**Predicting Evaporative Fluxes in Saline Soil and
Surface-deposited Thickened Mine Tailings**

by

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A thesis submitted to the Faculty of Graduate and Postdoctoral Affairs
In partial fulfillment of the requirements for the degree of

Doctor of Philosophy

in

Environmental Engineering

Ottawa-Carleton Institute for Environmental Engineering

Department of Civil and Environmental Engineering

**Carleton University
Ottawa, Ontario, Canada**

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ABSTRACT

Adedeji Samuel Dunmola. PhD, Carleton University Ottawa, ON Canada. April 2012.
Predicting Evaporative Fluxes in Saline Soil and Surface-deposited Thickened Mine Tailings. Thesis Advisor: Dr Paul H Simms.

Salinity lowers the rate of evaporation-driven densification and shear strength gain of surface-deposited thickened tailings (SDTT) via three mechanisms: albedo; salt precipitation, and; osmotic suction. Albedo is significant but not sufficient to explain the scale of reduction in desiccating SDTT. The relative contribution of the last two mechanisms is unclear. Better understanding of the relative contributions of these mechanisms is important for accurate predictions of evaporative densification of saline soil and SDTT.

By conducting a series of column drying studies, the 1D solute transport in salinized soil and acid-generating SDTT was characterized in detail and related it to evaporation. The relative contribution of salt precipitation and osmotic suction to observed salinity-induced reduction in evaporation was assessed. Based on experimental findings, a numerical framework for predicting evaporation in salinized soil and tailings that accounts for 1D solute transport was proposed and validated.

Salt accumulation was observed in the first 1-2cm of the soil and tailings, causing a decline in evaporation; the magnitude of the decline increases with initial pore-water salinity and evaporative demand. Osmotic suction alone was sufficient to explain the salinity-induced reduction in evaporation from soil and tailings columns up till the solubility limit. Further reduction in evaporation was attributed to salt precipitation restricting water flow. Notwithstanding the role of salt precipitates, numerical predictions of evaporation using a commercial unsaturated flow code generally agreed well with experimental values for a variety of simulated weather conditions and deposition scenarios, only considering the temporal increase in osmotic suction at the surface. Using this modelling approach, a number of hypothetical deposition scenarios for SDTT were explored, including using a solute transport code coupled to the unsaturated flow code to assess the effectiveness of sand as a capillary barrier against evaporation-driven surface salt accumulation.

A new prototype matric suction sensor that offers several advantages over some of the current devices for suction measurement was designed and tested. The prototype sensor correlates the volume change (strain) of its porous linearly-elastic material to a test material's negative pore-water pressure. The sensor compares favourably with tensiometer, axis-translation technique, heat dissipation sensor and relative humidity sensor.

ACKNOWLEDGEMENTS

My sincere appreciation to my Thesis Supervisor, Dr Paul Simms for his meticulous guidance throughout my doctoral studies at Carleton University. Dr Simms' constructive feedback during the conduct and writing of this thesis was immensely beneficial.

The scholarship funding provided by Carleton University, the Department of Civil and Environmental Engineering, as well as the Natural Sciences and Engineering Research Council of Canada (NSERC) during the course of my graduate program is gratefully acknowledged.

Many thanks to members of my thesis advisory committee - Drs Paul Van Geel, Sai Vanapalli and Burkan Isgor. Your insightful comments and feedback during my proposal defense were useful throughout the execution of my research program.

I am also grateful to the technical and administrative staff in the Department of Civil and Environmental Engineering at Carleton. Stanley Conley, Dr Marie Tudoret-Chow, Pierre Trudel and Jason Arnott were extremely helpful during the conduct of my experimental research program. Payal Chadha, Kay Casselman and Kristin Cooper-Holtz were of great administrative assistance throughout my studies.

The help offered by my colleague-Farzad Daliri during the conduct of the multi-layer tailings drying experiment is greatly appreciated. To my other friends and colleagues in the Department goes my appreciation for their friendship and collegiality.

To my Dad, Mum and Sister-`Demola Dunmola, Elizabeth Dunmola and Bola Aderibigbe, I owe a debt of gratitude. Their constant encouragement and unflinching support greatly boosted my courage to pursue my intellectual passion.

My lovely wife and friend, `Kemi Dunmola has been most giving and supportive throughout my doctoral program. Her love and encouragement has given me the inner strength to keep going in the most difficult of circumstances. To our adorable son, Temi' Dunmola, mere thoughts of you hardened my resolve to complete the writing of this thesis. Loads of love!

"Now to the King eternal, immortal, invisible, the only God, be honour and glory for ever and ever. Amen." 1Timothy 1:17.

PREFACE

This doctoral thesis is written in manuscript style, with a General Introduction, Literature Review and Detailed Methodology preceding a total of four manuscripts. Two of the manuscripts have either been published or under review and the remaining two are scheduled for submission to selected peer-reviewed journals. Generally, each manuscript consists of an abstract, introduction, background theory, material and methods, results and discussion, with the latter two combined or separate depending on journal preferences. The manuscript format for the *Journal of Geotechnical and Geo-environmental Engineering* published by the American Society of Civil Engineers (ASCE) was adopted in order to ensure consistency in this thesis. For this thesis, the general guidelines for thesis formatting specified by the Faculty of Graduate and Postdoctoral Affairs were also adhered to. The manuscripts are listed as follows in order of presentation in this thesis:

Adedeji Dunmola and Paul Simms. 2011. Effects of salinity and solute transport on evaporation and solute transport from an artificial silt. *Vadose Zone Journal*. (In Review)

Adedeji Dunmola and Paul Simms. Predicting salinity-induced reduction in evaporative densification of silt and thickened mine tailings. Intended for submission to the *Journal of Environmental Engineering*.

Adedeji Dunmola and Paul Simms. Numerical prediction of evaporative fluxes from saline thickened tailings stacks. Intended for submission to the *Journal of Geotechnical and Geoenvironmental Engineering*.

Adedeji Dunmola, Paul Simms and Manuel Padilla. 2010. Principle and prototype testing of a new matric suction sensor. *Geotechnical Testing Journal*, 33 (5): 416-421.

The above four manuscripts are then followed by a General Discussion, Conclusion and Recommendation in Chapter 8. A comprehensive list of references used throughout this thesis is provided at the end, followed by Appendices.

NOMENCLATURE

Ψ = total suction

Ψ_m =matric suction

Ψ_o =osmotic suction

G = gravitational acceleration

W_v = molecular weight of water vapour

R = universal gas constant

T = temperature

h_a = relative humidity of air

R_n = net radiant energy

H = sensible heat flux

L_e = latent heat of vaporization

E = evaporation rate

G = soil heat flux

T_d = dry bulb temperature

h_s = specific humidity

γ = psychrometric constant

C_{pm} = specific heat of moist air at constant temperature

P_{sv} = saturation vapour pressure

P_a = ambient vapour pressure of air directly above evaporating surface

Q/Q_n = net radiation

Γ = slope of saturation vapour pressure versus temperature curve at mean temperature of air

U_a = average wind speed

Q_e = latent heat flux

Q_h = sensible heat flux

Q_g = subsurface heat flux

ETP= potential evapo-transpiration

ETR=regional actual evapo-transpiration

ETP_o = evapo-transpiration when water supply is unlimited

H_w = total hydraulic head

P_v = partial pressure due to water vapour

$K_w/K(\psi)$ = coefficient of permeability as a function of matric suction

D_v = diffusion coefficient of water vapour in soil

c_w^I = consolidation coefficient with respect to water phase

c_w^V = consolidation coefficient with respect to vapour phase

Z = elevation

t =time

C_v = volumetric specific heat of soil as a function of water content

ρ_s =thermal conductivity of soil as a function of water content

P_{vs} = vapour pressure in the soil air phase at the surface

R_a = aerodynamic resistance

R_s = soil resistance

δ_s = net surface water balance of precipitation, evaporation and soil vapour flux

τ_{ff} = shear strength of an unsaturated soil at failure

c' = effective cohesion

σ = total stress

ϕ' =angle of internal friction associated with net normal stress variable

U_w = pore-water pressure

Φ^b = angle indicating the rate of increase in shear strength due to matric suction

F = diffusive flux

D = diffusion/dispersion coefficient

C = concentration

D_{eff} = effective diffusion coefficient

n = porosity

D_a^0 = free diffusion coefficient of oxygen in air at room temperature

Θ_w = volumetric water content of soil

Θ_a = volumetric air content of soil

H = Henry's constant

D_w^0 = free diffusion coefficient of oxygen in water at room temperature

P = tortuosity parameter

R_s = short-wave radiation flux

r = shortwave reflectivity (albedo) of soil

R_{in} = incoming long-wave radiation

R_{out} = outgoing long-wave radiation

E_{fw} = freshwater evaporative flux

E_{sw} = evaporative rate from saline water body or soil

V^v/V = pore-water flow velocity

D_d = effective ionic diffusion coefficient

D_m = mechanical dispersion coefficient

λ =dispersivity

$K^v(\psi)$ = water vapour conductivity in the air phase as a function of matric suction

m^w =derivative of the soil water characteristic curve as a function of matric suction or the slope of consolidation curve in the positive pore-water pressure range

N_i = shape function

Ω = domain of the system being modelled

$W(z)$ = weighing function

$R(z)$ = residual error

Q =heat flux

k =thermal conductivity of porous medium

W = water content

EC = electrical conductivity

RH_s = relative humidity of soil pore air

RH_a = relative humidity of the air

V^v = pore-water vapour velocity

ϵ = volumetric strain

ζ = change in fluid content of porous material

δV = change in bulk volume of porous material

l =length

S = degree of saturation

P =capillary pressure

K = bulk modulus of porous solid

K_s = bulk modulus of material that make up the solid frame of porous material

E_s = Young Modulus of solid backbone of porous material

μ = Poisson's ratio

G_s = shear modulus of solid backbone of porous material

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CHAPTER 1: GENERAL INTRODUCTION

1.1 Research Background

Over 95% of mined ore processed for extraction end up as reject in the form of mine tailings (Newman 2003). A daily throughput of tens of thousand tonnes is typical for most mining operations, giving rise to large global turnover of mine tailings (in excess of 3.5 billion annually) that need to be properly managed. Proper tailings management is crucial for hard-rock mining operations because tailings may contain iron sulphide minerals, which when oxidized in the presence of water, leads to acid mine drainage (AMD). AMD is a toxic effluent that dissolves and mobilizes heavy metals (such as lead, arsenic, cadmium and mercury) through seepage and / or runoff, contaminating underground and surface water resources (Jones et al. 1988; ICOLD 2001). Thus, for most hard-rock mining operations around the world, appropriate tailings management is crucial to meeting increasingly stringent regulatory requirements as well as fulfilling corporate sustainability and social responsibility objectives.

Mine tailings (usually in slurry consistency) are conventionally retained behind containment dams. However, there had been past incidents where tailings dams failed due to dynamic loading (from earthquakes) and structural problems (such as seepage and / or excessive rainfall causing liquefaction). Such catastrophic tailings dam failures have resulted in large-scale environmental devastation and sometimes, loss of life. The

liability from such disasters is often in the hundreds of millions of dollars (ICOLD 2001; Newman 2003). This has led to the gradual development and adoption of less-risky tailings management alternatives over the past three decades.

Thickened tailings technology is one of such alternatives. The technology involves dewatering tailings slurry to a solids concentration high enough for the tailings to develop a yield stress during deposition. This yield stress - the strength exhibited by the material at rest, while small (typically $< 200\text{Pa}$), is sufficient to allow the material form a self-supporting stack when pumped to the surface (Theriault et al. 2003). This minimizes or completely eliminates reliance on dams and the associated risk of catastrophic failure, enhancing the potential for successful closure and reclamation. Thickened tailings can also be mixed with suitable binders (such as Portland cement, fly-ash or slag) and used in underground mining as cemented paste backfill (CPB). CPB allows for backfilling mined-out stopes to ensure stabilization and allow for mining of adjacent standing ores.

'Paste' is a subset of thickened tailings, whereby the material is dewatered to the point where it can be transported as laminar flow in pipelines: this usually requires at least 15% of tailings particles having average grain size smaller than 20 microns, such that it can be transported along pipes as a plug flow without segregation of constituent particles. Thickened tailings are transported from the mill to the tailings disposal facility

(TDF) for sub-aerial deposition through a network of appropriate pipes and pumps. Surface-deposited thickened tailings (SDTT) desaturate and densify over time through three main mechanisms; hindered settling, consolidation and evaporation (Simms et al. 2009). Evaporation has been shown to significantly contribute to the densification and shear strength gain of thickened tailings stack in most climates (Rassam and Williams 1999a; Simms et al. 2009).

Evaporation from SDTT is crucial for the reduction in volume of thickened tailings disposed and footprint required for disposal. Also, the loss of water by evaporation is important in reducing the volume of seepage from TDF that requires treatment prior to discharge from site, translating to cost savings for mining operations. In addition, evaporation increases the rate of shear strength gain of stacks, enhances its bearing capacity for subsequent fresh layers, and improves trafficability during site closure and rehabilitation (Rassam and Williams 1999a; Dunmola and Simms 2010). However, excessive evaporation from thickened tailings stacks removes the hydraulic barrier to oxygen ingress, causing oxidation of sulphide minerals and consequently, acid mine drainage. Therefore, a balance between the extent of evaporation desirable for densification of SDTT and the point beyond which evaporation induces significant oxidation is required (Fisseha et al. 2010). The contribution of evaporation to shear strength gain of SDTT stack is affected by pore-water salinity (Fujiyasu and Fahey 2000; Newson and Fahey 2003; Dunmola and Simms 2010).

Pore-water salinity is known to lower the rate of evaporation from soils (Chen 1992; Fujimaki et al. 2006) and mine tailings (Newson and Fahey 1997; Fujiyasu and Fahey 2000; Dunmola and Simms 2010). In fact, as much as 90% reduction in potential evaporation rate has been reported for saline soil (Chen 1992) and mine tailings slurry deposit (Newson and Fahey 1997). Also, pore-water salinity has been shown to shut down evaporation completely just 3 weeks after surface deposition of thickened tailings (Simms et al. 2007). In saline soil and mine tailings, three mechanisms have been identified to cause this suppression in evaporative fluxes: increased albedo, increased osmotic suction, and physical resistance of salt crust to water flow (Yakirevich et al. 1997; Fujimaki et al. 2003; Newson and Fahey 1997; Fujiyasu and Fahey 2000; Simms et al. 2007). Salinity-induced reduction in evaporation from SDTT stacks is undesirable as it impedes the rate of densification and shear strength gain, prolonging the time lags between deposition cycles. In mine tailings management, the capability to predict the rate of evaporative densification is desirable for optimizing deposition plans to efficiently keep up with throughputs from mining operations. This optimization objective is difficult to achieve in saline tailings stacks, as the predictive accuracy of most unsaturated flow codes deteriorates with the onset of salt accumulation and precipitation at the tailings surface (Fujiyasu and Fahey 2000; Simms et al. 2007; Fisseha et al. 2010).

Evaporation in saline SDTT stack is coupled to pore-water solute transport. As previously mentioned, the transport to, and eventual accumulation of salts at the

tailings surface lowers the rate of evaporation, while evaporation in turn drives the advective transport of pore-water solutes to the tailings surface. Therefore, an understanding of the 1D transport and accumulation of salts at the surface of desiccating SDTT stack and implications for evaporative fluxes is important for improving current numerical capacity for predicting the rate of shear strength gain. This point has been reiterated by recent authors (Fisseha et al. 2010; Fredlund et al. 2011).

Past research efforts have focused on the process of evaporation from soil, slurried tailings (Wilson et al. 1991; Wilson et al. 1997; Rassam and Williams 1999a; Fujiyasu et al. 2000; Stolberg and Williams 2006) and thickened tailings (Theriault et al. 2003; Simms et al. 2007; Fisseha et al. 2010). Also, there have been previous investigations about the effect of pore-water salinity on surface evaporation from soil, slurried and thickened tailings (Chen 1992; Fujimaki et al. 2003; Fujimaki et al. 2006; Newson and Fahey 1997; Fujiyasu and Fahey 2000; Newson and Fahey 2003; Simms et al. 2007; Fisseha et al. 2010). However, these various investigators either made empirical correlations between pore-water salinity and evaporation in the case of soil, or made qualitative observations in the case of mine tailings. To the best of author's knowledge, detailed characterization of the 1D solute transport and surface salt accumulation in relation to the various mechanisms by which pore-water salinity suppresses evaporative densification in SDTT is not available in literature.

While the effects of albedo on evaporation from tailings has been previously studied (Fujiyasu and Fahey 2000; Newson and Fahey 2003; Simms et al. 2007), the relative contribution of osmotic suction and physical resistance of salt crust to salinity-induced reduction in evaporation is not clear. In fact, Simms et al. (2007) reported that the effect of albedo was important but not sufficient to explain the scale of salinity-induced reduction in evaporation observed in the laboratory and field for desiccating SDTT. The authors (Simms et al. 2007) concluded that both or either of the other two mechanisms is significant, and an improved understanding of their relative contribution is important for more accurate prediction of evaporation in saline tailings stacks. Also, to the author's knowledge, there is currently no framework for accounting for pore-water solute transport when implementing numerical solutions for predicting evaporative fluxes from saline SDTT.

