

THESIS

PROPOSED LABORATORY INVESTIGATION INTO ELECTROOSMOTIC
DEWATERING OF MINE TAILINGS

Submitted by

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ABSTRACT

PROPOSED LABORATORY INVESTIGATION INTO ELECTROOSMOTIC DEWATERING OF MINE TAILINGS

Geotechnical concerns of tailings storage facilities (TSFs) often depend on the water content of the tailings. Tailings with low hydraulic conductivity often have high-water contents with low undrained shear strength at the time of mine closure, which limits the ability to close the TSF. The purpose of this study is to explore undrained shear strength gain in surficial mine tailings using electroosmotic dewatering (EOD) to help promote closure and reclamation of TSFs. Electroosmotic dewatering uses electrodes to apply an electrical direct current to induce flow through a porous medium. An experiment was developed to assess the effectiveness of dewatering methods at bench-scale to increase undrained shear strength of tailings via three different methods: EOD, surcharge consolidation, and evaporation only. The proposed research will evaluate if EOD (1) increases undrained shear strength of saturated surficial mine tailings more rapidly and (2) increases undrained shear strength as a function of depth more effectively, compared to the other techniques. Factors that influence EOD were preliminarily evaluated and include electrodes used, pore fluid chemistry, degree of saturation, voltage gradient and electrode configuration. Additionally, electroosmotic dewatering of mine tailings has not been implemented on a large-scale possibly due to lack of developed procedure, difficult water removal, and lack of a commercially available EOD unit. A goal of the proposed research plan is to develop field-scale implementation methods and water removal techniques via a moisture wicking synthetic capillary

drain unit to be coupled with electroosmotic dewatering (i.e., *EO-Plant*) for field-scale applications.

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TABLE OF CONTENTS

ABSTRACT.....	ii
ACKNOWLEDGEMENTS.....	iv
LIST OF TABLES.....	vii
LIST OF FIGURES	viii
1 Introduction	1
1.1 Background & Motivation	1
1.2 Research Objectives & Hypothesis.....	3
1.3 Research Plan & Preliminary Trials.....	3
1.4 Summary of Future Research.....	4
2 Chapter 2: Background.....	5
2.1 Mining, Mine Waste, & Covers	5
2.2 Electroosmotic Dewatering.....	8
2.2.1 Electrokinetics.....	9
2.2.2 Electroosmosis	10
2.2.3 Electrochemical Reactions.....	13
2.3 Factors Affecting EO	15
2.3.1 Influence of Pore Fluid (Water) Chemistry	15
2.3.2 Influence of Saturation.....	16
2.3.3 Influence of Voltage Gradient	17
2.3.4 Influence of Electrode Configuration	18
2.4 Consolidation & Undrained Shear Behavior of Low Plasticity Soils.....	19
2.4.1 Consolidation.....	19
2.4.2 Shear Strength & Undrained Shear Strength Behaviors.....	21
2.5 Other Applications of EOD.....	22
3 Chapter 3: Methods	29
3.1 Material Characterization.....	29
3.2 EOD Procedure	30
3.2.1 Introduction.....	30
3.2.2 Experimental Procedure.....	31

4	Future Work.....	41
4.1	Why develop EOD?	42
4.2	Why EOD is not currently in use	42
4.3	Phase 1: Anticipated Results from Laboratory Experiments	44
4.4	Phase 2: Field-Scale Experiments	48
4.4.1	Grid Configuration.....	49
4.4.2	Voltage & Voltage Gradient	49
4.5	Phase 3: EO Plant.....	50
4.5.1	Current Challenges for Full-Scale Implementation	50
4.5.2	EO Plant	52
4.6	Potential Future Applications of EOD	54
4.6.1	Applications in Mine Tailings Management.....	54
5	Summary and Conclusions	64
	References.....	66
	Appendix A.....	73

LIST OF TABLES

Table 3-1. Summary of physical characteristics and classification of the mine tailings and fine synthetic tailings.	36
Table A-1 Trial Summary	90
Table A-2 Key Observations	92

LIST OF FIGURES

Figure 2-1.	Schematics depicting a tailings storage facility (TSF) in three states: (a) active filling via hydraulic discharge of tailings slurry; (b) cover placement during closure; and (c) closed facility for site reclamation.....	24
Figure 2-2.	Schematics of the electrokinetic concept in soils with details for the processes of electrophoresis, electroosmosis, and pore-scale plug flow.	25
Figure 2-3.	Electric field generated within a porous medium.	26
Figure 2-4.	Schematics illustrating the diffuse double layer of a net-negatively charged particle: the zeta potential is shown as the relationship between surface potential charge versus distance from the charged particle surface.....	27
Figure 2-5.	Electrode orientation for electroosmotic induced flow: (a) vertical electrodes with horizontal water flow; and (b) horizontal electrodes with vertical water flow.	28
Figure 3-1.	Particle size distribution (PSD) curves for mine tailings samples.	37
Figure 3-2.	Overview of proposed experiment cells to evaluate electroosmotic dewatering (EOD) relative to dewatering via evaporation or under a surcharge.....	38
Figure 3-3.	Schematic of the electroosmotic dewatering (EOD) experimental approach.....	39
Figure 3-4.	Schematics of the vane shear test approach.	40
Figure 4-1.	Anticipated temporal trends of average surficial (a) water content and (b) settlement within mine tailings for dewatering experiments that include electroosmotic dewatering (EOD), surface surcharge application, and evaporation.....	57
Figure 4-2.	Anticipated temporal trends in current (I) and resistivity (R) within the mine tailings during operation of the electroosmotic dewatering experiment.	58
Figure 4-3.	Anticipated trends of (a) average undrained shear strength as a function of time and water content and (b) shear strength as a function of depth in mine tailings for dewatering experiments that include electroosmotic dewatering (EOD), surface surcharge application, and evaporation.	59
Figure 4-4.	Ideal grid spacing for anodes (-) and cathodes (+) of an electroosmotic dewatering system in a tailings storage facility.	60
Figure 4-5.	Schematics of the EO-Plant: an artificial electroosmotic dewatering unit that couples	61
Figure 4-6.	Concept 1 schematic: electroosmotic dewatering system incorporated into a centerline tailings dam to promote dewatering and lowering of the phreatic surface.....	62

Figure 4-7. Concept 2 schematic: electroosmotic dewatering systems installed in a tailings impoundment during slurry placement that uses electrokinetic geocomposites installed between layers of deposited slurry tailings.....	63
Figure A-1. Photograph of Trial 0.	73
Figure A-2. Photograph of Trial 1.	74
Figure A-3. Photographs of Trial 2.....	75
Figure A-4. Photographs from Trial 3.	77
Figure A-5. Photograph of Trial 4.	78
Figure A-6. Photographs of Trial 5.....	79
Figure A-7. Photographs of Trial 6.....	81
Figure A-8. Photographs of Trial 7.....	82
Figure A-9. Photographs from EOD cells of Trial 8.....	84
Figure A-10. Photographs of evaporation cells of Trial 8.	84
Figure A-11. Temporal trend of water contents in the electroosmotic (EO) test cell and evaporation test cell based on mass loss. Final water content measurements conducted on exhumed samples from the EO test cell also are shown.	85
Figure A-12. Photographs of Trial 9 electroosmotic test cell.	86
Figure A-13. Photographs of Trial 9 evaporation test cell.....	87
Figure A-14 Temporal trend of water contents in the electroosmotic (EO) test cell and evaporation test cell based on mass loss. Final water content measurements conducted on exhumed samples from the EO test cell also are shown.	87
Figure A-15. Photographs of the FST Trial.	88
Figure A-16. Temporal trend of water contents in the electroosmotic (EO) test cell and evaporation test cell based on mass loss.	89

1 INTRODUCTION

The focus of this thesis is electroosmotic dewatering. The contents of the thesis are a description of electroosmotic dewatering of mine tailings, summary of relevant information from literature, compilation of preliminary experiments, and development of hypotheses and future research plan.

1.1 Background & Motivation

Tailings are a by-product of mining that are deposited and stored in tailing storage facilities (TSF) in perpetuity. There are approximately 15,000 TSFs worldwide (Hatton, 2019), of which the number of active TSFs is uncertain. An increased demand for raw materials combined with the depletion of high-grade ore has resulted in a trend towards mining larger, lower-grade ore bodies, which further increases the generation of tailings to be stored (Bussière, 2007; Valero et al., 2018).

Mine wastes are generated during ore processing, which includes milling and metallurgical processes to liberate the target product (e.g., gold, copper, silver, etc.). The end waste products include tailings, which commonly are fine-grained and may contain clay minerals depending on the parent rock. After processing, tailings are often deposited in a TSF, where slurry deposition behind a tailings dam is the most common approach. The discharged tailings settle slowly under self-weight consolidation due to low hydraulic conductivity (Robertson & Wels, 1999), which results in high-water content tailings deposits that can have low undrained shear strength at the time of mine closure.

Closure of TSFs requires a cover be placed over the impoundment as a reclamation technique to return the TSF to a more natural landform. Issues arise when tailings have insufficient strength

to support construction operations and cover material (Williams, 2005b). Reclamation activities can be constrained to areas of the tailings impoundment that are accessible and trafficable, but this approach can considerably slow TSF closure and be uneconomical for mine owners. Common methods to accelerate tailings dewatering and promote strength gain are (i) incremental loading via an earthen surcharge (e.g., cover) to induce consolidation and (ii) surface scarification to enhance desiccation via evaporation. These methods can be time-consuming and expensive due to (i) slow dissipation of excess pore water pressure or (ii) need for specialized equipment and dedicated personnel.

Electroosmotic dewatering (EOD) of mine tailings is a technique to increase shear strength of surficial tailings. Electroosmosis is a type of electrokinetic phenomena, which couples hydraulic and electrical potential gradients to induce flow of water within a porous medium. The concept of EOD involves placing two electrodes, a positive anode and negative cathode, into a porous material and applying an electrical direct current. Water migrates towards the cathode, where the water can then be removed. Although the physics of EOD have been demonstrated at bench-scale (e.g., Casagrande, 1949; Fourie et al., 2007; Hamir et al., 2001; Martin et al., 2019), to the authors knowledge, the technique has not been implemented for full-scale dewatering of high-water content materials.

A possible application for EOD is to accelerate consolidation of weak, highly compressible mine tailings to promote closure and reclamation of tailings impoundments. Electroosmotic dewatering of mine tailings has been demonstrated to be effective in the laboratory (e.g., Casagrande, 1949; Fourie et al., 2007; Hamir et al., 2001; Martin et al., 2019). However, constraints to implementation at field-scale include scaling-up, energy requirements, and methods to remove water from the vicinity of the cathode. The need to reclaim TSFs that have been

operated via slurry tailings deposition support the continued evaluation and innovation of in situ dewatering techniques such as electroosmosis.

1.2 Research Objectives & Hypothesis

The objectives of the proposed study include the following: (1) assess the effectiveness of dewatering methods at bench-scale using three different methods of EOD, surcharge consolidation, and evaporation only, to increase undrained shear strength of tailings as a function of depth; and (2) create a moisture wicking synthetic capillary drain unit to be coupled with electroosmotic dewatering (i.e., *EO-Plant*) that can promote dewatering of tailings surfaces. These objectives will be achieved via the evaluation of two main hypotheses: Hypothesis 1 – electroosmotic dewatering increases undrained shear strength of saturated surficial mine tailings more rapidly compared to other techniques; and Hypothesis 2 – electroosmotic dewatering increases undrained shear strength as a function of depth more effectively compared to other techniques. In addition to EOD, two other methods of consolidation via surface surcharge and evaporation only will be included as dewatering techniques for comparison. Laboratory-scale dewatering experiments will be conducted on tailings from a gold mine in Central America that experienced closure challenges due to soft tailings and a kaolin-silica flour blend (i.e., fine-synthetic tailings, FST).

1.3 Research Plan & Preliminary Trials

Classification of mine tailings was performed using standard geotechnical characterization tests, including particle-size distribution, specific gravity, and Atterberg limits. A research procedure was developed based on a literature review and preliminary trials. The goal of the proposed research is to evaluate the effectiveness of dewatering methods to increase the undrained

shear strength of mine tailings. The proposed research plan includes three dewatering methods: EOD, surcharge consolidation, and evaporation. A summary of preliminary experiments is in Appendix A, which included experiments conducted to provide insight on specimen preparation, EOD test procedure, and experiment design.

1.4 Summary of Future Research

Geotechnical concerns of TSFs, such as the stability of slopes and settlement of waste surfaces, depends on the water content of the tailings. Generally, advances in understanding EOD with regards to tailings is advantageous since dewatering tailings increases stability and accelerates settlement. Electroosmotic dewatering has the potential to stabilize soft, saturated tailings impoundments at mine sites globally with further development of large-scale implementation methods and water removal techniques. Although research has been done on the feasibility of this technique, EOD has not been implemented in the mining industry to the extent possible, which may be attributed to lack of developed procedure, difficult water removal, and lack of a commercially available EOD unit. A few potential large-scale implementation concepts are discussed to develop questions that must be considered in future EOD research for effective tailings in situ dewatering.

2 CHAPTER 2: BACKGROUND

2.1 Mining, Mine Waste, & Covers

Mining is the extraction of valuable minerals from the earth that provides necessary materials for our global society. Unfortunately, mining produces large volumes of waste in the form of fine-grained tailings and waste rock. Mine tailings are the residual material remaining after ore crushing and processing to separate the valuable fraction from the ore (Bussière, 2007). Tailings commonly are disposed in surface impoundments called tailings storage facilities (TSF), where they will be stored in perpetuity. There are approximately 15,000 TSFs worldwide (Hatton, 2019), of which the number of active TSFs is uncertain.

Mineral extraction processes typically produce a slurry of fine-grained tailings that are transported from the mill to the TSF as a slurry via pipelines to be deposited hydraulically (Blight & Bentel, 1983) as shown in Figure 2-1. Discharge of tailings into an impoundment from spigots results in an immediate loss of energy, whereby particles settle out of suspension at rates depending on particle size. Coarse-grained particles tend to settle out of the slurry near the discharge point, whereas fine-grained particles are carried into the impoundment and settle out of suspension as the energy for transport diminishes.

Tailing impoundments pose environmental risks to surrounding areas because tailings can contain residual heavy metals, harmful chemicals, and high salt concentrations (Kossoff et al., 2014). These factors can result in tailings being unable to support growth of plants and potentially contaminate groundwater and surface water resources. In tailings that contain sulfide minerals, interactions between the sulfide minerals (e.g. pyrite), water, and oxygen can generate acid (Verburg et al., 2009). In addition to contamination concerns in groundwater and surface water,

tailings exposed at the surface can desiccate and erode, leading to dust and air quality issues. The resulting spread of contaminants can create negative environmental impacts on surrounding areas.

The surface of a TSF must be covered as part of mine closure to return the area to a more natural state and protect human health and the environment (Figure 2-1). Covers typically are earthen material and function to separate tailings from the natural environment, which aids in controlling moisture and air transfer into and out of impounded tailings. Covers reduce contaminant transport to surrounding environments and reduce the potential for acid rock drainage (Verburg et al., 2009). Covers also support vegetation to provide protection from erosion via wind and water, and provide a final reclamation land surface and drainage system (Langseth et al., 2015).

The most common closure technique is a monolithic earthen cover, whereby a layer of fill (e.g., soil or inert mine waste) is placed on top of the tailings surface. To place an earthen cover, the surface of the tailings must provide sufficient strength for mobilization of earth-moving equipment. Strength gain within the surface of the impounded tailings can be achieved through consolidation or the use of geosynthetics (BGC Engineering Inc., 2010; Langseth et al., 2015; Robertson & Wels, 1999; Sobkowicz, 2012). The most common approach is to allow surface desiccation of the tailings such that a “crust” forms, which will have increased shear strength relative to saturated tailings to support construction operations and cover placement.

Many TSFs have been designed, constructed, and/or managed without considering reclamation and rehabilitation of tailings (Jakubick et al., 2003). A common challenge in slurry deposited tailings impoundments is the prevalence of low shear strength tailings at or near the surface of the impoundment, which develop from high rise rate of the TSF and limited available pore water drainage from the tailings. Evaporation from the tailings surface can aid in removing

water from the TSF. However, high rise rates limit evaporation because slurry is continuously placed, which reduces the time available for desiccation of the surficial tailings. Additionally, desiccating tailings that have high salinity can produce salt crusts on the tailings surface that hinder subsequent evaporation (Fujiyasu & Fahey, 2000). Tailings often contain an abundance of clay-sized particles and clay minerals, which can lead to high affinity for water and low hydraulic conductivity. These characteristics, combined with any lack of drainage, can cause tailings to have slow pore water pressure dissipation and slow self-weight consolidation (Robertson & Wels, 1999).

Shear strength of fine-grained soils is a function of water content, whereby soils with higher water content generally have lower shear strength. High initial water contents of slurry-deposited tailings combined with the water retention of fine-grained materials, can result in low tailings shear strength at time of mine closure that present challenges with cover construction. Insufficient shear strength to support construction equipment may, in worst-case scenarios, result in bearing capacity failures that cause equipment to plunge into the tailings, or in other scenarios, prolong the duration of cover material placement. At the time of mine closure, field measurements have indicated that tailings with undrained shear strength less than 5 kPa were present at the surface of a tailings impoundment (Robertson & Wels, 1999). The minimum undrained shear strength needed to support personnel is approximately 15 kPa (Williams, 2005a) and shear strengths greater than 25 kPa are necessary for tailings to be considered trafficable (Jakubick et al., 2003).

Reclamation of tailings impoundments is constrained to areas that have enough shear strength to be accessible and trafficable. Transitioning from saturated tailings with low shear strength to unsaturated tailings with higher shear strengths enables reclamation (Strachan & Goodwin, 2015). Methods to accelerate dewatering to increase tailings shear strength often are

required because allowing tailings to gain strength naturally via consolidation and desiccation may take many years, which is not conducive for closure and reclamation of TSFs.

Dewatering techniques that have been implemented in tailings impoundments primarily focus on inducing a hydraulic gradient to force water to the surface to promote drainage and/or increase evaporation. Installing vertical drains increases available drainage pathways but can often be problematic because equipment must be mobilized on the tailings surface for installation. A common dewatering technique is to place reinforcing geotextiles at the edges of the soft tailings and use staged cover construction to load the underlying material and promote drainage. The cover material is then placed incrementally in layers to allow time for the consolidation and strength gain in the tailings between increments (Williams, 2005a), as shown in Figure 2-1. Although this staged construction approach is faster than unaided self-weight consolidation of soft tailings, the method is time-consuming, and therefore, expensive due to operator and equipment demands. An alternative method to induce hydraulic flow in tailings that has been evaluated on an experimental basis is electroosmotic dewatering of mine tailings.

2.2 Electroosmotic Dewatering

Electroosmotic dewatering (EOD) of mine tailings is a dewatering method that uses an electric field to induce hydraulic flow as shown in Figure 2-2. An electrical direct current (dc) is generated via two electrodes inserted within a tailings deposit: a positive anode and a negative cathode. Electrokinetics within the tailings deposit describe the interaction of the induced electrical field with charges of the soil particles and water molecules. Electrokinetics include three phenomena: electrophoresis, electroosmosis, and electrochemical reactions. Electroosmosis (EO) is the induced flow of water through the porous medium, causing water to migrate towards the

cathode, where the water can subsequently be removed. The EO process depends on properties of the soil (e.g., clay mineralogy), pore fluid, and capillary flow (Mitchell & Soga, 2005).

2.2.1 *Electrokinetics*

An electrical current passed through a porous media, such as tailings, generates Coulomb forces and a corresponding electric field that induces flow of mobile electric charges in suspension (Figure 2-3). The electric force generated between two charges is described by Coulomb (1785) as

$$F = k \frac{q_1 q_2}{r^2} \quad (1)$$

where F = electric force, k = Coulomb constant, q_1 and q_2 = magnitude of charges, and r = distance of separation between the charges. Equation 1 defines the magnitude of the electric force between two point charges as proportional to the magnitude of the charges, and inversely proportional to the distance between them. The force of the interaction between the charges is attractive if the charges have opposite signs and repulsive if the charges are like-signed. The presence of an electric charge produces an electric field that has varying electric potential between the charges. The electric potential at a specific point in space is typically measured in volts.

Electrokinetics is the response to an applied electric field across a porous medium, where the positive and negative electrodes are used to apply the electric field. As the voltage between two electrodes increases from zero, the resulting Coulomb force between the electrodes applies a force on the charges throughout the materials within the electric field. Electrophoresis is the movement of charged particles in suspension. In the case of a tailing impoundment, the solid soil particles are not in suspension and are not free to move due to the electric field. Electrochemical reactions include electrolysis of water, generation of oxygen and hydrogen gases, and changes in

the pore fluid pH. Electroosmosis is the movement of water molecules through a porous medium. Both electroosmosis and electrochemical reactions are important for using electroosmosis as an alternative dewatering method.

