

ELECTROKINETIC DEWATERING OF GYPSUM CONTAINING TAILINGS

Julie Q. Shang

Department of Civil and Environmental Engineering
The University of Western Ontario
London, Ontario

Angelo R. Fernando and Edmond K. Lam
Innovation & Technology Development - Research Centre
Cameco Corporation
Port Hope, Ontario

ABSTRACT

Mine tailings are the end product of mining and mineral processing after the mineral has been extracted, which are discharged as slurry of low solid contents. Chemical flocculants, such as polymers and inorganic salts, are often used to assist tailings dewatering for subsequent disposal. However, in cases that tailings contain significant fraction of fine solids (in the micro meter range) and clay minerals, the dewatering process becomes increasingly difficult and time consuming. In this study, the water flow generated by electrokinetics on mine tailings from a mine site in Saskatchewan, Canada is investigated. The tailings contain mainly gypsum, quartz and clay minerals. The tailings are characterized for the geotechnical, physical, chemical and mineralogical properties first, and then electrokinetic cell tests are carried out to measure the coefficient of electroosmotic permeability, a key parameter on the response of tailings to electrokinetic dewatering. Two conductive materials are used as electrodes in the study, i.e., a stainless steel SS316 mesh, which is a high-grade corrosion resistant material; and an electrical vertical drain using a conductive polymer as the conductor. The results of the study show that the electrokinetic dewatering would be very effective on the tailings using SS316 mesh electrodes, indicated by the magnitude of the coefficient of electroosmotic permeability, quantity of water transported through the tailings specimen, duration of water flow, effective current density and applied voltage gradient. The stainless steel 316 mesh electrodes performed well over a period of 800 hours under an applied voltage gradient of 55 V/m and current density of 5 to 8 A/m². The corrosion rate of SS316 mesh anode was measured as 0.2 g/A-hour in this study. On the other hand, the electrical vertical drains performed satisfactorily in the first 100 hours then completely lost conductance. It is

also found that the tailings pore water pH is crucial in maintaining the water flow induced by electrokinetics.

INTRODUCTION

Mine tailings are the end product of mining and mineral processing after the mineral has been extracted. The extraction process often involves crushing and grinding, leaching, and separation. The final steps are thickening and subsequent dewatering of tailings before discharge to the tailings management facility (Figure 1). It is desirable that the tailings have a higher solid content for water conservation and reuse, whereas they can still be pumped through pipe lines for discharge. Chemical flocculants, such as polymers and inorganic salts, are used to assist tailings thickening and dewatering. However, in cases those tailings contain fine solids (in the micron-meter range) and significant fraction of clay minerals, the thickening and dewatering processes become increasingly difficult and time consuming.

Electrokinetic dewatering of mine tailings has been studied since 1960s. Applications included dewatering of coal and sand washeries and tailings from mineral recovery (Lockhart 1986). The treatments were implemented in tailings disposal ponds, and underground mines (Kelsh and Sprute 1976, 1981). The response of tailings to the electrokinetic treatment depends on the properties of the tailings, which vary in a broad range. Therefore, material characterization is always the first step in a feasibility study for developing an electrokinetic dewatering application. A major challenge in the engineering applications of electrokinetics is anode corrosion due to electrochemical reactions. Relatively inexpensive anode materials, such as steel, copper, aluminum, etc., deteriorate rapidly, leading to the loss of conductance and release of harmful metals to the

environment. Stainless steel and silicon steel have much lower corrosion rate and can be considered in applications. More recently conductive polymers such as electrokinetic geosynthetics (EKG) (Fourie et al. 2007) and electrical vertical drains (EVD) (Chew et al. 2004, Rittirong et al. 2008) have been used as electrodes. However, the performance of these products remains to be evaluated, especially over longer terms and under higher electrical current. Another notable anode material is coated titanium, which is virtually corrosion free. However, the issues such as the cost, ability to handle polarity reversal (serving as the anode and cathode alternatively) and durability of coating need to be addressed for large-scale geotechnical applications.

