Int. J. Electrochem. Sci., 11 **(2016)** 4149 - 4160

International Journal of
ELECTROCHEMICAL
SCIENCE
www.electrochemsci.org

Electrokinetic Dewatering of Mine Tailings Using DSA Electrodes

Joon Kyu Lee[1,*], *Julie Q. Shang*[2], *Yanqing Xu*[2]

[1] Dept. of Civil Engineering, University of Seoul, 163 Seoulsiripdae-ro, Dongdaemun-gu, Seoul 02504, Republic of Korea
[2] Dept. of Civil and Environmental Engineering, Western University, London, ON, N6A 5B9, Canada
[*]E-mail: jkleegeo@uos.ac.kr

Received: 24 September 2015 / *Accepted:* 15 November 2015 / *Published:* 1 April 2016

Electrokinetic dewatering has been shown to be a promising technology; however, one of the challenges in its practical application is the corrosion of anodes. Recently, dimensionally stable anodes (DSAs) were developed that are virtually corrosion free. This paper investigates the feasibility of using titanium anodes with iridium oxide coating (IrO_2/Ta_2O_5) in the electrokinetic dewatering of mine tailings slurries. Characterization of the tailings is presented, followed by the results of electrokinetic dewatering, including the gradually increased and decreased voltages applied during the treatment, polarity reversal, and surcharge pressure applied to tailings. The results show that electrokinetic treatment using DSAs can significantly dewater tailings with low density and minimize electrode corrosion. The electroosmotic permeability measured for the combination of voltages and surcharge pressures ranges from 6.39×10^{-9} m^2/sV to 5.30×10^{-8} m^2/sV. The results also show that the effectiveness and efficiency of the electrokinetic dewatering of tailings can be improved by first applying a high voltage and then reducing it gradually during treatment.

Keywords: Electrokinetics, dewatering, mine tailings, electroosmotic permeability, DSA electrode

1. INTRODUCTION

Tailings from mining activities consist of ground rock particles after valuable minerals are extracted. Generally, tailings are disposed of on site in the form of impoundments or backfill. Many tailings contain a significant proportion of fines with clay minerals, which settle slowly under self-weight consolidation. These tailings have high water content and low shear strength, posing instability. For example, in 1965, the catastrophic failure of the El Cobre tailings dam in Chile resulted from the seismic liquefaction of sand tailings with low density [1]. In 1971, the Chungar tailings facility storage

doi: 10.20964/1009160

in Peru collapsed due to earthquake-induced landslides [2]. The heavy rainfall event in 1976 caused the failure of the Bafokeng tailings dam in South Africa [3]. The mining industry experienced significant dam failures resulting from unusual weather and poor management [4]. Thus, the dewatering of tailings is a primary target in mining waste management.

Electrokinetic dewatering was first studied by Casagrande [5] for stabilizing weak fine-grained soils. This technique involves the application of a direct current (dc) voltage across electrodes placed in a wet porous medium. The electrical gradient induces the movement of pore water from the anode (positive electrode) to the cathode (negative electrode). The technique has been shown to be feasible for fine-grained mine waste. Sprute and Klesh [6] performed a field study on the electrokinetics of mine sediment and reported that after the treatment, the solid content was increased to 31 to 35% from the initial solid content of 17%. Lockhart [7] presented laboratory results of electrokinetic dewatering for a tailings slurry, progressing from an initial solid content of 55% to a solid content of 80% with an energy consumption of 5 to 8 kWh per dry ton. Lockhart [8] also examined the suitability of in situ electrokinetic dewatering of sand washery tailings and reported favorable dewatering with a low energy consumption of 1 kWh per dry ton. Bayat et al. [9] studied the electrokinetic dewatering of fine glass sand tailings (d_{80} finer than 2 μm) in the laboratory, where the solid content was increased from 3 - 5% to 39 - 44% after 10 h with a current density of 5.6 to 11.9 A/m^2. Fourie and Jones [10] conducted electrokinetic dewatering tests on two different mineral tailings and reported higher power consumption rates for smectite-rich tailings than kaolin-rich tailings.

