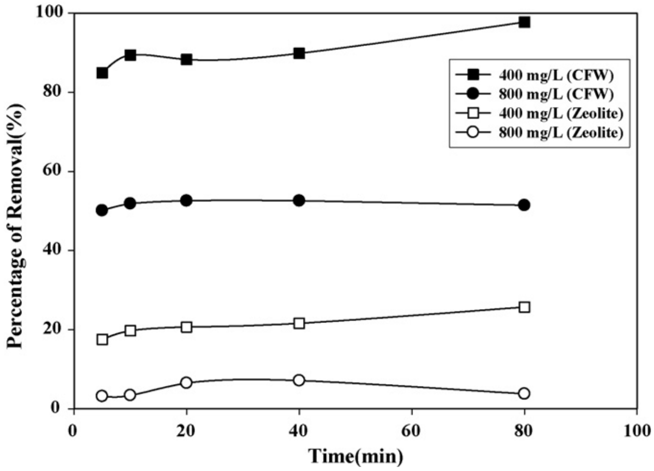


Fig. 2. Percentage removal of copper as a function of contact time.

To check the mass balance, Cu^{2+} absorbed in CFW was dried at 105 °C according to the Method of Soil Analysis [25]. The dried 0.2 g of Cu^{2+} was mixed with 10 ml HNO_3 (60%) and 3 ml $HClO_4$ (70%). The temperature was increased gradually to 180 °C using a hot plate. The quantitative analysis was performed by ICP under filtering as described in Section 2.2.1.

3. Results and discussion

3.1. *Batch test*

Fig. 2 shows the results of the batch test for CFW and Zeolite. For all testing results the adsorption equilibrium was reached within 10 min, and the removal rate of Cu^{2+} was 90–98% and 50–53% for CFW under a contaminated concentration of 400 and 800 µg/ml, respectively. The removal rates using Zeolite were 18–26% and 3–8% for the same contaminated concentrations. The adsorption capacity of CFW was 4–8 times better than that of Zeolite.

The comparison of absorption isotherms calculated from the Langmuir and Freundlich models of Cu^{2+} on both CFW and Zeolite are shown in Fig. 3. The results showed that experimental data are well fitted to the linear Langmuir isotherm, with the maximum per unit gram adsorption quantity of 30 mg/g.

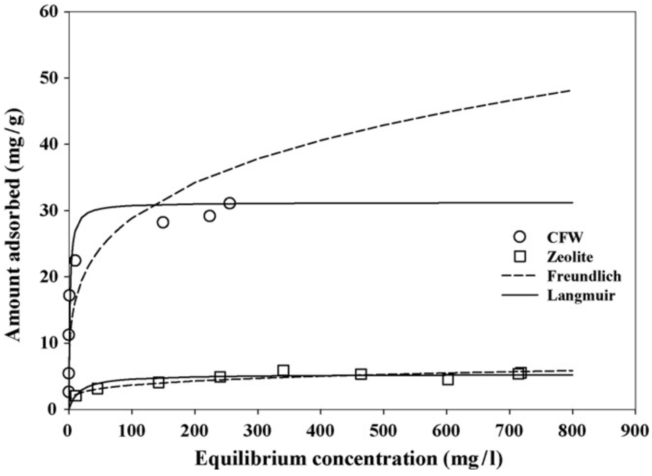


Fig. 3. Comparison of the experimental results with amount adsorbed values obtained by Langmuir and Freundlich isotherms.