Therefore, this thesis characterizes and relates the profile pore-water solute transport in desiccating thickened tailings to observed evaporative fluxes, under various experimental simulations of field conditions. Field condition was simulated by dry and dry-wet-dry cycles, as well as multi-layer deposition of thickened tailings. The impact of 1D solute transport on evaporative densification was under variable depositional management options was investigated. The relative contribution of osmotic suction and salt precipitation to salinity-induced reduction in evaporation was quantified using an empirical model that accounts for both the total suction at the tailings surface as well as the resistance to water flow as desiccation progresses. Also, based on experimental

observation, using a commercial unsaturated flow code, a numerical framework that accounts for 1D solute transport in predicting evaporative fluxes in desiccating thickened tailings is proposed. Numerical predictions of evaporative densification in thickened tailings using the proposed framework were compared to experimental data. A number of hypothetical scenarios for saline SDTT management were explored using the proposed numerical framework, after calibration with experimental data.

In addition to using acid-generating thickened gold tailings as test material in this thesis research, silt-sized artificial soil was also tested. This was undertaken to explore pore-water solute transport and the implications for evaporative fluxes in a relatively simple system. The alternate test material (soil) chosen has similar geotechnical properties as the tested thickened tailings, and served to broaden the applicability of research findings in saline soils and soil-like systems.

Most engineering properties of unsaturated soils and thickened tailings are dependent on matric or total suction (Fredlund et al. 1978; Fredlund and Rahardjo 1993). For instance, the coefficient of permeability and shear strength of unsaturated soil are dependent on its matric suction (Escario and Saez 1986; Vanapalli et al. 1996; Huang et al. 1998; Agus et al. 2003; Vu and Fredlund 2004). The rate of evaporation is known to be a function of total suction at the soil surface (Wilson et al. 1997). Also, the evolution of matric suction due to evaporation in mine tailings deposits has been shown to contribute significantly to its bearing capacity (Rassam and Williams 1999b). Long-term slope stability analyses and prediction of long-term performance of soil covers are

based on suction data (Feuerharmel et al. 2006; O'kane et al. 1998; Weeks and Wilson 2005). In addition, the design, deposition planning and management of mine tailings disposal facilities require an understanding of the evolution of matric suction and shear strength of stacks over time (Newson and Fahey 2003; Simms et al. 2007; Fisseha et al. 2010).

Considering the practical importance of matric and total suction data, improved capacity for rapid, accurate, and cost-effective determination is desirable for various geotechnical and geo-environmental applications. Currently, there are several devices and techniques used for field and / or laboratory determination of soil suction. Common examples include; the tensiometers, heat-dissipation sensor, axis-translation technique, filter paper technique and psychrometer (Rahardjo and Leong, 2006). All these devices and techniques are well-established and each has unique advantages. However, most of the devices and techniques have several limitations associated with their use. Examples of such limitations include issues relating to long-term reliability, narrow range of suction, inaccurate readings, high procurement cost, hysteresis, cavitation, and adaptability for field use.

Therefore, this thesis also documents the conception and design of a new prototype matric suction sensor, which was deployed to measure matric suction for the soil and thickened tailings tested in this research program. The prototype sensor is based on the

theory of change in matric suction (capillary pressure) of a porous material resulting from a change in its volume. The constituent porous material of the prototype sensor has a high air-entry value (AEV) of 8000kPa. Hence, in theory, for matric suction measurements below this AEV, the sensor will neither cavitate nor be subject to hysteresis, thereby providing the capability for a wide range of suction determinations. This thesis includes details of the theoretical background, conception, design and testing program for the new matric suction sensor, and its performance in comparison to commonly-used devices and techniques.

1.2 Research Problem Definition and Objectives

Improvement in the capacity of current numerical tools for predicting evaporative densification in saline thickened tailings deposits is important for optimizing deposition planning and management to achieve geotechnical and geo-environmental performance as well as regulatory compliance objectives. To this end, a better understanding of the mechanisms by which pore-water salinity reduces evaporation in tailings stacks is crucial. The individual impacts of these mechanisms on evaporation are fairly well understood in soils but not as well for thickened tailings. Also, the relative significance of these mechanisms in both soil and thickened tailings is not well understood. In addition, the detailed characterization of the 1D transport of pore-water solute and the implications for evaporative densification in thickened tailings deposits is lacking in literature. Furthermore, to the best of author's knowledge, there is currently no

numerical framework that accounts for the implications of solute transport for evaporation when predicting evaporative densification in saline thickened tailings. Thus, the central objective of this thesis is to advance current knowledge base with the aim of bridging these gaps in our current understanding, so that saline mine tailings deposition planning and management can be better optimized.

Also, current devices and techniques for suction determination in soils and mine tailings have certain limitations associated with their use: cavitation, hysteresis, long-term unreliability, narrow range of measurement, prohibitive cost and long equilibration times. Therefore, developing a new matric suction sensor that can overcome some of these limitations is important for many geotechnical and geo-environmental applications where matric suction determination is required.

Therefore, the specific objectives of this thesis are to:

- (i) Characterize the 1D pore-water solute transport in desiccating soil and thickened tailings;
- (ii) Examine the implication of the 1D pore-water solute transport on evaporative densification of soil and thickened tailings;

- (iii) Evaluate the relative contribution of osmotic suction and salt precipitation to salinity-induced reduction in evaporative fluxes from soil and thickened tailings;
- (iv) Based on experimental work, propose and evaluate a numerical framework that accounts for 1D pore-water solute transport in predicting evaporative fluxes from soil and thickened tailings, using a commercial unsaturated flow code (SVFlux);
- (v) Explore how different practical field scenarios (such as dry-wet-dry cycles, multilayer deposition, variable boundary conditions; thin-lift versus deep deposition) affects 1D solute transport and the implications for evaporative densification of thickened tailings using the numerical framework;
- (vi) Assess the capacity of using capillary barrier concept to limit surface salt accumulation and associated impact on evaporative densification in saline thickened tailings deposits;
- (vii) Conceive and design a new prototype matric suction sensor that avoids cavitation, hysteresis and measures a wider range of matric suctions compared to most current devices;

- (viii) Test the performance of the new sensor in the soil and thickened tailings used in this thesis against tensiometer, heat-dissipation and relative humidity sensors, as well as axis-translation technique.

1.3 Thesis Scope

In order to address the specific research objectives previously highlighted, this thesis is divided into four major studies, with each study constituting one of the four manuscripts included in this thesis. A detailed experimental program aimed at understanding the fundamentals of the relationship between 1D solute transport and unsaturated flow was designed and executed. Based on the findings from the experimental program, a numerical framework was proposed to model the systems studied in the experimental program. The numerical framework was then calibrated with experimental data and used for exploratory modeling of specific field-related tailings management applications. A brief description of each major study is provided as follows:

1.3.1 Experimental Investigation of Effects of Pore-water Salinity and 1D Solute

Transport on Evaporative Fluxes from Saline Soil

This study presents the findings from the laboratory characterization of 1D solute transport and its implication for evaporation in saline soil. Three different levels of pore-water salinities were investigated and the relative contribution of osmotic

suction and salt precipitation to salinity-induced reduction in evaporative fluxes was assessed. The test material for this laboratory study was a commercial inert granular soil (glass beads). The non-reactive soil was chosen for analysis to afford a simple system to study the fundamentals required for an improved understanding of a geo-chemically more complex porous medium like thickened tailings that was tested in the following study.

1.3.2 Experimental and Numerical Investigation of 1D Solute Transport in Thickened Tailings and Implications for Evaporative Densification

The findings from the laboratory characterization of 1D solute transport and implications for evaporative densification in thickened tailings are presented in this study. The relative contribution of osmotic suction and salt precipitation to observed salinity-induced reduction in evaporation is evaluated. Also, based on the fundamental understanding of the impacts of 1D solute transport on evaporative fluxes, a numerical framework that accounts for this coupling is proposed. Using a commercial unsaturated flow code, this numerical framework was implemented to predict evaporative fluxes from the desiccating saline soil and thickened tailings, and the predictions were compared to experimental data.

1.3.3 Numerical Simulation of Evaporative Densification of Saline Thickened Tailings Stacks

This study is intended to upscale the findings in the previous two studies to field conditions and assess various “what if” scenarios that are of practical significance in tailings deposition management. The numerical framework previously developed in study 2 was used to predict evaporative densification of thickened tailings under dry and dry-wet-dry cycles, variable boundary conditions and multi-layer deposition. Predictions were compared to laboratory measurements of evaporative fluxes. A numerical assessment of multiple depositions and drying of thin lifts of thickened tailings against deposition and drying an equivalent single deep deposit in terms of the total cycle time to reach a target profile water content was conducted. A numerical analysis of the sensitivity predictions of evaporative fluxes to deposit thickness and saturated hydraulic conductivity was also conducted. A 1D solute transport numerical code coupled to the unsaturated flow code was calibrated against laboratory data for the desiccating thickened tailings. The solute transport code was then used to assess the effectiveness of using a sand capillary barrier to mitigate salt accumulation at the surface of desiccating tailings deposit.

1.3.4 Principle, Design and Prototype Testing of a New Matric Suction Sensor

The conception, principle and prototype design of a new matric suction sensor is described in this study. The prototype matric suction sensor operates based on the principle of change in capillary pressure of a porous material associated with its volume

change when in equilibrium with the pore-water pressure of a test material. A brief background on the principle of poro-elasticity upon which the matric suction sensor was designed is provided in this study. Results from testing the prototype sensor in soil and thickened tailings, and comparison of its performance to tensiometer, heat dissipation and relative humidity sensors, as well as suctions established by axis-translation technique are presented.

1.4 Thesis Organization

This thesis is written in the “manuscript” format, according to the “Integrated Article Thesis” policy requirements of the Faculty of Graduate and Postdoctoral Affairs. Each of Chapters 4 to 7 is written as an independent stand-alone paper detailing the motivation, brief context, methodology, results and discussion for each study conducted in this research program. Chapters 1, 2 and 3 provide the General introduction to research, review of pertinent literature, and detailed research methodology, respectively. Chapter 8 presents the overall synthesis and discussion of research findings, as well as general conclusions and recommendations arising from the research. The list of references for all Chapters in the thesis is excluded from the main body of text. Instead, a detailed list of all references used in text is given at the end of the thesis, followed by Appendices containing additional data and information not included within the main body of this thesis.

CHAPTER 2: LITERATURE REVIEW

2.1 The Process of Evaporation from Soil

The inter-boundary exchange of water between the soil and atmosphere constitutes an important component of the hydrologic cycle (Wilson et al. 1991). This exchange occurs primarily through the processes of infiltration (inflow of liquid water into and within the soil) and evaporation (outflow of water from soil in vapour form into the atmosphere). Evaporation in soil is of interest to a wide range of researchers and practitioners. A geotechnical engineer is interested in the evolution of shear strength of earth structures resulting from evaporation-induced negative pore-water pressure, as well the contribution of evaporation to the stability of natural and engineered slopes. A geo-environmental practitioner may be interested in the long-term performance of soil cover deployed over mine waste when such cover is subjected to excessive evaporation. Also, an agricultural scientist or engineer may be interested in evaporation from the standpoint of its contribution to water deficit and salinization under irrigated cropping systems (especially in arid or semi-arid climates) and the implications for crop growth. In addition, a hydrologist or hydro-geologist may be concerned with the implications of evaporation for regional water balance and seasonal fluctuation in ground-water table and / or migration of contaminants within, and outside the boundaries of a given site. The following sections review in details, the process and stages of evaporation from soil, as well as the methods for measuring and predicting evaporation rate from soil. This review is provided within the geotechnical and geo-environmental context.

2.1.1 Evaporation: Process and Stages.

Evaporation involves the transfer of water (in vapour form) from the soil, across the soil-atmosphere interface, into the atmosphere. This inter-boundary flow of water is important in many geotechnical and geo-environmental applications (Wilson et al. 1991). Such applications include the use of soil covers as oxygen barriers for acid-generating pyritic mine tailings (Collin and Rasmuson 1990) and induction of negative pore water pressures for ensuring slope stability (Ng 1988). Others include the implications of evaporation for volume change of expansive soils encountered in many geotechnical structures (Satler and Fredlund 1991) as well as implications for shear strength gain of surface-deposited thickened tailings (Rassam and Williams 1999a; Newson and Fahey 2003; Simms et al. 2007).

The rate of evaporation from soil is controlled by the gradient in vapour pressure and temperature between the soil surface and the overlying atmosphere (Wilson et al. 1997), among other factors (such as solar radiation, wind speed, surface albedo etc). The gradient in vapour pressure is controlled by the difference between the relative humidities at the soil surface and in the atmosphere directly overlying the soil. The relative humidity (RH) of the soil, h_r , is a ratio of the actual vapour pressure of soil atmosphere (p_v) to the saturation vapour pressure of the soil at its current temperature (p_{sv}). Edlefsen and Anderson (1943) gave the equation relating the RH at the soil surface to its total suction as:

$$RH = e^{-\frac{\psi g w_v}{RT}} \quad (2.01)$$

where ψ is the total suction at the soil surface (m); g is the gravitational acceleration (m/s^2); w_v is the molecular weight of water vapour (0.018016 kg/mole); R is the universal gas constant (8.314 J/mole.K); and T is the absolute temperature (K).

A graphical representation of equation 2.01 is presented in Figure 2.01.

Figure 2.01. Variation of relative humidity of soil atmosphere with total suction at surface (Computed for a temperature of 20°C).

For a completely saturated soil, the RH of the infinitesimally-thin layer of air directly above the soil surface is 100%. The total suction at the surface of such saturated soil will be low (less than 1000kPa), and evaporation will proceed at the maximum rate for the prevalent atmospheric conditions. For almost all conditions in nature, there will be a finite time, past which evaporating water at the surface cannot be fully replaced from depth within the soil profile. At such a point, the soil begins to desaturate, the total suction at the soil surface rises, and the RH of soil atmosphere will correspondingly decrease according to equation 2.01. This decline in RH reduces the vapour pressure of soil pore air, and consequently the vapour pressure gradient driving evaporation is lowered. As can be seen in Figure 2.01, significant decrease in RH corresponds to total suctions greater than 3000kPa.

A column evaporation test was conducted by Wilson et al. (1994) to monitor evaporation from saturated fine sand columns. The total suction of the evaporating sand was back-calculated from its gravimetric water content (GWC) using its soil water characteristic curve (SWCC). For the first 3 to 4 days of drying the sand columns, actual evaporation rate was observed to close to the potential rate. It was observed that the GWC of the sand at a suction of 3000kPa is about 2%, at which point the rate of evaporation started to decline and substantially deviate from the potential evaporation. Beyond 3000kPa, the RH (and vapour pressure) began to fall rapidly, and a sharp decline in the rate of evaporation was observed. The residual water content of the sand after 42 days was found to be 0.6%, corresponding to a RH of 20% (total suction of 200,000kPa).

Therefore, from empirical observations made by Wilson et al. (1994) as well as others (Wilson et al. 1997; Hillel 1998), evaporation from soil is coupled to total suction at the soil-atmosphere boundary).

Evaporation from a porous medium (such as soil or mine tailings) can be broadly categorized into 2 stages: the non-limiting and soil-limiting stages. In the non-limiting stage, the soil is sufficiently saturated to meet evaporative demand and the rate of evaporation is solely controlled by atmospheric conditions (Fujiyasu et al. 2000). The rate of evaporation at this stage is called "Potential Evaporation". Potential evaporation (PE) is defined as "the quantity of water vapour which could be emitted by a surface of pure water per unit surface area and unit time under the existing atmosphere conditions" (Int'l glossary of Hydrology WMO 1974). Therefore, PE represents the upper limit of evaporation when water supply is non-limiting in soil. As the second (soil-limiting) phase is approached, the supply of water available at the soil surface starts to decline as the soil desaturates, causing a significant drop in the rate of evaporation (Hillel 1998; Fujiyasu et al. 2000). During this soil-limiting phase, water supply becomes insufficient and the rate of evaporation falls to a value lower than the PE, termed "Actual Evaporation" (AE). Actual Evaporation is "the quantity of water that could be emitted from an unsaturated soil per unit surface area and unit time under current atmospheric conditions" (Int'l glossary of Hydrology WMO 1974).

The relative evaporation (RE) from soil (a ratio of AE to PE) is known to be a function of the total suction at the soil surface given by Wilson et al. (1997) as:

$$RE = \frac{AE}{PE} = \left[\frac{e^{-\left(\frac{\psi g W_v}{RT}\right)} - h_a}{1 - h_a} \right] \quad (2.02)$$

Where ψ is the total suction at the soil surface (m); g is gravitational acceleration (m/s^2); W_v is the molecular weight of water (0.018016 kg/mol); R is universal gas constant (8.314 J/mol.K); T is the temperature of air above the soil surface (K) and h_a = relative humidity of air above the soil surface (as a fraction).

Specifically, evaporation proceeds in three stages as shown by Figure 2.02 for a typical sand soil (Gardner and Hillel 1962; Wilson et al. 1994); the curve is also similar for silt and clay soil (Gray 1970; Wilson et al. 1997). In stage I, the RE is approximately 1, with the soil being completely or nearly-saturated and with the total suction at its surface being less than 3000kPa. During stage I, the soil's degree of saturation is sufficiently high to ensure continuity in the liquid phase and hence, water flow occurs within the soil as liquid. As the AEV of the soil is approached, the soil starts to desaturate and Stage II evaporation eventually begins when the total suction value at the soil surface exceeds 3000kPa. During stage II, the RE decreases rapidly as the total

suction at the soil surface continues to increase and the soil pore-water phase becomes discontinuous. This discontinuity in the soil's liquid phase causes unsaturated water flow to proceed as a combination of liquid water and water vapour transport. The RE continues to decrease until stage III begins as the soil reaches its residual water content. At this stage, a new equilibrium between moisture supply and evaporation is reached and the evaporation rate becomes relatively constant. During stage III evaporation, the soil is sufficiently desiccated such that liquid water flow has stopped and unsaturated flow occurs only by water vapour diffusion (Wilson et al. 1994; Hillel 1998). The following subsection provides a review of the different methods used to measure and predict evaporative fluxes from the soil.