2.2.2 Electroosmosis

Electroosmosis is the transport of water through a porous medium due to the surface charge interaction within the diffuse double layer of clay particles (Mitchell & Soga, 2005). A clay particle carries a permanent net negative charge from isomorphous substitution, i.e. the replacement of higher valence cations within the crystal structure of the clay mineral by lower valence cations. Water molecules are dipoles whereby within the molecular structure there is a more positive charge near the hydrogen atoms and more negative charge near the oxygen atom. Water molecules can orient around ions in the pore space as hydrated cations. The negative charge of the clay particle is satisfied by the hydrated cations and further interacts with the positive charge of the water molecules to form a concentration of ions around the clay particle referred to as a diffuse double layer (DDL). A schematic of the DDL and dissipation of the electrical charge concentration from the clay particle is shown in Figure 2-4. The strength or size of the DDL can be estimated with the zeta potential, ζ , which is the electrical potential at the boundary between the adsorbed ions on the solid surfaces and mobile ions in water.

An electric current passed through soil medium will create an electrical potential. The net charge in the DDL is induced to move by the resulting Coulomb forces of the electrical field. The positive ends of the water molecules (hydrated cations) are attracted to the negative electrode (cathode), whereas and the negative soil particles (anions) are attracted to the positive electrode (anode). The solid soil structure is relatively rigid compared to the mobile diffused layer of

charged ions and water molecules within the DDL surrounding the clay particles. This mobile water within the DDL moves in response to the electrical potential. The movement of the DDL ions and water towards the cathode applies a drag force on the bulk region of fluid as shown in Figure 2-2.

There are several theories describing electroosmotic flow, including Helmholtz-Smoluchowski, Schmid, Spiegler friction model, and ion hydration (Mitchell & Soga, 2005). In general, these theories describe electroosmotic flow similar to Darcy plug flow through a capillary tube (Figure 2-2). The most commonly used electroosmotic flow equation in fine-grained soils was developed by Casagrande (1949):

$$q_e = k_e i_e A \quad (2)$$

where q_e = electroosmotic flow, k_e = electroosmotic conductivity, i_e = voltage gradient, and A = cross-sectional area perpendicular to flow. Equation 2 is similar to Darcy's law of flow through a porous medium due to a change in total pressure head. The fundamental difference is that electroosmotic conductivity depends on overall cross-sectional pore area (e.g. porosity or void space) and is independent of pore size, whereas hydraulic conductivity used in Darcy's law of flow is strongly dependent on pore size. Fine-grained soils have low hydraulic conductivities which hinder flow, and coarse-grained soils have high hydraulic conductivities, which allow flow. Most fine-grained soils have an electro-osmotic conductivity flow parameter, k_e , on the order of magnitude of 10^{-5} cm²/V·s (Casagrande, 1949; Mitchell & Soga, 2005), whereas the hydraulic conductivity of clay can be on the order of 10^{-7} cm/s to 10^{-9} cm/s, which implies that electroosmotic flow can be 1 to 4 orders of magnitude faster than hydraulic-induced flow at low gradients anticipated in a TSF (Glendinning et al., 2010). Hydraulic flow is more effective in coarse-grained soils due to high hydraulic conductivities, whereas electroosmotic flow can be more effective in

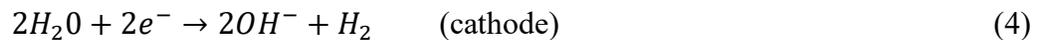
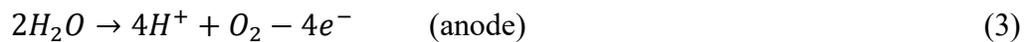
fine-grained soils (when an electric field is present) because the electroosmotic conductivity is greater than the hydraulic conductivity (Casagrande, 1949).

Casagrande (1949) performed the first geotechnical application of EOD of soils. Since then, EOD has been used in various geotechnical applications, including stabilization of slopes, excavations, and embankments (Chappell, Brian; Burton, 1979), stabilizing soils using prefabricated vertical drains (PVD) along with electrodes (Bergado et al., 2003), and increasing the stability of clays (Lo et al., 1991a, 1991b).

Electroosmotic dewatering has been investigated for use in mine tailings remediation. Chen et al. (1996) evaluated EOD of gold mine mill tailings using carbon graphite electrodes and reported that EOD was more effective than self-weight consolidation. Tailings with initial solids content of 60% increased to approximately 69% with 60 min of EOD treatment, compared to 6 hr of self-weight consolidation for equivalent results. Fourie et al. (2007) performed a small-scale laboratory test and a larger-scale test of EOD and reported an increase in undrained shear strength of the treated tailings from 1 kPa to 18 kPa. The water content of tailings in the laboratory test reduced from 147% to 109% with a voltage gradient of 0.24 V/cm. In comparison, water contents of tailings in the larger test decreased from 158% to 75% with a voltage gradient of 0.11 V/cm. In addition to the differing voltage gradients, EOD in the large test was induced for more than 2 mo. Guo (2012) investigated using EOD to increase consolidation and shear strength gain in oil sands tailings. Dewatering time was reduced by 60% comparing about 100 hr of EOD to 14 d of surcharge loading at 5 kPa. The undrained shear strength increased from less than 1 kPa to 31 kPa at the anode after EOD treatment.

2.2.3 Electrochemical Reactions

Electrochemical reactions occur when an electrical current is applied to soil, inducing electrolysis and hydrolysis at the electrodes. Oxidation occurs at the anode, which generates oxygen gas and reduction in pH that causes an acidic condition. Reduction occurs at the cathode, which generates hydrogen gas and increase in pH that causes an alkaline condition. These chemical reactions are shown in Equations 3 and 4 (Citeau et al., 2011).



The acidic conditions caused by the increase in pH around the anode cause issues for the electrode material, which are discussed in the following sections. The production of hydrogen and oxygen gas at the electrodes can desaturate the soil and increase electrical resistivity of the soil (Mahmoud et al., 2010). Chlorine gas may also form in saline environments (Mitchell & Soga, 2005).

2.2.3.1 Electrodes

Materials such as steel, copper, and aluminum have been used as electrodes because they are conductive and relatively inexpensive. However, electrodes made of consumable material, such as these metals, are prone to corrosion, specifically the anode (Lockhart & Stickland, 1984). Electrochemical reactions causing pH levels to decrease (become acidic) around the anode cause corrosion. Deterioration of the electrodes causes loss of conductivity and reduced flow. Alternative materials have been shown to be effective in minimizing corrosion while implementing EOD.

Lee et al. (2016) investigated the use of titanium mesh coated with iridium oxide as electrodes and observed the titanium to be corrosion free under acidic conditions during EO treatment. However, titanium can be expensive to use in EOD on a large scale. Electrokinetic geosynthetics (EKGs) are another alternative material, which are comprised of conducting elements coated in a corrosion-resistant material that is incorporated into a geosynthetic material. Hamir et al. (2001) and Karunaratne et al. (2003) reported that EKGs performed as well as copper electrodes, and did not corrode. Fourie et al. (2007) performed field EOD tests with EKGs and reported no deterioration after 2 mo of continuous outdoor testing. The EKGs were also able to function as a filter around the drain.

Most of the previous laboratory and field investigations of EOD have been performed using horizontal electrodes with soil placed in between. This arrangement was adopted from common laboratory tests (e.g., consolidation, hydraulic conductivity) and involved placing porous filters horizontally on the top and bottom of a soil specimen by which the system is constructed in a vertical manner (Figure 2-5). However, horizontal electrodes are not practical for in situ tailings dewatering. Vertical electrodes will be necessary for feasible installation into tailings ponds and for dewatering to extend to greater depths in a tailings impoundment. Lockhart and Stickland (1984) investigated EOD of coal washery tailings using vertically oriented electrodes and reported that they were effective dewatering to depths equal to the electrode and drain length. Fourie et al. (2007) showed similar results with field testing to electrode and drains depths of 0.75 m.

2.3 Factors Affecting EO

The volume of water that can be removed by electroosmosis defines the electroosmotic efficiency. This efficiency is dependent on the applied voltage, salt content, water content, and soil characteristics such as particle size and clay content.

2.3.1 Influence of Pore Fluid (Water) Chemistry

Equation 2 describes flow as dependent on electrical potential, $i_e = \Delta E / \Delta L$, and electroosmotic conductivity, k_e , which is defined in Equation 5 (Mitchell & Soga, 2005):

$$k_e = \frac{\xi D}{\eta} n \quad (5)$$

where ξ is zeta potential, D is relative permittivity or the dielectric constant of the fluid, η is viscosity of the fluid [Ns/m^2], and n is porosity of the medium. The magnitude of the zeta potential indicates the degree of electrostatic repulsion between adjacent, similarly charged particles in a dispersion. Zeta potential dictates how effective EOD will be for a given soil, with larger magnitudes of negative zeta potential producing higher water removal rates (Chen et al., 1996). Rabie et al. (1994) reported that changes in pH produced by electrode reactions affect the rate of water removal by changing the zeta potential. As pH increases, the magnitude of negative zeta potential tends to increase; conversely, as pH decreases, the magnitude of negative zeta potential decreases. This is seen as the pH increases at the cathode and decreases at the anode throughout the EO process due to electrochemical reactions occurring at the electrodes.

Equation 2 and Equation 5 illustrate that electrokinetic flow is proportional to zeta potential and electroosmotic conductivity. Adding electrolytes (e.g., salt) to the pore fluid of a porous material increases electroosmotic conductivity in proportion to the concentration; however, adding electrolytes decreases the zeta potential by compressing the diffuse double layer. The effects of

zeta potential and salt addition act oppositely on the rate of dewatering, where water removal increases with increase in salt concentration up to an optimum, then decreases with further salt addition. The initial increase is due to the increase in ionic conductance, and the later decrease is due to the decrease in zeta potential upon continued salt addition. Lockhart (1983b) showed that at high electrolyte concentrations ($> 0.1 \text{ M}$) strong electrolytic polarization occurs and electroosmotic dewatering is limited. If the electrical conductivity (EC) of the pore fluid is too low, i.e. there are no electrolytes or ions in the water such as de-ionized water, the current will not pass through the porous medium. Fourie et al. (2007) suggests that a material with conductivity of less than 2.5 mS/cm and lower than salinity corresponding to 10^{-2} mol/L would be most effective with electroosmosis. Additionally, zeta potential varies with time and space during EO because pH fluctuates throughout the process (Chen et al., 1996; Rabie et al., 1994).

2.3.2 Influence of Saturation

Electroosmotic dewatering is most effective in fully saturated soils. There is a gradual decline in the rate of water loss during EOD due to the decrease in water content, which reduces water availability (Mahmoud et al., 2010). Soil hydraulic conductivity decreases with decrease in saturation because the flow path of water becomes tortuous with fewer and smaller flow paths (Lu & Likos, 2004). Guo & Shang (2017) showed that once the degree of saturation of the material at the anode drops below 80%, the most efficient stage for EOD will end.

Karunaratne et al. (2003) observed that EO efficiency decreased with time as soil-electrode contact losses occurred, because not all the potential gradient applied was transferred to the soil. Guo (2012) also observed a drop in EOD efficiency at the interface of the electrodes and tailings due to a loss of contact between the electrode and the tailings. Loss of contact can be due to

tailings desaturation, tailings desiccation, and gas generation. An unsaturated zone can form in the vicinity of the anode, where flow is hindered due to pore air replacing pore fluid. Gas generation from electrochemical reactions can cause a loss of contact between the electrode and the tailings, which interrupt electrical conduction and hinders flow of water. Additionally, significant shrinkage occurs as tailings desaturate and desiccation results in the tailings pulling away from the electrodes.

2.3.3 Influence of Voltage Gradient

The driving force for water movement in EO is the electrical potential gradient. The relationship between voltage, resistance, and current is known as Ohms law:

$$V = IR \quad (6)$$

where V = voltage, I = current, and R = resistivity. Ohms law states that resistivity is independent of current. Current and voltage can be manipulated to achieve the most efficient EO process. Studies have shown that for EO a lower voltage gradient applied over a longer length of time is more efficient than applying a high voltage gradient for a short period of time (Lockhart, 1983a). Applying a constant voltage gradient is also preferred relative to applying a constant current. A constant voltage gradient maintains the most effective electrical field to induce flow of water in the soil because the electrical potential is the driving force in EO. Azad (2010) observed that the current reduced with time and resistance increased with time when voltage was kept constant (at 120 V/m). This is because the electrical resistance of the soil increases pore fluid chemistry changes and loss of contact at the tailings-electrode interface due to consolidation and dewatering. To maintain a constant voltage gradient as the resistance changes throughout the EO process, the current must decrease. Lockhart (1983) investigated the influence of voltage gradient on EO

treatment of kaolin clay and reported that the maximum dewatering efficiency was independent of applied voltage, but dewatering efficiency decreased with increasing voltage.

Applied voltage gradient affects the overall cost of using EOD by controlling the energy required to induce flow with an electric field. Previous investigation of EOD by Fourie et al. (2007) reported high operating costs have made the method economically impractical, but showed that lower operating costs were possible, and should be considered in the future, at lower voltage gradients due to more energy efficiency.

Another factor that EOD is affected by due to voltage gradient is the specimen dimensions. Research by Pugh (2002) notes that a linear voltage gradient will underestimate treatment time as voltage gradient is overestimated when assuming a fully 1-D electrical field. However, thin specimens were reported by Chen et al. (1996) to not have an effect when the electrodes are oriented at the top and bottom of the specimen as long as the voltage gradient was maintained.

2.3.4 Influence of Electrode Configuration

Azad (2010) evaluated the effects of electrode configuration on EO efficiency in soils. Three configurations of electrodes were analyzed, consisting of two tetrahedral arrangements and a rectangular arrangement. The results showed the tetrahedral arrangement that consisted of three anodes surrounding a central cathode exhibited a significant undrained shear strength gain (76% higher) compared to the other configurations. Although undrained shear strength gain was largest, water removal was lower (by 33%) compared to the configuration with three cathodes and one anode, due to more drainage paths being available. The undrained shear strength gain was attributed to consolidation, drying, and cementation of the soils from other factors. To the authors knowledge, there has not been extensive electrode configuration conducted at field scale.

2.4 Consolidation & Undrained Shear Behavior of Low Plasticity Soils

Electroosmosis moves water towards the cathode where a drain system removes the water. Dewatering mine tailings can yield increased consolidation and gain in undrained shear strength.

2.4.1 Consolidation

Consolidation is the mechanical process of volume change in saturated soil caused by the expulsion of pore water due to an applied stress. The reduction in volume can be related to a decrease in water content. In the case of mine tailings, an increase in load is typically due to subsequent deposition and aggregation of tailings, construction equipment, placement of cover material, or lowering of the phreatic surface. Consolidation is a stress-strain-time phenomenon that results in soil settlements. The simplest case of consolidation is described by Terzaghi's theory of one-dimensional consolidation. The theory states that changes in stress in a soil are a direct result of a change in effective stress,

$$\sigma' = \sigma - u \quad (7)$$

where σ' = effective stress, σ = total stress, and u = pore water pressure. When a load is applied to a saturated soil, the change in pressure must be carried by either the soil skeleton or the pore water. In a laterally constrained saturated soil, an applied load initially is carried by the pore water of the soil. This loading increases excess pore water pressure from hydrostatic because water is incompressible. The change in applied vertical stress initially causes an equal change in pore water pressure, resulting in no change to effective stress. Over time as the excess pore pressure dissipates, the applied stress is transferred to the soil skeleton, which increases effective stress. Assuming the soil particles are also incompressible, consolidation and settlement occurs as the

void spaces in the soil decrease as water drains, allowing the overall soil skeleton to gradually compress.

The rate of consolidation is proportional to hydraulic conductivity because this rate depends on the rate of pore water drainage. In a high permeability soil, such as sand, excess pore water pressure developed from loading will dissipate almost immediately. In low permeability soil, such as clay and fine-grained silts, excess pore pressure developed from loading will dissipate more slowly. Consolidation in low permeability soils and mine tailings can take an exceptionally long time due to the long time required for water to drain from the pores.

The nature of consolidation during EOD depends on the boundary conditions at the anode and cathode, with importance being placed on maintaining free drainage at the cathode and no addition of water at the anode (Hamir et al., 2001). Consolidation of tailings between the electrodes occurs in amounts equal to the amount of water removed. Consolidation initiates near the anode as water is forced to flow away in direction of the voltage gradient towards the cathode. Consolidation at the cathode occurs as water is removed via a drainage system or naturally via surface discharge and evaporation.

Previous investigation has shown EOD to be effective in stabilizing and consolidating soils both in the laboratory and in the field. Bergado et al. (2003) achieved 90% degree of consolidation 1.2 to 2.2 times faster using EOD and prefabricated vertical drains (PVD) compared to PVD only. Fourie et al. (2007) reported that the coefficient of consolidation increased from 1.5 m²/yr to 5.4 m²/yr when the applied voltage was increased from zero to 10 V. However, they also reported that a voltage gradient of 1.1 V/cm was considered high and likely not relevant for practical applications.

2.4.2 *Shear Strength & Undrained Shear Strength Behaviors*

Shear strength is the magnitude of shear stress that a soil can sustain prior to failure. Shear strength, s , commonly is represented by Coulombs equation:

$$s = \sigma' \tan \varphi' + c' \quad (8)$$

where φ' and c' are strength parameters for angle of internal friction and cohesion of the material. Shear resistance of a soil is a result of friction and interlocking of particles, and depends on soil composition, initial stress state (including the initial void ratio and stress history), soil structure (i.e. compaction and soil particle orientation and structure), and loading conditions (drained versus undrained). The undrained shear strength of a loose soil will be lower than the drained shear strength due to the contractive nature of a loose soil and generation of positive excess pore water pressure when sheared undrained.

The typical low hydraulic conductivity of tailings suggests that the rate at which excess pore water pressure dissipates is slow compared to the rate of loading, e.g., for construction operations and soil placement on the surface of a TSF. Thus, undrained conditions are likely to govern the response to shear deformation in saturated, surficial tailings. Considering that the magnitude of positive shear-induced pore water pressures in surficial tailings are unknown, the undrained shear strength, S_u , is used to assess shear strength.

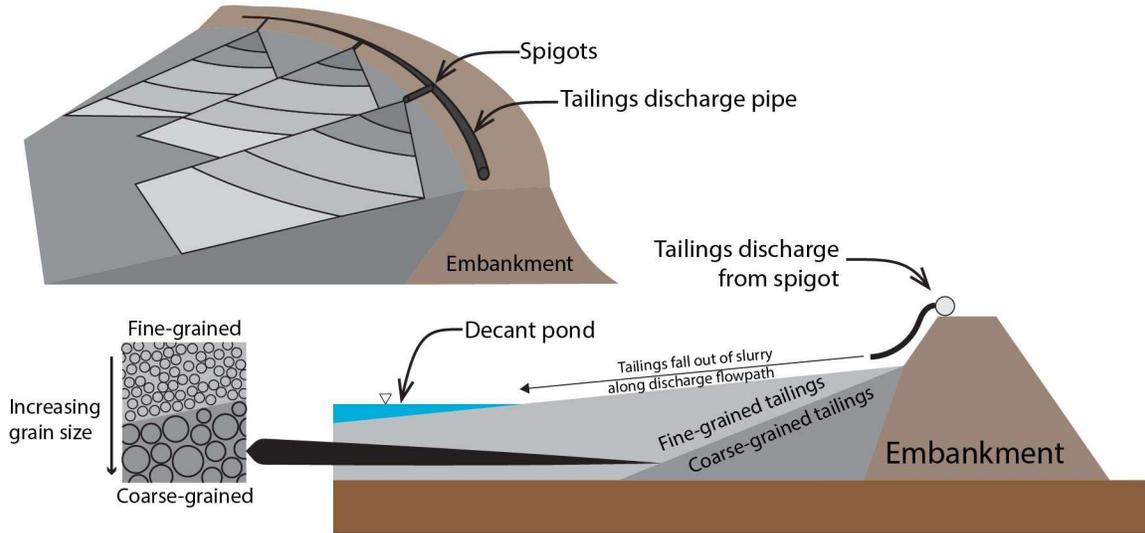
The increase of undrained shear strength due to EOD has been established. For example, Lo et al. (1991) indicated that undrained shear strength increased approximately 50% using EOD over a period of 32 d to the full depth of the electrodes in soft sensitive clays. Chew et al. (2004) showed that EOD combined with a vertical wick drain was significantly faster at increasing undrained shear strength compared to PVD alone. Fourie et al. (2007) observed an increase in undrained shear strength from less than 1 kPa to 18 kPa over the course of 2 mo applying EOD during a field

test on very fine tailings from South Africa. Rittirong et al. (2008) observed in field tests in marine clay an increase in undrained shear strength from 5-13 kPa to 22-39 kPa, on average, after approximately 5 d of EOD treatment using electroosmotic vertical drains (EVDs). They attributed the increased undrained shear strength to reduction of soil water content as well as soil hardening by electrochemical reactions. Guo (2012) showed an average undrained shear strength near the anode of 35.7 kPa after application of EOD compared to the average undrained shear strength of a control sample of 0.6 kPa, which was consolidated under a surcharge load of 5 kPa for the same duration of time.