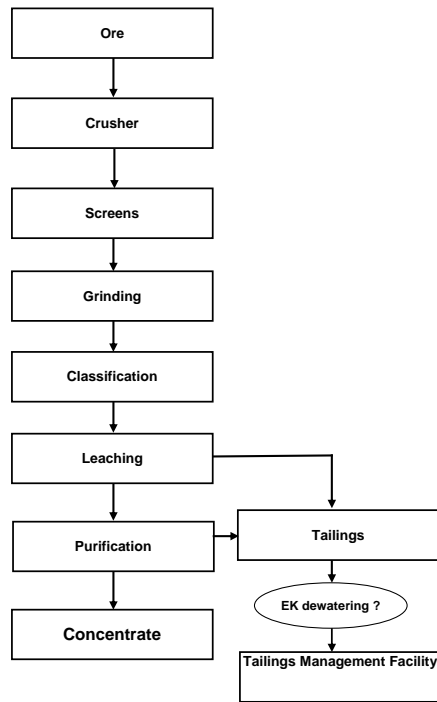


Figure 1. Flow chart of mineral processing

In this study, the effects of electrokinetics on tailings from a mine site in Saskatchewan, Canada, are investigated. The tailings contain mainly gypsum, quartz and clay minerals. At first the tailings are characterized in terms of geotechnical, physical, chemical and mineralogical properties. Electrokinetic cell tests are carried out to measure the coefficient of electroosmotic permeability, a key parameter on the response of the tailings to electrokinetic dewatering. The other factors, such as the voltage loss at the electrode-tailings interface, electrode corrosion, duration and rate of water flow, polarity reversal, and water chemistry, are also studied.

BACKGROUND

Electrokinetics is the general term for the response of fine solids suspended in water when a direct current (dc) is applied, which includes three dominant effects, i.e., electrophoresis, electroosmosis and electrochemical reactions. Electrophoresis generates the movement of tailings solids suspended in water, which is predominant in dilute suspensions such as tailings slurry before thickening. Electroosmosis generates water flow in tailings aggregates, which is representative of underflow from a thickener. Electrochemical reactions generate oxygen and hydrogen gases, pH changes at electrodes and reduction-oxidation of electrodes and tailings solids.

For thickened tailings, the coefficient of electroosmotic permeability relates the velocity of the water flow and applied voltage gradient;

$$q_{eo} = k_e E \quad (1)$$

where q_{eo} (m/s) is the flow velocity by electroosmosis, k_e (m^2/sV) is the coefficient of electroosmotic permeability, and E is the voltage gradient. k_e represents the water flow velocity induced by a unit voltage gradient (1 V/m). The values of k_e have been reported in the ranges from $1.5 \times 10^{-9} m^2/sV$ for clayey silt to $1.2 \times 10^{-8} m^2/sV$ for Na-Bentonite slurry (Mitchell 1993). Because mine tailings are highly variable in mineralogy, particle size and water chemistry, the coefficient of electroosmotic permeability of tailings must be measured and assessed in the feasibility study of electrokinetic dewatering.

In addition to the electroosmotic permeability, the feasibility of electrokinetic dewatering also depends on the hydraulic conductivity of tailings. It has been reported electroosmosis is effective when the hydraulic conductivity of soil is in the range of 10^{-10} to $10^{-8} m/s$ (Mitchell 1993, Rittirong and Shang 2005).

The water flow generated by electroosmosis is directly related to the zeta potential of solids. When in contact with water, almost all fine solids carry electric charges on their surfaces, which attract dissolved ions of opposite sign and form an electrical double layer. The response of tailings to an applied dc current depends on the magnitude and polarity of the surface charge on the solids, which can be estimated in terms of the zeta potential, ζ , defined as the electrical potential at

the boundary between the absorbed ions on the solid surfaces and mobile ions in water. Theoretically the velocity of water flow induced by electroosmosis is proportional to the zeta potential of solids (Helmholtz 1879). Therefore, the measurement of zeta potential provides an indication of both the direction and magnitude of water flow induced by electroosmosis. The zeta potential of tailings solids is a function of water pH and can be measured through pH adjustment using an acid or base.

Electrochemical reactions associated with the application of a direct current in tailings are complex, including electrolysis of water (generation of oxygen and hydrogen gases), reduction at the cathode and oxidation at the anode. As a result, the pore water pH of tailings decreases at the anode and increases at the cathode; the anode corrodes and/or deteriorates quickly if it is made of a consumable material. The impact of the electrochemical reactions to electrokinetic dewatering of tailings must be considered in the design and implementation.

CHARACTERIZATION

The tailings used in the electrokinetic tests were recovered from a tailings management facility in Northern Saskatchewan, Canada. The tailings and original supernatant were sent to the laboratory in sealed plastic containers and used in all tests.

The geotechnical, elemental, mineralogical and physical-chemical properties of the tailings are summarized in Table 1.

Table 1 Summary of tailings properties

Geotechnical		Mineralogical	
Specific Gravity	2.62	Quartz	
Liquid limit %	32.5	Gypsum	
Plastic limit %	25.9	Muscovite	
Elemental, %		Clinocllore (chlorite)	
O	52.7		
Mg	2.8	pH	7.3
Al	7.7	zeta	-14.2
Si	19.7		
S	6		
K	4		
Ca	4.5		
Ti	0.2		
Fe	2.7		

The grain size distribution is shown in Figure 2. The tailings have approximately 58% solids finer than 100 μm and 10% finer than 2 μm , indicating that the tailings solids consist of mostly fines. The tailings have low plasticity with a plasticity index of

6.6. Quartz and two clay minerals are identified (muscovite and chlorite) in the tailings, whereas gypsum is the other constituent. The original supernatant of the tailings has pH 7.3. The zeta potential of the tailings solids was measured using Zeta Plus (Brookhaven Instruments Corporation). The measurement was carried out on a tailings suspension, which was prepared by mixing 20 mg wet tailings solids with 100 ml original supernatant. As shown in Table 1, the tailings possess a stable negative zeta potential of -14.2 mV.

