

WASHING-ELECTROKINETIC DECONTAMINATION FOR CONCRETE CONTAMINATED WITH COBALT AND CESIUM

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A great volume of radioactive concrete is generated during the operation and the decommissioning of nuclear facilities. The washing-electrokinetic technology in this study, which combined an electrokinetic method and a washing method, was developed to decontaminate the concrete generated in nuclear facilities. The results of only an electrokinetic decontamination for the concrete showed that cobalt was removed to below 1% from the concrete due to its high pH. Therefore, the washing-electrokinetic technology was applied to lower the pH of the concrete. Namely, when the concrete was washed with 3 M of hydrochloric acid for 4 hours (0.17 day), the CaCO_3 in the concrete was decomposed into CO_2 and the pH of the concrete was reduced to 3.7, and the cobalt and cesium in the concrete were removed by up to 85.0% and 76.3% respectively. Next, when the washed concrete was decontaminated by the electrokinetic method with 0.01M of acetic acid in the 1L electrokinetic equipment for 14.83 days, the cobalt and the cesium in the concrete were both removed by up to 99.7% and 99.6% respectively. The removal efficiencies of the cobalt and cesium by 0.01M of acetic acid were increased more than those by 0.05M of acetic acid due to the increase of the concrete zeta potential. The total effluent volume generated from the washing-electrokinetic decontamination was 11.55L (7.2ml/g).

KEYWORDS : Electrokinetic, Flushing, Decontamination, Concrete, Cobalt, Cesium

1. INTRODUCTION

A great volume of radioactive concrete is generated during the operation and the decommissioning of nuclear facilities in Korea. In the past, it has been stored in radioactive waste storage facilities. The main radionuclides in the concrete are cobalt and cesium, and their concentrations are to below 3,000 Bq/kg. Therefore, if the radioactive concentration of the concrete is decontaminated to below a self-disposal basis concentration (about 100 Bq/kg), it can be disposed of in reclaimed land cheaper than disposal in a middle-low level radioactive repository. In this study, washing-electrokinetic technology was developed to decontaminate the concrete generated in nuclear facilities, which combined an electrokinetic method and a washing method.

Even though many methods have been developed for removal of radionuclides from contaminated concrete, the removal efficiency of nuclides from concrete is generally low. The electrokinetic process holds great promise for decontamination of contaminated soil as it has a high removal efficiency and it is time effective for a low

permeability. An electrokinetic technology has been used to treat concrete contaminated with radionuclide [1] and to study its effect on a chloride transport through cement-based materials [2]. The main mechanisms of a contaminants movement in an electrical field involved in electrokinetic technology are an electro-migration of ionic species and electro-osmosis. Electro-migration probably contributes significantly to the removal of contaminants, especially at high concentrations of the ionic contaminants and/or a high hydraulic permeability of the concrete [3]. The cathode reaction should be depolarized to avoid the generation of hydroxides and their transport in the concrete. The selected liquids, also known as purging solutions, should induce favorable pH conditions in the concrete, and/or interact with the heavy metals, so that these heavy metals are removed from the concrete [4]. Electro-osmosis moves a pore solution in response to an electric field, typically towards a cathode because of a negative surface charge of the soil. The magnitude of the transport velocity due to an electro-migration and electro-osmosis is directly related to the electric potential gradient. Recently, researchers have been investigating whether this method can be used to

remove subsurface contaminants, and they have published their research on the use of electrokinetic techniques to decontaminate fine-grained soils, and discussed some of the problems that occur during this process [5-7]. An equation for the electrokinetic process is as follows and the electro-osmotic permeability (k_o) is proportioned to the zeta potential of the concrete (ζ).

$$j = [(k_o + k_m)\nabla\phi + k_h\nabla p]C - \frac{D}{\tau^2}\nabla C \tag{1}$$

$$k_o = \frac{\epsilon\zeta}{\tau^2\mu} \tag{2}$$

Where j is the molar flux of the species per unit pore area, k_o is the electro-osmotic permeability, k_m is the electro-migration coefficient, k_h is the hydraulic permeability, p is the pressure, C is the molar concentration, D is the diffusion coefficient, τ is the non-dimensional tortuosity, ϵ is the permittivity of the pore liquid, ζ is the zeta potential of the concrete, and μ the viscosity of the pore liquid.