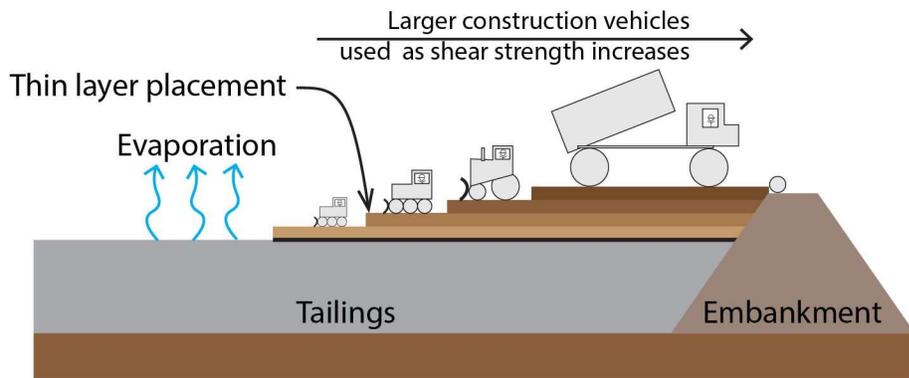
2.5 Other Applications of EOD

Use of electroosmosis has been investigated for a variety of geotechnical applications such as the remediation of contaminated soils and groundwater, described as electroreclamation and electroremediation, which use the electric current to extract contaminants from soils and slurries (Acar et al., 1995; Page & Page, 2002). Incorporating EOD with filter presses has also been investigated, described as electrofiltration in which electrophoresis and electroosmosis are used to prevent the formation of low-permeability fine solids cake blocking filtration progress. A review of electric field assisted mechanical filtration (electrofiltration) was performed by Mahmoud et al. (2010). Researchers have investigated the use of EOD for dewatering sludge with success in laboratory scale testing similar to EOD for mine tailings (Chen et al., 1996; Citeau et al., 2011; Glendinning et al., 2010; Mahmoud et al., 2010; Martin et al., 2019; Olivier et al., 2015). Hu et al. (2012, 2013) developed a finite element model to describe the process of electroosmotic consolidation based on several experimental tests. The model simulated EO-induced consolidation via nonlinear variation of soil parameters and showed accuracy for small-scale laboratory

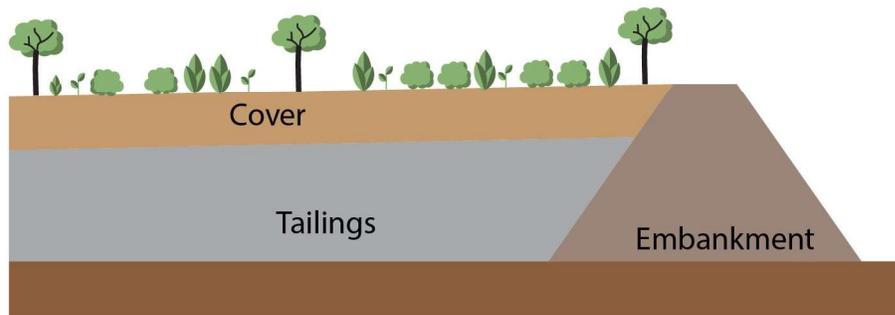
specimens. Guo & Shang (2017) developed a large strain one-dimensional model for oil sands tailings to predict the consolidation and dewatering time.



(a) hydraulic discharge of tailings slurry in an active TSF



(b) cover placement for TSF in closure process



(c) closed TSF

Figure 2-1. Schematics depicting a tailings storage facility (TSF) in three states: (a) active filling via hydraulic discharge of tailings slurry; (b) cover placement during closure; and (c) closed facility for site reclamation.

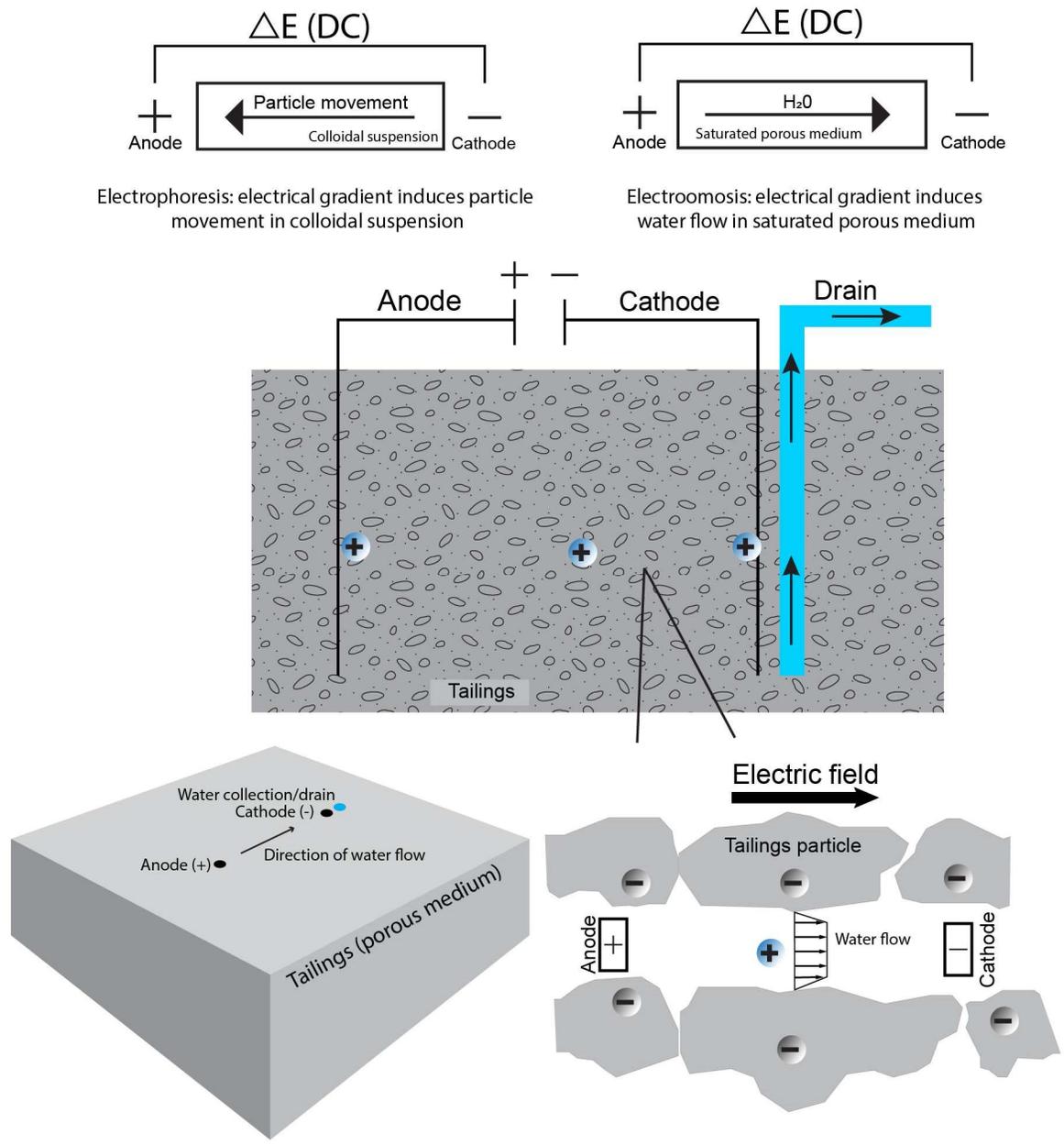


Figure 2-2. Schematics of the electrokinetic concept in soils with details for the processes of electrophoresis, electroosmosis, and pore-scale plug flow.

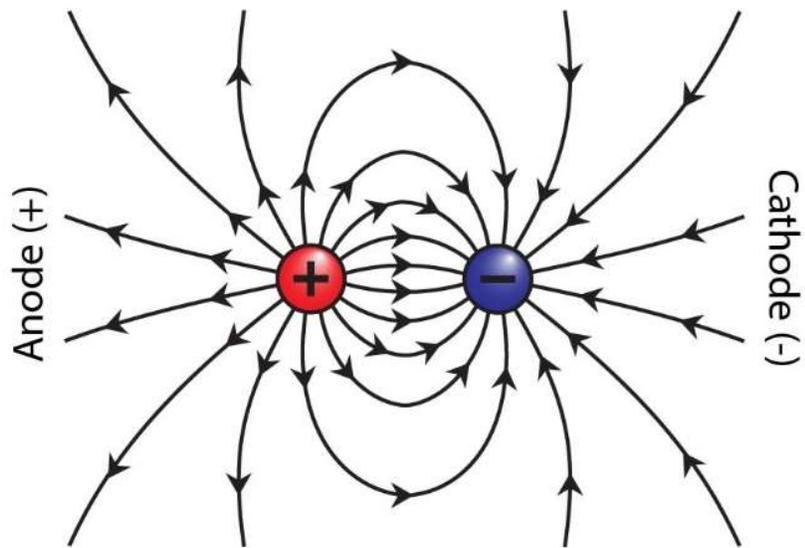


Figure 2-3. Electric field generated within a porous medium.

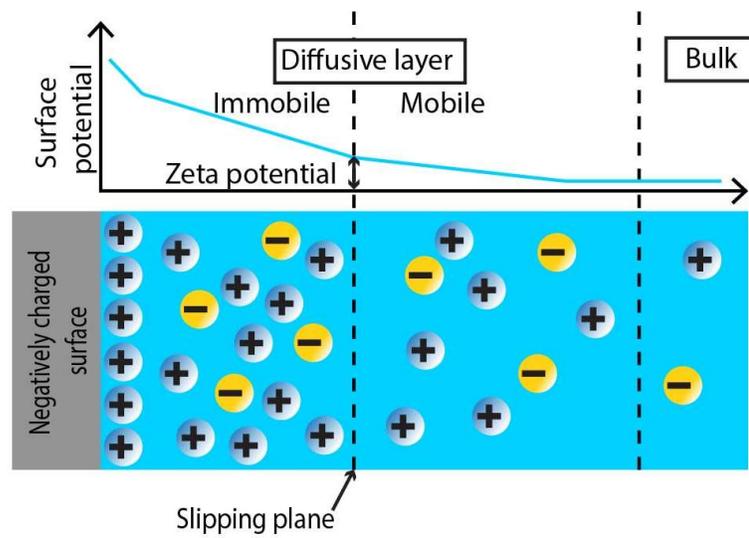


Figure 2-4. Schematics illustrating the diffuse double layer of a net-negatively charged particle: the zeta potential is shown as the relationship between surface potential charge versus distance from the charged particle surface.

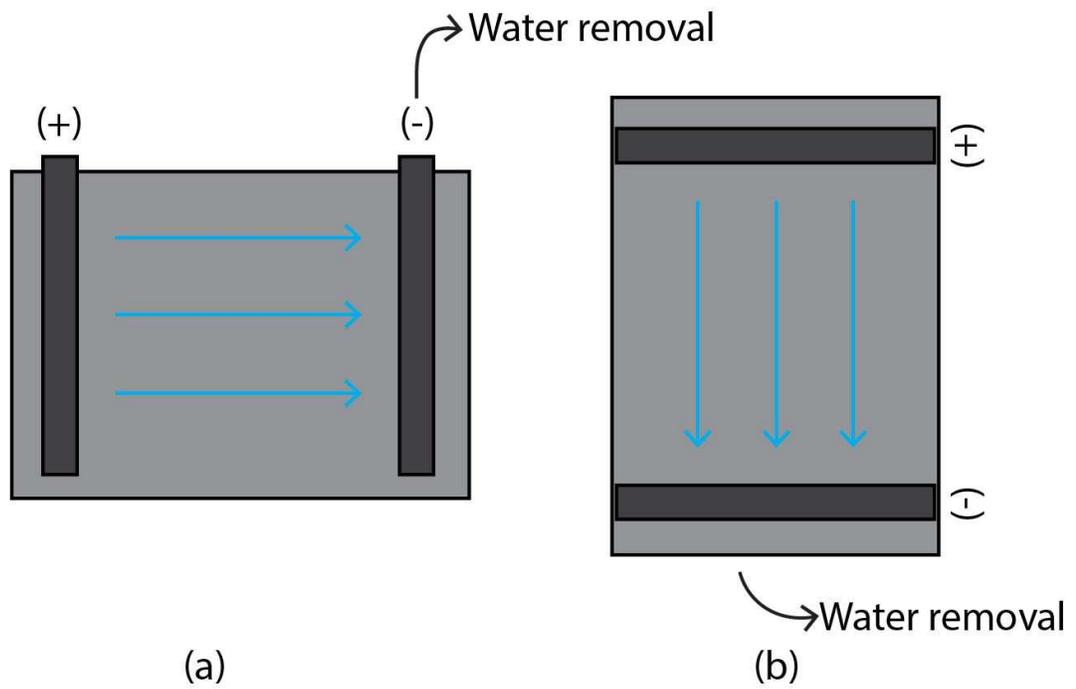


Figure 2-5. Electrode orientation for electroosmotic induced flow: (a) vertical electrodes with horizontal water flow; and (b) horizontal electrodes with vertical water flow.

3 CHAPTER 3: METHODS

3.1 Material Characterization

Two materials are proposed for testing: gold mine tailings and fine-synthetic tailings (FST). The mine tailings were collected from a gold mine in Central America, whereas the FST is a silty clay fabricated using commercially available materials. The FST was created to replicate the particle-size distribution of finer-grained mine tailings and has been used in numerous laboratory studies to develop a basis for comparison (e.g., Alhomair et al., 2017; Gorakhki and Bareither, 2017; Hamade and Bareither, 2019; Tian et al., 2020).

The mine tailings were characterized in their as-received condition. Shorthand reference herein is MT for “mine tailings” followed either by the sample number or X for “mixed” (e.g., MT1, MT2, MTX). Geotechnical characteristics for the tailings samples are tabulated in Table 3-1. Four tailings samples were collected from the TSF impoundment surface at three locations. The particle size distribution (PSD) curves for the tailings are shown in Figure 3-1. Hydrometer tests were conducted on each sample following ASTM D7928 and ASTM D1140. The mine tailings were predominately silt ($0.075 \text{ mm} > \text{diameter} > 0.002 \text{ mm}$) with clay-sized particles ($< 0.002 \text{ mm}$) ranging from 19% to 27% and less than 16% sand-sized particles ($> 0.075 \text{ mm}$). Atterberg limits were performed via ASTM D4318 to determine the liquid limit (LL) and the plastic limit (PL). The average LL was 38 and average PL was 23 (plasticity index, $PI = 15$), such that the material classified as low plasticity/lean clay (CL) according to Unified Soil Classification System (ASTM D 2487). Specific gravity (G_s) was determined using the water pycnometer method described in ASTM D 854; the G_s was 2.74.

The mine tailings included soluble salt in the pore fluid. Salt is in the liquid phase when dissolved in solution but is present as a solid when oven dried. The solid salt affects the

measurement of specific gravity and calculations of void ratio. Salt was removed from the tailings samples using dialysis as described in Gorakhki and Bareither (2016). Development of salinity correction factors is proposed for future research to create appropriate weight-volume relationships for the tailings (e.g., Noorany 1984).

Geotechnical characteristics for the FST are in Table 3-1 and were compiled from Hamade and Bareither (2019). The FST was blended in the laboratory as a mixture of 60% silica flour (U.S. Silica, Maryland, USA) and 40% kaolin (Thiele Kaolin Company, USA). The FST had $LL = 37$ and $PI = 15$, and classified as low-plasticity clay (CL) according to Unified Soil Classification System (ASTM D 2487).

3.2 EOD Procedure

3.2.1 Introduction

The goal of the proposed research is to evaluate the effectiveness of EOD compared with other dewatering methods to increase the undrained shear strength of mine tailings. The proposed research plan includes three dewatering methods: EOD, surcharge consolidation, and evaporation. Laboratory-scale dewatering experiments are proposed with additional variables of time and material. Undrained shear strength of the mine tailings will be measured as a function of depth using a laboratory vane shear apparatus. Water content samples will be exhumed as a function of depth from the dewatering experiments and compared to undrained shear strength versus water content relationships developed in controlled consolidation cells. The evaluation of water content as a function of depth will provide a redundant assessment of undrained shear strength gain due to dewatering.

A series of preliminary experiments were conducted that provided insight into specimen preparation, EOD test procedure, and experiment design. A summary of the preliminary experiments is in Appendix A, which includes detailed explanations of the experiments. The preliminary experiments were used in conjunction with identified knowledge gaps in the literature to develop the proposed experimental procedure and plan.

3.2.2 Experimental Procedure

3.2.2.1 Experiment and Cell Dimension Design

A schematic of the proposed laboratory dewatering experiment is shown in Figure 3-2. Three cells will be operated simultaneously to evaluate EOD, consolidation, and evaporation in a controlled environment (i.e., same temperature and humidity). The test cells are acrylic, rectangular boxes with the following dimensions: external height = 356 mm (14 inches); external length = 305 mm (12 inches); external width = 152 mm (6 inches); and wall thickness = 5 mm (3/16 inches). The dimensions of the containers were selected considering past studies (e.g., Karunaratne et al., 2003; Lee et al., 2016; Shang et al., 2009; Zhang et al., 2017), applicability of all three dewatering techniques in the same size cell, and sufficient depth and lateral spacing to conduct vane shear tests. A sufficient specimen depth was desired such that at least three vane shear tests could be conducted at different depths in each single spatial location. The vane shear test requires at least 25 mm of insertion from the surface for the first test and then 50 mm of insertion for each subsequent test. The width was selected to allow a titanium mesh electrode used in the EOD experiment to span the entire cell width to create one-dimensional flow. Finally, the length was determined considering available mine tailings quantity to create reasonable-sized specimens based on previous research.

A schematic of the EOD setup is shown in Figure 3-3. Titanium mesh will be used as electrodes. Sponges and geotextile filter will be used as a water removal unit, allowing water to accumulate in the sponge and evaporate from the top; the sponge will be approximately 51 mm (2 inches) taller than the specimen. The sponge and geotextile filter are henceforth referred to as a drain unit.

3.2.2.2 Test Cell Operation

Slurry mine tailings and FST will be prepared in bulk such that three specimens for the EOD, evaporation, and consolidation test cells can be created from a single homogenized mixture. Individual PSDs of the mine tailings samples were similar and a single composite material (MTX) was created for the test cells (Figure 3-1). The tailings and FST slurries will be poured into the containers to initial specimen heights of 300 mm (12 inches). Preliminary experiments with MTX indicated that a slurry consistency with gravimetric water content $\approx 95\%$ (solids content $\approx 51\%$) could be poured into the test cells without solid-water separation. Hamade and Bareither (2019) reported that an FST solids content = 60% represented the rheology of thickened tailings. However, considering that the MT and FST exhibited similar plasticity, the same solids content $\approx 51\%$ will be used for both materials to provide consistency between the experiments.

Cell 1 will evaluate evaporation (EV) and self-weight consolidation. The slurry will be poured into the test cell and then allowed to desiccate and self-weight consolidate.

Cell 2 will evaluate consolidation under a surface surcharge. A geo-composite drainage layer will be placed horizontally to cover the entire surface of the specimen. A PVC plate will be placed on top of the drainage layer to support and equally distribute dead weights to create the

surface surcharge. Water will accumulate within the drainage layer and in the vicinity of the PVC plate as consolidation progresses; this water will be removed via evaporation over time.

Cell 3 will evaluate EOD. The voltage gradient will be 0.3 V/cm and applied using a DC power supply. Past studies have shown that lower voltage gradients are the most energy efficient for electroosmosis. In addition, preliminary trials (see Appendix) indicated that higher voltage gradients generated gases (e.g., hydrogen and oxygen gases). Thus, the target voltage gradient of 0.3 V/cm and length of the test cell results in the need to apply 9 V to the electrodes in the EOD system. A constant voltage will be applied throughout the test; however, current will fluctuate as resistance in the materials change. The slurried materials will consolidate as water migrates towards the cathode and is removed via evaporation.

The total mass of slurry and initial volumes will be measured for each specimen at the beginning of the experiments. In addition, initial and intermittent water content measurements (ASTM D2216) of the slurry will be conducted during specimen preparation to assess similarity in slurry consistency and to compute weight-volume relationships of the test specimens. Specimen volumes will be measured based on known dimensions of the container and the measured specimen height using a millimeter scale adhered to the side of the container.

Specimen mass will be recorded initially, and throughout the test, by measuring the mass of the entire specimen plus container. Total specimen mass will be recorded at least once every 24 hr to a precision of 0.1 g. The EOD cell will temporarily be disconnected from the voltage source when placed on the scale and subsequently reconnected. The short duration of disconnecting the voltage source is assumed negligible to the overall migration of water. The dead-weight surcharge in the consolidation cell will be temporarily removed to weight the specimen and test cell, and then reapplied following the measurement. The removal and

reapplication of the load is necessary to not overload the scale and will be completed rapidly with negligible dynamic loading of the specimen.

Each set of three test cells will constitute a given experiment, and each experiment will be conducted for the same length of time (e.g., 1-2 mo). Temporal trends in mass loss will provide guidance on the efficiency of dewatering in each cell, and these trends will be used to assess termination time of each experiment. All test cells will be performed in a fume hood to manage any gas generation by the EOD test and maintain a consistent environment for evaporation.