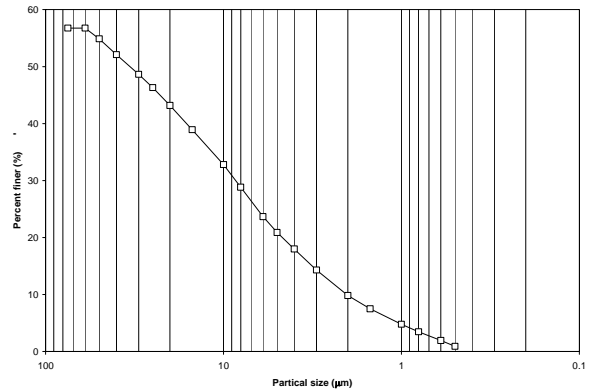


Figure 2. Particle size distribution of tailings for particles finer than 75 μm (passing #200 sieve)

The zeta potential of tailings solids as a function of water pH was measured by titration using 0.1 M NaOH and 0.1 M HNO_3 solutions. The results are presented in Figure 3, which shows that the zeta potentials of the tailings are stable in the range of -12 mV to -14 mV between pH 3 and pH 9. The point of zero charge (pzc) is located at $\text{pH} = 10.3$. The zeta potential becomes unstable at $\text{pH} > 9$ and turns positive at $\text{pH} > 10.3$.

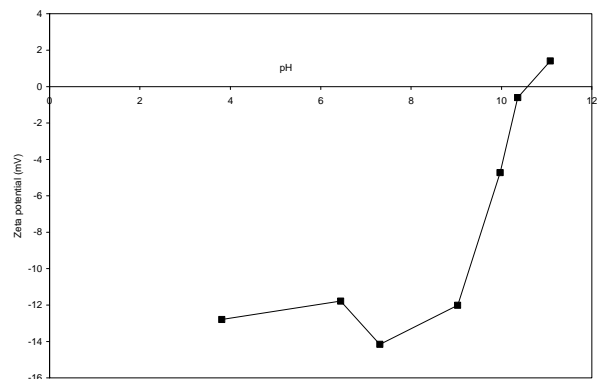


Figure 3. Zeta potential of tailings solids vs. water pH

EXPERIMENT

EK-cell

The Electrokinetic cell (EK-cell hereafter) shown in Figure 4 has been developed to measure the electroosmotic permeability in porous geomaterials under well-controlled boundary conditions (Mohamedelhassan and Shang 2002).

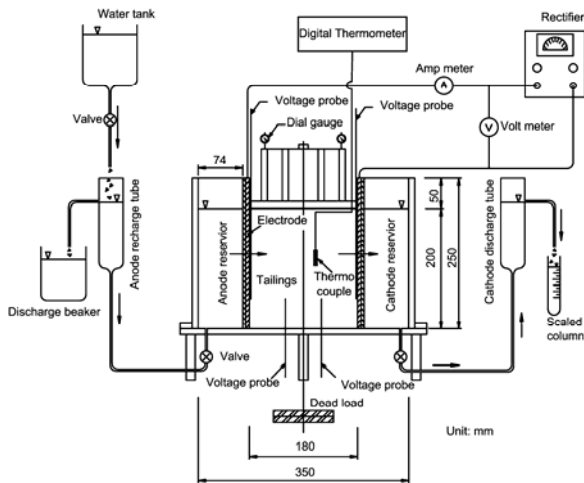


Figure 4. EK-cell

The EK-cell consists of an anode reservoir, a specimen compartment, and a cathode reservoir. The cell is made of 10-mm thick Plexiglas with the inside dimensions of $35 \times 10 \times 25$ cm (Length \times Width \times Height). The tailings are placed in the specimen compartment and a rubber sheet is placed on top of the tailings specimen so that the top and bottom of the EK-cell are impervious boundaries and the water flow through the tailings sample in the cell is one-dimensional (horizontal). The electrodes with the same width and height as the EK-cell (10 cm \times 35 cm) are placed at both ends of the specimen compartment, which are wrapped with a geo-textile for filtering and drainage. A dead load of 15 kg is applied via a loading plate (13.6 cm long \times 10 cm wide \times 2 cm thick) on the top of the specimen compartment, generating a surcharge pressure of 11 kPa. The purpose of applying the surcharge pressure is to obtain a specific density for the tailings specimen and to ensure full saturation. All EK-cell tests are carried out after the consolidation settlement of the tailings sample has virtually completed under the surcharge pressure of 11 kPa. The water in both reservoirs on the EK-cell is controlled at the same level via recharge and discharge tubes to ensure the hydraulic gradient across the tailings specimen is zero. Therefore, any water flow (discharge)