A major challenge in the application of electrokinetic dewatering is anode corrosion due to electrochemical reaction if the anode is made of a consumable material, such as structural steel, copper and aluminum. These anodes corrode rapidly, which reduces the dewatering effectiveness and efficiency (i.e., power consumption) of the treatment. Recently, electrodes using advanced conductive materials have been developed, including electrokinetic geosynthetics (EKGs), electrical vertical drains (EVDs), and dimensionally stable anodes (DSAs). Fourie et al. [11] performed laboratory and field studies on the use of EKGs in dewatering and the recovery of water from tailings. Rittirong et al. [12] evaluated the performance of EVDs in laboratory and field tests. Their results showed a significant increase in the undrained shear strength of the treated soils, but the electroosmotic flow stopped shortly after the electrokinetic treatment due to deterioration of the conductive polymer [13]. DSAs are composed of titanium protected with a coating, which typically consisting of iridium oxide (IrO_2) and ruthenium oxide (RuO_2), and are virtually corrosion free under acidic environments [14, 15]. Although DSAs have been shown to be a promising technology for the treatment of landfill leachate [16] and wastewater effluent [17], their application in geotechnical and mining applications needs further investigation.

In this study, tailings from a metallic mineral mining site in Northern Ontario, Canada are characterized for their physical, mineralogical and geochemical properties, followed by an experimental study of electrokinetic dewatering using iridium oxide-coated titanium (IrO_2/Ta_2O_5). The investigation is focused on the effects of electrokinetics as related to the gradually increased or decreased voltages applied during the treatment, polarity reversal, and surcharge pressure applied to tailings.

2. EXPERIMENTAL STUDY

2.1 Tailings

The mine tailings used in this study were recovered from a hydrometallurgical facility in Northern Ontario, Canada. The tailings were received with a natural water content of 83.4% and a specific gravity of 2.64. The tailings were primarily comprised of silt-sized solids (80%) with some clay-sized particles (20%), which is the typical grading of Canadian hard rock tailings [18]. The Atterberg limit tests on the tailings particles finer than 75 μm revealed that the material is non-plastic. Based on X-ray diffraction analysis, gypsum is the dominant constituent of the tailings (63%) and jarosite (36%) and quartz (1%) are also present. The pore water chemistry of the tailings is summarized in Table 1.

Table 1. Physical and mineralogical properties of tailings tested

Parameter	Value
Soils	
Water content (%)	83.4
Specific gravity	2.64
Hydraulic conductivity (m/s)	2.85×10^{-9}
Minerals	
Gypsum (wt. %)	63
Jarosite (wt. %)	36
Quartz (wt. %)	1
Water	
pH	7.6
Electrical conductivity (mS/m)	28
As (mg/L)	0.04
Cd (mg/L)	0.01
Co (mg/L)	0.05
Cr (mg/L)	1.48
Cu (mg/L)	32.62
Fe (mg/L)	19.71
Mg (mg/L)	119.59
Mn (mg/L)	0.67
Mo (mg/L)	0.02
Ni (mg/L)	2.33
P (mg/L)	0.27
Sb (mg/L)	0.04
Zn (mg/L)	4.54

2.2 Test System

Fig. 1 shows the test setup for electrokinetic dewatering, modified from a system developed by Mohamedelhassan and Shang [19]. The equipment includes an electrokinetic cell (hereafter, EK cell), electrodes connected to a direct current (dc) power supply (Model 1671A, BK Precision), dial gauges, and a pump providing water to the recharge tube on the anode side. The EK cell is made of electrically insulating Plexiglas and has the following dimensions: 0.35 m long, 0.1 m wide and 0.25 m high. The EK cell is divided by a perforated Plexiglas plate into the following three compartments: the anode reservoir, the cathode reservoir, and the specimen chamber. The length of the specimen chamber is 180 mm, which is the horizontal spacing between the electrodes. To simulate one-dimensional horizontal flow, an impermeable geomembrane is placed on the top of the specimen, followed by a loading plate, through which a designated surcharge pressure can be applied. Two dial gauges are mounted at the left and right sides of the loading plate to monitor the settlement of the tailings with time. Four voltage probes 1 mm in diameter are installed on the bottom of the specimen chamber to measure the voltage distribution across the specimen. Water is supplied by the anode reservoir, passing through the tailings specimen to reach the cathode reservoir, then discharging to the scaled column. A zero hydraulic gradient on the specimen is maintained across the specimen by adjusting the heights of the recharge and discharge tubes connected to the reservoirs.