3.2.2.3 Measurement and Analysis of the Test Cells

Data collected as a function of time during the experiments will include mass of the test cells, surface height of the slurry, voltage and current in the EOD cell, and temperature and humidity within the fume hood. The temporal change in mass of each test cell will be assumed to represent the loss of water to provide the average water content and progression of dewatering.

In situ undrained shear strength and water content will be evaluated on each test specimen at the end of the experiment. Undrained shear strength will be measured with vane shear at multiple depths and locations to evaluate the distribution of undrained shear strength throughout the test specimens as shown in Figure 3-4. After the vane shear tests, water content specimens will be exhumed on a spatial grid and at multiple depths to evaluate the distribution of water content through the test specimens. Observations will be noted throughout the test and may include desiccation and salt crust formation.

Tailings and FST undrained shear strength will be evaluated using the same laboratory vane shear device in test cells designed to control effective stress (Herweynen et al., 2019). Vane shear testing will be conducted following ASTM D4648 and Herweynen et al. (2019). A series of vane

shear tests will be conducted on mine tailings and FST consolidated to effective stresses ranging between 1 and 100 kPa, which encompasses the full range of effective stress anticipated within the dewatering experiments. Undrained shear strength in the vane shear test cells will be measured at the end of consolidation and water content will be measured on the materials after vane shear. Data from these experiments will yield relationships between undrained shear strength, effective stress, and water content.

Relationships created from the vane shear tests will be used to verify distributions of water content and undrained shear strength in the dewatering experiments. The average water content within the dewatering test cells and water contents at termination can be related to corresponding shear strength.

Table 3-1. Summary of physical characteristics and classification of the mine tailings and fine synthetic tailings.

Material	Gs			LL	PI	USCS Classification	Sand Content (%)	Silt Content (%)	Clay Content (%)
MT1	2.75	2.75	2.73	42	19	CL	6	66	27
MT2	2.75	2.76	2.81	37	14	CL	16	65	19
MT3	2.74	2.72	2.71	35	13	CL	12	64	24
MTX	2.75			38	15	CL	11	65	24
FST	2.63			37	15	CL	0	58	42

Notes: MT = mine tailings, with numbers identifying sample number and X identifying mixed; FST = fine-synthetic tailings; LL = liquid limit; PI = plasticity index; USCS = Unified Soil Classification System; Gs = specific gravity of solids.

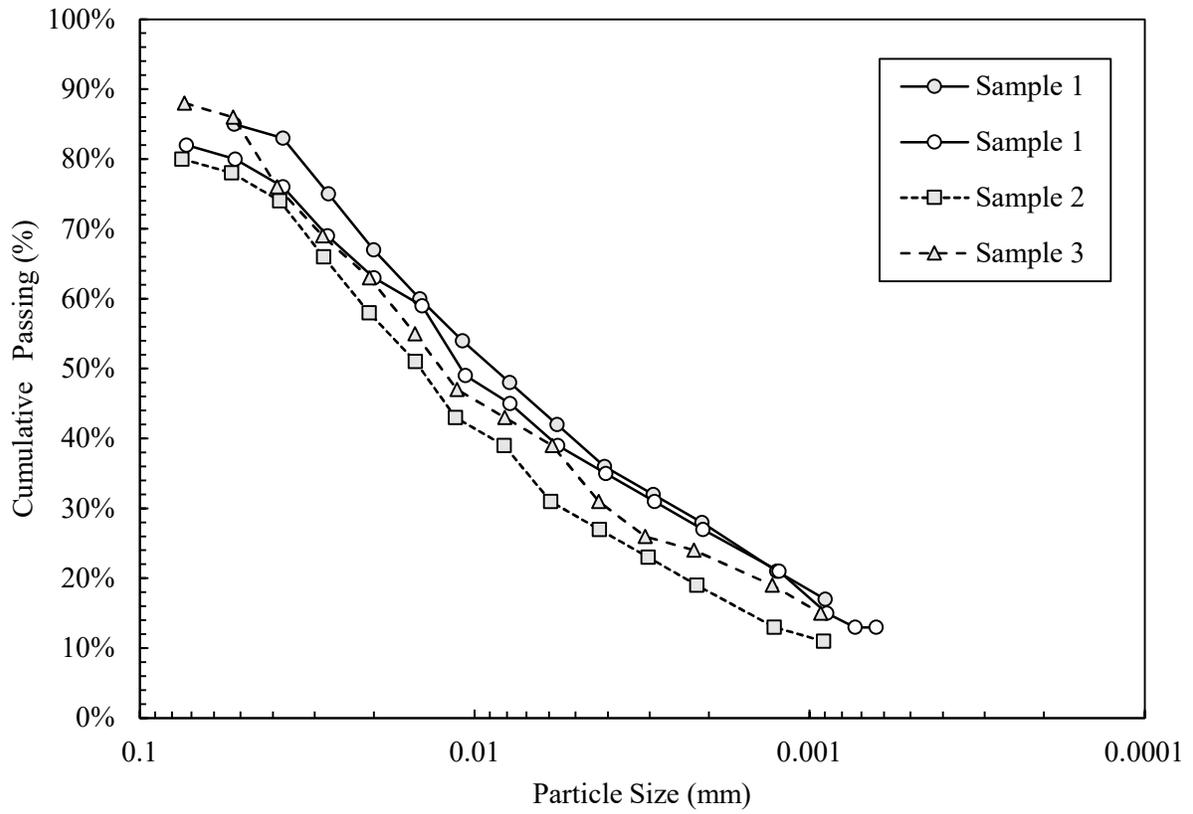


Figure 3-1. Particle size distribution (PSD) curves for mine tailings samples.

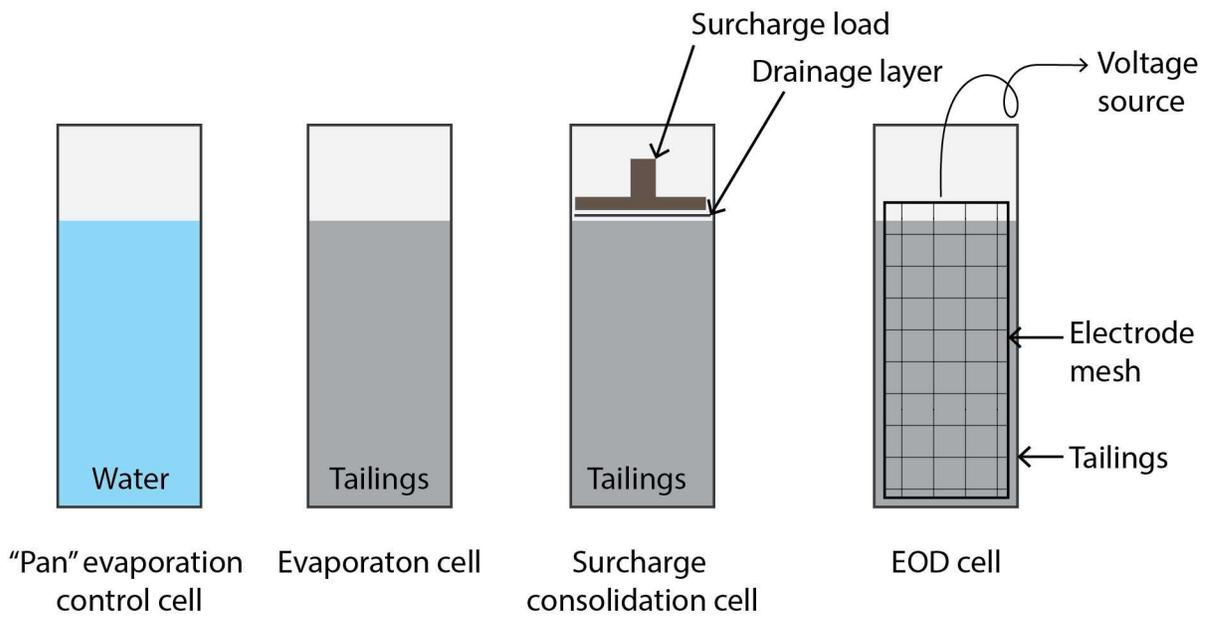


Figure 3-2. Overview of proposed experiment cells to evaluate electroosmotic dewatering (EOD) relative to dewatering via evaporation or under a surcharge.

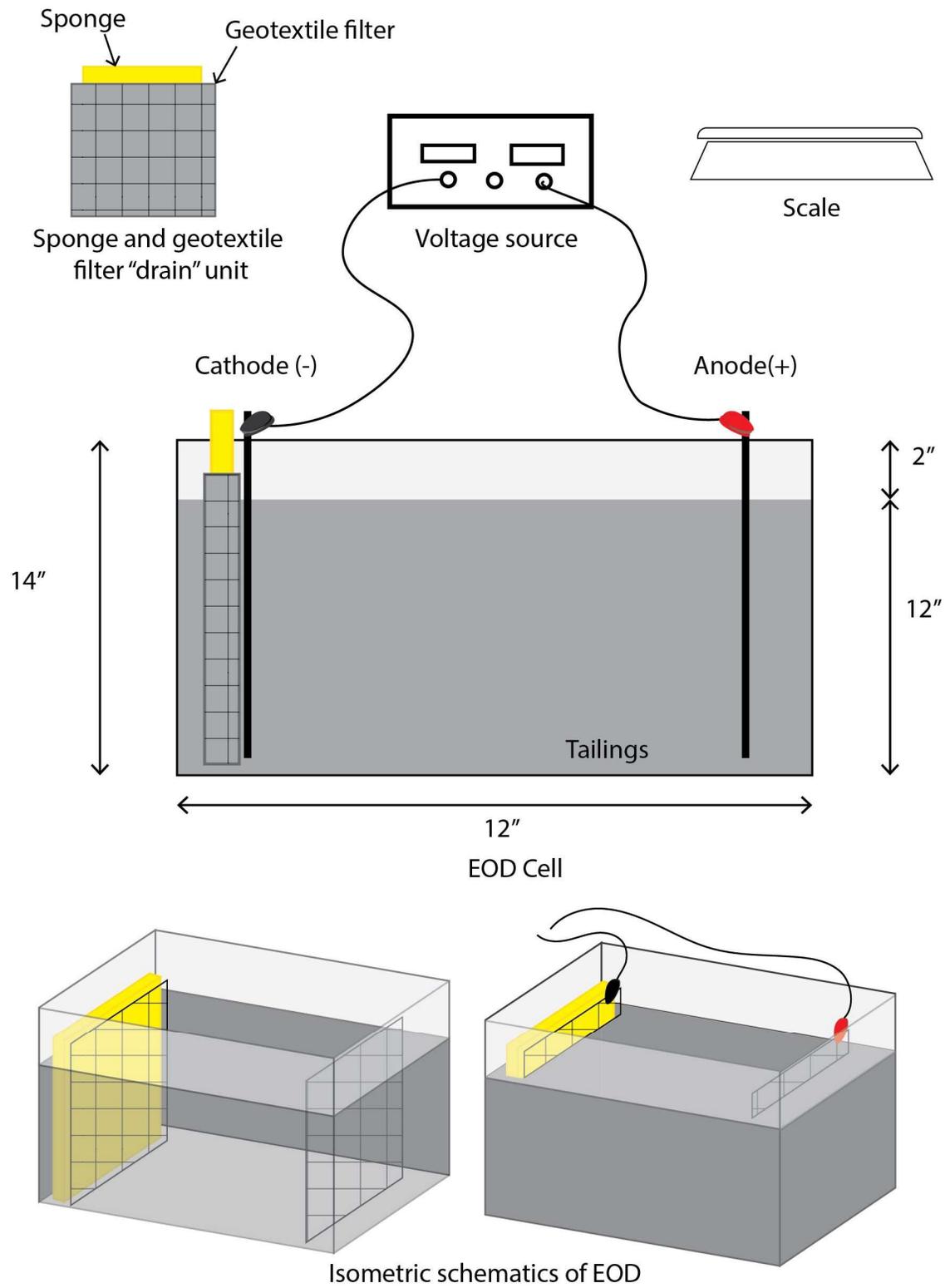


Figure 3-3. Schematic of the electroosmotic dewatering (EOD) experimental approach.

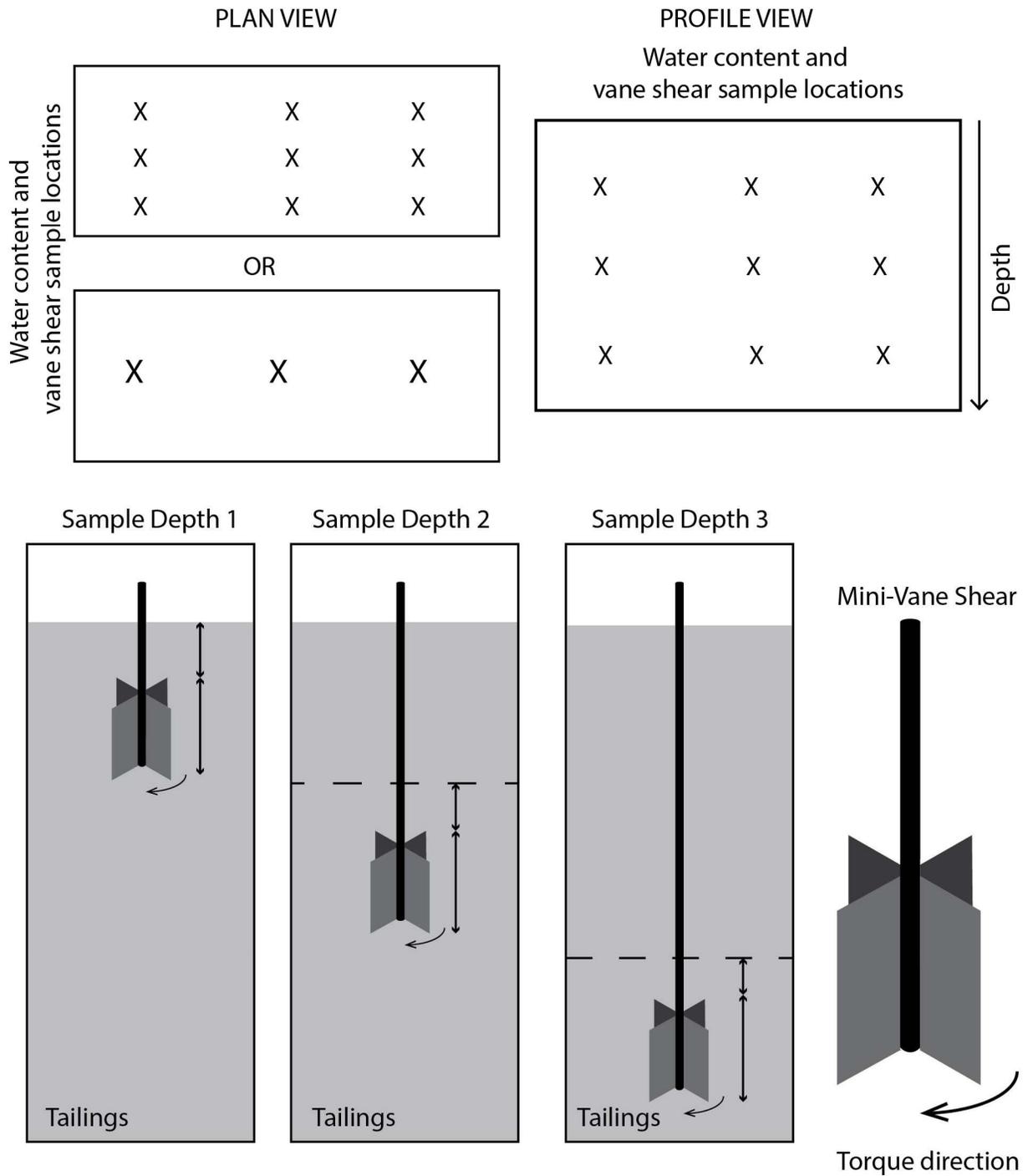


Figure 3-4. Schematics of the vane shear test approach.

4 FUTURE WORK

The objectives of the proposed study are to (1) assess the effectiveness of dewatering methods at bench-scale (EOD, surcharge consolidation, and evaporation) to increase undrained shear strength of tailings as a function of depth, and (2) create a moisture wicking synthetic capillary unit to be coupled with electroosmotic dewatering (i.e., *EO-Plant*) that can promote dewatering of tailings surfaces. Objective 1 will be achieved via evaluation of two hypotheses: Hypothesis 1 – electroosmotic dewatering increases undrained shear strength of saturated surficial mine tailings more rapidly compared to other techniques; and Hypothesis 2 – electroosmotic dewatering increases undrained shear strength as a function of depth more effectively compared to other techniques. Objective 2 will be accomplished via a proof-of-concept experimental approach to document that an *EO-Plant* is technically feasible to have potential application in the dewatering of mine tailings. Considerations on reasons to develop EOD and why EOD is not currently in use are established as motivation for the proposed project.

A proposed experimental plan to complete Objectives 1 and 2 is divided into 3 phases: laboratory scale experiments, field scale experiments, and a full scale *EO plant* application. Phase 1 of the testing program will test Hypotheses 1 and 2 via laboratory scale experiments described in Chapter 3, which will include comparisons between consolidation via surface surcharge, evaporation, and EOD as dewatering techniques. A proposed research plan for Phase 1 is developed herein. Furthermore, scaling the experiments from laboratory-scale to field-scale is proposed as Phase 2, which will build on results from Phase 1. Finally, development of an *EO-Plant* will be completed in Phase 3 to document proof-of-concept and further identify possibilities that incorporate an innovative *EO-Plant* for mine tailings dewatering.

4.1 Why develop EOD?

Electroosmotic dewatering has the potential to stabilize soft, saturated tailings impoundments at mine sites around the world. This method can be useful for dewatering tailings during mine operations, as well as in preparation for mine closure and cover placement. In particular, EOD is well suited to aid dewatering of fine-grained, low permeability tailings (e.g., mature fine tailings in the oil sands) that present unique reclamation and closure challenges.

Although dewatering tailings prior to deposition is the most stable and desirable condition, large-scale exploitation of low-grade ore bodies continues to increase the volume mine tailings generated (Blight & Bentel, 1983; Lagos et al., 2018), and scaling dewatering technology is often not economical for a given mine. High volume production of mine tailings often exceeds the capabilities of existing filter presses and pre-deposition dewatering methods despite the advancement in filter presses and alternative methods of dewatering tailings pre-deposition. Efforts are being made to transport and deposit tailings at lower water contents; however, transport of large volumes of tailings is easier and more economical as a slurry.

Geotechnical concerns of TSFs, such as embankment dam stability and impoundment surface settlement, depend on the water content of the tailings. An advanced understanding of EOD combined with relevant ideas for scaling the technology to TSFs is advantageous to promote tailings dewatering towards increasing stability and accelerating settlement.

4.2 Why EOD is not currently in use

Even though research exists on the feasibility of EOD in mine tailings, full-scale implementation in the mining industry has not occurred. The method likely has not been

implemented due to lack of a developed procedure, difficult water removal, and/or lack of a commercially available EOD unit.

There are no developed methods and procedures to guide the mining industry in application of EOD. Most research has been performed at the laboratory bench-scale, and there has not been comprehensive documentation and analysis to address whether EOD can be scaled-up to mine operations. There is a possibility that mines have implemented EOD and have not published results or methods of construction. However, considering the lack of any documented field-scale effort, most likely EOD has not seen full-scale implementation in the mining industry.

Water removal is the foremost issue with scaling EOD from bench-scale to field-scale. The literature suggests that the technique is feasible for tailings dewatering in the laboratory. However, whether the method can reasonably be used for in situ dewatering of tailings needs to be established. Previous research did not include water removal methods necessary when testing the effectiveness of EOD for tailings. Most research has been conducted with steps to ease data analysis and rely on laboratory conveniences (e.g., double drainage, horizontal electrodes, use of pumps to remove water). These conditions are not representative of field conditions. The vision of this research is application of in situ EOD in TSFs that lack effective drainage. Lack of effective drainage in TSFs may be due to no underdrainage (e.g., surface evaporation only), no pumps to remove water, and/or long drainage paths in low hydraulic conductivity tailings. Most EOD research has been conducted using gravity drainage or pumps. Gravity-induced drainage is not considered relevant for surface dewatering, and installation of pumps is not considered practical due to the difficulties of construction on soft tailings. Therefore, lack of EOD implementation likely is due to water removal challenges. A key question to be addressed in the proposed research is how to remove water from tailings once water has collected near the cathode.

Additional considerations for implementation of EOD are development of a commercially available EOD unit and ease of installation of the EOD electrodes. The appeal of EOD is to increase undrained shear strength in tailings to allow mobility of construction equipment on the surface; however, installing the EOD electrodes and drainage system must be considered as the initial conditions are most likely soft, saturated tailings surfaces that prevent traditional installation methods. Drones are a possible means of remote installation of EOD units. Although considered as a potential end-state means of deployment, drone installation is not included in the research proposal. The EOD units also are viewed as non-recoverable once installed in a TSF, and thus, the economic investment in the units needs to be minimal considering they will be sacrificial. Designing a single, economical EOD unit that can be brought to market and feasibly installed in a TSF are important considerations to the success of EOD.