measured during an EK-cell test is solely attributed to the applied dc current. The electrodes are connected to a dc power supply (B&K Precision 1671A 0-30V, 0-5 A) and the dc current and voltage are measured using a high precision multi-meter.

It should be noted that the main objective of an EK-cell test is to measure the electroosmotic permeability defined in Eq. (1). In this case, the tailings specimen in the EK-cell can be modeled as a rigid porous plug with minimum deformation (settlement). The EK-cell tests provide information on the electroosmotic permeability as a function of tailings density (porosity), applied dc current (current density), voltage (voltage gradient), time and water chemistry. In addition, the EK-cell tests provide information on voltage losses at interfaces of electrodes and tailings.

In this study, two types of electrodes were used in the EK-cell tests, i.e., the Electrical Vertical Drain (EVD) and stainless steel 316 mesh (SS316). The EVD, as shown in Figure 5, was originally developed for soil improvement applications. The conductive core of the EVD is made of a copper foil encapsulated in conductive polymer, 6 mm thick and 95 mm wide, which is wrapped with a textile filter. SS316 is the highest grade of corrosion-resistant stainless steel commercially available. The mesh used in the tests has a thickness of 0.7 mm, nominal opening 0.7 mm, and specific opening area 29.2 %. In the EK-cell test, the SS316 mesh is wrapped with the same textile filter as used in the EVD for filtration and drainage.

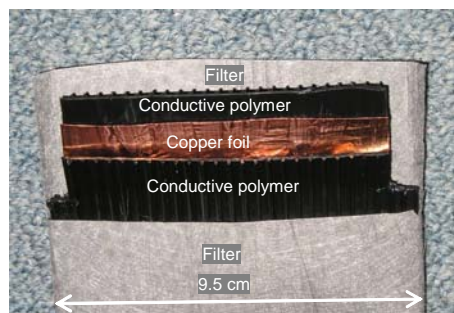


Figure 5. Electrical Vertical Drain (EVD)

Polarity Reversal

Polarity reversal has been applied in applications of electroosmosis in soil improvement applications, mainly to reverse differential settlements (Gray and Somogyi 1977). It is also recognized that polarity reversal may serve an important role in controlling

the pore water pH at the anode to prolong the water flow. For the tailings tested, since the zeta potential remains stable and negative in the pH range of 3 to 9, as shown in Figure 3, it is desirable to sustain the pH of tailings pore water in this range. One way of achieving this goal is polarity reversal, i.e. to reverse the anode and cathode periodically. The schematic of polarity reversal is illustrated in Figure 6. Under the normal polarity (NP) mode, the left electrode of the EK-cell is the anode and right electrode is the cathode. Under the reversed polarity (RP) mode, the applied dc voltage is reversed, i.e., the left electrode is the cathode and the right electrode the anode, whereas all other conditions remain the same. The water flow in the tailings reverses direction after the polarity reversal. The quantity of water discharge is measured at either right or left side of the EK-cell, depending on whether the EK-cell is under NP or RP mode.

Experiments and Results

Three EK-cell tests were carried out on the tailings, as shown in Table 2, i.e., EK-EVD, EK-SS316, and Control. The tests were set up in three identical EK-cells and carried out simultaneously. The hydraulic conductivity of the tailings was estimated in the Control cell by seepage under a constant hydraulic gradient, i.e., maintaining a constant total head difference (20 cm) between the left and right reservoirs. It was found that the hydraulic conductivity of the untreated tailings reduced approximately one order of magnitude over a period of 350 hours, Table 2.

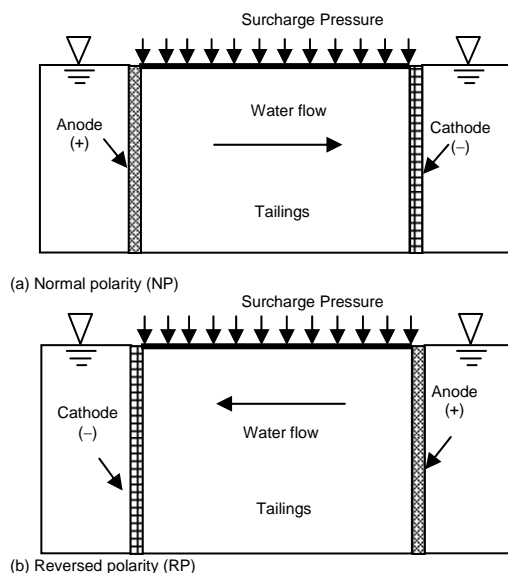


Figure 6. Polarity reversal during EK-cell test

Table 2. Summary of testing conditions

Surcharge pressure, kPa	11
Drainage path	Left and right reservoirs (2-way)
Tailings sample size, cm x cm x cm (height x length x width)	20 x 18 x 10
Applied voltage, V	10
Applied voltage gradient, V/m	55
Hydraulic gradient	0