Meanwhile, researchers have tried to develop washing techniques in which soil-bound contaminants are transferred to a liquid phase by desorption and solubilization. Several washing solutions have been investigated, such as water, acids, bases, chelating agents, alcohols, and other additives [8-9]. In practice, acid washing and chelator soil washing are the two most prevalent removal methods [10-11]. Recently, acetic acid or sodium dodecyl sulfate have been used as an electrolyte for an electrokinetic decontamination to increase the removal efficiency of metals [12-14].

In this study, in order to decontaminate crushed concrete under 0.5 cm in size, an electrokinetic decontamination was performed. However, the decontamination efficiency was very low because the pH of the concrete was more than 6. Therefore, a washing-electrokinetic decontamination process was developed, which combined an electrokinetic method and a washing method. First of all, when the concrete was washed with a high concentration of hydrochloric acid, a lot of cobalt and cesium was removed, and the pH of the concrete dropped to below 6. Secondly, the electrokinetic method was used to increase the removal efficiencies of the cobalt and cesium, which resulted in high removal efficiencies of more than 90%.

2. MATERIALS AND EQUIPMENT

2.1 Manufacturing of an Artificially Contaminated Concrete

The radioactive waste storage facilities take care of 20-50cm of concrete debris in 200L drums. Non-radioactive concrete in 200L drums were selected and crushed by a

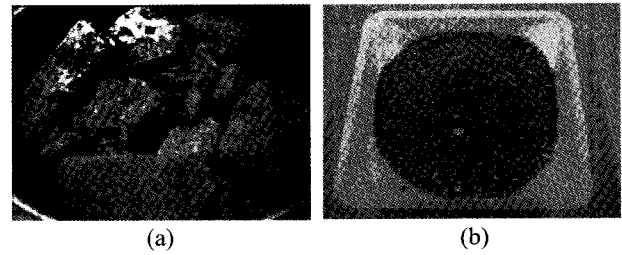


Fig. 1. (a) Concrete Debris in a 200L Radioactive Drum, (b) Concrete Particles Ground up by a Crusher

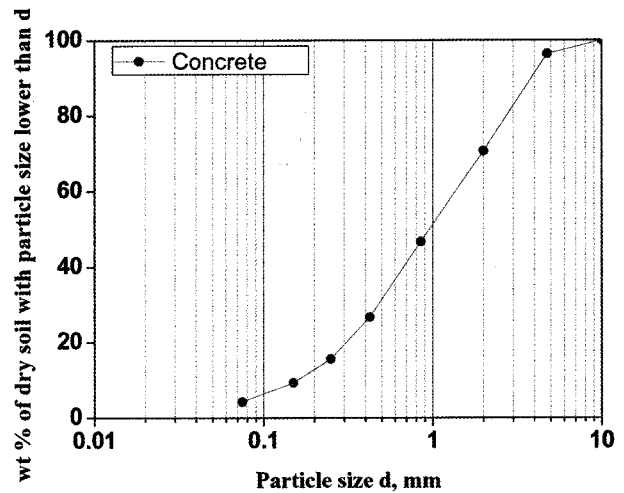


Fig. 2. Particle Size Distribution Curve of for the TRIGA Crushed Concrete

crusher to below 0.5 cm (Fig. 1). A particle size distribution curve of the crushed concrete is shown in Fig.2. The measurement results of hydraulic parameters of the crushed concrete were as follows. Namely, bulk density (g/cm^3) was 1.65, porosity (%) was 38.8, and hydraulic conductivity (cm/sec) was 2.7×10^{-3} . In order to fabricate the artificially contaminated concrete, the crushed concrete was combined and shaken with 0.01 M of cobalt and cesium and then it was dried more than a week for an equal concentration. A simulated crushed concrete was used in this study. Meanwhile, the zeta potential of a concrete particle was measured by ELS-8000.

2.2 Manufacturing and Experiment of 1L Size Electrokinetic Equipment

Electrokinetic equipment of a 1L size was manufactured for the experiment. It consisted of an acryl concrete cell, two electrode compartments, an electrolyte solution