Figure 2.02. Variation of relative evaporation (AE/PE) with soil water content (Modified from Wilson et al., 1994).

2.1.2 Measurement and Prediction of Evaporation from Soil and Tailings

The accurate determination or prediction of the rate of evaporation from soil (or mine tailings) is important for many applications, as previously discussed. There are a number of techniques for measuring evaporation (PE and AE) from soils or mine tailings. Class A Pan evaporation method has been used to measure the PE from tailings storage facilities (Fujiyasu et al. 2000; Newson and Fahey 2003). The class A pan is cylindrical with a diameter of 1.22m and depth of 0.25m placed on a level wooden base, and is usually enclosed by a bird net cage. Water loss from the pan is monitored by measuring the amount of water needed to fill the pan up to maintain a freeboard of 25mm at the end of 24 hours. A floating thermometer is used to determine the maximum and minimum water temperature over the 24 hour period. Also, direct measurement of surface evaporation from mine tailings or soil can be done using “microlysimeter” method of Boast and Robertson (1982).

The microlysimeter method is used for point measurement of evaporation rate by isolating the point from surrounding soil hydrology while determining AE by difference in mass of cut-out soil sample placed within the soil. One container is used to create a lined coring in the soil and the second container, which is sealed at the base, is used to obtain a weighed soil sample. The soil sample is inserted into the previously-cored hole and made to flush with the soil surface. PVC is a preferred material for microlysimeters as opposed to steel due to its lower thermal conductivity that minimizes heat losses. The microlysimetric method is typically used for a short period of

time (24 hours) in order to minimize the disparity in AE of sample compared to the isolated surrounding. The method has been found to be versatile, having been used for test materials with strengths ranging from a few kPa to very dry (Newson and Fahey 2003). Though the microlysimeter method is accurate and inexpensive, it is limited in scope as only a small area (point source) can be monitored at a particular time. Also, long-term and continuous monitoring of evaporative fluxes is not practical with this method (Fujiyasu et al. 2000).

The Bowen ratio method (Bowen 1926) can be used to compliment the microlysimeter method. The method is based on the theory that the difference between the energy fluxes incident at the soil surface and energy fluxes emitted away from it is partitioned to supply the latent heat required for evaporation. The energy balance is expressed as:

$$R_n = H + L_e E + G \quad (2.03)$$

Where R_n is the net radiant energy (W/m^2); H is the sensible heat flux (W/m^2); L_e is the latent heat of vaporization (J/kg); E is the evaporation rate ($kg/m^2.s$); and G is the soil heat flux (W/m^2). If the different heat fluxes can be determined through instrumentation, the steady-state evaporation can be determined using equation 2.03.

The Bowen method partitions available energy ($R_n - G$) into sensible heat (H) and latent heat ($L_e E$), expressing it as a ratio, β , given as:

$$\beta = \frac{H}{L_e E} = \frac{C_{pm}}{L_e} \left(\frac{dT_d}{dh_s} \right) = \gamma \frac{dT_d}{dh_s} \quad (2.04)$$

Where T_d and h_s are the dry bulb temperature ($^{\circ}\text{C}$) and specific humidity (kg/kg), respectively. γ is the psychrometric constant given as:

$$\gamma = \frac{C_{pm}}{L_e} \quad (2.05)$$

Where C_{pm} is the specific heat ($\text{J/kg} \cdot ^{\circ}\text{C}$) of moist air at constant pressure.

Thus, the Bowen ratio can be determined by measuring air temperature and RH at 2 different reference heights above the evaporating surface and fitting the data into equation 2.04. Typically, the Bowen station consists of: temperature and RH sensors at 1 and 2m above the soil (to measure β); pyranometer and net pyrradiometer (to measure R_n); as well as temperature and heat flux sensors buried within the soil (to measure G). The Bowen method was successfully employed to determine evaporation rates from a

freshwater tailings evaporation pond by Fujiyasu et al. (2000) and from saline tailings storage by Newson and Fahey (2003).

In addition to direct measurements, there are also a number of methods for predicting evaporation rate from soil or mine tailings. According to Gray (1970), PE is a function of the vapour pressure gradient between the saturated soil surface and the directly-overlying atmosphere. The PE from soil can therefore be estimated using a mass transfer equation, originally given by Dalton (1802) as:

$$E = f(u) (p_{sv} - p_a) \quad (2.06)$$

Where E is evaporative flux (mm/day); f (u) is a function that is dependent on mean wind speed, surface roughness and eddy diffusivity; p_{sv} is the vapour pressure of saturated evaporating surface and p_a is the ambient vapour pressure of air directly above evaporating surface.

The Penman method (1948) combines the mass transfer equation (equation 2.06) with the ground surface energy budget and is given as:

$$E = \frac{\Gamma Q + \gamma E_a}{\Gamma + \gamma} \quad (2.07)$$

Where E is PE (mm/day), Q is heat budget or all net radiation (mm/day), Γ is the slope of saturation vapour pressure versus temperature curve at mean temperature of air, and γ is psychrometric constant previously defined in equation 2.05. E_a is given as:

$$E_a = f(u) (p_{sa} - p_a) \quad (2.08)$$

Where p_{sa} is saturation vapour pressure at mean air temperature (mm-Hg) and $f(u)$ is an empirical function of the average wind speed with example for unsaturated soil given by Wilson et al. (1994) as:

$$f(u) = 0.35 [1 + u_a (0.146)] \quad (2.09)$$

Where u_a is the average wind speed (km/hr).

The Penman method was an improvement over Gray's mass transfer equation, which becomes indeterminate due to the difficulty associated with measurement of temperature of water surface needed for determining p_{sv} . The Penman method renders

the mass transfer equation determinate by introducing energy balance and net radiant energy available for evaporation (Wilson et al. 1994). The Penman method requires simple inputs of weather data (wind speed, air temperature and relative humidity) and energy budget data (which can be determined from charts and empirical formulae). Although the Penman method is most appropriate for open water surfaces, it was also successfully applied for bare soil and grass (Penman 1948). The Penman method is the most widely-used technique for estimating the PE from soil (Rosenberg et al. 1983; Wilson et al. 1991; Wilson et al. 1994) and mine tailings (Machibroda et al. 1993; Newson and Fahey 2003).

The method of Priestley and Taylor (1972) is also used for estimating PE based on energy fluxes; the combination of latent and sensible heat fluxes. For this method, PE is given as:

$$ET_p = \alpha \frac{r}{r+v} (Q_e + Q_h) = \alpha \frac{r}{r+v} (Q_n + Q_g) \quad (2.10)$$

Where α is an empirical constant; Q_e is latent heat flux (mm/day); Q_h , sensible heat flux (mm/day); Q_n is net radiation (mm/day); and Q_g is subsurface heat flux (mm/day). All other parameters remain as previously defined. Though this method has been used in humid regions, it is not widely used for determination of evaporation for arid regions (Rosenberg et al. 1983).

The foregoing methods for predicting PE are all predicated on the assumption of unlimited water supply (Wilson et al. 1994), and are therefore determined using climatic parameters (temperature, RH, radiation, wind etc) alone. However, in most practical geotechnical and geo-environmental applications, the soil is under some form of limited water supply, in which case the actual evaporation (AE) may need to be estimated. Hence, the use of these previously-discussed empirical methods to determine AE from soil under varying degrees of unsaturation is known to lead to over-estimation (Wilson et al. 1997). This necessitated the introduction and use of “complementary relationship” and “coupled soil-atmosphere” flux boundary models.

AE may be estimated using “complementary relationship” such as the one proposed by Bouchet (1963), which is based on the assumption that a relationship exists between AE and PE (Wilson et al. 1991). This relationship is given as:

$$ETP + ETR = 2ETP_o \quad (2.11)$$

Where ETP is the potential evapo-transpiration under ambient conditions if available energy is only limiting factor; ETR is the regional actual evapotranspiration; and ETP_o is rate of evapo-transpiration when water supply is unlimited (i.e. when $ETR = ETP$). From an empirical standpoint, the complimentary method is suitable for estimating AE, especially on regional basis (Wilson et al. 1991). The estimation of AE using this

approach requires that the properties of the soil (such as water potential, texture, hydraulic conductivity, porosity etc) be considered along with micro-climatic conditions.

Similarly, coupled soil-atmosphere flux models predict the AE from soil or mine tailings by using a combination of atmospheric conditions and soil properties (Schildge et al. 1982; Passerat De Silans et al. 1989; Wilson 1990). These coupled models generally calculate the AE rate from soil by using both heat and mass transfer equations. These models (except Wilson 1990) are based on the Philip and de Vries (1957) formulation, which has limitations in unsaturated soil applications as it considers water flow in soil to be driven by volumetric water content gradient, as opposed to hydraulic gradient. This assumption limits the predictive accuracy of these models to relatively short period of evaporation, typically a few days, and is only valid for homogeneous and isotropic soil systems (Wilson et al. 1994).

A soil-atmosphere flux model developed by Wilson (1990) couples water flux and heat flux to determine the AE from both saturated and unsaturated soils. The model incorporates the flux of water vapour from the soil surface into the atmosphere, as well as the flow of liquid water and water vapour below the soil surface. The governing equations for the liquid water and water vapour fluxes are given by the Darcy and Fick's Laws (Philip and de Vries 1957), respectively. The combined liquid and vapour mass flux equation implemented by the model is given as:

$$\frac{\partial h_w}{\partial t} = c_w^l \frac{\partial}{\partial z} \left(k_w \frac{\partial h_w}{\partial z} \right) + c_w^v \frac{\partial}{\partial z} \left(D_v \frac{\partial p_v}{\partial z} \right) \quad (2.12)$$

Where h_w is the total hydraulic head; p_v is the partial pressure due to water vapour; k_w is the coefficient of permeability as a function of matric suction; D_v is the diffusion coefficient of water vapour in soil; c_w^l is the consolidation coefficient with respect to water phase; c_w^v is the consolidation coefficient with respect to vapour phase; z is the elevation; and t is the time.

The governing equation for the heat flux component of the coupled model is expressed as:

$$C_v \rho_s \frac{\partial T}{\partial t} = \frac{\partial}{\partial z} \left(\lambda \frac{\partial T}{\partial z} \right) - L_e \left(\frac{p + p_v}{p} \right) \frac{\partial}{\partial z} \left(D_v \frac{\partial p_v}{\partial z} \right) \quad (2.13)$$

Where C_v is the volumetric specific heat of the soil as a function of water content; ρ_s is the thermal conductivity of the soil as a function of water content; T is the temperature; L_e is the latent heat of vaporization of water; and p is the total pressure of the air phase.

This coupled model was used to predict AE from a 30cm-thick fine sand column and compared to values obtained by monitoring the difference in mass of the

desiccating soil column over a period of 42 days. AE values and profile water contents predicted using the model were in agreement with values measured in the laboratory. AE from the soil column was close to corresponding PE for the first 3-4 days of drying-Stage I evaporation. During this stage, the sand surface and underlying depths maintained a high degree of saturation to keep suction below the AEV (3.8kPa) of the fine sand. Starting from day 4, the AEV of the sand was exceeded as it became sufficiently desaturated to restrict the flow of liquid water to the soil surface, causing a rapid decline in AE-Stage II evaporation. The AE measured from the sand column continued to decline until day 12 as the evaporating front receded further down the sand column. By day 12, the sand column had reached Stage III evaporation, with AE remaining low and somewhat constant over the remaining 30 days of the columns drying experiment. Profiles of matric suction predicted using the model was in good agreement with laboratory measurements mostly in the top 2cm and at depths below 8cm of the fine sand column. This discrepancy between predictions and measurements of matric suction at profile intervals between 2 and 8cm was attributed to uncertainties in the hydraulic conductivity function used in the model when the residual water content of soil is approached. This model has also been used to predict AE from thickened tailings (Simms et al. 2007; Fisseha et al. 2010), with reasonable degree of accuracy. Therefore, the problem of quantifying AE, especially for geotechnical and geo-environmental applications, is best approached by coupling soil properties with micro-climatic conditions above the soil-atmosphere boundary (Wilson et al. 1994). This is the

approach adopted in the numerical prediction of evaporative fluxes from the desiccating soil and thickened tailings in this thesis, as later discussed (Chapters 3, 5 and 6).

Other empirical relationships describing AE from unsaturated soil and tailings as a function of both the climatic and soil properties have been reported in literature. One of such is the expression of AE as a function of total suction at the soil surface according to the Wilson et al. (1997) empirical model previously given in equation 2.02. The empirical model was proposed and validated by Wilson et al. (1997) for sand, silt and clay soils and was reported to be independent of the soil texture, drying time and water content. In addition to the use of total suction at the soil surface to explain the evaporative behaviour of unsaturated soil, previous work explaining evaporation in terms of the soil resistance has been undertaken (Camillo and Gurney 1986; Van de Griend and Owe 1994; Bittelli et al. 2008). The approach is based on expressing the AE from soil in terms of the mass transfer equation given as:

$$AE = \frac{P_{vs} - P_a}{R_a + R_s} \quad (2.14)$$

Where P_{vs} is the vapour pressure in the soil air phase at the surface; P_a is the vapour pressure of the atmosphere directly overlying the evaporating soil surface; R_a is the aerodynamic resistance, and; R_s is the soil resistance to vapour flow. Equation 2.14 is similar to the mass transfer equation for computing the PE from water surface or

saturated soil previously given in equation 2.06. One main difference is that P_{sv} in equation 2.06, being the vapour pressure of the saturated soil or water surface is being replaced by the vapour pressure in the soil pore atmosphere at the surface (P_{vs}). Also, $f(u)$ in equation 2.06 (same as the inverse of R_a) is replaced by the inverse of the sum of R_a and R_s in equation 2.14. The resistance approach is predicated on the need to account for the sharp gradient in vapour pressure close to the surface of drying soil, such that the mass transfer equation (equation 2.06) can be applied to unsaturated soil (Alvenäs and Jansson 1997). Otherwise, equation 2.06 will over-predict evaporation for unsaturated soil.

Based on equation 2.14, two types of resistance are identified to impact the gradient in vapour pressure at the soil-atmosphere interface, which in turn determines the rate of evaporation. The aerodynamic resistance (R_a) describes the turbulence characteristics of the air directly overlying the evaporating surface, and is a function of the wind velocity and surface roughness (Gray 1970; Wilson et al. 1994). R_a is an indicator of the resistance of the air above the soil surface against the transport of water vapour away from the evaporating surface. The soil resistance, R_s , on the other hand, is the resistance offered by the soil against the diffusive transport of water vapour from the evaporation front within the soil to the soil surface. As the evaporating soil becomes drier, at some point, the evaporation front moves away from the soil surface deeper into the soil. Water is then partly transported as vapour from the evaporation front to the soil surface. Thus, the deeper the evaporation front recedes into the soil,

the longer the distance over which water vapour is transported to the soil surface and the higher the value of R_s . Based on empirical data, several equations have been proposed for calculating the value of R_s (Camillo and Gurney 1986; Kondo et al. 1990; Van de Griend and Owe 1994). The resulting R_s is combined with the corresponding value of R_a in order to estimate evaporation from soil. In implementing the resistance approach to model evaporation in a bare sandy loam, Alvenäs and Jansson (1997) introduced an empirical “correction factor”, E_c , as:

$$E_c = 10^{-\delta_s \Psi g} \quad (2.15)$$

Where δ_s is the net surface water balance of precipitation, evaporation and soil vapour flux (mm); Ψ is the average suction in the top soil layer, and; g is acceleration due to gravity. E_c was introduced to modify equation 2.14 in order to “compensate” for the difference observed between the soil suction for the bulk topsoil and the suction “at the soil surface”. The authors observed that applying the correction factor substantially improved the agreement between predictions of profile water content and evaporation with field measurements.

The foregoing discussed the process of evaporation from soil and tailings, as well as different methods of measuring, estimating and predicting evaporation. The following section provides a review of the process of sulphide mineral oxidation in mine tailings,

the geo-environmental implications of the process, and the technologies for mitigating the consequences.

2.2 Geo-environmental Consequence of Oxidation Process in Mine Tailings

Over the past several decades, there has been an increasing demand for precious metals alongside improvements in technologies for extracting more and more trace concentrations of precious metals from host rocks (Newman 2003). This has led to mining operations turning out large tonnage of wastes (as mine tailings or waste rocks), necessitating appropriate waste management options that minimize undesirable environmental impacts. Prior to mining, host rocks comprise of constituent minerals that are under reducing conditions. Mining and extraction operations expose these otherwise stable minerals to contrasting redox conditions compared to their native environment. The new oxidising environment triggers geo-chemical transformations of these minerals, ultimately causing acid mine drainage (AMD) from mine tailings disposal facilities. The following sections review the geo-chemistry and environmental implications of oxidation and AMD, as well as several measures of mitigating against AMD from tailings disposal (or containment) facilities.

2.2.1 Process of Oxidation and Acid Mine Drainage in Mine Tailings

Mine wastes are generally in the form of either mine tailings or waste rock. Mine tailings is the waste product from milling operation; a process whereby mined ore is

crushed into fine particles prior to metal extraction by various physical and chemical separation techniques. Thus, mine tailings typically contains comminuted host rock, gangue (ore with non-economic concentration of base metal), a small portion of unrecovered metal and some process water. Waste rock, on the other hand, is the leftover of blasted ore that was not hauled to the mill because of low concentration of base metal that makes the recovery uneconomical.