4.3 Phase 1: Anticipated Results from Laboratory Experiments

Phase 1 laboratory experiments will be conducted as described in Chapter 3. Anticipated trends were developed for EOD, surcharge consolidation, and evaporation experiments conducted on mine tailings prepared to identical initial conditions. All three test cells will be operated for a similar length of time to develop temporal trends of water content and surface settlement, which can be used to assess the overall consolidation process. In addition, temporal trends of applied current and electrical resistivity will be evaluated in the EOD cell to assess the effectiveness of the dewatering process. Upon termination of the three test cells, undrained shear strength will be measured via vane shear to test the two hypotheses of increasing undrained shear strength more rapidly and as a function of depth via EOD compared to other techniques.

A schematic of the temporal trends in water content for the three test cells is shown in Figure 4-1(a). Water content will be computed based on total mass loss during the experiment, which is assumed equivalent to water loss. The three tailings specimens will be prepared to an initial identical water content that subsequently will decrease with time as dewatering progresses. The anticipated trend is that water content in the EOD test cell will reduce more rapidly relative to the surcharge and evaporation cells. In the surface and evaporation cells, water removal from the tailings will occur at the specimen surface, albeit via different mechanisms (i.e., consolidation versus evaporation). However, the EOD cell will be exposed to a similar amount of evaporative energy on the specimen surface as the evaporation cell and include lateral flow to a vertical drain (Figure 3-2 and Figure 3-3). Thus, the EOD test cell is anticipated to have enhanced water removal potential and yield the lowest water content of the three test cells.

Anticipated temporal trends of surface settlement measured in the three test cells are shown in Figure 4-1(b). Settlement of the surface of the specimen will be recorded as an indicator of volume change and consolidation. The amount of settlement is attributed to the amount of water removed from the specimen; therefore, settlement is anticipated to be largest in the EOD compared with surcharge and evaporation. In the case of the surcharge cell, there would be no ponded water from drainage to the upper surface and the water content and settlement trends should show the same shape. There may be differences between the water content and settlement trends in the evaporation and EOD cells if they transition to an unsaturated state at the surface. An anticipated trend in the EOD cell is that the specimen surface around the anode will settle more than the surface around the cathode as water moves towards the cathode. The surcharge and evaporation cells are anticipated to have level settlement across the surface of the specimens.

The applied current in the EOD cell will be recorded during the experiment and the anticipated temporal trend is shown in Figure 4-2. The current is directly related to resistance of the soil, which will change as a function of water content and soil-electrode contact. The mine tailings will become more resistant during EOD due to the reduced water content and potential for reduced contact between the electrodes and mine tailings (e.g., as observed in preliminary experiments, Appendix A). Thus, a decreasing trend of current as a function of time in the EOD cell is anticipated for a constant applied voltage.

After termination of the experiment, vane shear tests will be conducted to evaluate undrained shear strength (S_u) with tests conducted at varying surface and depth locations (Figure 3-4). Anticipated temporal trends of average S_u and depth profiles of S_u in the EOD, surcharge, and evaporation test cells are shown in Figure 4-3. Undrained shear strength is a function of water content and the temporal trend of average S_u measurements is anticipated increase with overall decreasing water content.

Undrained shear strength increases linearly as a function of depth (i.e., effective stress) in saturated, normally consolidated materials (Holtz & Kovacs, 1981). An S_u -depth profile that would be representative of the initial conditions for the three test cells is shown in Figure 4-3(b) with a linear trend starting from $S_u \approx 0$ kPa at the surface and increasing with depth. The initial depth profile of S_u assumes self-weight consolidation under gravity forces within the slurry tailings.

Depth profiles for the three test cells are anticipated to vary relative to initial conditions, with pronounced differences near the surface, closer to the drainage / evaporation boundary (Figure 4-3(b)). Undrained shear strength in the evaporation test cell will increase near the surface due to desiccation-induced suction stress (i.e., increased effective stress) to form a soil crust of

higher strength; however, at some depth, desiccation will cease to influence S_u and the trend line will merge with initial conditions. The S_u trend with depth in the surcharge cell at complete consolidation is hypothesized to be linear and shifted to the right to reflect the increase in effective stress. However, the increase in S_u near the base of the test cell will require the longest time because this depth is furthest from the drainage boundary, and the actual S_u -depth profile may exhibit nonlinearity with lower S_u at depth for less consolidation. The hypothesized S_u -depth profile in the EOD cell is challenging to predict but is assumed to increase relative to the initial position, with some nonlinearity near the surface due to evaporation causing potential crust formation.

Analyzing S_u with space and depth variation in the test cells and conducting a comparison between the evaporation, surcharge loaded, and EOD cells will provide the data to test Hypotheses 1 and 2, and to complete Objective 1. The anticipated trends of average S_u versus time and S_u versus depth in Figure 4-3 indicate that EOD increases S_u of mine tailings more rapidly and more effectively as a function of depth compared to surcharge loading and evaporation, both of which support Hypotheses 1 and 2. These anticipated trends are representative of a single experiment, and multiple experiments will be conducted to develop a more robust data set to further support EOD and develop experimental conditions to guide the Phase 2.

Experiments in the EOD, surcharge, and evaporation cells will be performed to assess repeatability, composition effects (i.e., testing mine tailings and FST), voltage gradient, pore fluid chemistry, and drainage. A variety of voltage gradient applications can provide a better understanding of what range of gradients are applicable for effective EOD to be considered at field-scale. Another variable that is relevant to evaluate to further assess field-scale applicability of EOD is the initial water content of mine tailings. The water content of mine tailings varies with

space and time in a TSF, and evaluating EOD on mine tailings at a range of water contents will help assess potential for treating extremely high water content (low solids content) or low water contents to enhance undrained shear strength. All experimental iterations on EOD treatment will be conducted in parallel with comparable tests on evaporation and surcharge consolidation to build a robust data set to support EOD.

4.4 Phase 2: Field-Scale Experiments

Scaling EOD experiments to field-scale is necessary to document potential for full-scale mine applications. There have been few large-scale EOD experiments conducted (e.g., Azad, 2010; Chew et al., 2004; Fourie et al., 2007; Guo & Shang, 2017; Rittirong et al., 2008; Zhang et al., 2017), and potential large-scale implementation considerations are discussed in the following section to support future EOD research. Important considerations are to determine if EOD can be effective for dewatering tailings in situ relative to other methods and to determine what innovation can be developed to support in situ dewatering.

Phase 2 of the proposed research effort will be field-scale experiments conducted with three similar dewatering configurations (surcharge, evaporation, and EOD) in proportionately larger test cells and for longer lengths of time (e.g., 3-6 months). Field-scale test cells are proposed as large tank experiments ($\sim 1\text{-}2\text{ m}^3$) that can be conducted in a controlled laboratory environment as well as outside to subject the experiment to natural climate conditions. Key objectives of the test cell design will be to (i) simulate a single or multiple cathode-anode pair for a potential grid-configuration deployment on a tailings surface and (ii) assess variables such as electrode spacing and voltage gradient.

4.4.1 Grid Configuration

Proposed grid configurations of EOD units across the surface of the impoundment are shown in Figure 4-4, which is representative of the envisioned full-scale deployment of EOD to promote shear strength gain in the TSF surface. The first set of experiments for Phase 2 will evaluate a single anode-cathode pair that will be a scaled-up version of the experiments discussed for Phase 1. Additional field experiments for Phase 2 will evaluate multiple anode-cathode pair configurations. Some key deliverables from these preliminary field-scale experiments will be (i) reassessment of the research hypotheses at larger scale and (ii) evaluation of undrained shear strengths that can be measured with field vane shear devices that also are used in full-scale TSFs.

The research in Phase 2 will assess how differences in grid configurations change the electrical field that drives EOD. Bench-scale testing has been performed by Azad (2010), but did not consider how multiple sets of electrodes configured together would affect the EOD process. A key finding for this research phase will be to identify grid configurations of electrodes for EOD that minimize interference with each other and yield high efficiency for full-scale deployment. A better understanding of the electrical fields and potential interference of magnetic fields is needed to determine what grid configuration optimizes EOD for tailings.

4.4.2 Voltage & Voltage Gradient

Further research will be needed to determine what voltage is required to maintain flow of water between the electrodes for a specified low voltage gradient at field-scale. A short distance limitation between the cathode and anode due to voltage gradient and voltage source constraints will determine if the EOD method is relevant for full-scale deployment at mine sites. Evaluating how the voltage gradient and grid spacing affects EOD efficiencies is the next step in scaling the

test cells towards field applications. A dimensionally larger test cell operated for a longer duration will allow instrumentation to be installed that evaluates the voltage gradient in the specimen and evaluate the lower range of voltage supply that can feasibly be used to dewater mine tailings.

The power source to generate the voltage required for EOD will need to be produced using onsite equipment for deployment on mine sites. For example, a voltage of 42 was discussed in Chapter 2 as being a reasonable “safe” maximum for applied voltage, which results in a maximum distance of 1.4 m between electrodes to achieve a voltage gradient of 0.3 V/cm. The danger with higher voltages may be allowed at secluded mine sites where sign postings and trained personnel could be advised. However, if the TSF impoundment is 1 km and the voltage gradient required is 0.3 V/cm, a voltage of 30,000 V is needed, which is not practical. Thus, there is a need to assess the potential of lower voltage gradients to be sufficient to dewater the tailings in a reasonable time frame when applied at field-scale.

Additional research is needed to determine how the voltage changes over distance and through non-homogenous tailings material. Research discussed in Chapter 2 regarding the effects of voltage gradient on EOD indicates that for small-scale specimens the voltage gradient can be assumed 1-D and have no effect on EOD efficiency; however, more research is needed at larger scale to better understand multi-dimensional voltage gradient variations and EOD efficiency at field-scale applications.

4.5 Phase 3: EO Plant

4.5.1 Current Challenges for Full-Scale Implementation

Full-scale application of EOD as a relevant dewatering approach for TSFs requires a commercially available EOD unit that provides a cost-effective solution for mine owners.

Relevant challenges for an EOD unit are the power source, ability to remove water, functionality with varying pore fluid chemistry, and method of installation. An additional consideration for the EOD units is whether they can be removed and reused following dewatering in a TSF or if they are left in place during cover placement if the effort of removing them was not considered economical.

Solar energy as a power source for the EOD units can allow the units to be independent of mine site infrastructure with the potential to be installed across a large area typical of a TSF. Commercially available solar power panels produce 12 V per traditional panel; however, these traditional panels may be unreasonable for an EOD unit depending on the minimum voltage needed for powering the electrodes. The location of a given mine will need to be considered as this will govern how solar power can be used for EOD based on hours of sunlight, intensity of sunlight, and weather variation throughout the day that could either damage the solar power panels or limit access to sunlight.

Water removal is a major issue for implementation of EOD in the field since TSFs lack effective drainage pathways. Gravity-induced drainage is not considered relevant for surface dewatering, and installation of pumps is not considered practical. How to remove water from tailings once water has been collected near the anode needs to be addressed.

Capillary drains may be an approach for passive water removal from the tailings, whereby water will flow upward in a vertically-installed capillary tube in the tailings surface such that water can be removed from the capillary tube at the exposed end via evaporation. Capillary tubes would rely on suction rather than an electric pump system to remove water from the tailings.

The pore fluid of mine tailings can vary considerably between sites, and many mine tailings can have high salinity from ore extraction processes (e.g., Gorakhki and Bareither, 2016). Salt

accumulation on the tailings surface in a TSF and the surface of the sponges used in the preliminary trials (refer to Appendix A for description of findings from the preliminary trials) suggests that salt crusts may inhibit water evaporation in the field. Developing a method that can remove or prevent salt crust formation needs to be considered for practical application of an EOD unit.

Deployment of the EOD units is likely to be challenged by the soft, saturated tailings surfaces on the TSF that require dewatering. There are numerous installation methods that can be considered for EOD units, e.g., manually via hand auger, drill rig, or drone; however, based on difficult placement of cover material on soft tailings impoundments, installation of EOD units using physical mobilization on the tailings impoundment likely will not be practical. Drone installation of EOD units can be a potential solution that allows distribution over an entire TSF surface while not requiring physical mobilization on the surface.

4.5.2 *EO Plant*

A schematic of the *EO-Plant* is shown in Figure 4-5, which is an innovative solution to EOD of mine tailings. The proposed *EO-Plant* is an artificial transpiration-photovoltaic system to implement EOD in the field with water removal capabilities.

The *EO-Plant* will replicate transpiration-induced water uptake of plant root systems with capillary tubes. Kamchoom et al. (2015) used high-air-entry porous medium to form capillaries with vacuum pressures to replicate plant root systems during centrifuge tests investigating failure mechanisms of mechanically reinforced slopes with roots systems. The capillaries were sufficient in simulating the transpiration-induced suction of a root system. The capillary tubes for the *EO-Plant* should be capable of spreading under the tailings surface to capture water in the capillaries, therefore functioning as water removal for the EOD system.

The “stem” of the *EO-Plant* will encapsulate the capillary tubes and be made of conductive material to function as the electrodes to induce electrical flow. Water will flow to the cathode and be captured by the capillary tubes. The capillary tubes will draw water from the tailings into the upper part of the *EO-Plant*. This upper part of the *EO-Plant* also will include capillary tubes, but the material will be a flexible solar cell membrane where water can evaporate.

Current research indicates that solar panels can be printed on or with flexible material that is durable (Brucjstummer, 2018; Aube1, 2019). Power for the electrodes will be provided using solar energy. The capillary tubes will span from the tailings into the flexible material of the solar panels to create a larger surface area for evaporation of water. Hence, this flexible solar panel and capillary tube system will function as a “leaf”, using the sun for energy and evaporating water from the system.

The challenge with tailings salinity and salt crust formation during evaporation of water from the tailings will also be addressed with the “leaf” of the *EO-Plant*. The “leaf” will be flexible such that wind will continuously agitate the *EO-Plant* and the “leaves” can function as salt wicking membranes, continuously removing buildup of salt as the material moves in the wind. Research into the effect of increasing salinity on the effectiveness of EOD is needed because as water is removed from the tailings, salts may be retained within the tailings pore water or be returned to the tailings surface during the salt wicking processes.

The *EO-plant* system has no mechanical parts, allowing for simple installation and maintenance. Additional proof-of-concept testing for the *EO-Plant* will be completed via evaluating fundamental processes included in the *EO-Plant* with mine tailings. For example, moisture-wicking capillary tubes from commercially available geosynthetics will be used to simulate the capillary-tube concept of removing water from the tailings near the anode. In

addition, 3D printing will be used to create a prototype *EO-Plant* that includes all components of the final product and can be installed in laboratory test cells to evaluate functionality of the system.

4.6 Potential Future Applications of EOD

4.6.1 Applications in Mine Tailings Management

There are two additional potential applications of EOD in TSFs. A common concern for a tailings dam is the presence of a high phreatic surface close to the dam crest, which can reduce geotechnical stability by decreasing effective stress and adding additional water weight to the driving force. Concept 1 is shown in Figure 4-6 and is considered for the condition of a centerline TSF where an anode could be constructed within the centerline of the dam (e.g., as part of the jacking header used to support tailings discharge infrastructure), and the cathode constructed elsewhere in the TSF. The EOD system could draw water away from the tailings dam face and lower the phreatic surface. The continuous movement of water away from the dam face would require a water removal system or pump in place at the cathode. The anode would be elongated in the centerline dam (e.g., elongated as the jacking header is elongated) as the dam was raised with increasing tailings volume, while the cathode and pump must move with the TSF expansion.

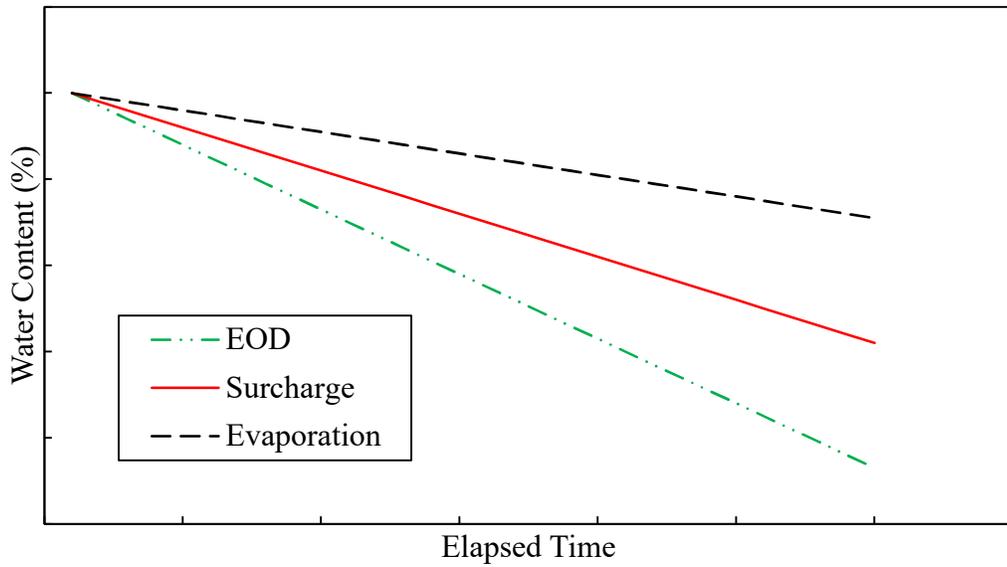
The research of EOD effectiveness concerning voltage requirements and electrode spacing is necessary for this tailings crest dewatering application. However, since this concept would be more focused on water removal from near the dam face versus shear strength gain in soft tailings, the cathode could be placed within the beach region to promote unsaturated conditions under the crest and control seepage through the dam. Therefore, the EOD system in Concept 1 would function as a method for stabilization of the embankment. Generally, EOD has been shown to not be very effective in unsaturated and coarse-grained soils, which are typically characteristics of the

beach zone. Research into the effects of unsaturated zones and the application of electrical currents should be considered to determine if there is a way to maintain the phreatic surface far from the dam face while also producing current within the unsaturated zones.

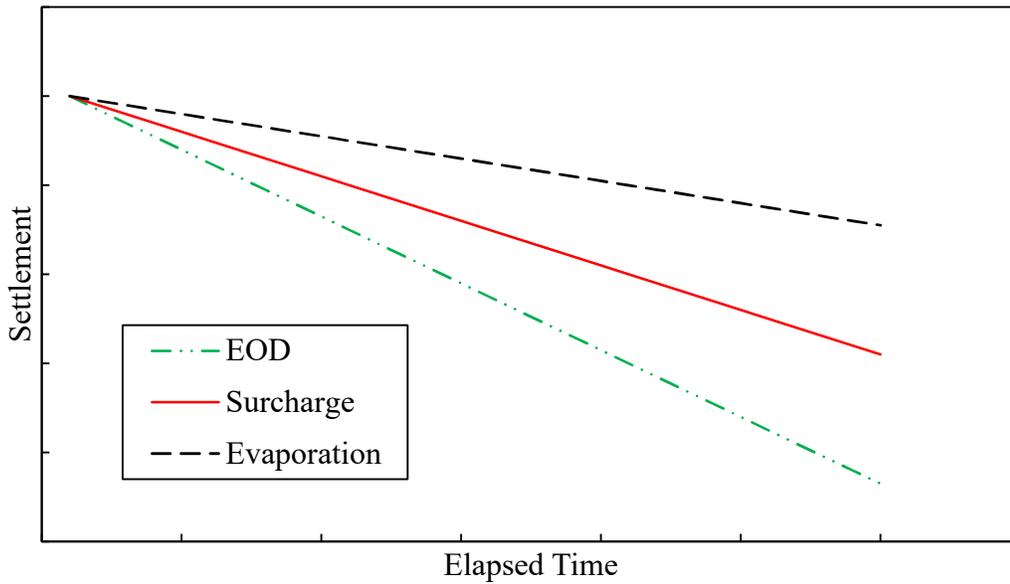
Concept 2 is shown in Figure 4-7 as a method applicable if installed prior to initial slurry placement and throughout tailings deposition within the impoundment. The method uses EOD geocomposites installed between layers of slurry tailings. The EOD geocomposites would include electro-kinetic geosynthetic (EKG) capabilities to promote EO flow vertically and horizontal drainage (Figure 4-10). This drainage layer will include an anode (-) element on the bottom, a drainage element in the middle, and a cathode (+) element on the top. Electroosmotic dewatering speeds up drainage time compared to simple drainage layers, relying on surcharge induced flow, gravity flow and EOD flow.

Steps of installation would begin during TSF construction with a drainage system installed at the base of the TSF. The bottom drainage layer would include a cathode (+) element that would draw water towards the drainage layer once the electrode is coupled with an anode (-). After deposition of some specified thickness of tailings (e.g., 3 m), deposition must be stopped so that the next EKG geo-composite drainage layer can be installed. Tailings slurry deposition may then continue on the layer of EKG geo-composite, and the cycle will continue. The tailings deposited above the newest EKG geo-composite layer will not be subjected to the process of EO as the electrode facing upwards will not be coupled with the opposite electrode until the next layer is installed, therefore, evaporation and gravity flow will be the only means of dewatering in the top layer during tailings deposition. Each intermittent drainage layer must be connected, via some means, to either the bottom gravity drainage or a pump system. As the tailings impoundment is

filled and more layers of EKG geo-composite are added the drainage system will need to be elongated and revised.