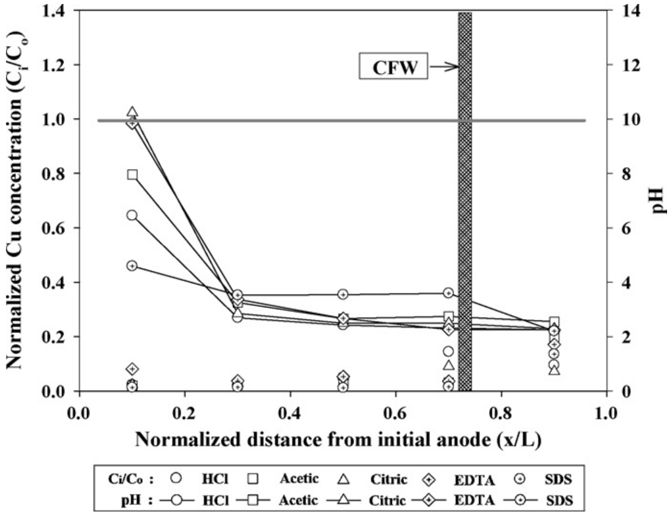


Fig. 4. Distribution of copper and pH at the end of solution select test.

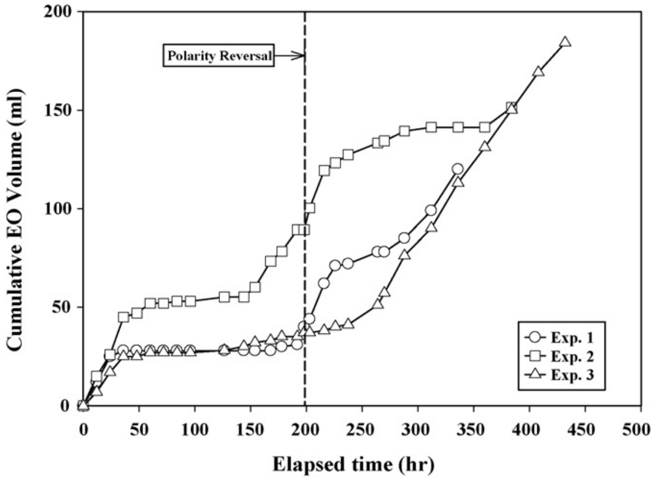
3.2. Enhanced solution test

Fig. 4 shows the test results for the enhancer chosen for use in E/K and shows the remaining concentration of Cu and the distribution of pH within the samples after the experiment. At $(x/L) = 0.1–0.7$, acetic acid, EDTA, and SDS showed no signs of Cu, but at the nearest cathode where $(x/L) = 0.9$, a higher than normal level of Cu was detected. EDTA has shown a high level of Cu at $(x/L) = 0.1$, and HCl and citric acid have also shown a high level of Cu at $(x/L) = 0.7$, which caused difficulties in measuring the relative elevation of remediation efficiency of the enhancers. A low pH level was maintained within the samples at $(x/L) = 0.3–0.9$ and a high pH level at $(x/L) = 0.1$. As shown in Fig. 4, the concentration of heavy metal residuals within the samples did not show many differences, and SDS maintained a mostly stable pH within the samples throughout the experiments. However, regulations under the Republic of Korea have banned SDS other than for functional health food as it can cause skin irritation upon contact that can lead to inflammation [26]. Therefore, to increase the remediation efficiency, acetic acid was selected for its stable electrical conductivity and environmentally friendly biodegradation factors [27].

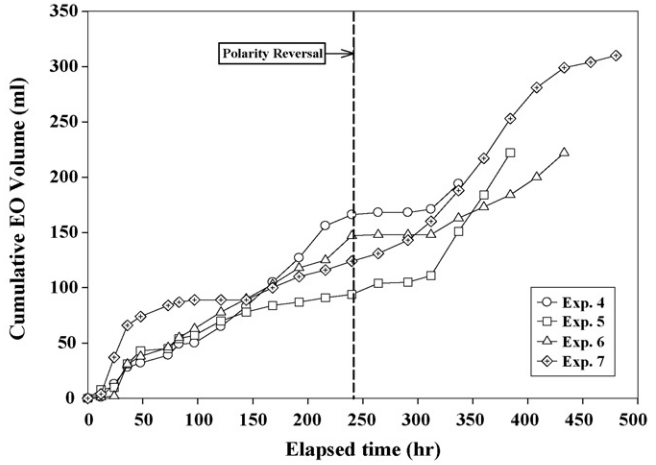
3.3. E/K experiment

3.3.1. E/O flow and permeability

Flux variation due to electro-osmosis is effected by complex factors such as changes in chemical properties, electricity con-