AMD results when sulphur-containing minerals (such as Pyrite, FeS_2 and Pyrrhotite, $Fe_{(1-x)}S$, with x ranging from 0-0.2) in mine waste are oxidized, consequently releasing hydrogen ions and sulphates into the pore water. The oxidation process may be microbially-mediated when Fe-oxidizing bacteria, *Thiobacillus ferrooxidans* facilitate the reaction in the presence of oxygen, especially within the optimum pH range of 1.5 to 3.5 (Nicholson et al. 1989). The oxidation can also proceed abiotically at pH values in excess of 4. According to Singer and Stumm (1970), the stoichiometry of abiotic Pyrite oxidation is given as:

The oxidation product, Fe^{2+} may become further oxidized to generate Ferric Iron (Fe^{3+}) according to the reaction:

For a pH in excess of 4, Ferric Iron will precipitate as follows:

The formation of Fe^{3+} is consequential as it may also serve as an oxidizing agent according to the reaction:

As shown by these chemical reactions, acid generation occurs strictly in the presence of both oxygen and water. Therefore, oxidation of pyrite (FeS_2) ultimately leads to the formation of sulphuric acid-containing seepage from mine tailings disposal facility, known as “acid mine drainage”.

2.2.2 Environmental Challenges of Acid Mine Drainage from Mine Wastes Disposal Facilities

AMD from mine tailings disposal / containment facilities constitutes a number of environmental problems. An environmental legacy of AMD in many mining jurisdictions

around the world is contamination of surface and subsurface water resources through surface run-off or seepage through the soil, respectively (Blowes and Gillham 1988; Nicholson et al. 1989). Also, AMD has been associated with the pH of groundwater in areas having poorly-engineered mine waste impoundments being as low as 2-3 (Kleinman et al. 1981). The acidic water solubilises heavy metals such as lead, arsenic and mercury (Aubertin et al. 1994) and may cause the contamination of both surface and ground waters if discharged without treatment. The costs associated with treating such contaminated leachate to regulatory levels before discharge can be extremely high. Therefore, minimizing the exposure of sulphide minerals in mine wastes to oxygen and / or restricting infiltration of water into mine waste deposits form the basis for the different measures / technologies for mitigating AMD. The following sub-section summarizes the various technologies commonly adopted to minimize AMD from tailings disposal facilities.

2.2.3 Mitigating Acid Mine Drainage from Mine Tailings Disposal Facilities

Over the years, a number of solutions have been developed for mitigating against oxidation and AMD from mine waste disposal sites. Examples include the implementation of water cover (Robertson et al. 1997; Simms et al. 2001) and soil covers (Frind et al. 1976; Williams et al. 1997; O’Kane et al. 1998) over mine waste impoundments. The use of water covers to limit oxidation and AMD from mine waste is predicated upon the fact that the effective diffusion coefficient of oxygen in water (D_e) is 10,000 times less than D_e in air (Robertson et al. 1997). The restricted diffusion of

oxygen into mine wastes by water cover is also enhanced by its low solubility (6.3 mL/L at 25°C and 1bar) in water (Nicholson et al. 1989; Adu-Wusu 2006). Also, the relatively reducing conditions provided by implementing water cover slows down the release of heavy metals from such submerged tailings (Robertson et al. 1997), especially if the tailings was not pre-oxidized prior to flooding. Thus, for sites with suitable local topography, hydrology and hydro-geology, water cover may be a viable option for mitigating against AMD from mine waste impoundments (Peacey et al. 2002).

However, the implementation of water cover may be limited in a number of ways. In the case of previously-oxidized tailings, the effectiveness of water cover against AMD may be much lower. Also, the implementation of water cover is not practical for most existing tailings impoundments (Nicholson et al. 1989) where the local topographic and hydro-geological configuration may not be suitable (Peacey et al. 2002). There is also the challenge of fines re-suspension by wave action and consequent sulphide oxidation. In addition, a prolonged drought can lead to water loss and reduced effectiveness of a water cover. Considering these limitations associated with water covers, the use of soil covers for controlling AMD from mine waste disposal sites has become more widely adopted in recent times.

The design objective for implementing soil cover is to reduce the ingress of oxygen and / or water infiltration into mine waste. Nicholson et al. (1989) showed that

theoretically, with a well-designed soil cover, it is possible to reduce the ingress of oxygen into mine waste deposits as well as AMD by up to four orders of magnitude. This potential effectiveness of soil cover was demonstrated at the Equity Silver Mine site (B.C, Canada) by O'kane et al. (1998). Similar results were reported from field experiments by Bussière and Aubertin (1999) and Bussière et al. (2007), where capillary barrier soil covers, consisting of non-reactive tailings and silt, respectively, were effective in reducing oxygen flux into mine waste deposits. Similarly, significant reduction of water percolation through a candidate soil cover to just 4% of total annual precipitation was demonstrated by Yanful and St-Arnaud (1991) and Woyshner and Yanful (1995). Other techniques of mitigating AMD from mine waste deposits include different types of backfills, liming, in-pit disposal, cemented paste backfill and surface disposal of thickened mine tailings. The surface disposal of thickened tailings is an emerging technology and a summary of its rationale and effectiveness is provided in the following section.

2.2.4. Paste and Thickened Tailings Technology for Mine Waste Disposal

As previously mentioned, most mining operations require that large tonnage of mine tailings be stored on a daily basis to keep pace with the intensity of mining, milling and extraction operations. Conventionally, mine tailings are disposed as slurry behind engineered or natural dams. Catastrophic failures of such dams in the past caused by dynamic loading and structural problems due to excessive seepage have led to large-scale environmental and ecological disasters, with human casualties in some instances.

Examples of such catastrophic tailings dam failures include: Omai Mine, Guyana, 1995; Los Frailes, Spain, 1998; Baia Borsa, Romania, 2000; Ajka Alumina Plant, Hungary, 2010. The cost implications of such dam failures in terms of cleanup operations and compensations are typically in millions of dollars (Newman 2003) in addition to the more-dreaded damage to corporate reputation.

Excessive pore-water pressure resulting from either process water or rainfall is the main precursor for most tailings dam failures. Excess pore-water pressure generation prevents solidification and stabilization, and can cause liquefaction of tailings ponds (Davies 2002). Therefore, dewatering the tailings prior to surface deposition is a suitable approach to reducing the fluidity of impounded mine tailings. Paste and thickened tailings technology is a way of achieving this structural stability. Thickened tailings is produced by dewatering slurried tailings to a solids concentration of about 65-72% (by weight) such that it can be deposited in an impoundment and exhibit a non-trivial yield stress, show little or no particle segregation and produce minimal bleed water. Thickened tailings is typically produced using high-density or deep-cone thickeners where flocculation of the tailings slurry promote particle aggregation and dewatering.

Paste is a special type of thickened tailings which is essentially a single-phase material with higher solids concentration (70 – 85%) compared to conventional

thickened tailings. Paste is produced using specialized paste or ultra-high density thickeners. Paste is transported in pipes using positive displacement pumps, and when deposited, also produces negligible bleed water with sufficient shear strength to exhibit limited slump. For most applications, a quality paste is expected to have a slump of between 175 and 250mm, with at least 15% of its total particulates being smaller than 20microns. These fines help ensure plug flow that eliminates pressure losses associated with turbulent flow of highly-concentrated slurries during transport in pipes (Newman 2003). While thickened tailings are mostly used for surface disposal, paste could be used for either surface or underground tailings disposal. Underground paste tailings disposal involves the addition of a suitable binder (such as Portland cement, fly-ash or slag) to the paste and pumping the cemented paste to back-fill mined out voids (stopes) to provide structural stability during the mining of adjacent ore. Paste technology was first developed in the Sudbury basin of Canada by INCO mines specifically for underground stope stabilization application (Newman 2003). Since, then the application of paste technology has been expanded to include surface deposition of thickened tailings.

Compared to a conventional tailings disposal, operating costs for SDTT is higher, but the potential reclamation costs associated with the latter is significantly lower. The total cost of running a conventional versus SDTT operations for a 1million-tonnes-per-year mining operation for 10 years was estimated by Golder Associates to be US\$ 15.3 million versus 16.2 million, respectively (Newman, 2003). The estimate did not take into account several aforementioned factors that could have demonstrated that SDTT

technology is a preferred alternative when compared with conventional tailings disposal.

2.3 Evaporation and Oxidation of Sulphide Minerals in Mine Tailings

Evaporation from SDTT stack is desirable for reduction in volume of tailings disposed, as well as minimization of disposal footprint and volume of leachate that requires treatment prior to discharge (Simms et al. 2007). Evaporation is also crucial for strength gain of SDTT and improving the bearing capacity of desiccating tailings for subsequent fresh lifts, as well as enhancing the trafficability of machineries and equipment during site closure and rehabilitation (Rassam and Williams 1999a). A rapid shear strength gain by tailings stacks due to evaporation shortens the time lag between deposition cycles, and allows deposition to keep up with the large tailings turnover characteristic of most mining operations. However, evaporation causes SDTT to desaturate, removing the hydraulic barrier to oxygen ingress into tailings, resulting in sulphide mineral oxidation and consequently acid mine drainage from disposal facilities. The following sections provide a detailed review of the geotechnical benefits of evaporation as well as the geo-environmental implications of evaporation on oxygen diffusion, sulphide-mineral oxidation and AMD from SDTT stacks.

2.3.1 Geotechnical Importance of Evaporation in Mine Tailings Management

Evaporation affects the engineering properties (shear strength, volume change and permeability) of unsaturated soil and tailings. For instance, Fredlund et al. (1978) gave the shear strength envelope of an unsaturated soil at failure as:

$$\tau_{ff} = c' + (\sigma_f - u_a)_f \tan \phi' + (u_a - u_w)_f \tan \phi^b \quad (2.16)$$

where c' is the effective cohesion; $(\sigma_f - u_a)_f$ is the net normal stress state on the failure plane; u_a is the pore-air pressure on the failure plane; ϕ' , the angle of internal friction associated with net normal stress state variable; $(u_a - u_w)_f$, the matric suction on the failure plane; ϕ^b the angle indicating the rate of increase in shear strength due to matric suction. In addition to matric suction, the shear strength of unsaturated soil at failure is also known to be a function of its water content (Das 2008) and void ratio (Sagae et al. 2006). Previous experimental work (Simms et al. 2007; Fisseha et al. 2010) has shown that the void ratio and water content of SDTT decrease over time as the deposit desaturates due to evaporation.

In unsaturated soil (and tailings), the additional contribution of matric suction to shear strength could be substantial. Rassam and Williams (1999a) investigated the bearing capacity of desiccating mine tailings by conducting a series of multi-stage, consolidated-drained tests using a modified triaxial apparatus. The saturated and

unsaturated shear strengths of the tailings were determined as per Rassam and Williams (1999b). The saturated shear strength was calculated from the effective frictional angle determined from the triaxial tests. The contribution of matric suction to shear strength was determined from the ordinate intercept of tangents to Mohr's circles drawn for the failure envelopes. This contribution from matric suction was then added to the saturated shear strength to calculate the unsaturated shear strength. The shear strength of the desiccating tailings was found to increase with matric suction, up to the AEV (Figure 2.03) of the tailings. Beyond the AEV, the contribution of matric suction to shear strength of the tailings becomes non-linear, and diminishes as the desiccating tailings gets to its residual water content (Rassam and Williams 1999b). A similar observation by Vanapalli et al. (1996) described the relationship between the shear strength of unsaturated soil and its matric suction, using the ratio of area of water (a_w) at any degree of saturation to a_w at saturation. Matric suction was found to contribute entirely to shear strength up to the AEV, over which range a_w is 1. Past the AEV, a_w decreases and consequently, the contribution of matric suction to shear strength declines.

Rassam and Williams (1999a) also investigated the matric suction profile and the ultimate bearing capacity of the desiccating tailings under both hydrostatic and evaporative conditions. The ultimate bearing capacity of the tailings under evaporative conditions was found to be higher compared to hydrostatic conditions, under both shallow (1.5m) and deep (2.5m) water table scenarios. This was attributed to the greater contribution from matric suction to the shear strength under evaporative conditions.

Upon rewetting the desiccating tailings however, the matric suction profile, shear strength and bearing capacity of the tailings were found to decrease significantly. Therefore, evaporation from SDTT causes the reduction in its void ratio and water content, and increases its matric suction, shear strength and bearing capacity, thereby enhancing its overall geotechnical properties.

Figure 2.03. Shear strength envelopes of desiccating tailings with respect to matric suction. ψ_e is the AEV. (From Rassam and Williams 1999a).

Likewise, evaporation influences the volume change behaviour of soil and mine tailings. A typical shrinkage curve for drying freshwater tailings is shown in Figure 2.04. At point A, the tailings' water content is well in excess of the liquid limit. As the material

continues to dry, its water content decreases past the liquid and plastic limits during which its volume continues to shrink proportionately. Within this range on the curve (A-B), shrinkage is entirely due to water loss from evaporation. Past point B however, shrinkage decreases and becomes disproportionate with water loss from tailings. The desiccating tailings desaturate, beginning with larger pores, and then smaller pores, resulting in air entry into the void spaces. Eventually, the shrinkage limit is reached; where no further increases in density of desiccating tailings occur but the hydraulic conductivity of the tailings continues to decrease with decreasing degree of saturation. Therefore, evaporation also contributes to the densification of SDTT by promoting desaturation and volume shrinkage, consequently enhancing the geotechnical performance of stacks.

Figure 2.04. Volume change behaviour of evaporating surface-deposited thickened tailings (After Newson and Fahey 2003).

In addition, evaporation affects the hydraulic conductivity of soil or tailings through its effect on the evolution of matric suction. The hydraulic conductivity of unsaturated soil is a function of its matric suction and water content (Fredlund and Rahardjo 1993). Several empirical equations have been proposed in literature relating hydraulic conductivity to water content (Buckingham 1907; Richards 1931) and matric suction (Gardner 1958; Brooks and Corey 1964). A graphical representation of the Gardner's equation is shown in Figure 2.05, where K_w and K_s are the unsaturated and saturated hydraulic conductivity, respectively; $(u_a - u_w)$, the matric suction; ρ , the density of water; and g , the gravitational acceleration. The empirical constant "a" relates to the breaking point of the function, and "n" defines the slope of the function. Evaporation contributes to increase in matric suction of desiccating tailings, thereby decreasing the hydraulic conductivity of stacks (Figure 2.05). This decrease in hydraulic conductivity is caused by increase in tortuosity of the void spaces available for water flow as well as discontinuity of the water phase as matric suction increases.

From the foregoing, evaporation is an important process that affects the geotechnical properties of shear strength, volume change and hydraulic conductivity of SDTT (Fujiyasu and Fahey 2000). Thus, in theory, the reduction in water content and compressibility resulting from evaporation of tailings stacks can be optimized by deposition of thin layers of thickened tailings. This approach can ensure an over-consolidated tailings profile having a high degree of densification and bearing capacity (Newson and Fahey 2003). While evaporation is beneficial from the perspective of

geotechnical performance of the tailings stack, desaturation may lead to detrimental geo-environmental impacts as detailed in the following sections.

Figure 2.05. Gardner's equation for water coefficient of permeability as a function of matric suction (From Fredlund and Rahardjo 1993).

2.3.2 Geo-environmental Implication of Evaporation for Mine Tailings Management

At the time of surface deposition, thickened tailings is saturated or near-saturated, with an approximate degree of saturation of 100%. Such saturated tailings is a two-phase system, where the total void space is completely filled with water. The rate

of sulphide mineral oxidation in SDTT is primarily controlled by the vertical diffusion of oxygen into the stack. According to Fick's first law, the diffusive flux of a compound (such as oxygen) in a porous medium (like tailings) is directly proportional to the concentration gradient existing across the flow boundary:

$$F = -D \frac{\partial C}{\partial z} \quad (2.17)$$

Where F is diffusive flux ($\text{mol/m}^2.\text{s}$); D is the diffusion coefficient (m^2/s); C is the concentration (mol/m^3) and $\frac{\partial C}{\partial z}$ is the concentration gradient ($\text{mol/m}^3.\text{m}$) across the flow boundary. A semi-empirical equation to calculate the effective diffusion coefficient of oxygen in unsaturated soil was given by Aachib et al (2004) as:

$$D_{eff} = \frac{1}{n^2} (D_a^0 \theta_a^p + H D_w^0 \theta_w^p) \quad (2.18)$$

Where D_{eff} is the effective diffusion coefficient of oxygen (m^2/s); n , the porosity; D_a^0 , the free diffusion coefficient of oxygen in air at room temperature; θ_a , the volumetric air content of soil; H , the dimensionless Henry's equilibrium constant (0.03 for oxygen at 20°C); D_w^0 , the free diffusion coefficient of oxygen in water at room temperature; θ_w , the volumetric water content of soil; and p is a tortuosity parameter (a fixed value of $p=3.4$

can be used without significant loss of accuracy; Bryan 2008). Hence, the higher the water content of the soil, the lower the effective diffusion coefficient of oxygen within it.

The diffusion coefficient of oxygen in water and air are 1.8×10^{-9} and 2.0×10^{-5} m^2/s , respectively (Elberling, 1996), implying that the rate of oxygen diffusion in air is about 10,000 times faster than in water. Due to its saturated condition at deposition, the D_{eff} of oxygen in freshly-deposited thickened tailings approaches that in water. This results in the formation of a “hydraulic barrier” to oxygen ingress into the fresh tailings layer. As evaporative drying of the layer continues, its degree of saturation decreases and D_{eff} of oxygen approaches that in air (Figure 2.06). Hence, the hydraulic barrier to oxygen diffusion into the tailings layer is gradually removed, eventually causing sulphide minerals oxidation and AMD. Thus, excessive evaporation inadvertently promotes sulphide minerals oxidation and may serve as a precursor to AMD from mine tailings disposal sites.