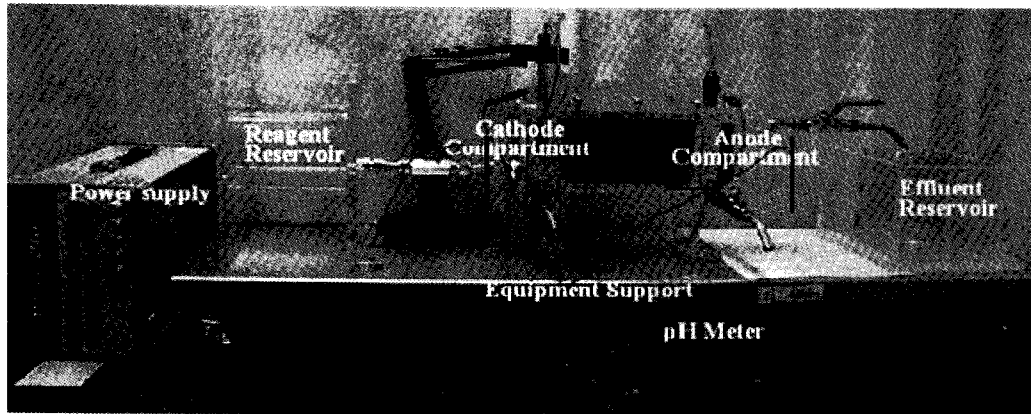


Fig. 3. The Developed Electrokinetic Equipment for the Concrete Decontamination

Table 1. The Co^{2+} and Cs^+ Removal Efficiencies and the Effluent Volumes for the Electrokinetic Decontamination with Different Experimental Conditions

Reagent (M)	Decontamination time (days)	Removal efficiency		Electric current (mA)	Potential gradient (V/cm)	Effluent volume (ml/g)	Remark
Acetic acid (1.0L, 0.1M)	15	Co(%)	0.8	40-400	4	2.7	
		Cs(%)	55.0				
Hydrochloric acid (1.0L, 0.2M)	15	Co(%)	1.0	50-500	4	2.8	
		Cs(%)	65.0				
Acetic acid (1.0L, 0.05M)	15	Co(%)	97.7	50-500	4	5.9	After washing with 3M hydrochloric acid for 4 hours for 4
		Cs(%)	95.8				
Acetic acid (1.0L, 0.01M)	15	Co(%)	99.7	30-300	4	5.7	After washing with 3M hydrochloric acid for 4 hours for 4
		Cs(%)	99.6				

reservoir, an effluent storage reservoir, and a power supply (Fig. 3). The contaminated concrete was placed into an acrylic concrete cell of $10.0 \times 11.5 \times 15.0$ cm. A $0.2 \mu\text{m}$ size paper filter was inserted between the electrode compartments to prevent an influx of the concrete particles into the electrode compartments. The electrolyte solution reservoir supplies the reagent solution to the anode compartment. The effluent storage reservoir receives the concrete waste-solution. An outlet was constructed at the bottom of the left electrode compartment to discharge the contaminated solution. The cathode electrode used titanium and the anode electrode used a dimensional stable anode (DSA) to prevent the electrode from melting. The concrete in an acrylic concrete cell was saturated with reagent by solid-liquid ratio, 4.2:1 and potential gradient (V/cm) was maintained 4 by DC power supply. The pH in the cathode compartment and the generated waste solution (effluent) volumes in both electrode compartments were periodically measured.

3. DECONTAMINATION EXPERIMENT

The experiment conditions and results with the manufactured electrokinetic equipment are shown in Table 1. Effluent volume ml/g in Table 1 means the waste solution volume, ml, generated through electrokinetic experiment per unit gram of concrete.

3.1 Electrokinetic Decontamination with Acetic Acid

Ethylenediaminetetraacetic acid can attach to a metal ion for up to six sites because each of the acetate groups and two nitrogen atoms have the free electron pairs necessary for a coordinate bond formation. The feasibility of this compound as a solubilizing or complexing agent has been reported in several works. This is especially due to its strong chelating ability for a variety of heavy metals [15]. Also, because citric acid is relatively inexpensive, rather easy to handle, and has a comparatively low affinity

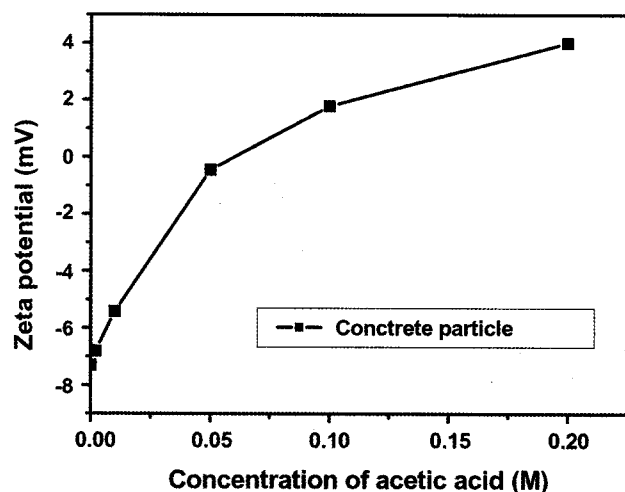
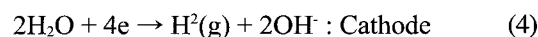
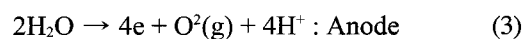