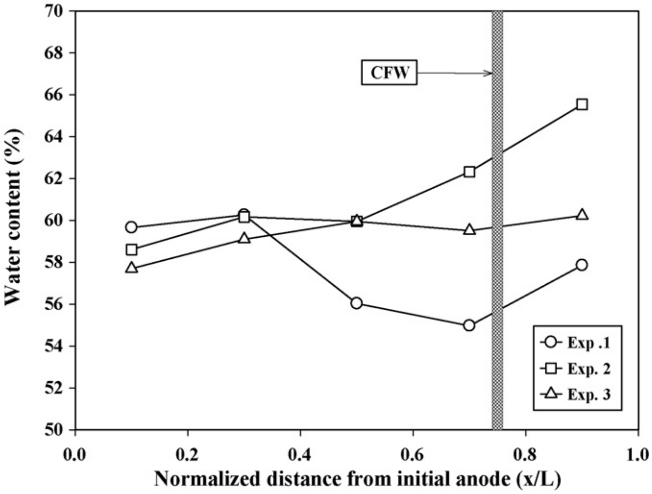


(a) Exps. 1-Exps. 3

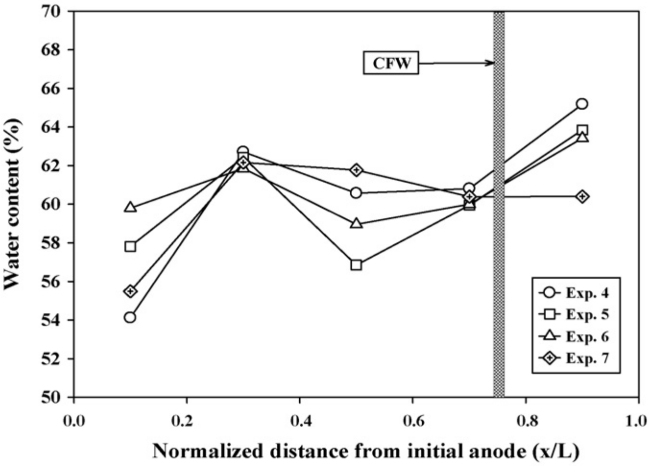


(b) Exps. 4-Exps. 7

Fig. 5. Cumulative of EO flow vs. time. Collected in (a) Exps. 1–3 and (b) Exps. 4–7.



(a) Exps. 1-Exps. 3



(b) Exps. 4-Exps. 7

Fig. 6. Distribution of water content at the end of E/K treated. (a) Exps. 1–3 and (b) Exps. 4–7.

sumption by electrolysis and the charging condition of soil samples. It was shown that the difference between experimental results was due to a discontinuous flow in the samples, and the reduction of effluent was mainly due to restrictive movements of the electrolyte in the samples [28]. Fig. 5(a) and (b) shows the eighth day, and Exps. 4–7 show the tenth day of efflux level after the electrode reversal.

The efflux showed a nearly proportional relationship to the operating time, which was increased after the electrode reversal. These results were primarily due to the change in outflow at the anodic area, which had a high level of water content at the beginning of the experiment due to the reverse of electro-osmosis by the electrode exchange. As shown in Fig. 6, the decrease in water content then led to an increase in the effluent. Fig. 6 describes the level of water content at different locations after the experiment.