Therefore, it is desirable in tailings deposition management to maximize the geotechnical benefits of evaporation while minimizing the geo-environmental consequence of excessive evaporation. This is the philosophy behind the deposition strategy employed at the Bulyanhulu Gold mine in Tanzania, where a thin layer (10 – 30cm) of thickened tailings is covered every 5 – 30 days by a fresh layer of tailings or

non-reactive material (Deschamps et al. 2008). The thin layer ensures rapid shear strength gain during the short deposition cycle while the fresh tailings layer helps to minimize oxidation and AMD from the tailings stack by maintain the hydraulic barrier to oxygen diffusion.

Figure 2.06. Variation in effective diffusion coefficient of oxygen in a porous medium as a function of degree of saturation (From Aachib et al. 2004).

2.4 Effects of Pore-water Salinity on Evaporation from Soil and Mine

Tailings

Pore-water salinity is known to decrease the rate of evaporation from soil (Salhotra et al. 1985; Chen, 1992; Shimojima et al. 1996; Fujimaki et al. 2006). This salinity-induced reduction in evaporation has also been observed for saline tailings deposits (Newson and Fahey 1997; Fujiyasu and Fahey 2000; Simms et al. 2007; Fisseha et al. 2010; Dunmola and Simms 2010). In fact, salinity has been reported to reduce evaporation to just a few percentage of the potential rate in both soil and mine tailings (Chen 1992; Fahey and Fujiyasu 1994; Fujimaki et al. 2006; Newson and Fahey 2003; Dunmola and Simms, 2010). Salinity is therefore undesirable for evaporative densification of SDTT as it slows down its rate of consolidation and shear strength gain.

Figure 2.07 is a conceptual model by Newson and Fahey (2003) showing the different stages of evaporation for a drying saline tailings in comparison to a freshwater tailings. In stage I, which is prior to the formation of salt crusts, the rate of evaporation from the saline tailings is slightly lower compared to freshwater tailings. The slope of the evaporation curve at this stage is decreasing due to accumulation of dissolved mass and osmotic suction at the soil surface, and is dependent on the initial pore-water salinity of the tailings, with a lower initial salinity giving a steeper slope. As the salinity at the tailings surface increases with salt accumulation, the pore-water solution becomes saturated and salt precipitation and salt crusts formation occurs, initiating the beginning

Figure 2.07. Temporal variation in relative evaporation from freshwater and saline soil / tailings (After Newson and Fahey, 2003). Note that RE is relative evaporation (AE/PE) and PE is potential evaporation.

of stage II. During Stage II, evaporation rate drops very sharply due to the development of salt crust on the tailings surface.

Throughout stage II, the drying tailings remains saturated due to suppressed evaporation, unlike the case of freshwater tailings where desaturation takes place at this stage. The tailings eventually desaturate in stage III as the salt crusts disintegrate. In stage IV, the rate of evaporation approaches zero as the tailings reaches its residual water content. In contrast to freshwater tailings, the pore-water salinity and hydraulic

conductivity of saline tailings controls actual evaporation right from the beginning of stage I. This makes the upper limit of evaporation (stage I) for saline tailings to be considerably less compared to freshwater tailings given the same incident radiant energy. Therefore, it is the case that during stage I, the pore-water solute composition of saline tailings controls the evaporation since the effects of soil factors resisting water flow is relatively small.

Fahey and Fujiyasu (1994) demonstrated the effects of salinity on relative evaporation (RE) from tailings by mixing artificial tailings with different concentrations of NaCl solutions. The RE for the freshwater tailings ($C=0$) fell from 1 to 0.6 in 10 days and remained constant afterwards. However, for the saline tailings treatments, reduction in RE was more rapid and deeper, falling to just between 0.1 and 0.2 in few days. The reduction in RE was observed to increase with the initial pore-water salinity treatment of tailings, with the reduction being almost immediate for the most saline treatment ($C=0.23$). Irrespective of the initial pore-water salinity of the tailings, the final RE was comparably low. The authors concluded that even a moderate level of pore-water salinity is capable of reducing the RE in tailings stacks. Similar observation has been reported for salt-encrusted surface lakes and playas around the world (Malek et al. 1990).

Shimajima et al. (1996) investigated the relationship between evaporation and salinization in saline soil. The study conducted a column evaporation test, under

controlled conditions, for sand dune, silica sand and glass beads prepared with Ca and Na salts solutions. As the sand columns dried, pore-water Ca and Na salts were observed to cause significant salinization near the soil surface. Slight difference in how each salt affects vapour density and gradient, as well the implications for surface evaporation, was observed. The more readily soluble salt (Na) caused a rapid enrichment of the pore-water near the surface of the silica sand and glass bead columns. This salt enrichment lowered the vapour density and vapour gradient at the surface of the silica sand and glass beads, consequently reducing evaporative fluxes by 70 and 30%, respectively. In the case of the glass beads, salt crust formation at the surface increased resistance to mass transfer by 3 to 10 times. For the dune sand column, the increase in resistance to mass transfer caused by salt crust was only 30%, which was attributed to the easier penetration of applied airflow into the cracks within the salt crust.

2.5 Sources and Determination of Pore-water Salinity in Soil and Mine

Tailings

Common sources of salinity in mine tailings include: chemical additives (during ore preparation and extraction), unweathered minerals, salinity from rainfall (oceanic aerosols), fossil salts from former marine materials and salinity from recycled process water. In addition, under oxidizing conditions, ongoing geo-chemical transformations in mine tailings deposits may constitute a source of salinity. In arid and semi-arid regions (such as Western Australia), gold mines have historically used hyper-saline water (having

concentrations of up to 0.2g solute / g of solution, or 7 times the salt concentration of sea water) for ore processing. Such ore processing method results in tailings storages with extremely high salinity approaching saturation salinity of $C = 0.26$ (Newson and Fahey 1997). In soils, pore-water salinity may result from naturally-occurring mineral salts (such as carbonates and sulphates) or salts applied as fertilizers to enhance crop growth and development. Salinity in soil may also be caused when the groundwater is saline and net water loss by evaporation pulls the saline water to the crop rooting zone (Yuvaniyama et al. 2008).

Pore-water salinity in soil or mine tailings can be quantified by determination of the electrical conductivity (EC) of soil solution extracts. Salinity is conventionally expressed in terms of the EC of the saturated paste extract, but getting pore-water samples from soil or tailings may not be feasible for most applications. It is more common to quantify salinity by the determination of the EC of 1:1 (mass of soil: mass of water/slurry), 1:2, or 1:5 water extracts. For the current thesis research, pore-water salinity was quantified as EC measurements of 1: 5 (soil: slurry) extracts of soil/ tailings. This approach was adopted as it was impractical to obtain saturated paste extracts due to the generally limited amount of profile soil or tailings samples obtained from destructive sampling of soil or tailings columns, as later explained in Chapter 3.

2.6. State-of-the-art on Mechanisms of Salinity-induced Reduction in Evaporative Fluxes from Saline Soil and Mine Tailings

There are three mechanisms by which salinity reduces the rate of evaporation from soil and thickened tailings. These include: increased surface reflectivity (albedo); increase in osmotic suction; and changes in hydraulic properties of the tailings due to salt precipitation and crust formation (Fujiyasu and Fahey 2000). The effect of albedo on surface evaporation from soil and mine tailings have been widely investigated (Malek et al. 1990; Newson and Fahey 1997; Simms et al. 2007). The following is an expanded form of equation 2.03 previously given, which expresses the energy balance from the solar system to soil or mine tailings:

$$R_s (1-r) + R_{in} - R_{out} = L_e E + H + G \quad (2.19)$$

Where R_s is shortwave radiative flux; r is the shortwave reflectivity (albedo) of soil surface; R_{in} is the incoming long-wave radiation; R_{out} is the outgoing long-wave radiation; L_e is the latent heat of vaporization; E is the evaporation rate; H is the sensible heat flux (into atmosphere); and G is the soil heat flux. An important parameter in this energy balance is the albedo of soil surface (r), which is a ratio of reflected to total incident short-wave radiation. As shown by equation 2.19, the amount of short-wave radiation absorbed by a surface is a function of its albedo. The higher the albedo of the soil / tailings surface, the lower the proportion of incident radiation partitioned to the

soil or tailings for driving evaporation. The albedo of a surface is known to vary with its water content and is affected by salt crust formation. Malek et al. (1990) reported that the shortwave albedo of salt-encrusted surface of a desert in Utah ranged from 0.24 when wet to 0.75 when dry. Also, Chen (1992) observed that the formation of a thin (few centimetres) salt crust can increase the albedo of the soil significantly enough to reduce evaporation to just a few percentage of the potential rate, even with the underlying soil being saturated. For a SDTT, Simms et al. (2007) observed that albedo was significant to the reduction in the rate of evaporation observed under both laboratory and field conditions.

Salinity also reduces evaporation rate by increasing the osmotic suction of tailings pore-water, thereby lowering the vapour pressure gradient at the soil / tailings-atmosphere interface. According to Brutsaert (1982), Dalton's evaporation theory relating evaporative flux to saturated vapour density at soil-atmosphere interface and meteorological conditions can be written as:

$$E_{fw} = \frac{\rho_{sv}(T_s) - \rho_a}{R_a} \quad (2.20)$$

Where E_{fw} is the freshwater evaporative flux; $\rho_{sv}(T_s)$ is the saturation vapour density above freshwater surface as a function of surface temperature, T_s ; ρ_a is the actual

vapour density of air at a reference height; and R_a is the aerodynamic resistance, which is an empirical function that depends on wind profile, atmospheric stability and elevation. Equation 2.20 is similar to equation 2.06, except that R_a is the inverse of $f(u)$ contained in the latter. Dalton's evaporative flux equation has also been extended to saline condition (Salhotra et al. 1985; Fujimaki et al. 2006). Under saline condition, the presence of salts not only decreases the number of water molecules per unit volume, but also reduces the effect of molecular interactions on thermal energy of water molecules (Brutsaert 1982). Thus, equation 2.20 was modified, taking into account the effect of salinity on evaporation from saline water, soil or tailings as:

$$E_{sw} = \frac{\rho_{sv}(T_s, S_s) - \rho_a}{R_a} \quad (2.21)$$

Where E_{sw} is the evaporation rate from saline water body or soil; $\rho_{sv}(T_s, S_s)$ is the saturation vapour density above saline surface as a function of its surface temperature, T_s and salinity S_s . The higher the pore-water salinity of the soil / tailings, the higher its osmotic suction, the lower the value of $\rho_{vsat}(T_s, S_s)$, and the lower the value of E_{sw} . Therefore, salinity lowers evaporation from soil or tailings by increasing its osmotic suction, thereby lowering the vapour pressure gradient driving evaporative fluxes across the soil/ tailings-atmosphere boundary.

In addition, pore-water salinity reduces evaporation from soil or tailings through physical restriction to water flow due to salt crust. Salt crusts are formed when precipitation occurs as the pore-water solute concentration at or near the soil / tailings surface reaches the solubility limit of the solute(s). The pore-water solute concentration increases by a combination of upward advective transport of solute and desaturation of soil / tailings at or near the surface due to evaporation. Salt crusts typically form at the evaporation front, but may also occur below the soil / tailings surface in cases where such surface is very dry (Fujiyasu and Fahey 2000). Observations from encrusted tailings dams have shown salt crusts to be porous aggregates that shrink when drying, preventing the effective transfer of water from underlying tailings through evaporation (Newson and Fahey 2003). The salt crusts have higher average pore diameter in comparison to soil or tailings particles, thereby reducing the capillary rise of water through the crust to the evaporating surface (Malek et al. 1990; Chen 1992; Newson and Fahey 2003). Zawislanski et al. (1992) reported the “mulching” effect of salt crusts on evaporating soil surface leading to reduction in evaporative fluxes. Thorburn et al. (1992) also suggested physical clogging of soil pores by salt precipitates, causing reduced permeability that restricts the upward flow of water required to meet evaporative demand. A number of other studies have looked at each of these 3 mechanisms of salinity-induced reduction in evaporation for soil and mine tailings.

Fujimaki et al. (2003) conducted a column study relating salt accumulation and water content to albedo for two soils (sandy loam and loam) drying under natural

conditions. For the same water content, a higher albedo was observed for the saline soil compared to non-saline soil, with an increase of up to 0.3 for the former compared to the latter. Albedo was found to correlate with the soil water content and amount of salt accumulated at the surface for both soils tested. Soil albedo generally increased with decreasing water content and increasing salt accumulation. However, surface salt accumulation and associated increase in albedo was reduced when evaporation rates were low. When the water content of the soils became low, vapour flow dominated and salt crusts were formed at depths, which had no effect on surface albedo measurements. The authors proposed empirical equations relating albedo to water content at the soil surface as well as to mass of salt accumulated above a certain depth in soil. These relationships worked well for both tested soils when the depth of sampling was 20mm, but not when a sampling depth of 5mm was considered.

The effect of pore-water salinity on evaporation and evaporation-driven solute transport was investigated by Fujimaki et al. (2006) under isothermal condition. Columns of loamy sand and sand soils, initially saturated to uniform pore-water concentrations using NaCl and KCl solutions were allowed to evaporate under ambient conditions. The columns were kept relatively wet throughout the evaporation test by maintaining a constant pressure head at the bottom of columns by means of a porous plate and salt solution reservoir. Evaporation rates were measured throughout the experiment and profiles of water contents and solute concentrations were determined on three occasions during the experiment. Salinity was observed to cause a reduction in

evaporation rates, matched by an accumulation of salts at the top 1cm of soil columns. Numerical solution gave evaporation rates that were significantly higher than measured values, and this discrepancy was attributed to the effect of salt crust, which was not included in the simulation. When the resistance to flow due to salt crust was included, the numerical solution gave better correlation with observed evaporation rates. The authors concluded that the decrease in evaporation due to pore-water salinity could not be explained by osmotic suction alone, but also by the effect of salt crust.

A study on the influence of salinity and compaction on evaporation from soil was conducted by Nassar and Horton (1999). The authors tested a clay and loam soils under different initial salinity and compaction conditions: Non-compacted, Non-saline (NC, NS); Non-compacted, saline (NC,S) for both soils; as well as compacted, saline (C,S) for clay soil only. The initial volumetric water contents (VWC) of the NC clay, NC loam, and compacted clay soils were 27.1, 18.1, and 39.3%, respectively. The initial pore-water KCl concentrations for the saline clay and loam soils were 1.11 mol.kg^{-1} (82.5ppt) and 0.92 mol.kg^{-1} (69ppt), respectively. The soil columns were exposed to natural radiation over a period of 28 days, with cumulative evaporation, water content and solute concentration monitored on days 14 and 28. The ratio of cumulative evaporation from the saline treatment to non-saline treatment for the NC clay and loam soils increased over time from 0.78 to 0.89 and 0.90 to 0.95, respectively. The larger ratio for the loam was attributed to its lower initial pore-water solute concentration, water content and

smaller specific surface area. The ratio of cumulative evaporation for the non-compacted to compacted clay soil increased over time from 0.73 to 0.77.

A study by Newson and Fahey (2003) investigated the effect of salinity on evaporation from 4 test cells in a hyper-saline tailings storage facility. Hyper-saline tailings ($C=0.1$) was deposited in lifts of thicknesses ranging from 1 to 2m in the test cells and left to desiccate for 6 months. The AE for the field study was measured using meteorological methods, with the profile GWC and salinity also determined at intervals. A decrease in AE was recorded as the tailings dried, falling below the values for freshwater tailings, even prior to the formation of salt crusts. Once salt crusts were formed at the tailings surface, RE dropped even more rapidly to values less than 0.2, a trend similar to laboratory observation. Also, the trend for the profile salinity observed in the field was similar to laboratory data: surface salt accumulation and decreasing salt concentration with depth that eventually approached the as-deposited values. Interestingly, despite the fact that full salt crust did not develop in the field, salinity-induced reduction in evaporation as the tailings dried was comparable to laboratory data.

Fujiyasu and Fahey (2000) studied the mechanisms responsible for the reduction in evaporative fluxes from drying artificial tailings initially prepared to different pore-water NaCl concentrations. Incident solar radiation and wind were simulated in the

laboratory throughout the drying period, and the evaporation rates from all treatments were monitored. Throughout the study, the highest RE was observed for the non-saline tailings. The higher salinity treatment showed a more pronounced reduction in evaporation, with its RE falling to less than 0.2 immediately after the onset of drying. The low-salinity treatment showed a more gradual decline in RE. Irrespective of the salinity treatment of the tailings, a rapid accumulation of salts at the surface of tailings was observed. On occasions, following the manual removal of salt crust at the surface of desiccating tailings, a rapid but brief spike in evaporative fluxes was observed. As the tailings dried and GWC decreased, there was an increase in surface reflectivity and resistance of salt crust to water flow. Salt crust resistance was found to be a function of evaporative demand, water content and thickness of the salt crust. It was concluded in the study that both surface reflectivity and salt crust resistance to moisture transfer were important mechanisms responsible for salinity-induced reduction in evaporative fluxes from saline tailings.

From the foregoing, the surface accumulation of salt in saline soil and tailings and the associated reduction in surface evaporative fluxes are coupled to the 1D transport of pore-water solutes. Thus, an understanding of the profile transport of pore-water solute is important for better understanding of the mechanisms of salinity-induced reduction in evaporation. The following section describes the mechanisms of solute transport in desiccating saline soil and mine tailings.