Fig. 4. Zeta Potential of the Concrete Versus the Concentration of the Acetic Acid

for alkaline earth metals (Ca, K and Mg), it is a suitable candidate for a soil washing [16]. Citric acid was used to improve the removal efficiency of metals from soil because of it being readily available, relatively inexpensive, and environmentally benign [17]. Shiau et al. showed that citric acid can remove copper by up to 80% from wood waste [18]. HNO_3 and hydrochloric acid also show a significant potential to extract metal ions from the concrete. However, their in-situ use is associated with a number of disturbing physical, chemical and biological properties of soil [19]. Oxalate was tested as a soil metal extractant because it is biodegradable, naturally occurring and relatively inexpensive, and forms moderately stable metal complexes [20]. Moreover, oxalate is one of the strongest organic acids, and therefore it is able to attack and dissolve hydrous oxides [21]. Acetic acid has been used for an electrokinetic-flushing, which consists of two carbons, four oxygens, and four hydrogens. In order to select the optimum reagent suitable to concrete's characteristics, EDTA, oxalate, citric acid, and acetic acid were selected as the candidate reagents. Four candidate reagents were used for a vertical electrokinetic decontamination. Acetic acid was used from a comparison of the removal efficiencies of the cobalt ions and cesium ions by each reagent through electrokinetic experiments [22]. Therefore, acetic acid was used as a reagent for this electrokinetic decontamination.

First, an electrokinetic decontamination was executed with acetic acid as the reagent for the simulated concrete for 15 days. The simulated concrete was saturated with 0.1M of acetic acid and the pH in a concrete cell was 12.0. The crushed concrete was put into a concrete cell of the 1L electrokinetic equipment as shown in Fig. 3. Meanwhile, the zeta potential of the concrete versus the acetic acid concentration is shown in Fig. 4. When the concentration

of the acetic acid was more than 0.1M, the zeta potential of the concrete was positive and the acetic acid solution in the concrete cell flowed to the anode compartment due to an electro-osmosis. Therefore, the electrode location in this experiment was in the opposite direction to that of the soil electrokinetic experiment. The electric current across the concrete cell, the flow rates of the waste solution and the concentrations of the waste solution in both electrode compartments, and the pH in the cathode compartment were measured periodically throughout the duration of an experiment. The pH in cathode compartment increased with time elapse due to the generation of hydroxide as the following equations.



If the pH in the concrete increases to more than 6, it is difficult to remove Co^{2+} from the concrete due to the formation of $\text{Co}(\text{OH})_2$. Therefore, in order to maintain the pH of the concrete near the cathode at lower than 6, acetic acid was periodically injected into the cathode compartment. Also, after the completion of the experiment for 15 days, the concrete in the concrete cell was divided into 6 sections and dried for more than 3 days to analyze the removal efficiency of the cobalt and cesium ions from the concrete. Each 5 g of dry concrete and about 10 ml of undiluted nitric acid solution were combined, heated at 150 °C on a hot plate for 3 days, filtered by a 0.2 μm size filter, diluted to 50 ml, and then the concentrations of the cobalt and cesium ions in the diluted solution were measured by AAS.

3.2 Electrokinetic Decontamination with Hydrochloric Acid

Secondly, in order to lower the pH of the concrete, an electrokinetic decontamination was executed with 0.2M of hydrochloric acid for the simulated contaminated concrete for 15 days. At that time the pH in the concrete cell was 11.5. The electrode location in this experiment was like the previous experiment. The electric current across the concrete cell, the flow rates and the concentrations of the waste solution in both electrode compartments, and the pH in the cathode compartment were measured periodically throughout the duration of the experiment. In order to maintain the pH of the concrete near the cathode at lower than 6, acetic acid was injected periodically into the cathode compartment. Also, after the completion of the experiment for 15 days, the concrete in the concrete cell was divided into 6 sections and dried for more than 3 days to analyze the removal efficiencies of the cobalt and cesium ions from the concrete.