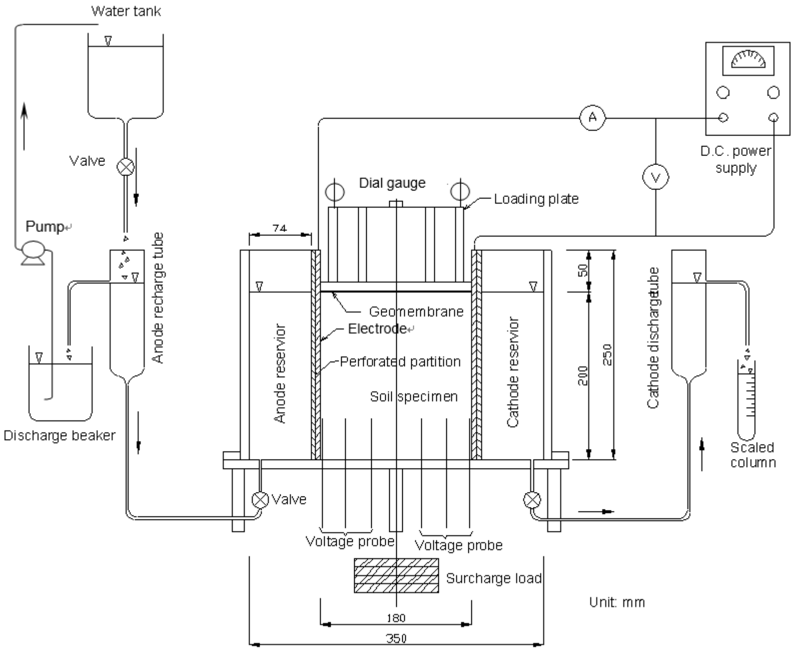

Figure 1. Schematic diagram of electrokinetic cell

The anode used in this study is a titanium mesh coated with iridium oxide (IrO_2/Ta_2O_5) (hereafter, IrO_2/Ta_2O_5 anode), supplied by De Nora Industries. The IrO_2/Ta_2O_5 anode has high chemical and mechanical stability in acidic conditions. The cathode is made of stainless steel (SS316) mesh (hereafter, SS cathode). Both electrodes have a thickness of 1.6 mm, a width of 97 mm and a height of 250 mm with a 30% opening area. The electrodes are installed vertically in the cell, in direct contact with the tailings specimen. In all illustrations presented, the anode is at the left side of the EK cell, and the cathode is at the right side.

2.3 Test Program

The laboratory study includes two phases, EK test 1 and EK test 2. EK test 1 was designed to investigate the effect of polarity reversal on the electrokinetic dewatering of tailings. EK test 2 was designed to assess the viability of electrokinetic dewatering on tailings under gradually reduced voltage. The key parameters related to electrokinetics, i.e., the flow rate of water, electroosmotic permeability, efficiency factor, and pH, were measured during the tests. The detailed procedures for the two distinct tests are described below.

2.3.1 EK Test 1

The slurry of tailings was thoroughly mixed and placed in the EK cell. A surcharge pressure of 5 kPa was gradually applied to the tailings specimen in two increments over the period of 2 days via the loading plate to consolidate and simulate the in situ stress conditions in tailings storage facilities. The settlement with time was monitored until primary consolidation was nearly completed prior to the next loading increment. The specimen after the preloading consolidation had dimensions of 0.18 m long, 0.1 m wide and 0.2 m high, with a void ratio of 2.2. The water levels in the anode recharge tube and the anode and cathode compartments were adjusted to the same level. The specimen was then ready for electrokinetic testing.

The applied voltage was gradually increased incrementally. Initially, a voltage of 8 V was applied for 18 h, which was then increased to 14 V for 60 h (IrO_2/Ta_2O_5 anode and SS cathode). Afterward, the polarity of the electrodes was reversed. The applied voltage was maintained at 14 V for 72 h, then raised to 19 V for 24 h. During the entire period of voltage application, the surcharge pressure was sustained on the specimen. The settlement of the tailings specimen and the water pH in both electrode reservoirs were monitored. After the electrokinetic test was completed, the zeta potential of the tailings solids was measured using a Zeta Plus analyzer (Brookhaven Instruments).

2.3.2 EK Test 2

EK test 2 was conducted on the tailings specimen without surcharge pressure to simulate the surface condition of the tailings dams. The applied voltage was gradually reduced in increments, i.e., initially, a voltage of 19 V was applied for 42 h, then decreased to 14 V for 24 h and finally to 8 V for 24 h. During the electrokinetic test, the pH of water in the electrode reservoirs was monitored.

3. RESULTS AND DISCUSSION

3.1. EK Test 1

Fig. 2 shows the variation of current density with elapsed time, in which the polarity reversal is denoted as the change of the sign of the current. For a given voltage, the current density decreases slightly with time, e.g., by 24% when the treatment time lasted for 72 h (applied voltage = -14 V). The reduction of current density is reported for other electrodes in literature [20, 21], although they exhibit higher rates of reduction due to the electrode corrosion. Fig. 2 also presents the efficiency factor of the electrokinetic treatment with the elapsed time, defined as [12]

$$\beta = \frac{U_e}{U_0} \times 100 \qquad (1)$$

where U_e is the effective voltage measured directly in the soil mass, and U_0 is the voltage between the anode and cathode. The efficiency factor explains the difference between the applied electrical gradient and the effective electrical gradient. The calculated efficiency factor ranges between 67 and 81%, comparable to the values reported for carbon and EVD electrodes in previous studies [12, 22]. It was further observed that the increase in the applied voltage improves the efficiency factors, regardless of polarity reversal. However, higher applied voltages can lead to increased heating, desiccation and electrochemical reactions, which diminish treatment effectiveness.