2.7. Mass Transport of Pore-water Solutes in Desiccating Soil and Tailings

The transport of solutes in a porous medium may occur through a number of mechanisms, namely; advection, dispersion and diffusion (Shimajima et al. 1996). Depending on the nature of the porous medium as well as flow and solute properties, either a combination of these processes may be taking place or a particular process may be predominant (Muñoz and Rengifo 1995). Advection involves the co-movement of solute with pore-water flow in the medium, and the flow behaviour is governed by Darcy's Law. Dispersion is the flow mechanism whereby pore-water suspended mass is spread by molecular mixing beyond the region it would normally occupy due to advection alone. Dispersion may be either hydrodynamic or mechanical. Hydrodynamic dispersion entails both mechanical dispersion and diffusion. Mechanical dispersion occurs at the pore scale and results from the mixing of solute as a result of local velocity gradients. Diffusion, on the other hand, results from the movement of solute from one region of the porous medium to another due to concentration gradients and random molecular movement. Diffusion in unsaturated soil is governed by Fick's law.

The classical advection-dispersion equation (ADE) is a mechanistic model often used in characterizing solute transport by advection and dispersion in soil and mine tailings (Elrick et al. 1994; Lennartz and Kamra 1998; Fujimaki et al. 2006; Fisseha et al. 2010). The steady-state form of ADE in 1D for a non-reactive solute is given as:

$$\frac{\partial C}{\partial t} = D \frac{\partial^2 C}{\partial z^2} - V \frac{\partial C}{\partial z} \quad (2.22)$$

Where $C(z, t)$ is the concentration of solute in soil / tailings pore-water; D , the dispersion coefficient; V , the flow velocity of pore-water; z , the vertical space coordinate (zero at the surface and negative below the surface for upward flow) and; t , the time.

The dispersion coefficient, D , is given as:

$$D = D_d + D_m \quad (2.23)$$

Where D_d is the effective ionic diffusion coefficient; and D_m is the mechanical dispersion coefficient given as:

$$D_m = \lambda V \quad (2.24)$$

Where λ is the dispersivity. D_m is known to be a function of the scale of investigation, with values ranging between 0.0001-0.01m for laboratory experiments (Domenico and Schwartz 1990) to between 0.001-5500m for field experiments (Gelhar et al. 1985) previously reported.

The transient form of equation 2.22 is expressed as:

$$\frac{\partial C}{\partial t} = D \frac{\partial^2 C}{\partial z^2} - V \frac{\partial C}{\partial z} - C \frac{\partial V}{\partial z} \quad (2.25)$$

In desiccating soil and mine tailings, evaporative demand induces a net upward flow of pore water, causing the advection of solutes towards the surface, with the physics of the transport described by the transient form of ADE (equation 2.25). Given an initial uniform profile distribution of pore-water solute, the evaporation-induced flow of water to the surface causes accompanying solute to be transported upwards. This leads to the accumulation of solute at or near the surface in desiccating soils and mine tailings. Once the solubility limit of the solute is reached, salts precipitate out of pore solution and a salt crust is formed. Therefore, solute transport is coupled to evaporation and better understanding of this coupling is important for improved numerical prediction of evaporative fluxes in saline soil and tailings. The following section chronicles the current understanding of this coupled relationship, citing a few pertinent studies from literature.

2.8 Solute Transport and Evaporation in Soil and Thickened Tailings

As previously discussed, adequate tailings management seeks to maximize the geotechnical benefits of evaporation from deposited thickened tailings while minimizing the side effect of excessive evaporation. The effect of solute transport and surface salt accumulation on evaporative fluxes from deposited mine tailings further complicates

achieving this objective. Numerical analysis offers a way of optimizing tailings deposition operations to achieve the desired objective. Current numerical tools for predicting evaporative densification of saline tailings stacks have the limitation of numerical solutions deviating from experimental data following the precipitation of salts at the surface. Thus, a numerical framework that account for the coupling between solute transport and evaporation in modeling evaporative densification of saline tailings is necessary. There have been a few qualitative observations or empirical correlations on 1D solute transport and its relationship to evaporative fluxes in saline soils and mine tailings (Shimajima et al. 1996; Fujimaki et al. 2006; Simms et al. 2007; Fisseha et al. 2010).

Shimajima et al. (1996) conducted a column drying experiment to investigate the relationship between 1D solute transport and evaporation in dune sand (DS), silica sand (SS) and glass beads (GB). Packed columns (120cm high) of DS, SS and GB were saturated with NaCl solution from the base, followed by gravity drainage after which the surface of columns were allowed to desiccate under ambient air at controlled temperature and RH. Water table, with depths ranging from 15 to 105cm below the soil column surface was maintained during drying by means of a Mariot bottle connected via a tube to the base of columns. The duration for drying the columns ranged from 3 – 107 days, depending on the depth of water table applied. At the end of the drying period, the soil columns were sectioned into 1-2cm thick profile samples and analysed for water content and solute concentration. Salt accumulation in the top 3-4 cm of the

DS was observed, with the drying front in the column reaching 5cm below the surface at the end of drying. For SS, the drying front advanced downwards to a depth of about 6cm over 3 days, with salt accumulation observed at depths immediately above the drying front. Shallow water table did not significantly increase surface salt accumulation in the SS column. In the case of the GB column, after about 10 days, the drying front had receded to a depth of 8cm below the surface, with the depth of salt accumulation just above the front. For all three soil columns, the evaporation rates dropped below values measured for the non-saline control columns with similar water table depths. This was associated with the accumulation of salt at the surface of the treated soil columns.

Fujimaki et al. (2006) investigated the effect of salinity on evaporation and evaporation-driven solute transport in loamy sand and sand soils under isothermal conditions. Soil packed in acrylic ring columns was hydraulically saturated with NaCl or KCl solutions through a porous cup at the base by maintaining a pressure head, following which column was drained by gravity. The soil columns were thereafter subjected to evaporation under ambient conditions, but with simulated solar radiation and wind. Profiles of water content and solute concentration were determined at three different times on sectioned soil columns using oven-drying and electrical conductivity analyses, respectively. Numerical analysis of evaporative fluxes involved solving combined liquid and vapour flow equation by finite element method using atmospheric condition and applied pressure head as top and bottom boundary conditions, respectively. Solute transport was predicted by solving ADE using implicit finite

difference scheme and adopting the same boundary conditions, spatial discretization and time steps as the numerical solution for water flow. A sharp initial decrease in evaporation rates from all columns was followed by a more gradual decrease, characteristic of desiccating saline soils. This reduction in evaporative fluxes was attributed to salinity, as the water potential at the surface of soil columns was maintained at a range that should not affect relative humidity. For all salinity treatments, the solute concentration profiles over time showed an accumulation of salts in the top 0.5cm of soil columns. Predicted evaporation rates were substantially over-estimated compared to measured values as a result of the numerical code under-estimating solute concentrations at the surface of desiccating soil. This disparity was attributed to ionic diffusion and mechanical dispersion being lumped together into one single term in ADE, resulting in over-estimation of the downward diffusion of solute near the evaporating surface. When the dispersivity term (in ADE) in the top 2cm were reduced by a factor of 2, better predictions of evaporation and solute concentration profiles were obtained. It is noteworthy that the soil column experiments in Fujimaki et al. (2006) were conducted under low matric suctions, and therefore the observed reduction in evaporation rate was not due to water supply limitation. The current thesis seeks to improve on current knowledge by characterizing, in great detail, solute transport and associated reduction in evaporative fluxes in soil and mine tailings desiccating under varying degrees of water supply limitation. This evaporative flux boundary condition is more representative of field conditions in most tailings disposal facilities, especially under arid and semi-arid climates.

Small and large-scale drying tests were conducted by Simms et al. (2007) on acid-generating thickened tailings (the same as the material being tested in this thesis), combined with the analysis of some field data. Wind and solar radiation were simulated over the 3-week drying period, using fan and metal halide lamps, respectively. The albedo of the tailings surface was quantified from pyranometer readings, while weather data (RH and temperature) and profiles of matric suctions were determined over the drying period. The PE rates during the period of drying tailings were monitored and were approximately 10 and 2mm / day for the test with and without wind simulation, respectively. The small-scale drying test was conducted under conditions similar to the large scale test with wind simulation. Numerical simulations of water fluxes in the large scale test was conducted with a FEM unsaturated flow code (SoilCover) that solves the coupled soil moisture and heat transport equations previously discussed (equations 2.12 and 2.13, Section 2.1.2). For the simulations, a no-flow boundary was imposed at the base of tailings and the hydraulic conductivity function was adjusted for volume change. A higher albedo was recorded for the test conducted under a higher evaporative demand, due to the advective transport to, and eventual precipitation of salt at the surface of stack. Field data showed an increase in albedo was initially proportional to decrease in GWC, but after steady-state water content has been reached, the albedo continued to increase. This pattern was again attributed to salt accumulation and eventual precipitation at the surface. The range of albedo measured in the field was similar to those observed in the laboratory. Cumulative evaporation simulated for the small scale test agreed well with experimental observations only when the saturated

hydraulic conductivity measured from falling head test was used. Simulated GWC values agreed well with field data up to three weeks after deposition, following which measured GWC remained constant while the numerical code continued to predict a decline in moisture. This observation was consistent with salt precipitates locking down moisture within the stack; secondary evidence of the tailings being moist immediately below the salt crust was reported. The range of albedo observed both in the field and laboratory (0.1 to 0.25) was insufficient to explain the scale of reduction in evaporative fluxes from the tailings observed. The authors concluded with a recommendation for a numerical framework that incorporates the effect of 1D solute transport and salt accumulation in predicting evaporative fluxes from saline tailings deposit.

Fisseha et al. (2010) conducted a follow-up study to Simms et al. (2007) by investigating unsaturated flow, evaporation and salt accumulation in a multi-layer deposits of the acid-generating thickened tailings tested in the latter. Having shown that albedo was insufficient to explain the salinity-induced reduction in evaporation as per Simms et al. (2007), the authors suspected that either or both other 2 mechanisms (osmotic suction and salt crust resistance) was important. Thus, Fisseha et al. (2010) excluded the effect of albedo by conducting small- and large-scale tailings drying tests under ambient lighting alone with simulated wind, considering a 2-layer deposit. For the tests, evaporative fluxes, matric suction, GWC and electrical conductivity at the surface of stack were measured. After the deposition and drying of the second lift of tailings for the large scale test, the stack was rewetted to simulate rainfall and thereafter left to

dry. Two commercial FEM codes (Soilcover and SVFlux) were used to model unsaturated flow in the desiccating stacks. Numerical predictions of AE agreed well with experimental data up till when the multi-layer was rewetted, after which the models over-predicted fluxes. This discrepancy was attributed to the 1D transport of salts during evaporation and eventual precipitation at the surface of stack immediately after rewetting. An attempt was made by the authors to quantify the role of salts by measuring the EC of saturated paste extracts obtained at the surface of stacks, but it was impossible to squeeze out pore extracts beyond a few days after deposition or rewetting. Nonetheless, the few datapoints obtained showed an increase in osmotic suction as the stacks dried after deposition and rewetting. After rewetting, there was rapid accumulation of salts and osmotic suctions were significantly high to explain the reduction in evaporative fluxes observed, which the numerical codes did not account for. Fisseha et al. (2010) concluded that future work characterizing how solute transport to the surface of stacks, salt accumulation and precipitation couple to evaporative densification of saline thickened tailings is warranted.

From the foregoing, a few gaps in understanding of the role of pore-water salinity in evaporative densification of surface-deposited thickened tailings can be identified. The relative contribution of osmotic suction and salt precipitation to reduction in rate of evaporative densification of SDTT is unclear. Also, to the best of author's knowledge, detailed characterization of 1D solute transport and its relationship to evaporative fluxes in SDTT is lacking. In addition, there is currently no numerical

framework that incorporates 1D solute transport and salt accumulation in predicting evaporative densification of SDTT. As previously discussed, numerical modeling offers a great tool for understanding the unsaturated flow and solute transport behaviour in soil and mine tailings, and can assist in tailings deposition planning and management. The following section summarizes the use of finite element method (FEM) in modeling evaporative fluxes in unsaturated soil or tailings.

2.9 Finite Element Modeling of Unsaturated Flow in Soils and Tailings

Finite Element Method (FEM) is a numerical scheme that discretizes a domain of interest into “finite elements” and solves the governing partial differential equation (PDE) / sets of PDEs for all elements within the domain represented by the geometry of the modelled system. FEM is widely adopted for solving unsaturated flow problems in soils and tailings (Thomas 1987; Noborio 1995; Fujimaki et al. 2006; Simms et al. 2007; Fisseha et al. 2010). FEM is particularly preferred to other numerical methods (like Finite Difference Method) due to its versatility in handling complex geometries and heterogeneity of material properties most common for unsaturated soils (Noborio 1995; Kuang 2000). Also, FEM affords the capability for variable mesh generation to deal with spatial and temporal variability of the field variable, which is characteristic of most unsaturated flow problems. For instance, smaller-sized elements could be generated in areas within a domain where the field variable is changing rapidly, while larger elements are created elsewhere (Kuang 2000). Therefore, FEM provides an efficient

approximation of a physical process (such as unsaturated flow) within a spatial domain by solving the PDE(s) governing the process.

The PDE governing 1D transient unsaturated flow (of water as liquid and vapour) in soil and tailings is given by:

$$\frac{\partial}{\partial z} \left[(K^w(\psi) + K^v(\psi)) \frac{\partial h}{\partial z} - K^v(\psi) \right] = -\gamma m^w \frac{\partial h}{\partial t} \quad (2.26)$$

Where z is elevation (m); $K^w(\psi)$ is the hydraulic conductivity (m/s) as a function of matric suction, ψ ; $K^v(\psi)$ is the pore-water vapour conductivity in the air phase as a function of matric suction; h is head (m); γ is the unit weight of water; m^w is the derivative of the soil water characteristic curve (SWCC) with respect to matric suction or the slope of the consolidation curve in the positive pore-water pressure range; t is time (s).

This PDE is inherently non-linear as the material properties of K^w , K^v and m^w vary with matric suction (SoilVision Systems Ltd 2008). This h -based formulation of the PDE is the most commonly used for unsaturated soils, but is known to present some mass-balance problems in transient analyses. To address this, a “mixed formulation” in which

water content replaces head as the field variable, was introduced (Celia and Bouloutas 1990; Furman 2008), and is expressed as:

$$\frac{\partial}{\partial z} \left[(K^w(\theta) + K^v(\theta)) \frac{\partial h}{\partial z} - K^v(\theta) \right] = \frac{\partial v}{\partial t} \quad (2.27)$$

Where V is the volumetric water content (%).

FEM solves the PDE for unsaturated flow (equation 2.26) by approximating the solution for V (h as a derivative of time) for all finite elements across the entire domain of the modelled system. The approximation is done (between the nodes of elements) in terms of nodal values of V , using shape functions that are specific to each element. This numerical approximation is given as:

$$V \approx V_t = \sum_{i=1}^{\Omega} N_i(x, z) V_i(t) \quad (2.28)$$

Where N_i is shape function specific to an element within the domain; and Ω is the domain of the system being modelled. The approximation obtained from equation 2.28 is then substituted into the governing PDE (equation 2.26), leading to a “residual error”, $R(z)$. The Galerkin formulation introduces a “weighing function”, $W(z)$, such that:

$$\int_0^{\Omega} W(z)R(z) = 0 \quad (2.29)$$

Thus, the Galerkin formulation minimizes the error of the numerical approximation by ensuring that the average weighted error integrated over the entire domain of the system being modelled is zero (Thomas 1987). FEM handles the non-linearity associated with solving the PDE for unsaturated flow by implementing an appropriate algorithm. Examples of such algorithms include simple iteration and Newton-Raphson (NR) iteration. The NR iteration provides a more stable solution compared to the simple iteration, but has the limitation related to non-convergence for systems with strong non-linear material properties (such as unsaturated soil). The performance of the NR scheme can however be improved by implementing an indirect algorithm such as Incomplete Cholesky Conjugate Gradient (ICCG), Pichard and modified NR schemes (Kuang 2000).

The use of FEM requires that the geometry of the domain and an appropriate procedure for discretizing the domain into finite elements be specified by the user. Generally, for unsaturated soils, triangular elements are preferred over other shapes due to their versatility in fitting any geometry, no matter how irregular (Noborio 1995; SoilVision Systems Ltd 2008). The boundary condition needs to be specified, and in the case of transient problems, an initial condition of the system in terms of the field variable is required. The boundary condition could be specified as either Newman or

Dirichlet. A Newman boundary condition specifies the flux while a Dirichlet boundary specifies a given value of the field variable. The material properties (such as hydraulic conductivity function, vapour conductivity function and m^w) are also needed for the numerical solution of the PDE. Such material properties may either be the same or vary across different regions within the problem domain. Most FEM numerical codes have some in-built or ancillary format for post-processing and visualization by the user. An example of a commercial FEM numerical code that is used in this thesis is SVFlux from SoilVision Systems Ltd (Saskatoon, SK). Details about SVFlux and how it was applied to the problems addressed in this thesis are provided in Chapter 3.

2.10 Determination of Suction in Unsaturated Soils

Suction is the “free energy” with which water is held in an unsaturated soil, and is equivalent to the amount of energy needed to extract a unit weight of water held by such soil at its current condition (Edlefsen and Anderson 1943). This “free energy” (total suction) is made up of a component that is due to capillary forces in soil (matric suction) and a component resulting from the presence of dissolved solutes in soil’s pore water (osmotic suction). Above the ground water table, water is held by the solid matrix of an unsaturated soil at a suction value greater than zero. The matric suction of the soil is an important engineering property of unsaturated soil, being one of the three stress-state variables that influence its engineering behaviour. Matric suction arises as the two-phase saturated soil (soil solid matrix and pore-water) desaturates and becomes a

three-phase system of soil matrix, pore water and pore air. As a saturated soil desaturates and matric suction evolves, its engineering properties of shear strength, coefficient of permeability and volume change are affected. The capability to accurately quantify the suction of an unsaturated soil is therefore very important for many geotechnical and geo-environmental applications as outlined in following section.