(a)



(b)

Figure 4-1. Anticipated temporal trends of average surficial (a) water content and (b) settlement within mine tailings for dewatering experiments that include electroosmotic dewatering (EOD), surface surcharge application, and evaporation.

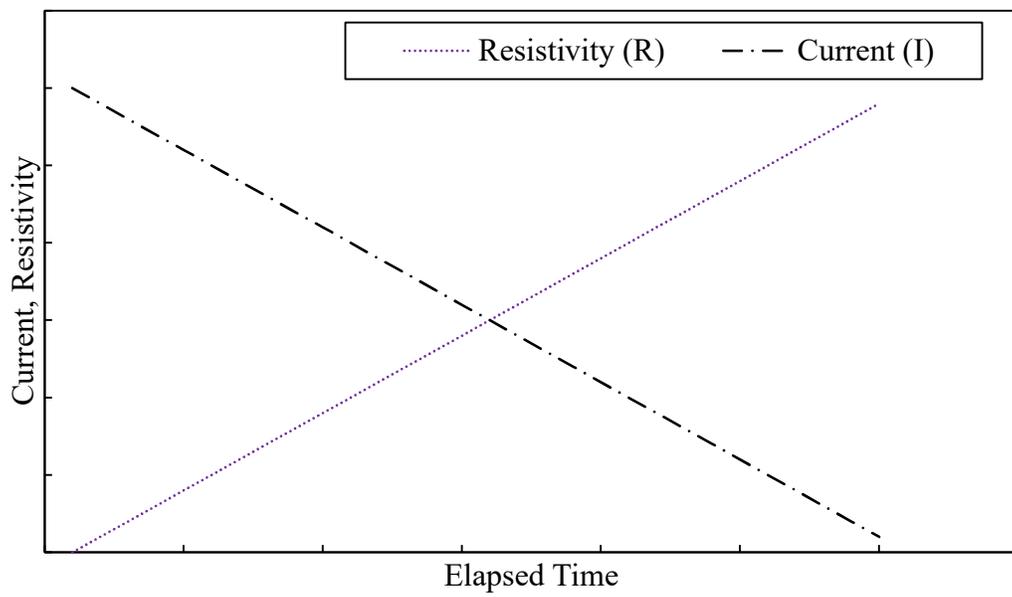
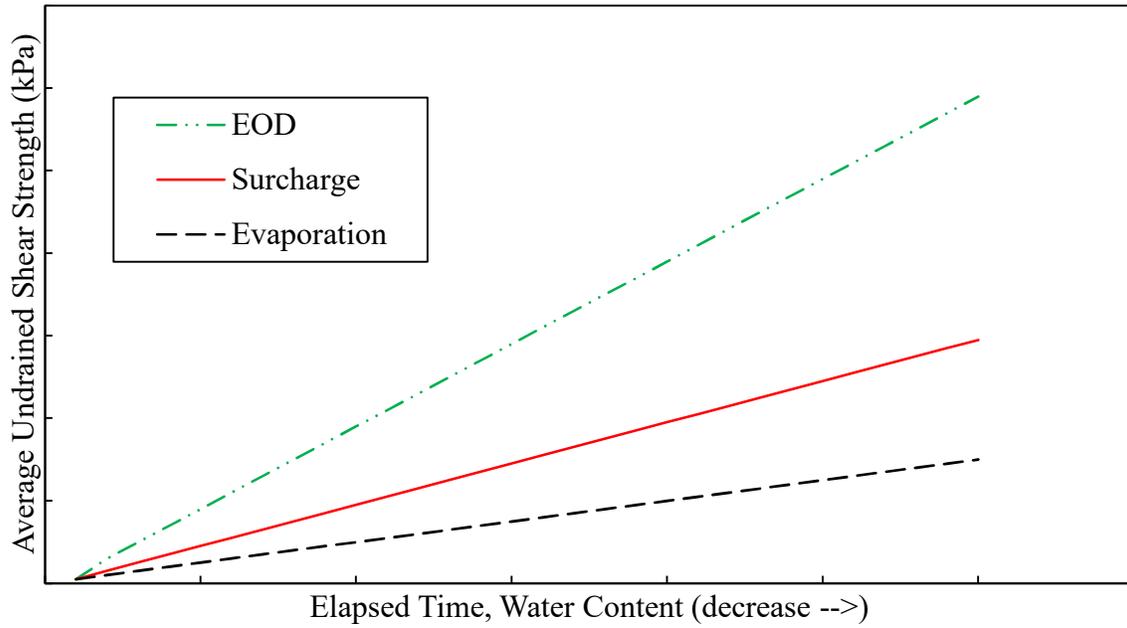
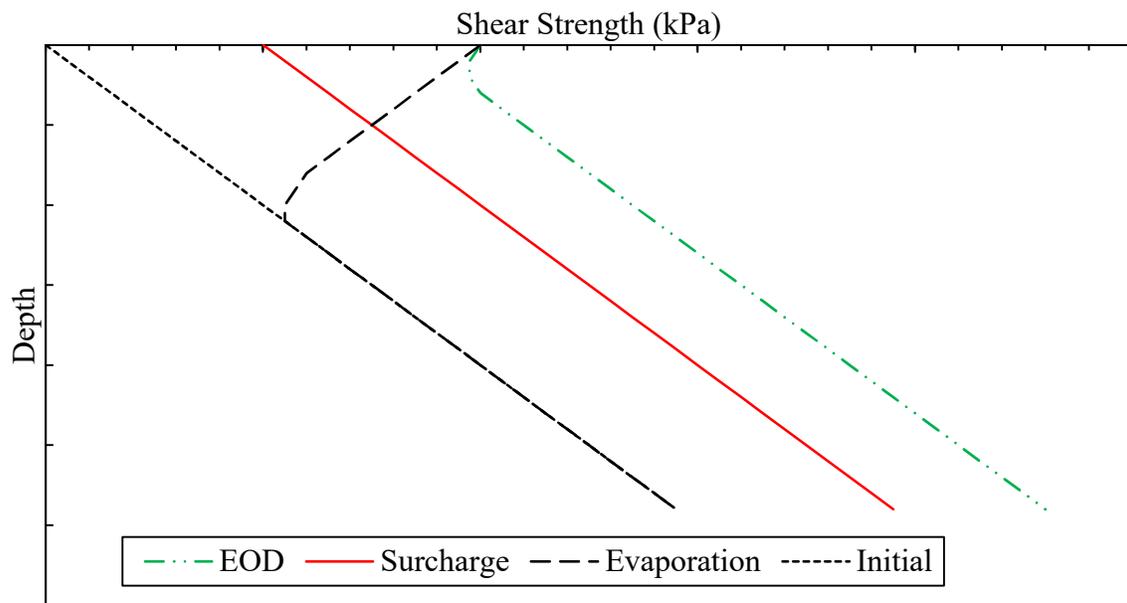


Figure 4-2. Anticipated temporal trends in current (I) and resistivity (R) within the mine tailings during operation of the electroosmotic dewatering experiment.



(a)



(b)

Figure 4-3. Anticipated trends of (a) average undrained shear strength as a function of time and water content and (b) shear strength as a function of depth in mine tailings for dewatering experiments that include electroosmotic dewatering (EOD), surface surcharge application, and evaporation.

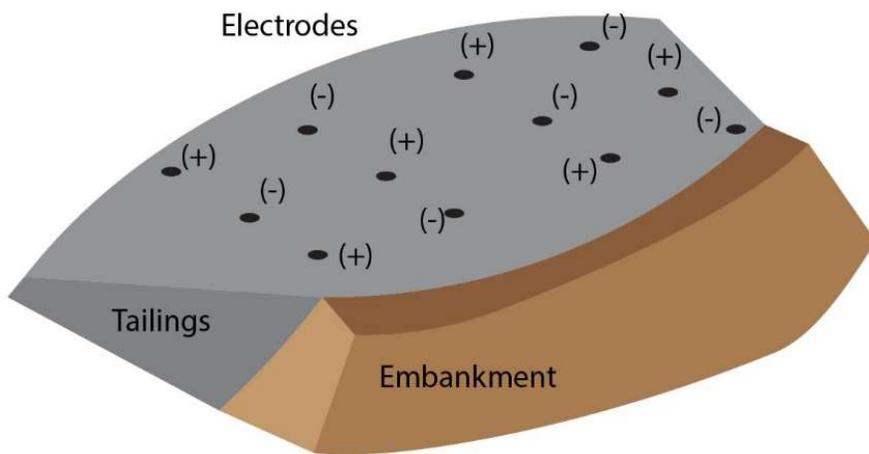


Figure 4-4. Ideal grid spacing for anodes (-) and cathodes (+) of an electroosmotic dewatering system in a tailings storage facility.

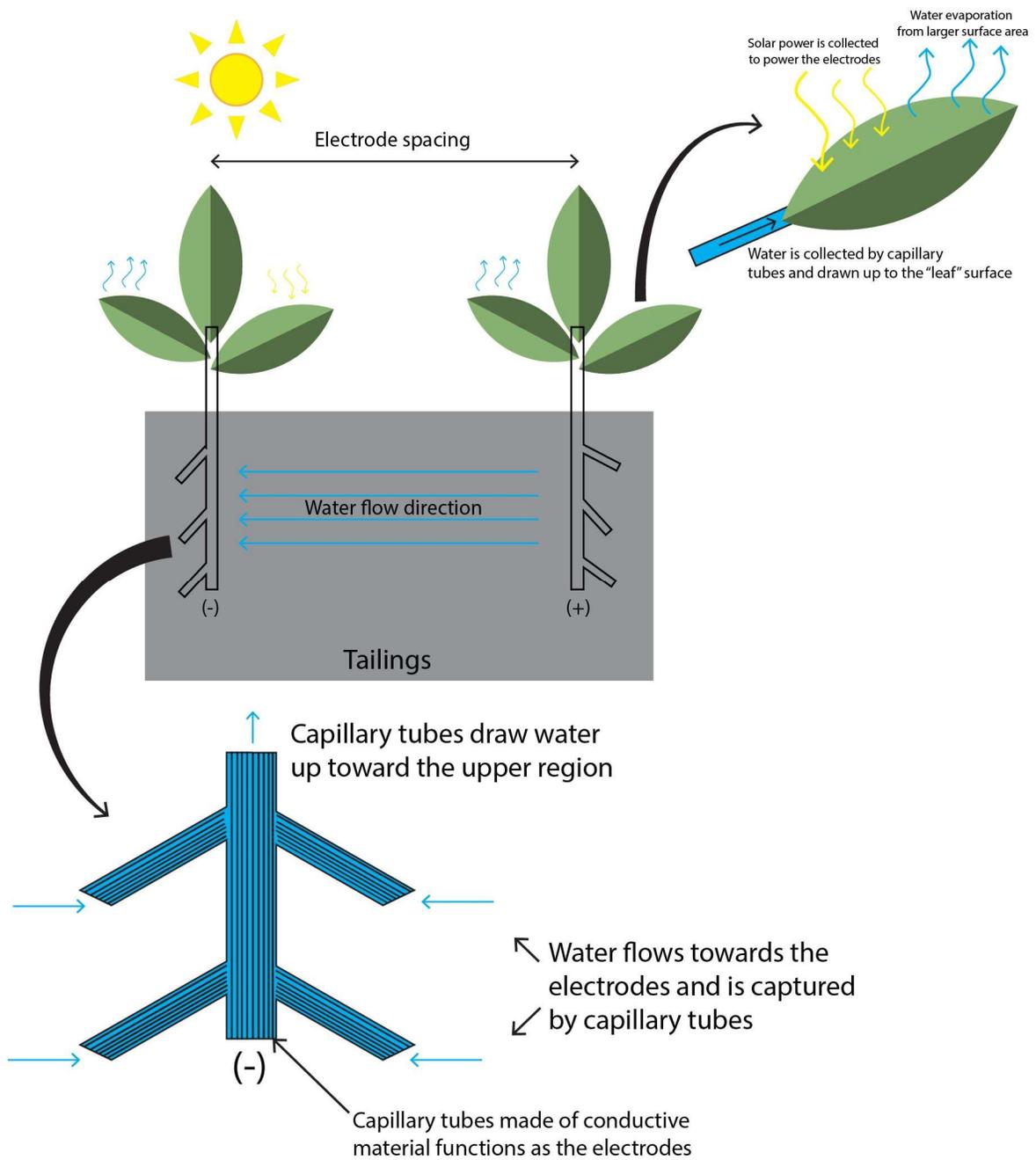


Figure 4-5. Schematics of the *EO-Plant*: an artificial electroosmotic dewatering unit that couples transpiration and photovoltaics.

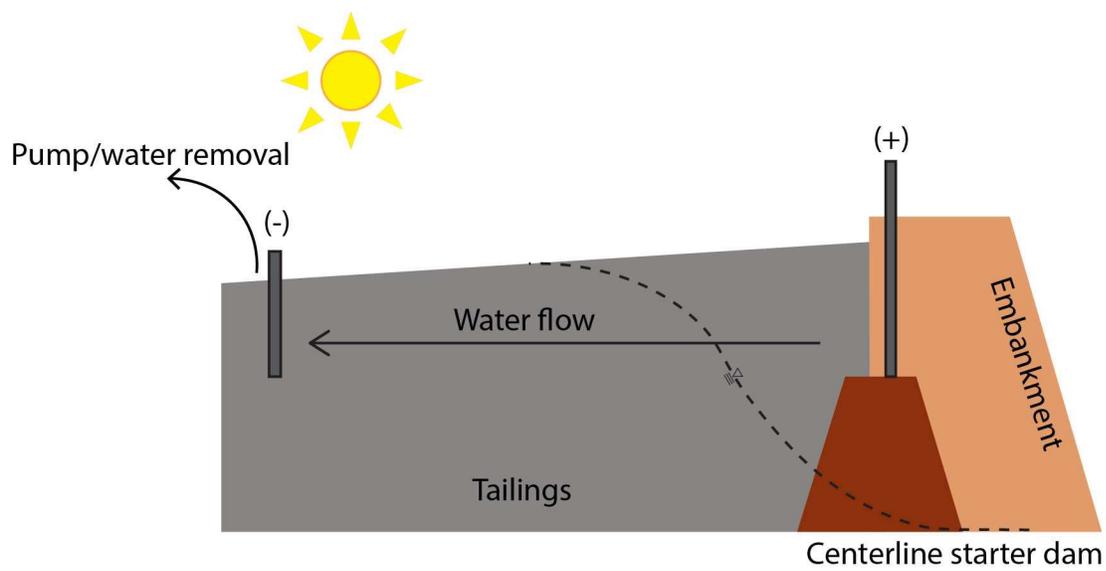


Figure 4-6. Concept 1 schematic: electroosmotic dewatering system incorporated into a centerline tailings dam to promote dewatering and lowering of the phreatic surface.

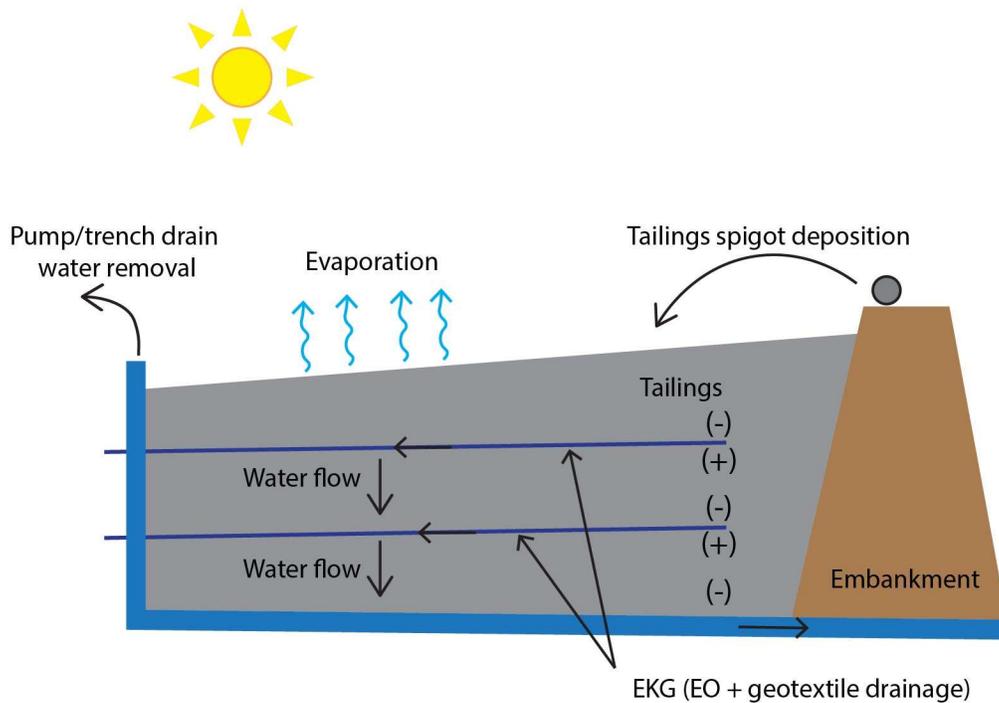


Figure 4-7. Concept 2 schematic: electroosmotic dewatering systems installed in a tailings impoundment during slurry placement that uses electrokinetic geocomposites installed between layers of deposited slurry tailings.

5 SUMMARY AND CONCLUSIONS

This thesis focuses on electroosmotic dewatering of mine tailings with the purpose of increasing undrained shear strength of surficial mine tailings. A literature review was conducted, and relevant information compiled to provide context and explanation of the intended method and potential applications for stabilizing tailings impoundment surfaces.

Background on mine tailings, electroosmotic processes, and undrained shear strength behaviors in mine tailings are discussed in Chapter 2. Factors that influence EOD of tailings include electrodes used, pore fluid chemistry, degree of saturation, voltage gradient and electrode configuration. A series of experimental trials were conducted to provide guidance on method procedure development and future work plan, as documented in Appendix A.

Proposed research methods and a bench-scale experiment were described in Chapter 3. Laboratory-scale dewatering experiments are proposed on tailings from a gold mine in Central America that experienced closure challenges due to soft tailings and a kaolin-silica flour blend (i.e., fine-synthetic tailings, FST). The experiment will allow the assessment of the effectiveness of EOD to increase undrained shear strength compared to methods of surcharge loading and evaporation. Research hypotheses include the following: (1) electroosmotic dewatering increases undrained shear strength of saturated surficial mine tailings more rapidly compared to other techniques; and (2) electroosmotic dewatering increases undrained shear strength as a function of depth more effectively compared to other techniques. Anticipated data trends are proposed and show that EOD is expected to be more effective for increasing undrained shear strength more quickly and as a function of depth, compared to other techniques.

Possible reasons why EOD has not been implemented at larger scales in the mine industry are lack of a developed procedure, difficult water removal, and/or lack of a commercially available

EOD unit. The proposed experimental plan is broken into three phases including anticipated results of bench-scale experiments, field-scale experimental considerations and full-scale application considerations. An EOD unit consisting of a moisture wicking synthetic capillary drain unit coupled with electroosmotic dewatering is proposed and termed the *EO Plant*.

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APPENDIX A

Preliminary Electroosmotic Tests

Summaries of the preliminary electroosmotic dewatering trial experiments are in Table 0-1 and Table A-2. Mine tailings specimens were prepared as slurry using a stand mixer or spatula. Tap water was added to the slurry until the consistency visually exceeded the liquid limit, and then allowed to sit for 24 hr to promote hydration. Water content of each slurry was measured prior to creating test specimens. The preliminary trials, described herein, were used qualitatively to inform the proposed experimental procedure. The materials included tailings from a gold mine in North America, tailings from a gold mine in Central America, kaolin, and fine-synthetic tailings (FST).

Trial 0

The objective of Trial 0 was to determine if a current was transmitted through the mine tailings. A photograph of Trial 0 is shown in Figure 0-1. A small light bulb was inserted into the slurry mine tailings to confirm that a current was transmitted through the material. The bulb lit up, which indicated that voltage transferred through the slurry tailings and a current developed.

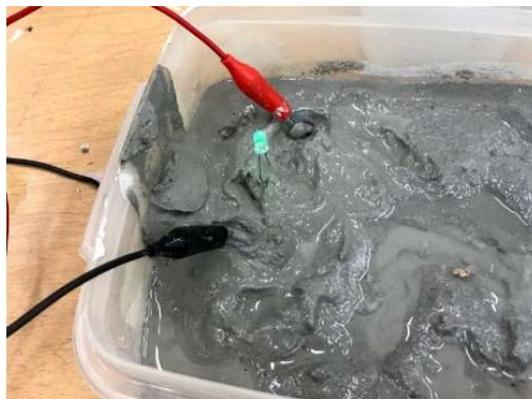


Figure 0-1. Photograph of Trial 0.

Trial 1

Trial 1 was performed on mine tailings from a gold mine in North America to evaluate voltage capacity of laboratory equipment. A photograph of Trial 1 is shown in Figure 0-2. Voltage up to 102 V was applied for 1 hr. Applying a high voltage is dangerous and does not agree with proposed low voltage applications for EOD systems. A voltage < 42 V was identified as a safe upper-bound (as 42 V tends to produce less than 200 mA of current). In addition, corrosion was observed from the steel screws used as electrodes. Trial 1 revealed that a non-corrosive material is required for electrodes in EOD.