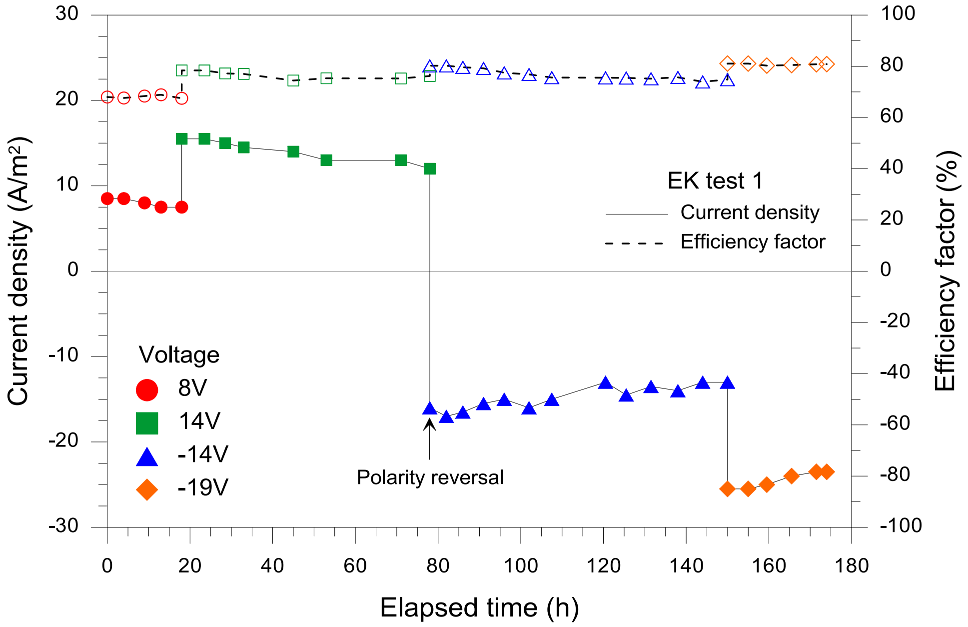

Figure 2. Current density and efficiency factor during electrokinetic treatment

Fig. 3 shows the accumulated volume of water flow during the electrokinetic treatment, where the water was driven to the cathode. Note that the direction of water flow was reversed in the EK cell when the polarity was reversed. The cumulative water flow over 174 h is 1,383 mL, and the ratio of discharged water to total pore water (2,475 cm^3) in the specimen is 55.9%. Fig. 3 also illustrates the change in water flow rate with time, varying between 2.2 and 16.3 mL/h. The average flow rate is 1.10 $\times 10^{-9}$ m/s. It is noted that when the applied voltage is changed, the flow rate increases and then gradually decreases with time.

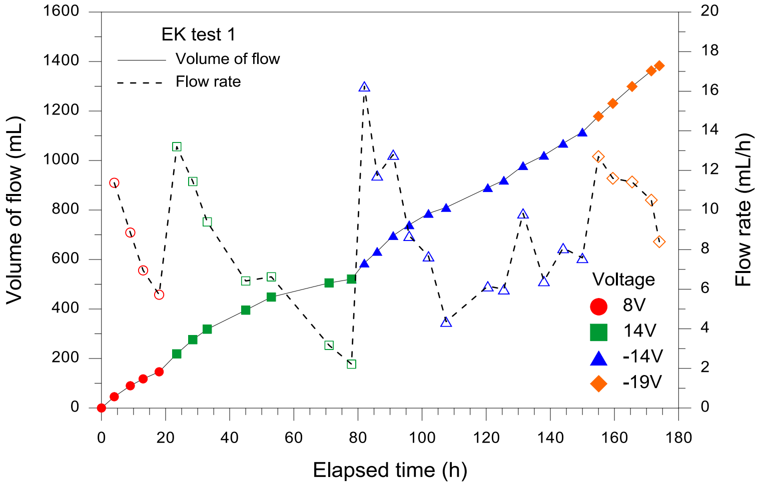

Figure 3. Volume and rate of water flow during electrokinetic treatment

The electroosmotic permeability k_e (m^2/sV) can be calculated by [23]