2.10.1 The Concept and Relevance of Soil Suction in Geotechnical and Geo-environmental Applications

The total suction of the soil comprises of both its matric and osmotic suctions. Matric suction results from capillary and sorptive forces of the soil solid on its liquid and gas phases, while osmotic suction arises from the presence of dissolved salts in the soil (Hillel 1998; Agus and Schanz 2005). The matric suction of soil is directly related to its water content, while below a certain water content, the osmotic suction becomes independent of changes in soil water content (Romero and Vaunat 2000; Mata et al. 2002). Matric suction (ψ_m) is the difference between the ambient pore-air pressure, μ_a and the soil pore-water pressure, μ_w ($\psi_m = \mu_a - \mu_w$; Fredlund and Rahardjo 1993). In order to quantify the matric suction in a soil, its pore-water pressure will have to be less than the pore-air pressure, making the former negative when the latter is atmospheric (Ridley and Burland 1993). This is commonly the case for unsaturated soils where the pore-air pressure is usually assumed atmospheric. For unsaturated soil therefore, matric suction is the negative pore-water pressure with respect to atmospheric pressure.

Many geotechnical properties of soil are known to be dependent on suction (Fredlund and Rahardjo 1993). The coefficient of permeability of the soil is dependent on its matric suction (Huang et al. 1998; Agus et al. 2003), while the soil's shear strength is also a function of matric suction (Escario and Saez 1986; Fredlund et al. 1996; Vu and Fredlund 2004; Kayadelen et al. 2007). Also, matric suction data is used to predict the long-term stability of slopes (Feuerharmel et al. 2006), and evaluate long-term performance of soil covers in a waste-rock disposal site (Weeks and Wilson 2005). In addition, matric suction data is important for the design and management of landfills and mine tailings disposal facilities (Simms et al. 2007; Fisseha et al. 2010). Suction in an unsaturated soil is determined by a number of direct and indirect methods as described in the following section.

2.10.2 Determination of Soil Suction: Direct and Indirect Methods

The matric suction of an unsaturated soil can be determined by either direct or indirect methods. The direct methods measure soil suction by an interchange of water between the instrument and soil, the negative pore-water pressure driving the water exchange (Ridley and Burland 1993). Soil suction is determined through the direct measurement of matric suction by partitioning between the air and water phases of test material using a ceramic disc (Agus and Schanz 2005). The instruments involved usually consist of: (a) a porous disc (with high AEV), (b) a measuring instrument (such as a manometer, pressure gauge or transducer) and (c) a fluid (water) reservoir, which

ensures continuity between the soil water and measuring gauge, via the porous disc. Since direct methods measure the pore-water pressure directly, they are typically restricted to very low suctions (such as for tensiometers) or require that the air pressure be raised in order to measure high suction (such as in axis-translation technique).

Conversely, indirect methods are used in measuring high suction values under atmospheric air pressure. The methods involve the calibration of other physical properties such as humidity, water absorption, thermal conductivity and electrical resistance that are related to, and vary with, soil water content and matric suction (Ridley and Burland 1993). Soil matric suction may be measured indirectly using a standard porous material like filter paper (Houston et al. 1994), fibreglass (Knutson et al. 1993), gypsum (Polak and Wallach 2001) or clay ceramic (Guan and Fredlund 1997). Such porous material is first equilibrated with the matric suction of the test sample prior to taking measurement (Flint et al. 2002; Agus and Schanz 2005). The matric suction of the porous material is inferred from its water content (by means of a calibration curve) after equilibration, with the water content correlated to its thermal or electrical properties. Examples of indirect methods include: heat-dissipation sensor (Shaw and Baver 1939; Shuai and Fredlund 2000; Flint et al. 2002), filter paper method (Chandler and Gutierrez 1986; Houston et al. 1994; Bulut et al. 2001) and Psychrometers (Spanner 1951; Merayyan and Miller 2000). The following sections describe some individual direct and indirect methods of suction determination, highlighting the advantages and limitations of each.

2.10.2.1 Tensiometer

Tensiometer is one of the most commonly-used devices for the direct determination of soil matric suction. Tensiometer measures the matric suction of the soil by ensuring continuity between the soil pore-water and a water reservoir by means of a porous cup (Figure 2.08). The device measures the negative pore-water pressure directly by equilibration of its water reservoir with the pore-water of test soil. The equilibrium water pressure is read by means of an attached vacuum gauge, manometer or pressure transducer. Tensiometers are generally the best option for low range of soil suctions as they measure the negative pore water pressure directly, and respond very rapidly to changes in soil pore-water pressure (Rahardjo and Leong 2006). There are several types of tensiometers including jet-fill, small-tip, osmotic and quick-draw tensiometers.

Though tensiometers are very useful in measuring the low-range matric suctions in the soil, considerable effort and high level of instrumentation are required in its preparation and deployment (Vaz et al. 2002). Also, the range of soil matric suction that can be measured is restricted (Bruce and Luxmoore 1986), commonly between 0 and 100kPa. When the matric suction is in excess of 100kPa, cavitation inside the water reservoir develops, leading to inaccurate readings. However, higher matric suctions (up to 1500kPa) can be measured by carefully de-airing the tensiometer (Ridley et al. 2003) using cycles of pressure and vacuum (Guan and Fredlund 1997), or minimizing the volume of the water reservoir (Tarantino and Mongiovì 2001). Matric suctions in excess

of 100kPa can also be measured using tensiometer with a porous material of very high AEV (Hoffman et al. 2006), as the AEV of the constituent porous disc limits the extent of matric suction that can be determined. In addition, the long-term reliability of tensiometer is a concern due to diffusion of air from the test material through the porous cup. Diffused air may serve as cavitation nuclei, causing inaccurate readings and necessitating the need for the tensiometer to be re-conditioned.

Figure 2.08. Schematic of a Pressure-transducer tensiometer (Not drawn to scale).

2.10.2.2 Axis-translation Technique

The axis-translation technique, originally proposed by Hilf (1956), is a direct approach for establishing or measuring soil matric suction over the intermediate range. The technique derived its name from the translation of standard reference for pore-water pressure from atmospheric to the final air pressure of the chamber used for the technique. The technique was originally introduced to circumvent the problem of cavitation associated with the determination of matric suction values above 1 atmosphere (101.3kPa). The device used (Figure 2.09) comprises of: (a) a stainless steel chamber with a porous disc at the base for holding sample, (b) some weight to ensure firm contact between test sample and porous disc, (c) a graduated glass cylinder to measure the volume of water drained from soil sample by an applied air pressure (d) pressure-measuring device (such as pressure transducer) and (e) a reservoir for holding and supplying a flow of de-aired water (Feuerharmel et al. 2006).

The pore-water pressure of test sample is raised by increasing the air pressure inside the apparatus, thus minimizing the possibility of cavitation occurring for matric suction values in excess of atmospheric pressure. The raised pore-water pressure also allows for measuring soil matric suction values higher than those that can be handled by standard tensiometers. At equilibrium, the air pressure applied above the sample within the enclosed chamber is the same as the matric suction of test sample as the pore-water pressure is atmospheric (i.e. $\psi_m = \mu_{(a)\text{applied}}$ since $\mu_w = 0$). The equilibration time for the technique may vary from 30 minutes to few hours or even days (Stenke et al. 2006),

Figure 2.09. Schematic of typical axis-translation cell (Not drawn to scale).

depending on soil type and the AEV of porous ceramic disc. It is important that the AEV of the porous disc be higher than the matric suction to be measured or established in order to prevent air diffusion through the porous ceramic disc. Depending on the AEV of the porous disc, matric suction values up to 1500kPa can be measured or established using this technique (Rahardjo and Leong 2006). However, the axis-translation technique is restricted to laboratory measurement alone, as it is not practical to introduce high ambient air pressures in-situ, such as would be needed for field determinations (Ridley and Burland, 1993).

2.10.2.3 Heat-Dissipation Sensor (HDS)

HDS (also known as “Thermal conductivity Sensor”) is an indirect method of matric suction determination that was first described by Phene et al. (1971). The sensor consists of a porous block, a central heating element and a temperature-sensing element (Figure 2.10). The porous block equilibrates with the soil matric suction by contact with the test soil prior to taking measurement. The interchange of water between the test soil and porous block is facilitated by the pore-water pressure head. The sensor operates on the theory that the thermal conductivity of the porous block is a function of its water content. The change in the thermal conductivity of the porous block is indicated by a change in temperature sensed with time, ΔT . The change in temperature of a line heat source inside a porous medium is given by Shiozawa and Campbell (1990) and modified by Flint et al. (2002) as:

$$\Delta T = T_f - T_o = (q/4\lambda k) \ln(t_f - t_o) \quad (2.30)$$

Where T_f and T_o are the final and initial temperatures ($^{\circ}\text{C}$), q is the heat flux (W m^{-1}), k is thermal conductivity of porous medium ($\text{W m}^{-1}\text{C}^{-1}$), t_f is the final time (s) and t_o is the initial time (s) when T_o was taken. With a constant heat flux, q , applied to the HDS over a time period ($t_f - t_o$), a temperature change (ΔT), which is dependent on the thermal conductivity (and water content) of the porous block is sensed by the temperature-sensing element (Figure 2.10). The thermal conductivity of the porous block increases

Figure 2.10. Schematic diagram of a Heat-dissipation Sensor (Source: Rahardjo and Leong 2006).

with increase in its water content, causing a reduction in ΔT as more heat energy is being conducted. As the porous block becomes drier, its thermal conductivity decreases, less heat energy is conducted and ΔT increases as more heat is dissipated (Figure 2.11). The matric suction of test soil can then be determined indirectly from ΔT through calibration since the water content of a porous medium is related to its matric suction (Rahardjo and Leong 2006).

The HDS is adaptable for field determination of matric suction, and has been used for monitoring the evolution of suction in soil covers for waste-containment structures (Weeks and Wilson 2005). HDS is theoretically capable of matric suction

Figure 2.11. Response of change in temperature with time shown by HDS in water and air (Source: Rahardjo and Leong 2006).

measurements ranging from 10 to 100,000 kPa, sensitive to changes in matric suction of dry soils, and relatively inexpensive and easy to read (Flint et al. 2002). Also, the sensor's performance is not significantly affected by the presence of salts in the soil (Nichol et al. 2003). However, the reliable range of this sensor is typically restricted to the range of calibration using other techniques, such as axis translation. Also, the reliability of HDS is reported to be low, with as low as only 67% of attempted measurements resulting in actual measurements due to decay with time of sensors under environmental stresses, including freeze-thaw and wet-dry cycles (Weeks and Wilson 2005).

Furthermore, the equilibration time depends on the soil matric suction, and can take several hours depending on contact between HDS and test soil (Rahardjo and

Leong 2006). The performance of HDS is also affected by hysteresis, necessitating the need for separate calibration curves for wetting and drying cycles (Sattler and Fredlund 1989).

2.10.2.4 Filter Paper Method

The filter paper is a widely-used indirect method for matric suction determination in unsaturated soil (Houston et al. 1994; Ridley et al. 2003 and Feuerharmel et al. 2006). The technique involves the placement of wet soil in contact with a dry filter paper (usually Whatman No 42) inside a sealed container (Feuerharmel et al. 2006). The filter paper absorbs water from the soil until equilibrium of suction and water is reached. If there is no contact between the soil and the filter paper, water moves to the latter by vapour flow and there is no exchange of dissolved solutes in the soil's pore-water and the filter paper, in which case the total suction is measured. If there is contact between the filter paper and the soil however, both water and dissolved salts moves freely between filter paper and the soil, in which case the matric suction is measured (Rahardjo and Leong 2006). At equilibrium, the water content of the filter paper is used to determine the suction by means of a calibration equation, an example of which is reported for Whatman No.42 filter paper by Leong et al. (2002) as:

$$\log \psi_m = 4.945 - 0.0673W \quad (\text{for } W < 47\%) \quad (2.31)$$

$$\log \psi_m = 2.909 - 0.0229W \quad (\text{for } W \geq 47\%) \quad (2.32)$$

Where W is the water content (%) of the filter paper and ψ_m is the matric suction (kPa).

The filter paper method has been reported to measure suction ranging from 3 to 30,000kPa, corresponding to absorption capacity of 175 and 6%, respectively (Leong et al. 2002). The method is simple, relatively cheap and allows for multiple suction measurements to be made concurrently. However, the accuracy of measurement using this method is affected by the presence of dissolved salts in the soil pore water, condensation droplets on filter paper due to temperature fluctuation (Houston et al. 1994), as well as the type of contact between the filter paper and the soil. The direction of flow of water between filter paper and soil and time available for equilibration also affects the accuracy of this method (Feuerharmel et al. 2006). In addition, the equilibration time for the method is typically long; 5-7 days for total suction and 2– 5 days for matric suction determination (Rahardjo and Leong 2006).

2.10.2.5 Psychrometer

The psychrometer method, first introduced by Spanner (1951), is an indirect method for the determination of very high range of total suction in soil. The device is based on the principle that the total suction of soil is related to the water vapour pressure in the interstitial pores, which can be determined from the relative humidity of pore air (Rahardjo and Leong 2006). Thus, by measuring the RH of a test sample, psychrometer can be pre-calibrated and used to indirectly infer the total suction of the

sample. Thermocouple and Chilled-mirror psychrometers are two types of psychrometers that have been used for total suction determination in soil (Leong et al. 2003; Agus and Schanz 2005).

The Chilled-mirror psychrometer measures the RH of test soil placed inside a sealed chamber, under isothermal conditions (Leong et al. 2003; Rahardjo and Leong 2006). The sealed chamber containing test sample has a condensation detector that measures the dew-point. R.H is the ratio of the saturation vapour pressure (S.V.P) of water at the air temperature to the S.V.P of water at the dew-point. At equilibrium, the R.H of air inside the sample chamber is the same as the RH of sample being tested. The chilled-mirror psychrometer is the most accurate device for measuring dew-point, and has been used for the laboratory determination of total suction of soil samples (Leong, et al. 2003; Dunmola et al. 2010; Dunmola and Simms 2010). The psychrometer consists of a mirror, a dew-point photo detector and an infrared thermometer placed inside the air-tight chamber containing the test soil (Figure 2.12). The photo detector records the dew-point inside the chamber from which the saturation vapour pressure (p_o), is computed. If the vapour pressure of air within the sealed chamber is p , the RH of chamber is computed as p/p_o , which is equal to the R.H of test sample at equilibrium.

The total suction (ψ) of sample is calculated from the psychrometric law:

$$\psi = \frac{RT}{g W_v} \ln(R.H) \quad (2.33)$$

Where R is universal gas constant (8.314 J/ mol.K), T is temperature(K), g is gravitational acceleration, and W_v is the molecular mass of water vapour (0.018016 kg/mol). This equation is a rearrangement of the equation proposed by Edlefsen and Anderson (1943) previously given in equation 2.01 (section 2.1.1).

Figure 2.11. Schematic diagram showing cross-section of a chilled-mirror dew-point Psychrometer (after Leong et al. 2003; not drawn to scale).

A fan is typically installed within the enclosed chamber to facilitate equilibration of RH of test sample with that of chamber. An equilibration time of less than 20 minutes was reported for the chilled-mirror psychrometer, allowing for rapid determination of total suction (Rahardjo and Leong 2006). Notwithstanding, there is the disadvantage of over-estimating the sum of matric and osmotic suctions, especially when the osmotic

suction of such soil is very low, necessitating the need for a correction factor when using the psychrometer (Leong et al. 2003). Also, when used for acid soil, corrosion of the thermocouples negatively affects the accuracy of data obtained (Hamilton et al. 1981). In addition, while chilled-mirror psychrometers are generally adaptable for determining high suctions (several tens of thousands kPa) in the laboratory (Stenke et al. 2006; Dunmola and Simms 2010), it is not suitable for in-situ determination due to non-isothermal field conditions (Fredlund and Rahardjo 1993). However, in recent times, there are commercial psychrometers with in-built temperature compensation to improve the accuracy of total suction determinations.

CHAPTER 3: DETAILED RESEARCH METHODOLOGY

3.1 Characterizing Profile Solute Transport and Evaporative Fluxes in Desiccating Soil and Thickened Tailings

3.1.1 Introduction

The 1D transport of pore-water solute in desiccating unsaturated medium is coupled to evaporation. This section provides the detailed methodology used in characterizing the profile transport of solute in salt-treated soil and acid-generating thickened tailings and its relationship to evaporative fluxes. Therefore, the details provided in this section were generally followed in the single-layer column and multi-layer column drying experiments reported in the manuscripts contained in Chapters 4, 5 and 6 of this thesis. Any modification(s) specific to each chapter is clearly stated in the respective manuscript. The following subsections give a full description of the test materials, single-layer column and multi-layer drying tests, the sampling methodology as well as various analyses conducted on test soil and thickened tailings samples.

3.1.2 Test Materials

The materials tested in this thesis are silt-sized spherical glass micro-beads (Potter Industries Inc. LaPrairie, QC) and thickened gold tailings. The geotechnical properties and particle size distributions of the silt and tailings are similar, and are

presented in Table 3.01 and Figure 3.01, respectively. The thickened tailings and silt also have similar soil water characteristic curves (SWCC), as shown in Figure 3.02. The saturated hydraulic conductivity for both test materials was determined by falling head test at a void ratio of 0.8 (more details can be found in Fisseha 2007 and Fisseha et al. 2010).

Table 3.01. Geotechnical properties of thickened tailings and silt tested throughout this thesis

Parameter	Thickened Tailings	Silt
Specific Gravity	2.9	2.48
D ₁₀ , D ₅₀ , D ₆₀ (microns)	2, 35, 55	1, 31, 41
Cu (D ₆₀ /D ₁₀)	27.5	41
Liquid limit (%)	20	19
Plastic limit (%)	19	13
Saturated hydraulic conductivity (m/s)*	2.0E-7	1.7E-6

*Values were obtained from falling head tests on samples at a void ratio of 0.8 (Fisseha et al. 2010; Fisseha et al. 2007).