E/O is proportional to the current slope and E/O permeability. The E/O permeability equation is as follows:

$$K_e = \frac{Q_e}{i_e \times A} \tag{2}$$

where Q_e is the E/O flow (ml/day); i_e is the electric gradient (V/cm); and A is the cross-section area of the experimental cell (cm^2). The calculated K_e values according to Eq. (2) are 4.77×10^{-6}, 7.76×10^{-6}, 4.13×10^{-6}, 7.49×10^{-6}, 6.96×10^{-6}, 7.04×10^{-6} and 1.01×10^{-5} cm^2/V s for Exps. 1–7, respectively. The obtained K_e values are in excellent agreement with the literature data of 1.0×10^{-7} to 4.0×10^{-5} cm^2/V s for all soils [9,10]. Tests showed that CFW has no effect on the E/O flow in the E/K method. In comparison with Fig. 7, the result from the test shows that high current density value of K_e or E/O has an effect on the increase of K_e or on the E/O flow value. The result of the increase in K_e and E/O flow due to high current density is similar to the results of other studies [16,29].

3.3.2. *Current density*

Fig. 7 shows the density variation of the electric current depending on the elapsed time in the E/K experimental results considering both the time of the electrode exchange and the operating time after the electrode exchange. The density calculation of the electric current was based on the total electric currents through the cross-section divided by the soil compartment's dimensions. The density of electric current was at the highest value between 30 and 50 h of operating time, thereafter it gradually decreased indicating a remarkably low value after 100 h. These results were similar to those of other researchers [16,30]. Additionally, the electric conductivity rapidly increased at the anodic area after the electrode exchange initially decreased.

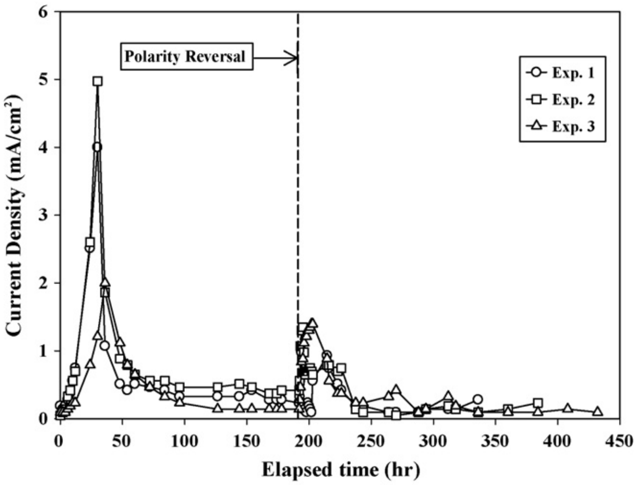
The time-consuming process of melting the Cu^{2+} and transferring it by electrolysis from the water tank to the soil causes an initial low electric current in all experiments. The maximum electric current values due to the effect of an acid front are created by the injection of the acetic acid and the increase of hydrogen ions by electrolysis. This causes an increase of conductivity in the parts of the anode due to ion concentration in porous water by melting of the base or desorption of Cu^{2+} from the soils. The decrease of electric current is due to the formation of water at the pH rising zone and to the increase of resistance caused by the decreasing of ion concentration in porous water with either the adsorption/sedimentation Cu^{2+} on CFW or the extraction from the cathode of Cu^{2+}. The stable state of the electric current is due to the constant depletion velocity of ion during the motional/removal or adsorption/sedimentation process of heavy metals.

The above mentioned conditions also have similar results after electrode exchanges, because of the lower electric current density after the exchange compared to the initial states of the experiment. This might be because a large quantity of Cu^{2+} had been removed from the soil and adsorbed/sedimented by the CFW prior to the electrode exchange.