3.3 Hybrid Decontamination Combining Washing Technology and Electrokinetic Technology

The results of the two previous electrokinetic decontaminations showed that it is impossible to remove cobalt and cesium from the concrete by only the electrokinetic technology. So, a washing-electrokinetic decontamination by combining washing technology and electrokinetic technology was used. Namely, the concrete was washed with a high concentration of hydrochloric acid and then it was decontaminated by electrokinetic technology. First, the concrete was washed with 3.0 M of hydrochloric acid with a 1.5ml/g ratio in a scrubbing tank for 4 hours. The CaCO_3 in the cement of the concrete was decomposed to CO_2 by a reaction with hydrochloric acid. The pH of the concrete was reduced to below 4. The hydrochloric acid solution from the mixture was removed and the remaining concrete was put into the 1L electrokinetic equipment. The electrokinetic decontamination was executed with 0.01 M of acetic acid as an electrolyte reagent under 4 V/cm during 14.83 days (washing: 0.17 days). The electrode location in this experiment was in the same direction as that of the soil electrokinetic experiment. Namely, the left is the anode compartment and the right is the cathode compartment (Fig. 3). Because the pH of the concrete was lowered to below 4 due to the hydrochloric acid washing, the effluent reagent flowed to the cathode compartment. 1,600 g of concrete was put into a concrete cell, whose pH was lowered to below 4. The electric current across the concrete cell, the flow rate and the concentration of the waste solution in the cathode compartment, and the pH in the cathode compartment were measured periodically throughout the duration of the experiment. In order to maintain the pH of the concrete near the cathode at lower than 6, acetic acid was injected periodically into the anode compartment. Also, 0.05 M of acetic acid was used as a reagent to define the optimum concentration of the nitric acid for an electrokinetic decontamination. Meanwhile, after the completion of the experiment for 15 days, the concrete in the concrete cell was divided into 6 sections and dried for more than 3 days to analyze the removal efficiency of the cobalt and cesium ions from the concrete. The reaction equation of CaCO_3 in the concrete and hydrochloric acid was as follows.



4. RESULTS AND DISCUSSIONS

4.1 Electrokinetic Decontamination with Acetic Acid

The experimental results of the electrokinetic decontamination with 0.1M of acetic acid are shown in Fig. 5. The acetic acid solution in the concrete cell flowed to

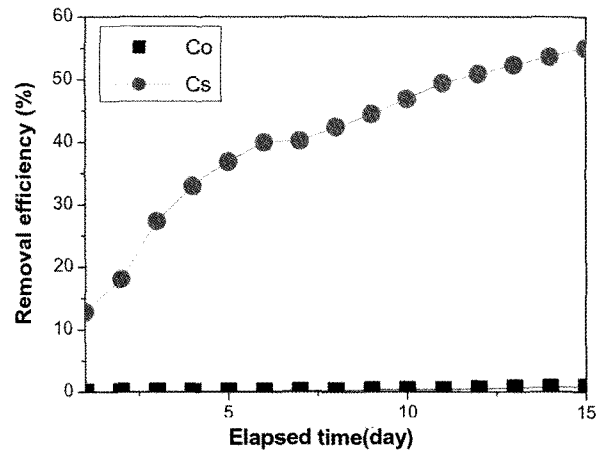


Fig. 5. Total Co^{2+} and Cs^+ Removal Efficiencies with the Decontamination Time for the 0.1M Acetic Acid Reagent

Table 2. Precipitation Ratios of Contaminants According to a pH Change by the NaOH Addition

pH	Cs(%)	Co(%)	Fe(%)	Ni(%)
9	18	99.7	98	98.4
10	21	99.9	100	98.6
11	22	99.9	100	98.6

the anode compartment due to electro-osmosis. Therefore, it was thought that the electro-osmosis direction of the cobalt and cesium ions is to the anode compartment side, while the migration direction of the cobalt and cesium ions is to the cathode compartment side. Cesium ions were removed by up to 55% from the concrete, but the cobalt ions were removed by only 0.8%. The reason was that the cobalt ions were not moved by an electro-osmosis and an electro-migration due to their formation of a hydroxide at above pH 6, but the cesium ions were moved by an electro-osmosis and an electro-migration due to their remaining in an ion state at above pH 6. Table 2 shows precipitation ratios of contaminants according to a pH change by the NaOH addition. Many positive ions including cesium ions in the concrete cell were moved to the cathode compartment by an electro-migration, and some ions were moved to the anode compartment by electro-osmosis. Namely, 52% of the cesium ions were moved to the cathode compartment and 3% of the cesium ions were moved in the anode compartment. Therefore it was found that an electro-migration (52%) removed more cobalt and cesium than electro-osmosis (3%).