$$k_e = Q_e / EA \tag{2}$$

where Q_e (m^3/s) is the electroosmotic flow rate, and E (V/m) is the electric field intensity (or electrical gradient), defined as $E = -\nabla U$, where U (V) is the electric potential, ∇ is the del vector with respect to spatial coordinates, and A (m^2) is the cross-sectional area normal to the flow direction. Fig. 4 plots the measured value of k_e against the elapsed time of the test. In general, the electroosmotic permeability decreases with time, as has been observed by many researchers [24, 25]. This result shows that the electroosmotic permeability for the tailings is in the range of 5.26×10^{-9} to 0.53×10^{-9} m^2/sV. It is also found that the applied voltage and regular polarity reversal increase the electroosmotic permeability. The average electroosmotic permeability is evaluated by

$$k_{e(ave)} = \frac{1}{t}\int_0^t k_e dt = \frac{1}{t}\sum_{i=1}^{N}\left(\frac{k_{e(i)} + k_{e(i+1)}}{2}\right)(t_{i+1} - t_i) \tag{3}$$

where t is the test duration for a specific voltage application, and $k_{e(i)}$ is the electroosmotic permeability at time t_i. Based on Eq. (3), the average electroosmotic permeability for the tailings tested is 1.99×10^{-9} m^2/sV.

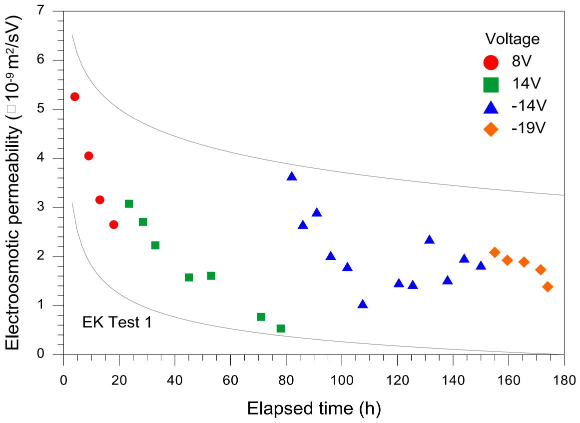

Figure 4. Electroosmotic permeability during electrokinetic treatment

Fig. 5 shows the consolidation settlement during the electrokinetic treatment. The normalized settlement, defined as the settlement divided by the untreated specimen height $\Delta H / H_0$, is also presented. With the normal polarity, similar settlements at the left and right sides were recorded. After the polarity reversal, however, a larger settlement was registered at the right side than at the left side.

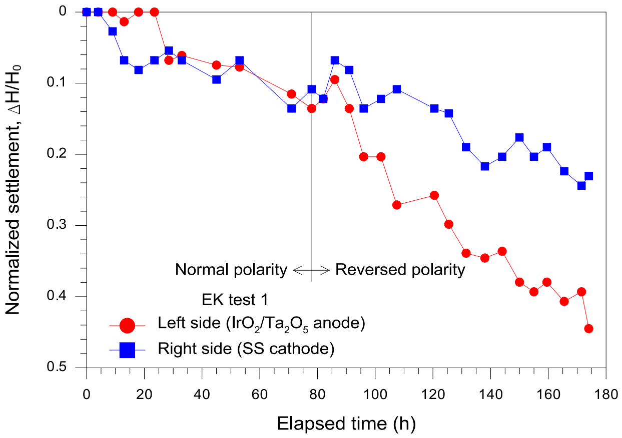

Figure 5. Settlement during electrokinetic treatment

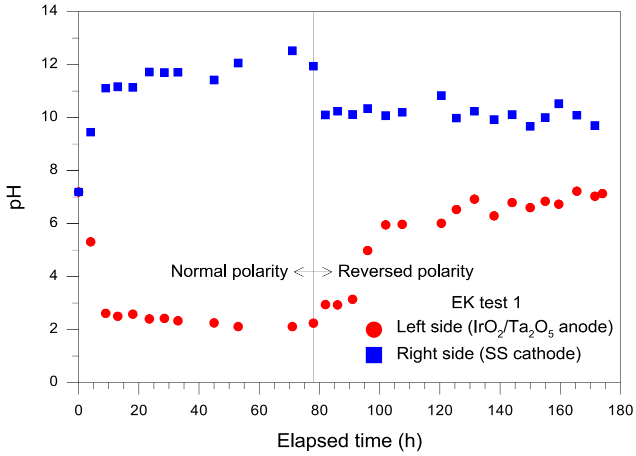

Figure 6. pH of water in electrode reservoirs

Fig. 6 shows the water pH in the electrode reservoirs. Immediately after the voltage application, a significant decrease in pH at the left side and increase at the right side were observed, and then the pH remained constant. The results confirm the electrolysis reactions at the anode and cathode, including oxidation at the anode and reduction at the cathode during the electrokinetic process:

At anode: $2H_2O - 4e^- \rightarrow O_2 + 4H^+$ (4)

At cathode: $4H_2O + 4e^- \rightarrow 2H_2 + 4OH^-$ (5)

The reactions lead to the generation of acidic and alkaline conditions at the anode and cathode. The primary reactions will evolve to more complex interactions in the electrokinetic process, leading to changes in the soil physiochemical properties such as salinity, porosity, decomposition and precipitation of minerals, and microstructure. In addition, the electrical current will generate heat in the soil, causing changes in the water content and surface desiccation. The polarity reversal served as a neutralization of water pH, i.e., the water pH in the left side increased and the water pH in the right side decreased. The pH change at the left side was more prominent than that at the right side, which might correlate to the settlement behaviors presented in Fig. 5.

The zeta potential is an indicator of the particle surface charge, which in turn reflects the influence of the effectiveness of electrokinetic dewatering. It is well known that the zeta potential of clayey soils strongly depends on the pH of the pore fluid [26, 27]. Therefore, the pH change during the electrokinetic process will affect the efficiency of the treatment. The zeta potential as a function of water pH was measured and presented in Fig. 7. For the tailings tested, the zeta potential remains negative over a broad pH range of approximately 1.5 to 13.5, indicating that electrokinetic treatment would be effective.

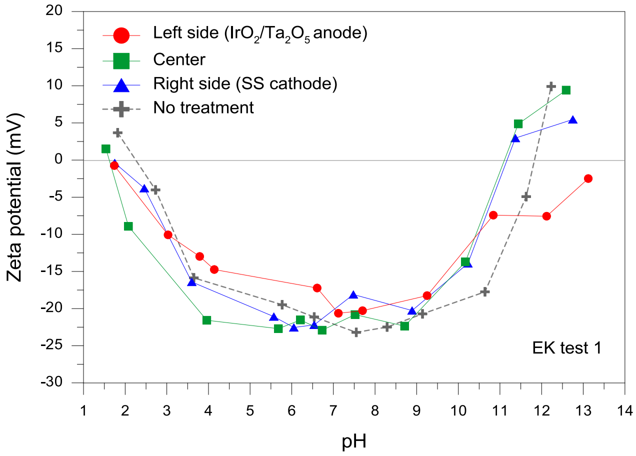

Figure 7. Zeta potential of tailings before and after electrokinetic treatment

3.2 EK Test 2

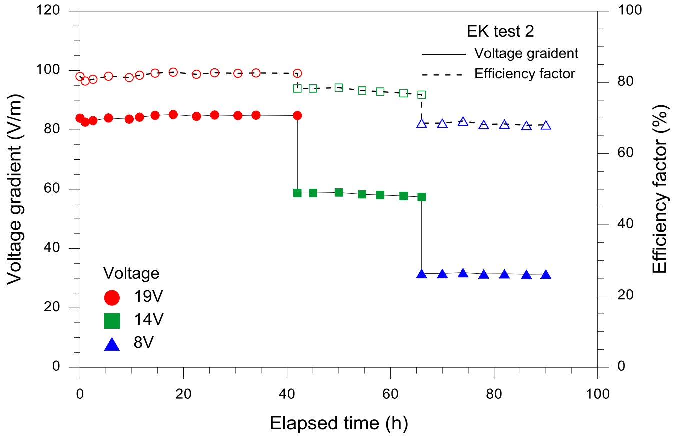

Figure 8. Change in voltage gradient and efficiency factor with treatment time

To compare with the gradually increased voltage implemented in EK test 1, EK test 2 was designed to apply gradually reduced voltage to unconsolidated tailings.

Fig. 8 shows the voltage in the tailings and efficiency factor versus elapsed time. The voltage gradients are constant over a specific time. The result also indicates that although the efficiency factors decrease with decreasing voltage, they are in the ranges of 0.6 to 0.9, which is consistent with the suggestions by Casagrande [28] for the design of electrokinetics.

Fig. 9 shows the accumulated volume of water flow and water flow rate during the electrokinetics treatment. The rate of water flow normally decreases in 72 h, then remains constant with further increases in treatment time. The average flow rate for the entire testing period is estimated to be 1.77 × 10^{-9} m/s, which is slightly higher than in the EK test 1. On the other hand, as shown in Fig. 10, the electroosmotic permeability decreases during the electrokinetic treatment. The average electroosmotic permeability is calculated to be 2.61 × 10^{-9} $m^2/(sV)$, which is 31% higher than in EK test 1. Fig. 11 shows that a significant decrease in pH at the anode reservoir and increase at the cathode reservoir occurred during the first day of testing. Based on the results in Figs. 9-11, the use of gradually reduced voltage is generally more effective for the dewatering of unconsolidated tailings.