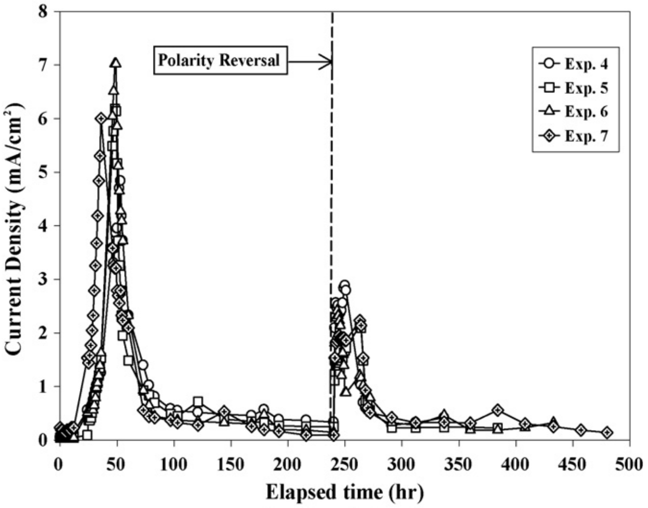
3.3.3. *Heavy metal removal*

Fig. 8 describes the remaining concentration and pH levels of the corrected samples after the experiment was completed, and Fig. 8(a) shows the results of the electrode exchange after 8 days of experiment. Heavy metals at the front of the PRB installed location could not be detected and the residual concentration of heavy metals at the rear PRB location $(x/L) = 0.9$, either exceeded or showed similar conditions to the initial contaminated concentration, which was due to sedimentation. The residual concentration in the precipitated area decreased because of heavy metal movement from the cathode to the anode region. After the experiment was completed, the mean level of pH at each location was 5–6, implying that the movement of H$^+$ and OH$^-$ ions due to electrode exchange had been marginally influenced overall.

Alternatively, in the case of electrode exchange (Fig. 8(b)), after 10 days of experiment, the distribution of pH levels in the samples were transformed similarly to those of the general E/K experiments. In this case, the distribution of the pH level at the anode area, given the reversal of flow in the soil due to electrode exchange, caused the reduction of residual concentrations in the cathode area. As shown



(a) Exps. 1-Exps. 3



(b) Exps. 4-Exps. 7

Fig. 7. Variation of current density with time. (a) Exps. 1–3 and (b) Exps. 4–7.

in the figure, the residual concentration at $(x/L) = 0.9$ dramatically decreased. In the case of Exp. 7, at an operating time of 10 days after electrode exchange, the residual concentration decreased to about 20% of the initial contaminated concentration. However, as the operation time increased, it appeared that the residual concentration between $(x/L) = 0–0.7$ also increased. These results were due to the precipitated heavy metal in the PRB outflow into the soil by the electrode exchange. It may also have occurred due to the excess of adsorption capacity of the packed material in the PRB.

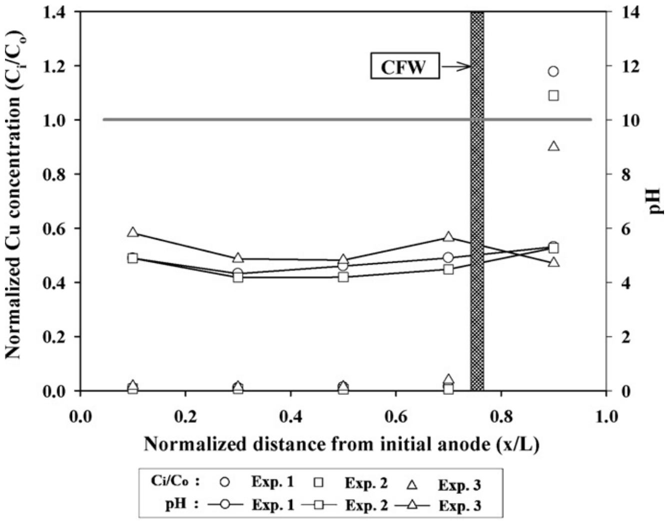
As a result, the proper volume of PRB, the exchange time of the electrode, and the operation time could have a significant impact on the results depending on the contaminated concentration in the soil and the adsorption strength of the packing material in the PRB.