Properties of Tailings Specimens (Average of three tailings specimens)

Dry density (g/cm ³)	Water content (%)	Degree of saturation (%)	Void ratio	Hydraulic conductivity* (m/s)	
				Before EK-cell test	After EK-cell test
0.95	66.9	99	1.8	1.3x10 ⁻⁶	2.2x10 ⁻⁷

* Estimated by seepage test in the Control test
 Test EK-EVD – EVD electrodes
 Test EK-SS316 – SS316 mesh electrodes
 Test Control – no voltage application

In both EK-cell tests, a constant dc voltage of 10 V was applied across the electrodes, generating constant electric field intensity (voltage gradient) of 55 V/m (with an electrode spacing of 18 cm). The corresponding dc current across the sectional area of tailings specimen (10 cm x 20 cm) was monitored and presented as the current density versus time, as shown in Figure 7, showing the range of current density in the tests was between 5 to 8 A/m², with exceptions on the EK-EVD test, which will be explained later. Figure 8 shows the accumulated water flow induced by the dc current. Both EK tests started with the normal polarity (NP) (the left and right electrodes served as the anode and cathode, respectively, see Figure 6). The water flow was triggered immediately towards the cathode, collected at the right side of the cell) and measured in real time by a graduated cylinder. The dc current passing through the tailing specimens in both EK-cells increased with time at first, reached a peak after about 100 hours, and then leveled off (see Figure 7). The water flow stopped in both cells after about 100 hours, as shown in Figure 8. In an attempt to re-activate the water flow, the reversed polarity (RP) mode was applied at hour-191 with the same applied voltage of 10V in both cells.

In Test EK-SS316 using stainless steel electrodes, the water flow resumed immediately (see Figure 8) towards the left side of the cell (cathode) and continued until hour-700 before it stopped again. At this time the electrode polarity was switched back to NP mode for another 100 hours but it did

not trigger further flow. The test was then terminated at hour-800. The total water discharge in Test EK-SS316 was 900 ml, or about 25% of the volume of the tailings specimen, and 40% of the tailings pore volume. In other words, 40% of water filled in the pore space of tailings has been replaced by the water driven into the tailings specimen by the dc current.

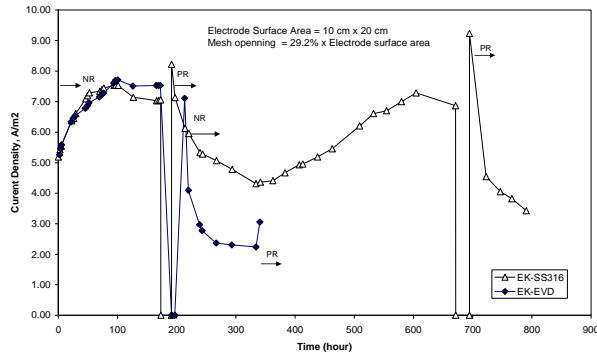


Figure 7. Electrical current density in EK-cell tests, applied voltage = 10 V, voltage gradient = 55 V/m.

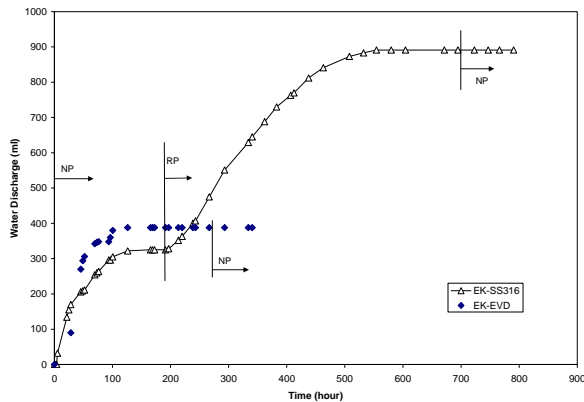
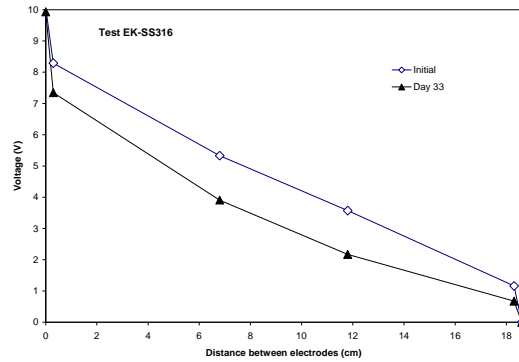