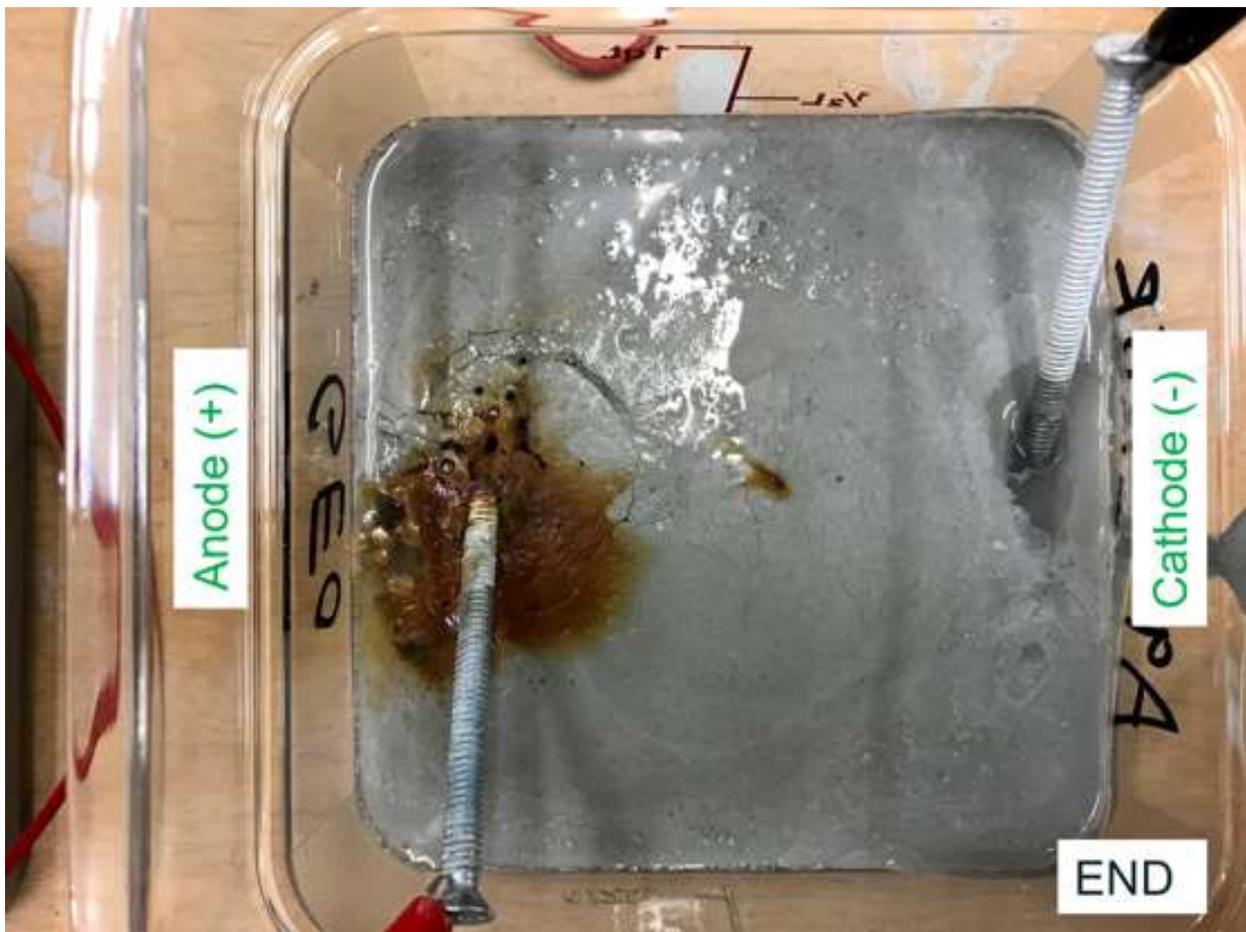


Figure 0-2. Photograph of Trial 1.

Trial 2

Trial 2 was performed on mine tailings from a gold mine in North America. A photograph of Trial 2 is shown in Figure 0-3. The objective of Trial 2 was to begin designing a drain system for the EO test. The trial ran for 6 hr with voltage in the range of 40-70V. Extensive corrosion was observed of the anode electrode. A first attempt at a drain was created by using thick walled tubing, with small holes drilled into the sides. Geotextile filter was wrapped around the drain tubes and the drain units were connected to the electrodes on the anode and cathode side using tape. The mine tailings from the gold mine in North America were too coarse to provide helpful information on the effectiveness of EO. The drain unit had potential effectiveness with modifications.

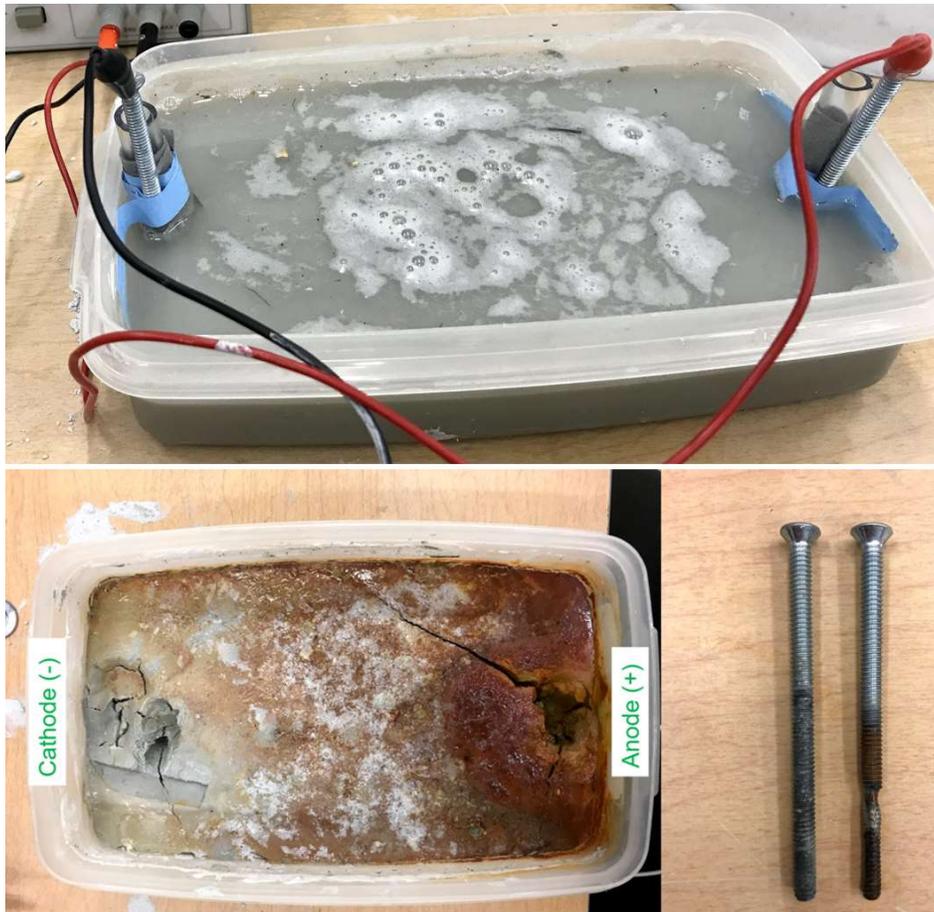


Figure 0-3. Photographs of Trial 2.

Trial 3

Trial 3 was performed on kaolin. A photograph of Trial 3 is shown in Figure 0-4. Galvanized steel electrodes were used that minimized corrosion during the 18 hr trial. Applied voltage ranged from 10-90 V for the first 3 hr, and 12 V for 15 hr overnight. Voltages were varied to observe soil and water behavior, with the final 12 V chosen for overnight because this voltage would be safe to leave unattended.

The initial water content was 137%. A separate container of soil was set out as an evaporation test to determine water loss from evaporation compared to water loss from EOD. The final water content in the evaporation test was 121%, which resulted in 16% water loss. The final water content in the EOD test at the anode was 114% and at the cathode was 120%. In theory, water is migrating away from the anode (drying the soil out) and moving towards to the cathode. The water content at the cathode was anticipated to be similar to evaporation water content levels because water is continually replenished at the cathode.

Filter paper was used to remove water from the drain, expose water to a larger surface area for evaporation, and wick salt from the surface. Cracks were observed near the cathode and may have developed from consolidation due to EOD, rather than desiccation. Red dye was added to holes made in the center of the specimen, in an attempt to see water migration. However, the dye particles must not have had any charge and remained in the holes while water separated from the dye particles and was removed.

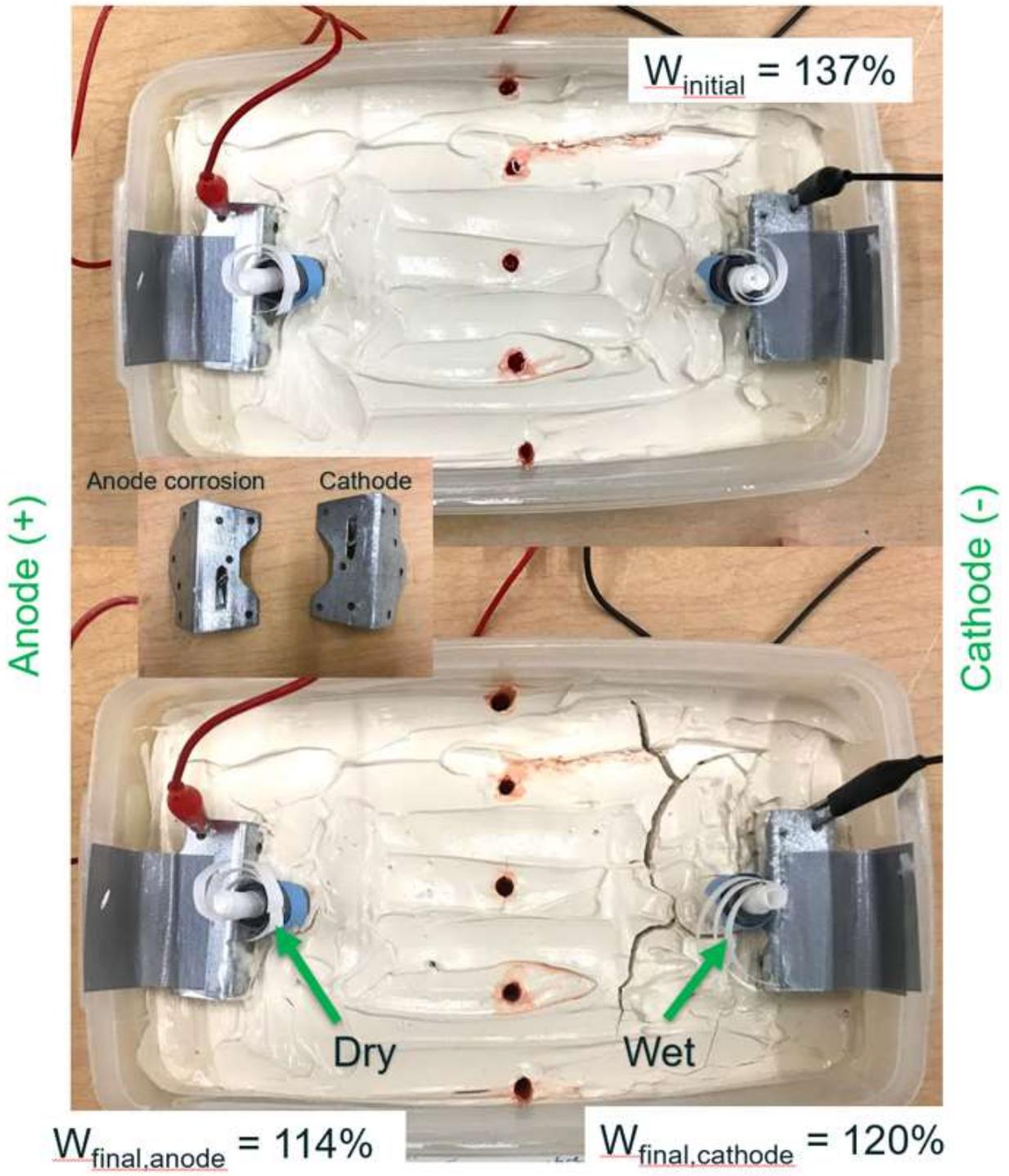


Figure 0-4. Photographs from Trial 3.

Trial 4

Trial 4 was performed on kaolin, with added NaCl (salt). A photograph of Trial 4 is shown in Figure 0-5. The objective of Trial 4 was to determine if water migration could be accelerated in soil that contains a highly conductive pore fluid. Despite high current application, only low voltage was obtained. The trial was terminated after 1 hr and the electric conductivity (EC) measured. The soil EC was 75 mS/cm, and may have been too conductive. According to Ohms law, ($V = IR$, voltage = current x resistivity), the limited resistance in the soil was attributed to the conductive salt solution requiring a high current to obtain a voltage. The trial revealed that a very conductive solution will require a high current to produce a voltage.



Figure 0-5. Photograph of Trial 4.

Trial 5

Trial 5 was performed on MT1. A photograph of Trial 5 is shown in Figure 0-6. The objective of Trial 5 was to determine if EOD would be feasible on the MT samples. The trial operated for 21 hr at 12 V and had a voltage gradient of 1.5 V/cm. The initial water content was 63%. The final water content at the anode was 42% and 54% at the cathode. On average, water loss was 10%. Water loss due to evaporation was not evaluated during this trial. Trial 5 indicated that EOD was feasible on the mine tailing intended for the larger laboratory experiment. Consolidation cracks around the cathode and salt crust formation on the “flag” drain filter paper were observed.

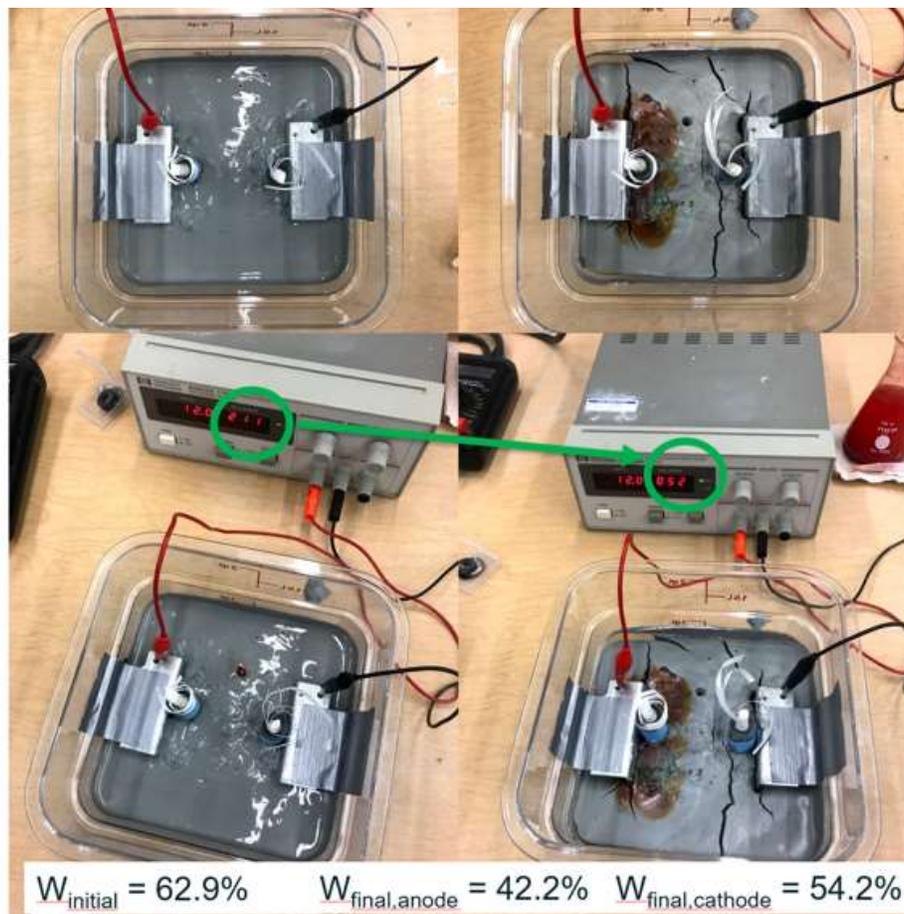


Figure 0-6. Photographs of Trial 5.

Trial 6

Trial 6 was performed on MTX with titanium mesh used as the electrodes. A photograph of Trial 6 is shown in Figure 0-7. The objective was to test an experimental design representative of anticipated larger-scale laboratory experiments. The trial was run for 23 hr with 12 V applied across a 14 cm cathode-to-anode spacing that yielded a voltage gradient 0.9 V/cm. The current reduced from 117 mA at the start of the test to 32 mA at the end. This trial demonstrated that the mine tailings becomes more resistant with time, which was attributed to de-saturation, reduced contact with the electrodes, and/or consolidation. Increased resistance results in a lower amperage for a constant applied voltage. Gas bubbles were observed at the anode and cathode. Previous trials demonstrated that the rate of generation of gas was dependent on the voltage gradient.

The initial water content of the MTX slurry was 50%, and the final water content based on mass loss was 38%. Water content samples were exhumed across the specimen and the distribution of the water contents is shown in Figure 0-7. Although the difference between initial and final average water contents indicated a reduction of 12%, higher water contents were observed near the cathode and lower water contents near the anode. In addition, surface cracks formed near the cathode, suggesting that the tailings experienced shrinkage during consolidation and de-saturation. These changes contribute to how much current can pass through the specimen and influence overall effectiveness of EOD. As discussed in Chapter 2, the presence of cracks would indicate less than saturated conditions; therefore, cracks would reduce EOD efficiency while also indicating an increase in shear strength.

A further research query would be to investigate how deep the cracks form in regards to the electrodes (e.g., do the cracks go to the same depths as the electrodes). The shrinkage was non-uniform, which made volume calculations difficult. Water was leaving through the cathode

side, and no drainpipe was placed at the anode. The drain potentially hinders dewatering; an alternative drain unit would consist of a geotextile filter and a sponge, whereby the sponge can act as a capillary drain.

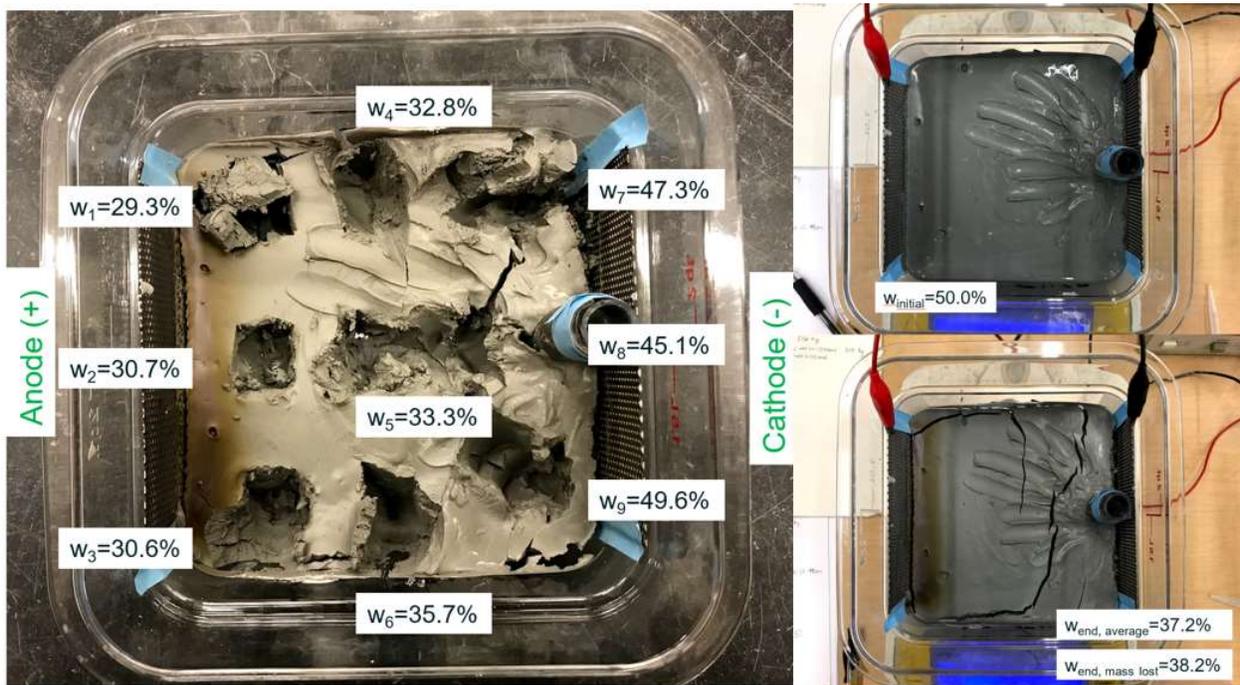


Figure 0-7. Photographs of Trial 6.

Trial 7

Trial 7 was performed on MTX to evaluate if a vertical “evaporation drain” composed of a sponge wrapped in geotextile would be capable of removing water adjacent to the cathode. A photograph of Trial 7 is shown in Figure 0-3. The trial was run for 42 hr with a voltage gradient of 0.9 V/cm (12 V applied across 14 cm). Titanium mesh was used as the electrodes.