3.3.4. *Mass balance*

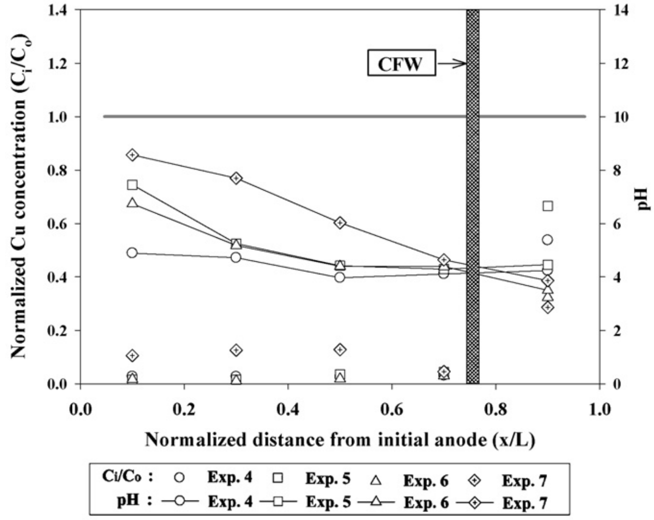
After the E/K experiment, the calculation of the heavy metal copper's mass balance was performed [22]. Extraction of the remaining Cu^{2+} in CFW and the packing material in the PRB was carried out according to the Section 2.2.3, and the extraction in the soil samples was performed according to the Section 2.2.2. The water tank was measured after combining the anode and cathode water tanks, and the calculations of the mass balance for Exps. 1–7 were 89.51%, 116.73%, 82.29%, 96.27%, 115.27%, 89.20%, and 111.59%, respectively, as shown in Table 3. The amount of Cu^{2+} desorbed purely from CFW was between 75 and 150 mg, which implies that 40–83% of the Cu^{2+} in the soil has been adsorbed. This is because Cu^{2+} in soil moves toward CFW proportionally to the increase of operating times.

Table 3
Mass balance of Cu removed.

Test no.	Initial amount of copper (mg)	Residual in the soil bed (mg)	PRB (CFW) (mg)	Amount removed by EOF (mg)	Residual amount in reservoir (mg)	Mass balance (%)
Exp. 1	180	83.90	75.66	0.12	1.43	89.51
Exp. 2	180	76.20	128.36	0.09	5.47	116.73
Exp. 3	180	67.85	77.48	0.33	2.46	82.29
Exp. 4	180	44.50	121.11	1.11	6.58	96.27
Exp. 5	180	53.85	150.64	0.16	2.83	115.27
Exp. 6	180	27.74	115.06	0.8	16.95	89.20
Exp. 7	180	45.63	150.67	0.69	3.87	111.59



(a) Exps.1-Exps.3



(b) Exps. 4-Exps. 7

Fig. 8. Distribution of copper and pH at the end of E/K treated. (a) Exps. 1–3 and (b) Exps. 4–7.

3.3.5. *Cost analysis for E/K process*

The electric power expenditure per cubic meter of treated soil, E_e (Wh/m^3), is calculated as follows:

$$E_e = \frac{P}{V_S} = \frac{1}{V_S}\int VI\ \mathrm{d}t \qquad (3)$$

where E_e is the energy expenditure (Wh); V_S, the soil volume (m^3); V is the applied voltage (V); I is the current (A); and t is the processing time (h). In this test constant condition, the energy expenditure is directly related to the integral time of the electric current across the cell. The calculated energy consumptions are 188, 246, 166, 433, 547, 500 and 599 kWh/m^3 for the Exps. 1–7 tests, respectively. Table 4 shows an evaluation of economical factors of the electric current research. As shown in the table, the removal rates of Cu^{2+} and E_e will proportionally increase with the operating time of E/K. Table 4 includes the electric cost for E/K remediation and enhancer cost, but the CFW cost was excluded.

Table 4
Cost analysis of EK system.