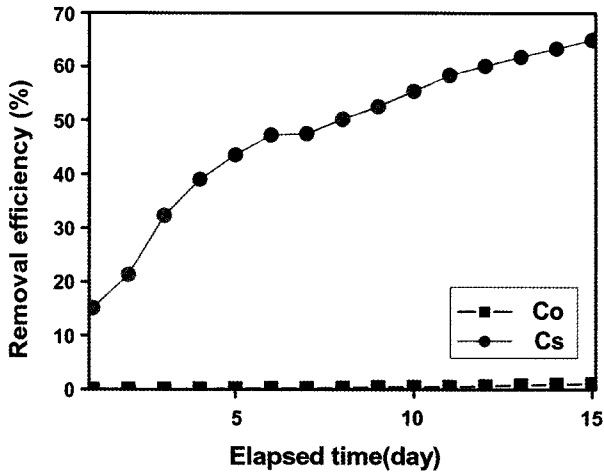


Fig. 6. Total Co^{2+} and Cs^+ Removal Efficiencies with the Decontamination Time for the 0.2M Hydrochloric Acid Reagent

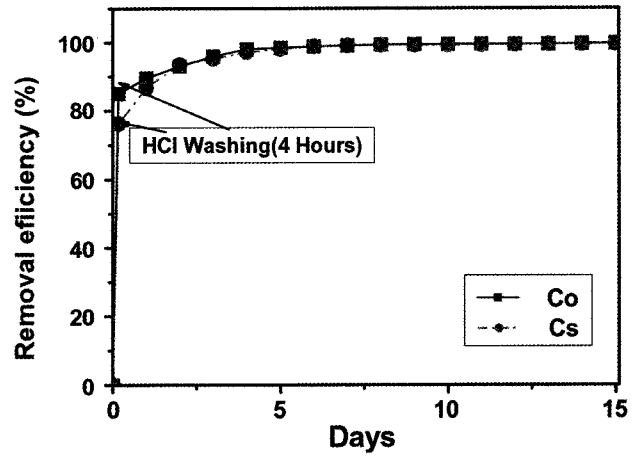


Fig. 7. Total Co^{2+} and Cs^+ Removal Efficiencies with the Decontamination Time for the 0.01M Acetic Acid Reagent after a Washing with 3.0 M Hydrochloric Acid for 4 Hours

4.2 Electrokinetic Decontamination with Hydrochloric Acid

The results of an execution of an electrokinetic decontamination with 0.2M of hydrochloric acid to lower the pH of the concrete are shown in Fig. 6. Cesium ions were removed by up to 65% from the concrete, but the cobalt ions were removed by only 1%. The reason was that the cobalt ions were not removed by electro-osmosis and electro-migration due to their forming a hydroxide at above pH 6, but the cesium ions were moved by electro-osmosis and an electro-migration due to their remaining in an ion state at above pH 6. Many positive ions including the cesium ions in the concrete cell were moved to the cathode compartment by electro-migration, and some ions were moved to the anode compartment by electro-osmosis. Namely, 61% of the cesium ions were moved to the cathode compartment and 4% of the cesium ions were moved to the anode compartment. Therefore it was found that electro-migration (61%) removed more of cesium ions than electro-osmosis (4%).

4.3 Washing-Electrokinetic Technology

The results of the previous two electrokinetic decontaminations only showed low removal efficiencies. The results of the concrete washing with 3.0 M of hydrochloric acid for 4 hours are shown in Fig. 7. The CaCO_3 in the concrete was reacted with hydrochloric acid, and it was decomposed to CO_2 , and the pH of the concrete was reduced to 3.7 after the concrete washing. Cesium ions were removed by 76.3% from the concrete, and the cobalt ions were removed by 85.0%. The hydrochloric acid solution from the mixture was removed, and the remaining concrete was put into the 1L electrokinetic equipment. The