Consolidation cracking and non-uniform shrinkage were observed on the surface as shown in Figure 0-8, which may have developed due to unceremonious pouring of the slurry into the container when the specimen was created. The initial water content was 93% and final water content based on mass loss was 65% (average water content reduction $\approx 28\%$). The average final water content based on water content samples exhumed from the specimen was 58%; 49% near the anode and 67% near the cathode. These measurements indicate the tailings near the cathode remained at water contents higher than the average while tailings near the anode desaturate.

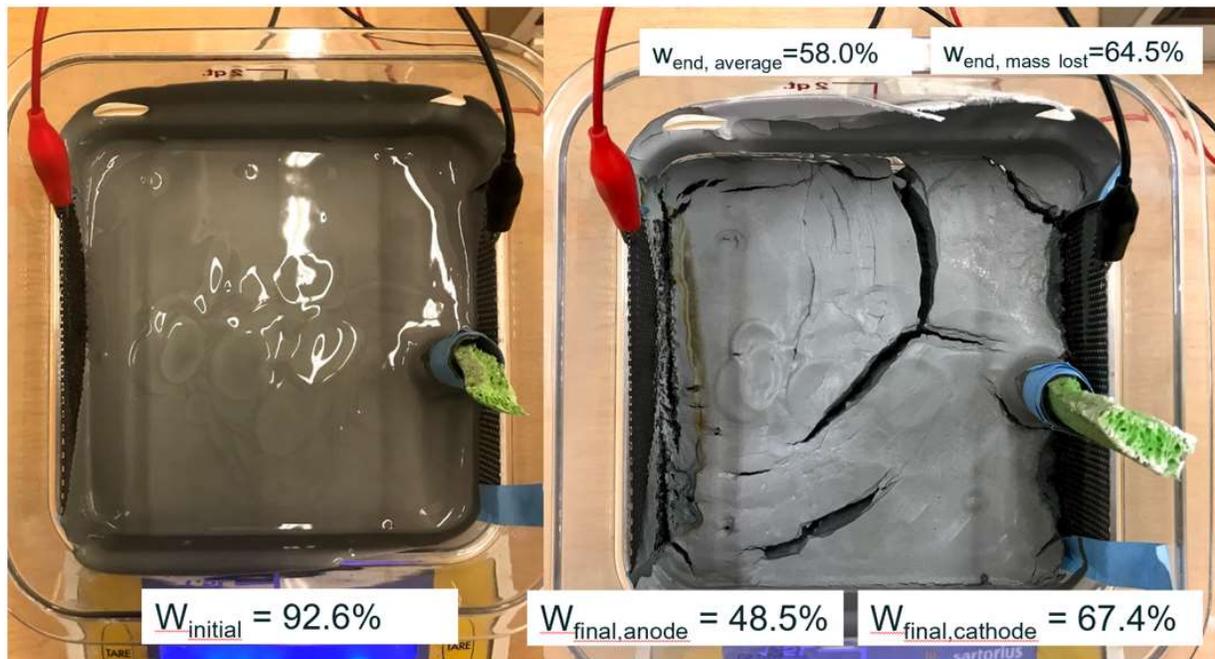


Figure 0-8. Photographs of Trial 7.

Trial 8

Trial 8 was performed on MTX to evaluate how water migration is affected with an electrode configuration of a single, central cathode and two anodes on either side as shown in Figure 0-9. The test ran for 95 hr at a voltage gradient of 0.3 V/cm (3 V applied across 10 cm in both directions). Titanium mesh was used as electrodes and a sponge/geotextile drain was used for water removal adjacent to the cathode.

Extensive loss of contact between the tailings and electrode developed (Figure 0-9), which reduced efficacy of establishing a current across the specimen. Observations from Trial 8 suggested that specimen depth and material boundaries are important factors when designing an EOD experiment. For example, the container used (as seen in Figure 0-9) had rounded edges and a bowed bottom, which resulted in a thinner specimen towards the center of the container compared to the left and right sides of the container. The electrode used in the center cut through almost the entire width of the specimen, causing the specimen to crack significantly down the center. Because the edges were slanted outwards, the electrodes separated from the tailings as water moved, and had to be repositioned (e.g., see angle of the outer electrodes in the figure on the left compared to the angle of the electrodes in the figure on the right). Based on these observations, the EOD specimen should have straight edged sides, the electrodes should be secured on the edges rather than positioned in the center, and thickness of the specimen should be consistent.

A separate specimen was used to evaluate evaporation from the surface of test specimens, as seen in Figure 0-10, considered the evaporation cell. Comparable surface area was observed to be important when creating the evaporation tests.

The temporal trend of water content for the EOD and evaporation cells based on total mass measurements are shown in Figure 0-11. The results show that evaporation was as effective at

lowering the water content relative to EOD. However, the sponge in the EOD cell crusted over with salt, which may have decreased water removal effectiveness. In addition, factors such as specimen surface area and depth must be considered in future trials to more appropriately compare water removal effectiveness between evaporation and EOD.



Figure 0-9. Photographs from EOD cells of Trial 8.



Figure 0-10. Photographs of evaporation cells of Trial 8.

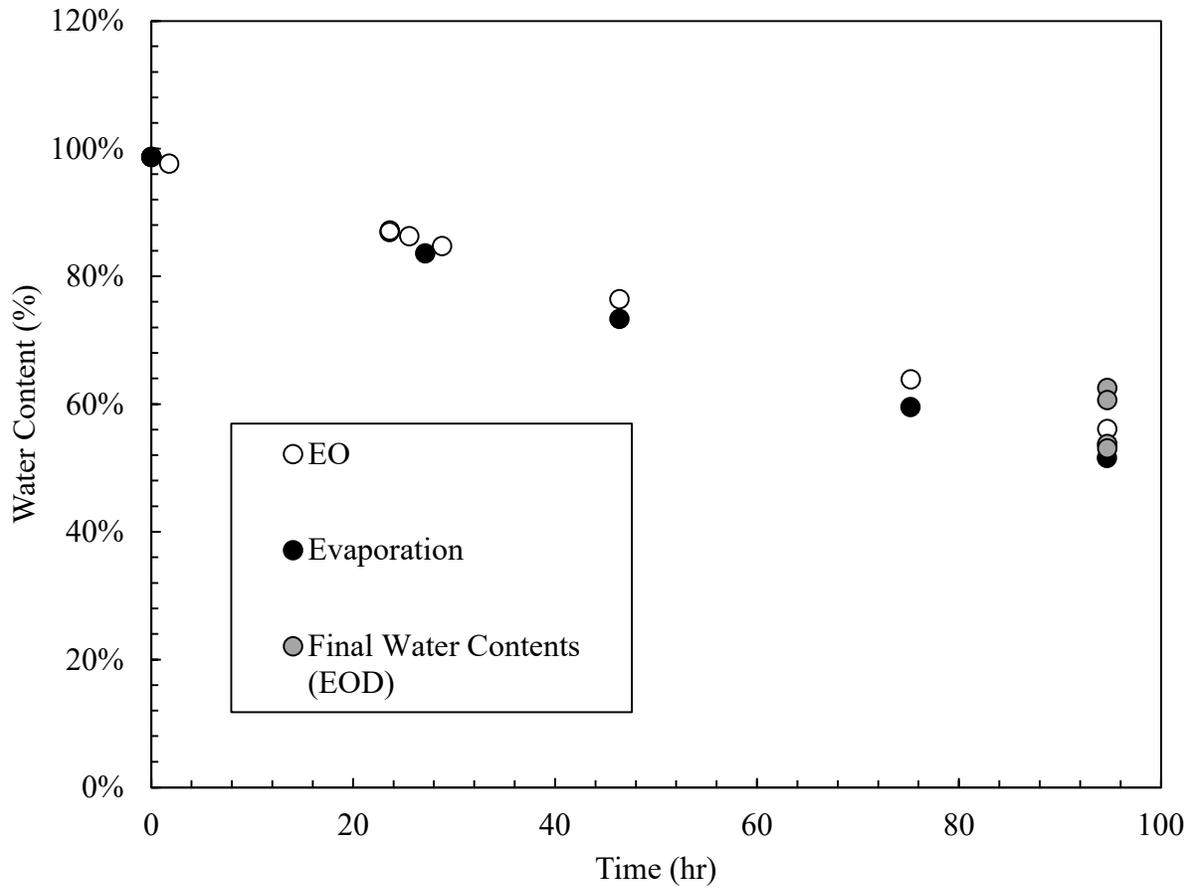


Figure 0-11. Temporal trend of water contents in the electroosmotic (EO) test cell and evaporation test cell based on mass loss. Final water content measurements conducted on exhumed samples from the EO test cell also are shown.

Trial 9

Trial 9 was performed on MTX to evaluate more uniform test specimens and consider the voltage gradient to use for the EOD experiment. The specimens included a 6 cm height by 16 cm wide specimen with a larger sponge for the drain as shown in Figure 0-12. The test ran for approximately 111 hr at a voltage gradient of 0.7 V/cm (9 V applied over 13 cm). Titanium mesh was used as electrodes. The sponge was fixed in place with tape to prevent the sponge from floating out of the tailings due to buoyance forces.

An objective for this test was to see if a larger sponge would increase evaporation; however, the sponge tended to float above the tailings and was therefore not in direct contact with much the specimen. The initial water content was 136% and the final water content was 95%. The results informed the process of inserting pre-wet sponges, lower voltage gradients to generate less chlorine and hydrogen gas, and starting from lower water contents (100% or less) would provide the necessary data. An evaporation test was performed for the trial, as seen in Figure 0-13; however, the surface areas of the tests not comparable and results in lower water contents in the evaporation test at the end of testing compared to the EOD test, as seen in Figure 0-14.



Figure 0-12. Photographs of Trial 9 electroosmotic test cell.



Figure 0-13. Photographs of Trial 9 evaporation test cell.

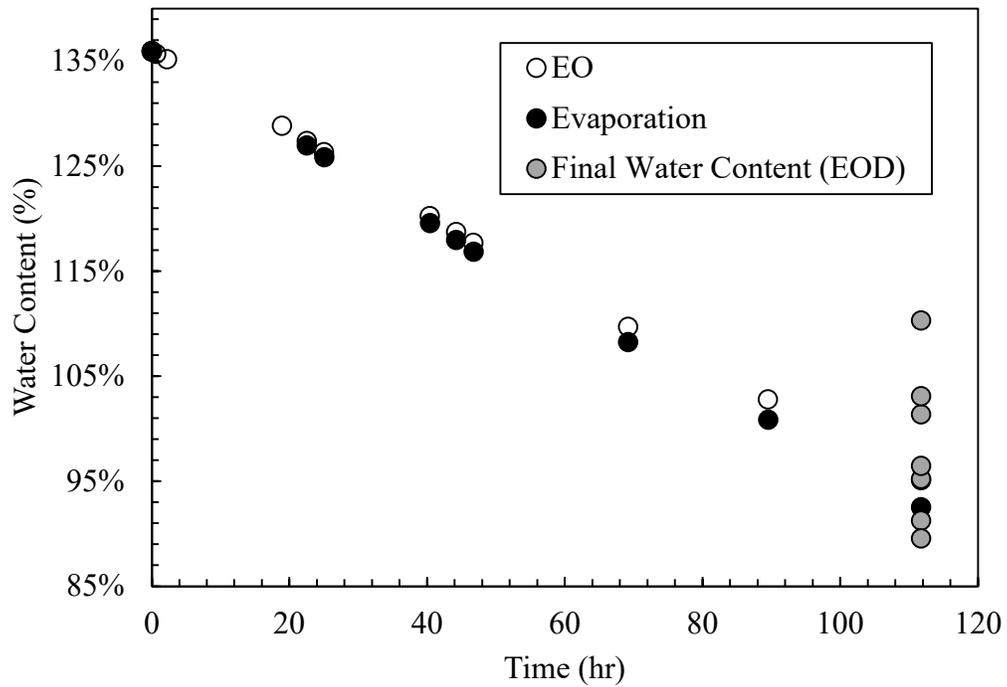


Figure 0-14 Temporal trend of water contents in the electroosmotic (EO) test cell and evaporation test cell based on mass loss. Final water content measurements conducted on exhumed samples from the EO test cell also are shown.

Trial: FST Trial w/ DI water

The objective of this trial was to use fine-synthetic tailings (FST) to evaluate the relationship between EO and pore fluid chemistry. This trial was performed, but no termination analysis was possible to the extent desired due to external factors. Figure 0-15 shows the sponge and geotextile drain unit used in the EV and EO specimens, the initial specimens, and the initial and final surface areas of the EOD specimen, and the cracks with depths of the EOD specimen at termination. Figure 0-16 shows the water contents with time as mass decreases with time.

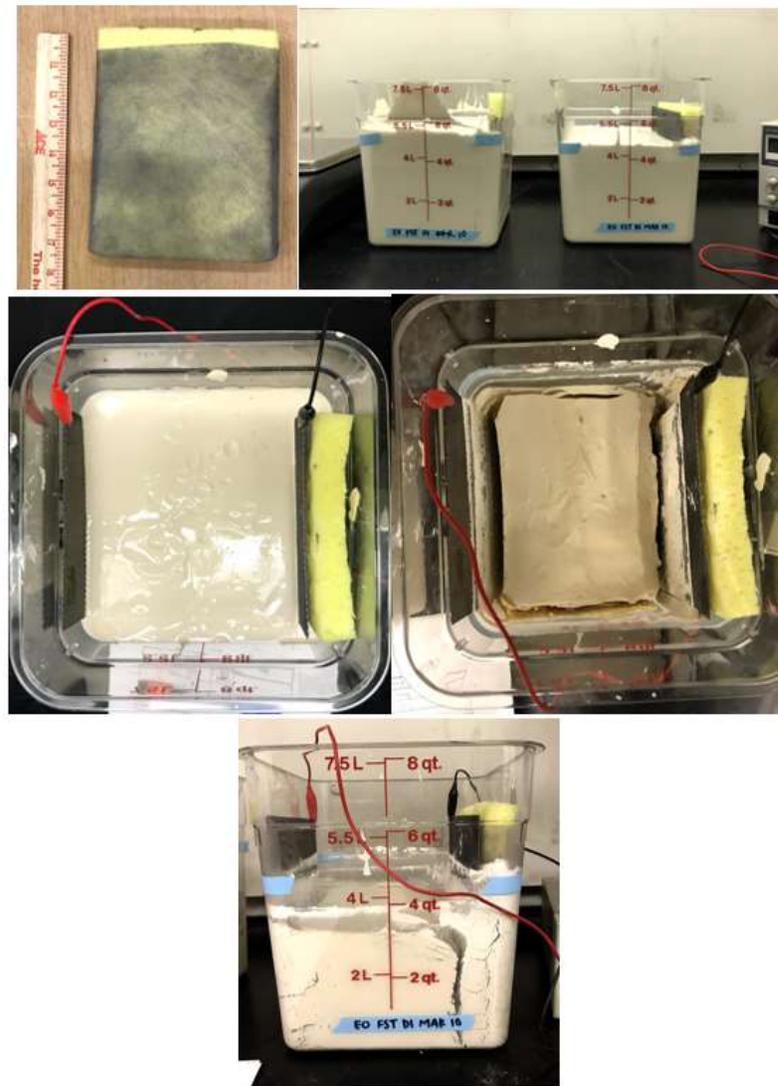


Figure 0-15. Photographs of the FST Trial.

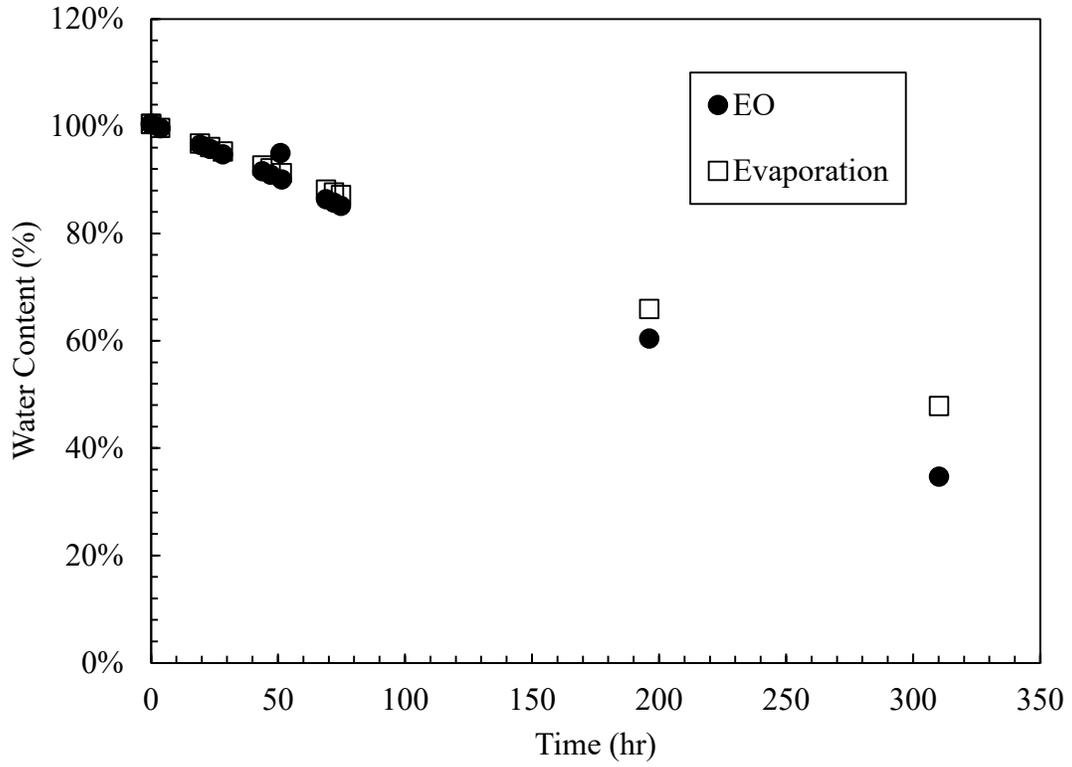


Figure 0-16. Temporal trend of water contents in the electroosmotic (EO) test cell and evaporation test cell based on mass loss.

Tables

Table 0-1 Trial Summary

Trial No.	Material	Electrode Material	Cathode-Anode Spacing	Voltage	Voltage Gradient	Duration	Initial Amps	Final Amps	Initial Water Content	Final Water Content
0	Coarse tailings gold mine in North America	Galvanized steel washers								
1	Coarse tailings gold mine in North America	Steel screws		up to 102 V		1 hr				
2	Coarse tailings gold mine in North America	Steel screws		40-70V		6 hr				
3	kaolin	Galvanized steel		10-90V		18 hr			137%	114% (anode) 120% (cathode)
4	kaolin, with added NaCl (salt)	Galvanized steel		n/a		1 hr				

Notes: Blank cells indicate n/a = not analyzed.

Table 0-1 Trial Summary (continued)

Trial No.	Material	Electrode Material	Cathode-Anode Spacing	Voltage	Voltage Gradient	Duration	Initial Amps	Final Amps	Initial Water Content	Final Water Content
5	MT1	Galvanized steel	8 cm	12 V	1.5 V/cm	21 hr			63%	42% (anode) 54% (cathode)
6	MTX	Titanium mesh	14 cm	12 V	0.9 V/cm	23 hr	117 mA	32 mA	50%	38%
7	MTX	Titanium mesh	14 cm	12 V	0.9 V/cm	42 hr			93%	65% 49% (anode) 67% (cathode)
8	MTX	Titanium mesh	10 cm	3 V	0.3 V/cm	95 hr			98.7%	54% 54%, 61% (anode) 63% (cathode)
9	MTX	Titanium mesh	13 cm	9 V	0.7 V/cm	111 hr			136%	95%
10	(FST)	Titanium mesh	15 cm	4.8 V	0.3 V/cm	310 hr			100%	35%

Notes: Blank cells indicate n/a = not analyzed.

Table 0-2 Key Observations

Trial No.	Key Observations
0	Applied voltage can be transferred through the slurry mine tailings and a current will develop.
1	Voltage < 42 V was identified as a safe upper-bound for voltage application and a non-corrosive material is required to be used as electrodes in EOD.
2	A drainage system can be designed for the EO test using geotextile and tubing.
3	Higher water contents are present near the cathode as water migrates from the anode to the cathode. A more developed drain system was used with a filter paper.
4	A very conductive solution or soil will require a very high current to produce a voltage.
5	EOD was feasible on the mine tailings intended for the full experiment.
6	Mine tailings becomes more resistant with time due to de-saturation, reduced contact with the electrodes, and/or consolidation. The drain potentially hinders dewatering; an alternative drain unit would consist of the geotextile filter and a sponge.
7	Consolidation cracking and non-uniform shrinkage were observed on the surface and tailings near the cathode remaining at evaporation water contents while the tailings surrounding the anode de-saturates.
8	Observations from Trial 8 suggested that specimen depth and material boundaries are important factors when designing an EOD experiment.
9	The process of inserting pre-wet sponges, lower voltage gradients generate less chlorine and hydrogen gas, and starting from lower water contents (100% or less) would provide the necessary data.
10	Test terminated prior to obtaining results.