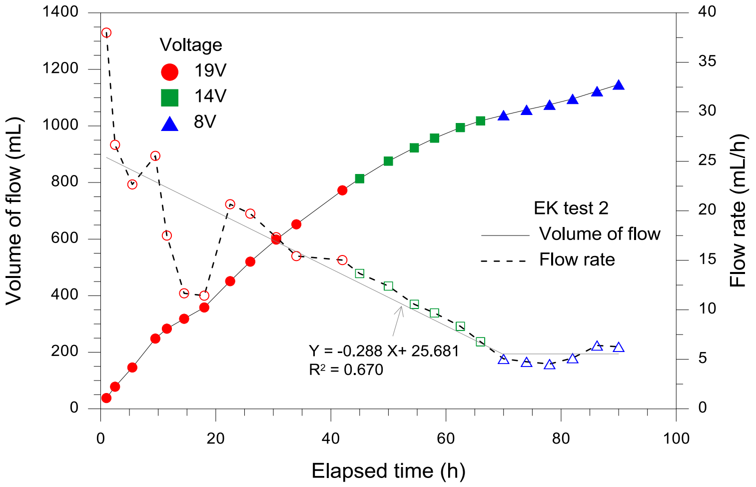

Figure 9. Cumulative discharge and flow rate with treatment time

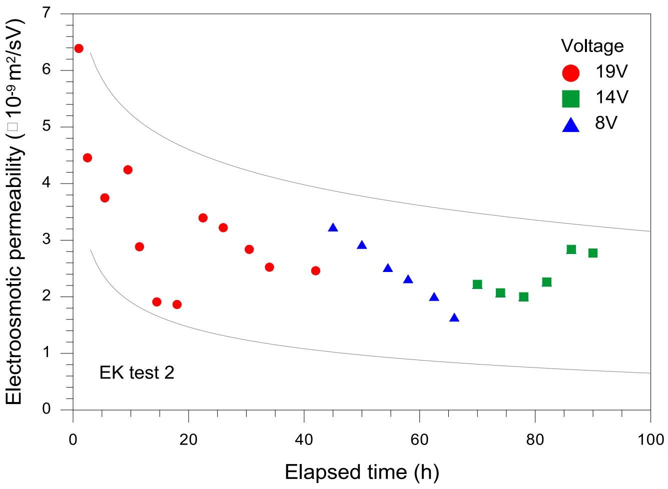

Figure 10. Change in electroosmotic permeability with treatment time

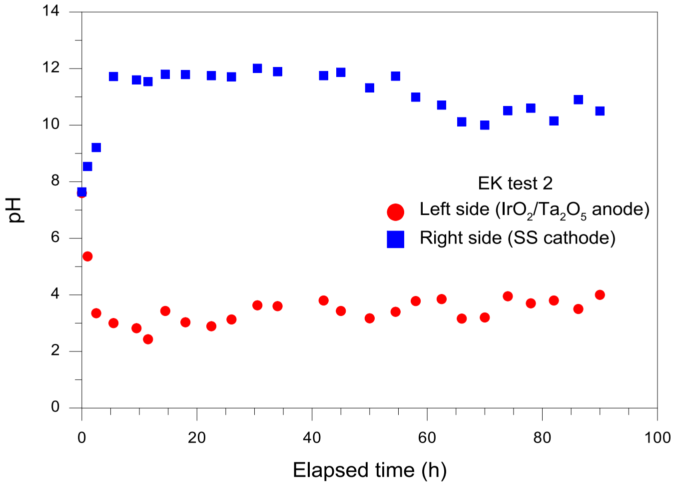

Figure 11. Change of pH water in electrode reservoirs

4. CONCLUSIONS

The electrokinetic dewatering of mine tailings from Northern Ontario, Canada, using a titanium anode with iridium oxide coating (IrO_2/Ta_2O_5) was investigated. Two phases of laboratory tests (EK tests 1 and 2) were performed, which involved applying either increased or decreased voltages during the treatment, polarity reversal, and surcharge pressure applied to tailings. From the results of the experiments, the following conclusions were drawn:

1) The electrokinetics treatment generated a significant dewatering effect on the tailings slurry. The water discharged by electrokinetic treatment was equivalent to approximately 56% of the tailings pore volume over 174 h (EK test 1).