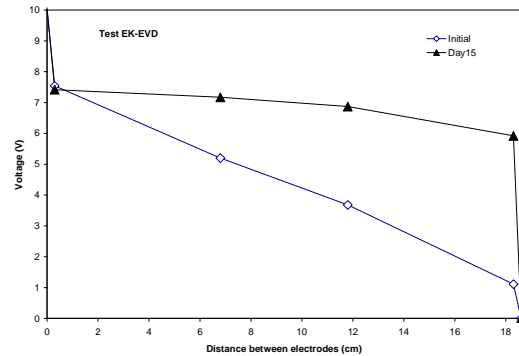
Figure 8. Electroosmotic induced water discharge, NP = normal polarity, RP = reversed polarity (refer to Figure 6)

In Test EK-EVD the current density drastically reduced to 2 A/m² after the polarity reversal, and no further water flow was registered. It is quite obvious that the EVD electrodes have lost the capacity to conduct current. Two more polarity reversals were made at hour-191 and hour-269 without inducing any water flow. Therefore Test EK-EVD was terminated at hour-340. The total water discharge was 388 ml in Test EK-EVD, which was approximately 10% of the volume of the tailings specimen.

The voltage profiles across the two EK-cells were monitored by voltage probes and are shown in Figure 9. The total voltage loss at the anode and cathode during the normal polarity mode were about 2 V in Test EK-SS316 and 4 V in Test EK-EVD, respectively. The total voltage loss at the SS316 electrodes and tailings interface was about 35% of the applied voltage, which is consistent with previous studies using steel electrodes (Casagrande 1983). The noticeable increase in the voltage loss at the anode (from 2.8 V to 3.8 V) is attributed mainly to the increase in tailings electrical resistivity at the vicinity of the anode. On the other hand, the EVD on the right-hand-side of the EK-cell has lost its capacity of conducting current, as indicated by the sharp voltage drop evident at the tailings electrode interface after 15 days, Figure 9 (b).



a)



b)

Figure 9. Voltage losses at electrodes-tailings interface and voltage distributions in the tailings specimens: (a) Test EK-SS316; (b) Test EK-EVD

The settlement of the tailings specimens during the EK-cell tests is shown in Figure 10. In all three tests, the settlements of the tailings specimens were measured by two dial gauges mounted on the top of the loading plate, 3 cm from the left and right electrodes, respectively. Tests EK-EVD and

EK-SS316 electrodes showed similar patterns of settlement, i.e., nearly negligible settlement at the right-side of the specimen and about 1.7 ~ 1.8 % at the left side of the specimen. The settlement registered from the Control test during the same testing period was negligible. The higher settlement at the left side of the specimen was obviously induced by the negative pore pressure at the anode due to electro-osmosis. It is of interest to note that in Test EK-SS316, the settlement on the left side of the specimen reached a limit after 150 hours and was not affected by polarity reversal. This indicates that the tailings specimen behaved as a rigid (to some extent, cemented) porous plug for water transport, which may be attributed to cementation generated by electrokinetics (Mohamedelhassan et al. 2005).

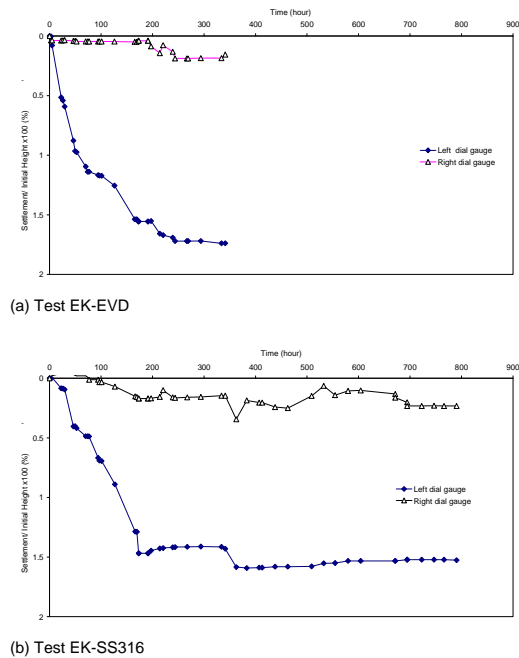


Figure 10. Settlement of tailings specimens during EK-cell tests

The coefficients of electro-osmotic permeability of two tailings specimens are calculated from Eq. (1) and presented in Figure 11. The initial k_e values measured from tests EK-EVD and EK-SS316 are $6 \times 10^{-9} \text{ m}^2/\text{Vs}$ and $4 \times 10^{-9} \text{ m}^2/\text{Vs}$, respectively, which quickly decreased with time and approaches zero after 113 hours of voltage application. The polarity reversal resulted in further flow in Test EK-SS316, and the k_e values sustained in the magnitude between 10^{-10} and $10^{-9} \text{ m}^2/\text{Vs}$ over 300 hours, then it gradually decreased to zero. These results show that k_e is highly dependent of time.