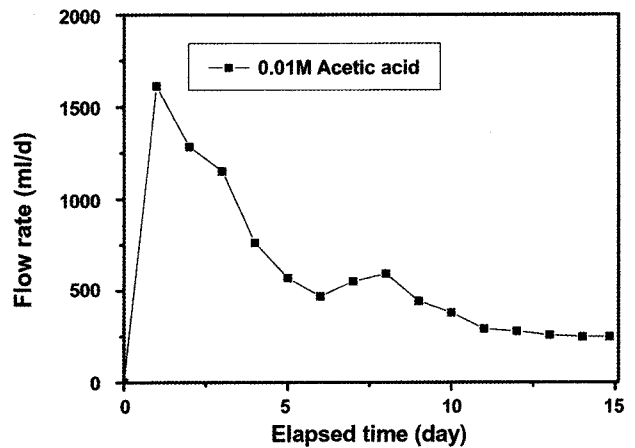


Fig. 8. Flow Rate of the Effluent with the Electrokinetic Decontamination Time for the 0.01M Acetic Acid Reagent

results of an execution of electrokinetic decontamination with 0.01 M of acetic acid under 4 V/cm during 14.83 days are shown in Fig. 7. Cesium ions and cobalt ions were removed slowly by electrokinetic decontamination. Cesium ions were removed by 98.1% from the concrete by this washing-electrokinetic decontamination after 5 days and the cobalt ions were removed by 98.5%. Cesium ions were removed by 99.6% from the concrete after 15 days and the cobalt ions were removed by 99.7%. The reason why the cobalt ions and cesium ions were mostly removed by electro-osmosis and electro-migration was thought to be due to them remaining in an ion state at below pH 6. Also the removal efficiencies of the cobalt and cesium by

0.05 M of acetic acid were reduced rather than those by 0.01M of acetic acid due to a reduction of the concrete zeta potential as shown in Fig. 4 and Eq. (2). Meanwhile, the effluent generated from the washing-electrokinetic decontamination versus the number of days is shown in Fig. 8. The flow rate of the effluent at the outset was higher but it was reduced with the passage of time. The waste-solution volume generated from the washing-electrokinetic decontamination was 2.4L(1.5ml/g) for the concrete washing and 9.15L(5.7ml/g) for the electrokinetic decontamination. So, the total volume of the decontamination effluent was 11.55L(7.2ml/g).

5. CONCLUSION

A washing-electrokinetic decontamination method was developed to decontaminate the concrete generated in the nuclear facilities in Korea, which combined an electrokinetic method and a washing method. The experimental results of the electrokinetic decontamination with 0.1M of acetic acid were that the cesium ions were removed by up to 55% from the concrete, but the cobalt ions were only removed by up to 0.8%. The results of the execution of electrokinetic decontamination with 0.2M of hydrochloric acid were that the cesium ions were removed by up to 65% from the concrete, but the cobalt ions were only removed by up to 1%. The reason why the cobalt ions were not removed by electro-osmosis and electro-migration was due to their forming a hydroxide at above pH 6. While the cesium ions were removed by electro-osmosis and electro-migration due to their remaining in an ion state at above pH 6. When the concrete was washed with 3 M hydrochloric acid for 4 hours (0.17 day) to lower the pH of the concrete, the CaCO_3 in the concrete was decomposed into CO_2 and the pH of the concrete was reduced to 3.7, and the cobalt and cesium in the concrete were removed by up to 85.0% and 76.3% respectively. Next, when the washed concrete was decontaminated in the 1L electrokinetic equipment for 14.83 days, the cobalt and cesium in the concrete were removed by up to 99.7% and 99.6% respectively. Also, the removal efficiencies of the cobalt and cesium by 0.01M of acetic acid were increased more than those by 0.05 M of acetic acid due to the increase of concrete zeta potential. The effluent volume generated from the washing-electrokinetic decontamination was 11.55L(7.2ml/g), namely, 2.4L(1.5ml/g) for the washing and 9.15L(5.7ml/g) for the electrokinetic decontamination.