2) The electrokinetic treatment efficiency increased with the applied voltage in terms of the efficiency factor (defined as the ratio of the effective and applied voltages), which ranged between 68% and 83% for EK tests 1 and 2.

3) The electroosmotic permeability as measured under different applied voltages varied from 6.39×10^{-9} m^2/sV to 5.30×10^{-8} m^2/sV, decreasing with treatment time.

4) Polarity reversal has been proven to be an effective measure to balance tailings water pH during the electrokinetic process.

5) The effectiveness and efficiency of the electrokinetic dewatering of tailings can be improved by first applying a high voltage and reducing it gradually during treatment.

ACKNOWLEDGEMENTS
The authors acknowledge support in this research from the National Science and Engineering Research Council of Canada (NSERC) and the National Research Foundation of Korea (NRF) (Grant No. 2011-0030040 and No. 2013R1A6A3A01023199).

References

1. R. Dobry, L. Alvarez, *J. Soil Mech. Found.*, 93 (1967) 237-260.
2. M. Rico, G. Benito, A.R. Salgueiro, A. Diez-Herrero and H.G. Pereira, *J. Hazard. Mater.*, 152 (2008) 846-852.
3. G. Villavicencio, R. Espinace, J. Palma, A. Fourie and P. Valenzuela, *Can. Geotech. J.*, 51 (2013) 449-464.
4. S. Azam, and Q. Li, *Geotechnical News*, 28 (2010) 50-53.
5. L. Casagrande, *Geotechnique*, 1 (1949) 159-177.
6. R.H. Sprute and D.J. Klesh, Electrokinetic Densification of Solids in a Coal Mine Sediment Pond - A Feasibility Study, *US Bureau of Mines, Report of Investigations* 8666, (1982).
7. N.C. Lockhart, *Fuel*, 60 (1981) 919-923.
8. N.C. Lockhart, *Drying Technol.*, 6 (1992) 415-423.
9. O. Bayat, O. Kilic, B. Bayat, M. Anil, H. Akarsu and G. Poole, *Water Res.*, 40 (2006) 61-66.
10. A.B. Fourie and C.J.F.P. Jones, *Geotext. Geomembranes*, 28 (2010) 181-190.
11. A.B. Fourie, D.G. Johns and C.J.F.P. Jones, *Can. Geotech. J.*, 44 (2007) 160-172.
12. A. Rittirong, R.S. Douglas, J.Q. Shang and E.C. Lee, *Geosynth. Int.*, 15 (2008) 1-13.
13. J.K. Lee and J.Q. Shang, *Geotech. Eng. J. SEAGS AGSSEA*, 44 (2013) 25-36.
14. W.Y. Liang, J.H. Qu, L.B. Chen, H.J. Liu and P.J. Lei, *Environ. Sci. Technol.*, 39 (2005) 4633-4639.
15. S.S. Kim and S.D. Kim, *Thin Solid Films*, 516 (2008) 3673-3679.
16. E. Turro, A. Giannis, R. Cossu, E. Gidarakos, D. Mantzavinos and A. Katsaounis, *J. Hazard. Mater.*, 190 (2011) 460-465.
17. D. Valero, V. Garcia-Garcia, E. Exposito, A. Aldaz and V. Montiel, *Sep. Purif. Technol.*,123 (2014) 15-22.
18. B. Bussiere, *Can. Geotech. J.* 44 (2007) 1019-1052.
19. E. Mohamedelhassan and J.Q. Shang, *Ground Improv.*, 5 (2001) 3-11.
20. P. Asavadorndeja and U. Glawe, *Bull. Eng. Geol. Environ.*, 64 (2005) 237-245.
21. J.Q. Shang, Q.H. Tang and Y.Q. Xu, *Geomech. Eng.*, 1 (2009) 23-29.
22. E. Mohamedelhassan and J.Q. Shang, *Can. Geotech. J.*, 40 (2003) 1185-1199.
23. J.K. Mitchell and K. Soga, *Fundamental of Soil Behaviors*, John Wiley & Sons, New Jersey (2005).
24. V. Jeyakanthan, C.T. Gnanendran and S.C.R. Lo, *Can. Geotech. J.*, 48 (2011) 1788-1802.
25. A.N. Alshawabkeh and T.C. Sheahan, *Ground Improv.*, 7 (2003) 177-185.
26. L.M. Vane and G.M. Zang, *J. Hazard. Mater.*, 55 (1997) 1-22.
27. A. Kaya and Y. Yukselen, *Can. Geotech. J.*, 42 (2005) 1280-1289.
28. L. Casagrande, *J. Boston Soc. Civil Eng.*, 69 (1983) 255-302.