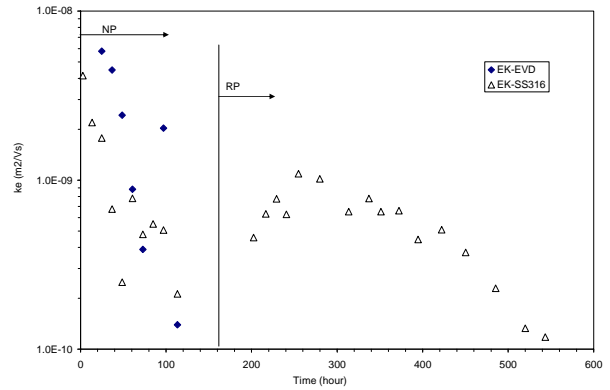


Figure 11. Coefficient of electroosmosis, k_e , versus testing time

The hydraulic conductivity of Test EK-SS316, as estimated by the seepage test on the tailings specimen after the test, was $5 \times 10^{-8} \text{ m/s}$, compared to $2.2 \times 10^{-7} \text{ m/s}$ on the Control specimen. Again, this maybe attributed to cementation and blockage of pores in the tailings associated with electrokinetics.

The temperature of tailings specimens were monitored during the EK-cell tests and the results showed that under the applied voltage gradient (55 V/m), there was no significant heating effects and the temperature of tailings samples was consistent with the room temperature.

The tailings were removed from the EK-cell after test EK-SS316 to measure the tailings pore water pH near the left and right sides of the cell. The tailing pore water pH is 11.5 on the left side and 5.5 on the right side of the tailings specimen, compared to the original water pH 7.3. The changes in the tailings pore water pH provide insight to the stop of water flow during the EK test. As shown in Figure 8, the water flow was from the left side to the right side of the EK-cell under the NP mode; and from the right side to the left side of the EK-cell under the RP mode. The tailings pore water pH increases at the cathode and decreases at the anode. Based on the results of zeta potential measurement shown in Figure 3, the surface charge of tailings solids approaches zero at $\text{pH} = 10.3$ and becomes positive with further increase in the water pH. Therefore it is inferred that the stop of water flow in both EK-cell tests after about 100 hours was caused by the increases in tailings pore water pH at the cathode. The resume of water flow in test EK-SS316 after the polarity reversal is attributed to the decrease in the tailings pore water pH at the right side electrode,

which served as the anode under the RP mode. Finally, the water flow stopped again in test EK-SS316 when the tailing pore water pH increases to 11.5 (above pH = 10.3) at the cathode (left side electrode). The results demonstrate the importance of pore water pH control in the EK dewatering applications. To maintain dewatering effects, the tailings pore water pH must be controlled such that the zeta potential of tailings solids remains negative. This can be achieved by polarity reversal, as shown in this study, as well as other means such as pH adjustment by chemicals (Mohamedelhassan and Shang 2003) and agitating tailings during the dewatering process (Kelsh and Sprute 1975).

The tailings water content after Test EK-SS316 is 55% to 60% throughout the tailings specimen, decreased from the original 67% (Table 2). The decrease in the tailings water content was primarily attributed to settlement during the EK-cell tests (Figure 10). Note this is not representative of EK dewatering effect because the EK-cell is configured to measure k_e , which serves mainly as a porous plug with open drainage at both anode and cathode.

Table 3. Mass loss of SS316 electrodes and corrosion rate

Mass of Electrode				Operation Time as Anode		Ave current*	Corrosion rate		
Original		After EK test		Loss		h	mA	g/A-hr	
g	g	g	g	g	g			Left	Right
Left	Right	Left	Right	Left	Right	Left	Right	Left	Right
101.7	104.4	77.6	64.1	24.1	40.3	273	509	0.21	0.19

* Normalized against mesh opening area 29.2 %

The mass loss of SS316 mesh electrodes were measured after test EK-SS316 and the corrosion rate was calculated, as shown in Table 3. The results show that for the tailings tested the corrosion rate of the SS316 mesh is 0.19 to 0.21 g/A-hour, compared to the corrosion rate of 0.7 ~ 1.04 g/A-hour of mild steel as reported in the literature (Lockhart 1986). In dewatering applications, the electrode material should be selected based on factors such as duration of treatment, cost, environmental considerations, etc.