Test no.	Removal efficient (%)	Removal amount (mg)	Enhanced solution consumption		Energy consumption		Total cost (US$/m^3)
			Acetic acid expenditure (ml/m^3)	Acetic acid cost[a] (US$/ml)	Power expenditure (kWh/m^3)	Energy cost[b] (US$/m^3)	
Exp. 1	53.4	96.1	644.0	3.9	188	9.4	13.3
Exp. 2	57.7	103.8	805.0	4.8	249	12.5	17.3
Exp. 3	62.3	112.2	983.1	5.9	166	8.3	14.2
Exp. 4	75.3	135.5	1037.6	6.2	433	21.7	27.9
Exp. 5	70.0	126.15	1198.6	7.2	547	27.4	34.6
Exp. 6	84.6	152.26	1198.6	7.2	500	25.0	32.2
Exp. 7	74.7	134.37	1663.7	10.0	599	30.0	40.0

[a] The current acetic acid fee is approximately US$ 6.0/l.
[b] The current electricity fee in Republic of Korea is approximately US$ 0.05/kWh.

The cost for CFW is zero or close to zero, because it is a byproduct of the waste reduction process and is not charged to consumers in Korea. Therefore, the purchase costs of CFW can be disregarded for the cost of ZVI, Zeolite or any other materials. Based on electric charges in Korea, the energy required per cubic meter for purification is 188–599 kWh/m^3, which is a cost of about US$ 8.30–30. When adding the acetic acid cost, the total cost becomes US$ 13.30–40.

The complete extraction of heavy metals was premised in this study. However, conditions in the field for factors such as concentration ratio and purification goals of contaminants of each different regions, etc., will vary considerably. Therefore, the remediation cost must increase or decrease depending on the operating time. Overhead costs such as capital costs, the construction cost of PRB using CFW, the maintenance cost, and other additional costs required in the field must be taken into consideration. Further reports on such costs will be conducted through the actual field test.

4. Conclusions

This research was conducted to investigate the remediation efficiency by installing PRB and enhancers on the E/K method to purify contaminated kaolin by Cu^{2+}. CFW was used as PRB material. The absorption efficiency of CFW was about 4–8 times more effective than Zeolite, and fitted well with the Langmuir isotherms. The considerable economic advantage and removal efficiency of heavy metal (Cu^{2+}) of CFW, one of the byproducts of food waste, could be substituted against other PRB materials. Acetic acid was selected for the enhancer because of its ability to maintain stable current conductivity of soil and for its biodegradation effect resulting from the indiscrimination of remediation efficiency during the enhancer selecting tests. In the E/K experiments in which acetic acid was implemented, the E/O flow increased with an increase in the operating time, and increased proportionally to the electric current density. That is, installation of CFW did not influence the electric osmosis flow. The electric current density following the electrode exchange was lower than it was prior to the exchange. This was due to the large amount of Cu^{2+} being adsorbed or sedimented by CFW. The test results of the remaining concentration in front of PRB showed that the adsorption/sedimentation of the Cu^{2+} in CFW prior to the electrode exchange was carried out in a relatively short period. Heavy metal located behind the CFW took a longer time to be removed, even after the exchange.

The accumulated Cu^{2+} at the cathodic area prior to the electrode exchange showed the furthest transport after 10 days of operating time after the exchange. However, the sedimentation of heavy metal in the PRB was transported from the PRB into the soil within the elapsed operating time after electrode exchange. This may be caused by the excess adsorption capacity of the packed material in the PRB. Therefore, the maximum adsorption capacity of the packed material of the PRB, the exchange time of the electrode, and the elapsed operation time could have significant impacts on the results depending on the contaminated concentration in the soil.

The quantity of Cu^{2+} was investigated after the desorption test, and about 75–150 mg of Cu^{2+} in contaminated soil was absorbed by CFW, which demonstrates that the majority of Cu^{2+} was absorbed by CFW. Considering the porous structure of CFW and the fact that the adsorbed quantity of Cu^{2+} was higher than the quantity of non-adsorbed Cu^{2+}, it can be concluded that research goal of using CFW to separate and remove heavy metals has been achieved. The cost of the E/K method which implements a 1 V/cm voltage slope to eliminate Cu is about US$ 13.30–40, including the cost of acetic acid. The amount of removal of Cu^{2+} will increase proportionally with the operating time. Therefore, the actual required cost of the current and enhancer for purification could vary depending on the quantity of the contaminating heavy metals and the purification quality objectives.

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