REFERENCES

- [1] K. Popov, I. Glazkova, V.Yachmenev and A. Nikolayev, "Electrokinetic Remediation of Concrete: Effect of Chelating Agents," *Environmental Pollution*, **153**, 22(2008).
- [2] D. Voinitchi, S. Julien and S. Lorente, "The Relation between Electrokinetics and Chloride Transport through Cement-Based Materials," *Cement & Concrete Composites*, **30**, 157 (2008).
- [3] M. T. Harris, D. W. Depaoli and M. R. Ally, "Modeling the Electrokinetic Decontamination of Concrete," *Separation Science and Technology*, **32**, 827(1997).
- [4] M. T. Harris, D. W. Depaoli and M. R. Ally, "Investigation of Electrokinetic Decontamination of Concrete," *Separation Science and Technology*, **32**, 387(1997).
- [5] F. Braud, S. Tellier and M. Astruc, "Modeling of Decontamination Rate in an Electrokinetic soil Processing," *International Journal of Environmental Analytical Chemistry*, **68**, 105(1998).
- [6] S. O. Kim, S. H. Moon, and K. W. Kim, "Removal of Heavy Metals from Soils Using Enhanced Electrokinetic Soil Processing," *Water, Air, and Soil Pollution.*, **125**, 259 (2001).
- [7] M. M. Page and C. L. Page, "Electroremediation of Contaminated Soils," *Journal of Environmental Engineering*, ASCE, **128**, 208(2002).
- [8] C. Chaiyaraksa and N. Sriwiriyanuphap, "Batch Washing of Cadmium from Soil and Sludge by Mixture of $\text{Na}_2\text{S}_2\text{O}_5$ and Na_2EDTA ," *Chemosphere*, **546**, 129(2004).
- [9] C.G. Rampley and K.L.Ogden, "Preliminary Studies for Removal of Lead from Surrogate and Real Soils Using a Water Soluble Chelator, Adsorption and Batch Extraction," *Environ. Sci. Technol.*, **32**(7), 987(1988).
- [10] B. Sun, F.J. Zhao, E. Lombi and S.P. McGrath, "Leaching of Heavy Metals from Contaminated Soil Using EDTA," *Environ Pollut.*, **113**, 111(2001).
- [11] R. Abumaizar and L.L. Khan, "Laboratory Investigation of Heavy Metal Removal by Soil Washing," *J. Air Waste Manage. Assoc.*, **46**, 765(1996).
- [12] B. Kornilovich, N. Mishchuk, K. Abbruzzese, G. Pshinko and R. Klishchenko. "Enhanced Electrokinetic Remediation of Metals-Contaminated clay," *Colloids and Surfaces A:Physicochem. Eng. Aspects.*, **265**, 114(2005).
- [13] A. Giannis, E. Gidaracos and A. Skouta, "Application of Sodium Dodecyl Sulfate and Humic Acid as Surfactants on Electrokinetic Remediation of Cadmium-Contaminated Soil," *Desalination*, **211**, 249(2007).
- [14] K. Popov, I. Glazkova, A. Petrov and E. Sedykh, "Zeta-Potential of Concrete in Presence of Chelating Agents," *Colloids and Surfaces*, **299**, 198(2007).
- [15] B. Sun, J. Zhao, E. Lombi and S.P. McGrath, "Leaching of Heavy Metals from Contaminated Soils Using EDTA," *Environ. Pollut.*, **113**, 111(2001).
- [16] R. Bassi, S. O. Prasher and B. K. Simpson, "Extraction of Metals from a Contaminated Sandy Soil Using Citric Acid," *Environ. Prog.*, **19**(4), 275(2000).
- [17] G.M. Nystrom, "Investigations of Soil Solution during Enhanced Electrodialytic Soil Remediation," Report No. BYG-DTU R009, Denmark Technical University, 21, (2001).
- [18] R. J. Shiau, R.L. Smith and B. Aveller, "Effects of Steam Explosion Processing and Organic Acids on CCA Removal from Treated Wood Waste," *Wood Sci. Technol.*, **34**, 377 (2000).
- [19] S. Tampouris, N. Papassiopi and I. Paspaliaris, "Removal of Contaminant Metals from Fine Grained Soils, Using Agglomeration, Chloride Solution and Pile Leaching Techniques," *J. Hazard. Mater.*, **B84**, 297(2001).
- [20] H.A. Elliot and N.L. Shastri, "Extractive Decontamination of Metal-Polluted Soils Using Oxalate," *Water Air Soil Pollut.*, **110**, 335(1999)
- [21] W. Stumm, *Chemistry of the Solid-Water Interface*, p. 165,

Wiley-Interscience, New York (1992).
[22] G. N. Kim, Y. H. Jung, J. K. Moon, and C. H. Jung,
“Development of Electrokinetic Flushing Technology for

Remediation of the Contaminated Site Around Nuclear
Facilities,” *Journal of Korea Society of Waste Management*,
24(4), 146(2008).