CONCLUSIONS

A dc current delivered by stainless steel 316 electrodes generated significant water flow in gypsum containing tailings originated from a mine site in Northern Saskatchewan. The water flow across the tailings specimen sustained for more than 400 hours under an applied voltage gradient of 55 V/m. The corresponding dc current density

was in the range of 6 to 8 A/m². The total volume of water discharged by the dc current was equivalent to about 40% of the tailings pore volume. The coefficient of electro-osmotic permeability (k_e) of the tailings was measured in the order of 10⁻¹⁰ to 10⁻⁹ m²/Vs. Combined with the low hydraulic conductivity of the tailings (~10⁻⁸ m/s), the results indicate the tailings responds favorably to electrokinetic dewatering. The selection of electrode material is crucial in an EK dewatering application. The electrical vertical drain electrodes made of conductive polymer failed to sustain water flow under a voltage gradient of 55 V/m. On the other hand, SS316 mesh electrodes performed reasonably well for 800 hours under the applied voltage and current in the EK test. The corresponding corrosion rate of the SS316 mesh has been established as 0.2 g/A-hour, which was about one order of magnitude lower than mild steel. The pH control for tailings pore water is required to sustain water flow under a dc current. Polarity reversal has proven to be an effective measure to balance tailings pore water pH during EK treatment.

ACKNOWLEDGEMENT

The research is funded by Cameco Corporation and Natural Science and Engineering Research Council of Canada. The contribution of Dr. Amnart Rittirong, Dr. Yanqing (Bruce) Xu, Dr. Patrick Landine and Ms. Anooradha Nursimulu to the research is greatly appreciated.

REFERENCES

- Casagrande, L. (1983). Stabilization of Soils by Means of Electro osmosis - State of the Art. *Journal of Boston Society of Civil Engineers, ASCE* 69(2), 255-302.
- Chew, S.H., Karunaratne, G.P., Kuma, V.M., Lim, L.H., Toh, M.L. and Hee A.M. (2004). A Field Trial for Soft Clay Consolidation Using Electrical Vertical Drains. *Geotextiles and Geomembranes*, 22, 17-5.
- Mohamedelhassan E, Shang J. Q, Ismail M.A. and Randolph M.F. (2005). Electrochemical Cementation of Calcareous Sand for Offshore Foundations. *International Journal of Offshore and Polar Engineering (IJOPE)*. Vol.15, No.1, 71-79.
- Fourie, A. B., Johns, D. G. and Jones, C. J. F. P. (2007) Dewatering of Mine Tailings Using

Electrokinetic Geosynthetics. *Canadian Geotechnical Journal*, 44(2), 160–172.

Gray, D. H. and Somogyi, E. (1977) "Electroosmotic Dewatering with Polarity Reversals" *J. Geotech. Eng. Div. ASCE* 103 (GTI) 51-54.

Helmholtz, H.L.F. (1879). Studies of Electric Boundary Layers. *Wied. Ann.*, Vol. 7, pp. 337-382. In Abramson, H.A., Moyer, L.S. and Gorin, M.H. (1942). *Electrophoresis of Proteins*, Reinhold Publishing Corporation.

Kelsh, D.I. and Sprute, R. H. (1975). Limited Field Tests in Electrokinetic Densification of Mill Tailings. U.S. Bureau of Mines RI 8034.

Kelsh, D.I. and Sprute, R.H. (1976). Electrokinetic Consolidation of Slimes in an Underground Mine. U.S. Bureau of Mines RI 8190.

Kelsh, D. I. and Sprute, R.H. (1981). Dewatering Fine Particle Suspensions with Direct Current -

Field Applications" 2nd World Congress Chem. Eng. 4, 142-145.

Lockhart, N.C. (1986). Electro-dewatering of Fine Suspensions. *Advances in Solid-Liquid Separation*. 241-274.

Mitchell, J.K. (1993). *Fundamentals of Soil Behavior*. 2nd Ed., John Wiley & Sons, New York.

Mohamedelhassan, E. and Shang, J.Q. (2002). Feasibility Assessment of Electroosmotic Consolidation of Marine Sediment. *Ground Improvement*. Vol. 5, No.2, 1-8.

Mohamedelhassan, E. and Shang, J.Q. (2003) Electrokinetics Generated Pore Fluid and Ionic Transport in an Offshore Calcareous Soil". *Canadian Geotechnical Journal*, Vol.40, 1185-1199.

Rittirong, A. and Shang, J.Q. (2005). *Ground Improvement – Case Histories*, Edited by B. Indraratna and J. Chu, Chapter 34 (Theme 5), pp. 1127-1162, Elsevier Publishers.