The thickened tailings were pumped at a GWC of 38% and shipped to the laboratory from the Bulyhanhulu gold mine (Tanzania) in 2006. The thickened tailings was received in sealed plastic bags placed inside 5-gallon plastic buckets with process water added to cover the sealed plastic bags in order to minimize the potential for

sulphide oxidation. This excess process water was removed prior to mixing and packing the thickened tailings inside wax columns to adjust the GWC to the as-deposited value of 38%. The thickened tailings buckets were stored inside wooden shipping boxes until laboratory analyses were conducted. Solid- phase mineralogy of the thickened tailings is composed of silicates (80%), pyrite (6%) and ankerite (4%) (Golder 2005). Gypsum (calcium sulphate) was the predominant solute in the thickened tailings pore-water as shown in Table 3.02. The thickened tailings is reported to be net acid-generating, with a net acid-generating (NAG) pH of 2.2 (Bryan 2008).

Figure 3.01. Particle size distributions of thickened tailings (determined by hydrometer and sieve analyses) and silt (determined by hydrometer method).

Figure 3.02. Soil water characteristic curves (SWCC) for silt and thickened tailings obtained using the axis-translation technique in a pressure plate apparatus (more details in Simms et al. 2007).

3.1.3 Petroleum Jelly-Wax Column Technique for Characterizing Profile Solute

Transport in Unsaturated Soils

The petroleum jelly-wax column (PJWC) technique for studying 1D solute transport in soils was first described by Khasawneh and Soileau (1969). Prior to the introduction of PJWC technique, soil columns were commonly used for physical and chemical investigations of transport processes such as diffusion of water and ions. Great importance was attached to easy sampling at relatively small and consistent intervals as well as an acceptable control over water regimes of such soil column. Sampling intervals of 1cm or greater required taping together previously-cut sections of soil into a single "soil column". Thus, this method was cumbersome

Table 3.02. Pore-water solute composition of gold thickened tailings (From Bryan 2008)

Ion	Concentration (mg / L)
SO ₄ ²⁻	2140
Ca ²⁺	545
Mg ²⁺	125
K	283
Al	<0.1
Cu	0.07
Fe	<0.3
Pb	<0.01
Mn	2.8
Si	5
Zn	0.8
pH	6.93
Saturated thickened EC (mS/cm)	4.25

and needed to be replaced with a more efficient technique, especially for sampling intervals less than 1cm (Khasawneh and Soileau 1969). The alternative method of Brown et al. (1964) utilized a refrigerated microtome to slice quick-frozen soil columns into thin sections, but this method required very specialized and expensive equipment. Therefore, PJWC technique was introduced to provide a simple but efficient technique

to prepare soil columns that can be sectioned into small portions as thin as 5mm (Khasawneh and Soileau 1969). Several researchers have used the PJWC technique, especially for studying the 1-dimensional diffusive transport of fertilizer ions in soils (Khasawneh et al. 1974; Akinremi and Cho, 1991; Hao et al. 2000; Kumaragamage et al. 2004; Olatuyi et al. 2009). For the purpose of this thesis, a modified PJWC technique, described below, was utilised.

The petroleum-jelly wax column (hereafter referred to as “wax column”) was made from a molten mixture of paraffin wax and petroleum jelly. Various ratios of wax and jelly were evaluated based on workability of resulting wax column during sampling, and an optimal ratio of 1 part (by mass) of petroleum jelly to 2.5 parts of paraffin wax was adopted for this thesis. The wax-jelly mixture was melted over a water bath under a ventilation hood. Wax column moulds made of empty 1.89 L milk / juice cartons with a rectangular cavity (dimension of 9.5 X 9.5 X 19.5cm) were utilized. A pre-cut plexi-glass (dimension 9.5 X 9.5cm) was placed at the base of the rectangular wax mould. An empty cylindrical Aluminum (Al) can, open at one end, with an internal diameter (i.d) of 7cm and height of 17cm was placed at the center of each wax column mould with the open end facing upwards. Molten wax-jelly mixture was then poured in the space between the Al can and the mould in 3 increments. Instalment pouring of the molten wax-jelly mixture was to allow for partial hardening before pouring next increment, and also to eliminate internal spaces around the Al can. The height of poured molten jelly-wax mixture was chosen based on the height of wax column (and soil/tailings column)

desired (12 or 17cm). The poured wax-jelly mixture was left to set for 24 hours before the Al can was removed by pouring hot water inside the can to melt the jelly-wax mixture immediately surrounding the can. The wax mould (milk or juice carton) was then carefully cut away from the wax column to give rectangular (9.5 X 9.5 X 17cm) columns with 7cm i.d for packing and sampling soil or thickened tailings (Figure 3.03). The resulting wax columns provided an experimental unit for characterizing 1D transport of solute in the soil and / or thickened tailings tested in Chapters 4, 5 and 6 of this thesis. The following sub-section describes the procedure for preparing, drying and sampling the soil and thickened tailings columns.

3.1.4 Preparation, Drying and Sampling of Soil and Thickened Tailings Columns

The soil and thickened tailings were prepared with NaCl solutions (or distilled water) and bleed water, respectively, and thoroughly homogenized using a mechanical mixer before packing into the wax columns. The cylindrical cavity of each wax column (Figure 3.03) was packed with soil or thickened tailings at 30 and 38% GWC, respectively. Once packed, the wax column was gently tapped 3 times on the bench to ensure the dislodgement of any entrapped air pocket. At the beginning of each drying experiment, the total mass of wax column including packed soil or thickened tailings was recorded and the packed columns were left to desiccate under ambient laboratory conditions on a wooden platform as shown in Figure 3.04. The ambient temperature

and RH during each column drying experiment was monitored using a USB-502 RH / Temperature Data Logger (Measurement Computing, Norton, MA).

Figure 3.03. Schematic of petroleum jelly-wax column for packing, drying and sampling soil and thickened tailings.

In order to vary the evaporative demand, either of 2 boundary conditions was imposed on the desiccating soil and tailings columns: one with wind simulated using an oscillatory fan (SW), and the other with no simulated wind (AW). A number of replicate soil or tailings columns were prepared for each drying experiment and one replicate was destructively sampled at pre-determined intervals to obtain profile samples that were

analysed as described in sub-section 3.1.6. Destructive sampling entailed sectioning the soil or tailings column into 1cm thick slices using an adjustable hacksaw (Mastercraft Canada, Toronto ON) and a Jobmate plastic mitre box (Trileaf Distribution Canada, Toronto ON) used as a cutting guide to ensure uniformity. The resulting profile samples were retrieved, placed and manually mixed inside sealed plastic Ziploc bags before sub-samples were taken for analyses. Thus, the parameters determined for each profile sample would represent the average for the corresponding 1cm depth.

Figure 3.04. Generalized experimental set-up for drying and sampling silt and thickened tailings columns.

3.1.5 Drying and Sampling of Multi-layer Thickened Tailings Deposit

Two multi-layer drying tests were conducted for the thickened tailings to investigate the effect of scale and multi-layer deposition on how solute transport affects evaporative densification. One test was conducted inside a plastic column (37cm high, 29cm i.d) with sequential deposition of three lifts of thickened tailings, each 12cm high. The second test was conducted inside a plastic column (75cm high, 33cm i.d), with sequential deposition of five lifts of thickened tailings. The columns used for the multi-layer drying tests were sealed at the base, with the schematic of the drying tests shown in Figure 3.05. A sampling core (12cm high, 7cm i.d) was placed inside the column prior to pouring thoroughly-mixed thickened tailings up to a rise of 12cm, filling the core at the same time. The assembly was placed on an electronic scale for monitoring the change in mass of the deposit over time. A system of two fans, blowing at a height of 0.68 and 0.30m from the top of the column for the first and second tests, respectively, was placed to simulate wind. Similar columns were filled with distilled water to comparable depths and placed near the thickened tailings deposits for concurrent determination of PE throughout the multi-layer drying test. The ambient RH and temperature were monitored throughout the drying test as previously described.

Figure 3.05. Schematic of the multi-layer thickened tailings drying tests.

Once the GWC in the top 1cm of the thickened tailings layer was below 15%, the sampling core was removed with the intact thickened tailings sample. The core sample was retrieved and destructively sampled into 1cm-thick sections, as previously described, and the profile samples were analysed accordingly. The time interval between sample core retrieval and destructive sampling was minimised to less than 30 minutes and profile samples were immediately kept inside sealed Ziploc bags to minimize evaporative loss. An empty sampling core was then placed in another location on top of the old thickened tailings layer and a fresh layer of thickened tailings was deposited inside the plastic column, filling the core simultaneously. The cavity created by the retrieval of the previous sampling core was plugged with fresh thickened tailings

during the deposition of new layer of material. The multi-layer deposit was thereafter left to desiccate under simulated wind and the procedure for core retrieval, destructive sampling and fresh layer deposition was repeated. In between deposition of fresh tailings layer and sample core retrieval, at least 1 sample of the top 1cm of tailings deposit was taken for analyses. The multi-layer deposition was continued until the final layer of thickened tailings had been deposited, left to dry and the final sample core was retrieved. At the end of the multi-layer drying experiment, profile samples at depths of 0-5, 10-15, 15-20, 20-25 and 25-30cm for the first drying test was taken for analyses. Similarly, for the second multi-layer drying test, samples at depths of 0-5, 10-15, 20-25, 30-35 and 40-45cm was taken for analyses.

3.1.6 Profile Soil and Thickened Tailings Sample Analyses

From the profile samples retrieved for the soil or thickened tailings columns as well as multilayer tests, sub-samples were taken for gravimetric (GWC), electrical conductivity (EC), and total suction analyses. GWC of samples was determined by mass difference after placement in oven at 105°C for 24 hours. EC analysis was conducted by extracting the pore-water of 1 part of soil or tailings by mixing with 4 parts of deionised water using an orbital shaker operated at a speed of 175 rpm for a duration of 30 minutes. The slurry was then centrifuged at 3000rpm ($1000 \times g$) for 2.5 minutes and the EC of the clear supernatant was determined by means of a previously-calibrated Traceable Conductivity Meter (VWR International, Friendswood, TX). The accuracy of

the conductivity meter is reported by the manufacturer as $\pm 0.3\%$ for measurement range of 0.1 to 199.9 mS. In order to account for the dilution of the sample pore water during the extraction, the EC of the supernatant was multiplied by the corresponding dilution factor based on the amount of deionised water added and the initial GWC of slurried sample. It was understood that this pore-water extraction process would dissolve any salt precipitates, and thus the measured EC reflects both dissolved solute and precipitated salt.

For the soil columns prepared with NaCl solution, profile NaCl concentration was calculated from the EC data using a calibration curve (Figure 3.06) previously obtained for standard NaCl solutions (Fisher Scientific, Ottawa ON). Total suction of the profile samples were measured using a WP4-T Dewpoint PotentiaMeter (Decagon Devices Inc., Pullman, WA). The WP4-T is a temperature-compensated chilled-mirror dew point psychrometer with an accuracy of ± 0.1 MPa for total suction values of between 0 to 60 MPa. Osmotic suction was also calculated for both soil and thickened tailings samples from the respective EC data using the USDA (1954) equation given as:

$$\psi_o = 0.36 * EC * 101.325 \quad (3.01)$$

Where ψ_o is osmotic suction (kPa) and EC is the electrical conductivity (mS/cm) of the 1:4 extract multiplied by the dilution factor. In addition, from the profile GWC data for

the soil and thickened tailings, the matric suction was inferred using the respective soil water characteristic curves (Figure 3.02) fitted with the Fredlund and Xing (1994) equation. The following sub-section describes the measurement and prediction of evaporative fluxes from the desiccating soil and thickened tailings columns as well as for the multi-layer drying test.

Figure 3.06. Calibration curve of pore-water NaCl concentration against electrical conductivity (EC).

3.1.7 Measurement and Prediction of Evaporative Fluxes from Desiccating Soil and Thickened Tailings

For both the single-layer soil / tailings and multi-layer tailings drying tests, the change in mass over a 24-hour period was monitored and used to calculate the

respective actual evaporation rates (AE). In the case of the soil column drying test, apart from preparing and drying the salinized soil columns, a non-saline (control) soil column was also prepared at the same initial GWC (30%), but with no NaCl addition. In all the drying tests, potential evaporation rate (PE) was concurrently determined from similar column filled with distilled water. Daily relative evaporation (RE) was calculated from corresponding measured AE and PE by dividing the former by the latter.

The Wilson et al. (1997) model given in equation 2.02 was derived and validated for sand, silt and clay soils drying under controlled RH and with the underlying assumption that the temperatures of the air, water and soil are approximately equal. This assumption was validated for the soil tested in the current research and the results of the validation experiment are presented in Appendix A1. The model was tested for the non-saline (control) soil columns using the total suction measured in the top 1cm and the measured weather data (temperature and RH). Comparison of predictions of RE with measured data for three independent replicate experiments as presented in Figure 3.07 showed no agreement. Wilson et al. (1997) validated equation 2.02 for different soils with sample thicknesses ranging between 0.2 and 0.7mm under controlled climatic conditions. Extremely thin samples were chosen as the main objective in Wilson et al. (1997) was to find a property at the “soil surface” that controls evaporation. This excluded any other flow process(es) at depths below the soil surface that control the rate at which water is delivered to satisfy evaporative demand.

Figure 3.07. Relative evaporation (RE) measured from 10cm-thick Non-saline (NS) soil columns and predictions from total suction in the top 1cm of desiccating column using equation 2.02. Results shown are for three independent replicate drying experiments.

To further validate the Wilson et al. (1997) model for the test soil in this thesis, three independent replicate experiments were conducted by drying 2mm thick soil samples under simulated wind. For each drying experiment, several replicates of the NS soil were concurrently dried inside total suction sampling cups (1.5cm high, 4.2cm i.d). AE from the soil samples were determined from change in mass and PE was concurrently determined from change in mass of cups containing distilled water. Once the mass of a replicate sample was determined, its total suction was immediately measured using the WP4-T psychrometer. RE was predicted from the total suction of the soil samples and the weather data measured during the experiment using the Wilson et al. (1997) model. Predictions of RE obtained showed better agreement with experimental data (Figure 3.08) compared to the 10cm NS soil columns (Figure 3.07). Thus, it was inferred that in the case of the 10cm NS soil columns, other water transport process(es) at depths below the soil surface affects the evaporation rate, in addition to total suction at the surface.

Starting from stage II evaporation, the rate of evaporation is known to be controlled by the diffusion of water vapour from the evaporation front to the soil surface (Van de Griend and Owe 1994). In the case of the Wilson et al. (1997) and 2mm soil samples, the samples are sufficiently thin such that the evaporation front is right at the soil surface and the distance for water vapour to travel to the soil-atmosphere boundary is negligible. Hence, total suction at the surface mainly controlled surface evaporation. However, for the desiccating 10cm soil columns, the depth to evaporation

Figure 3.08. Relative evaporation measured from 2mm-thick soil samples and predictions from total suction using equation 2.02. Results of 3 independent replicate drying experiments are shown.

front would increase over time, causing an increase in soil resistance to vapour diffusion as the soil column dried. Thus, in addition to total suction at the surface, soil resistance to vapour diffusion is expected to control evaporative fluxes for the 10cm NS soil columns. Therefore, for the purpose of analyzing the 10cm NS soil columns tested in this thesis, a model that accounts for soil resistance to vapour diffusion to the surface, in addition to total suction at the surface was appropriate.

A supplemental drying experiment was conducted to profile the total suction in the top 1cm of the 10cm-thick NS soil columns. Total suction of samples obtained at 2mm intervals using a spatula was determined with the WP4-T. The profiles of total suctions in the top 1cm thus obtained showed a generally curvilinear shape (Figure 3.09). The curvilinear shape in Figure 3.09 implies that total suction at the soil surface is expected to be significantly higher than the average values measured at 2mm intervals within the top 1cm of the soil column. Hence, an extrapolation procedure to obtain the total suction at the surface of the 10-cm thick NS soil columns from values obtained at 2mm intervals of the top 1cm was required. Power function was found to give the best correlation (R^2 values of 0.89-0.98) when fitted to Figure 3.09 (Appendix A2). A plot of RE measured from the NS soil columns against the total suction measured for sample obtained in the top 1cm of the columns (Figure 3.10) shows 3 regions identified as:

$0 < \psi < 3\text{MPa}$; Region 1

$3 < \psi < 15\text{ MPa}$; Region 2

$\psi > 15 \text{ MPa}$; Region 3

Where ψ is the total suction of the top 1cm sample of the NS soil column.

Thus, an extrapolation function for obtaining the total suction at the surface of the NS soil column ψ_e , is defined as:

$$\psi_e = \psi^a \quad (3.02)$$

Where “a” is an extrapolation coefficient specified, based on the region of the RE versus total suction curve (Figure 3.10), as:

$a=1.35$, 1.2 , and 1.1 for Region I, II, and III, respectively. Using this extrapolation procedure gave reasonable values of total suctions at the surface of the desiccation 10cm-thick NS soil columns (Figure 3.09), at least in terms of extrapolating the observed trend of measured total suction to the surface. Equation 3.02 is similar in concept to the need for adjusting the average total suction measured in the top layer of the soil with a “correction factor” in order to obtain the total suction “at the soil surface” required to compute evaporation from bare sandy loam soil reported by Alvenäs and Jansson (1997) as previously given in equation 2.15.

Considering the bulk transfer equation (Noborio et al. 1996; Bittelli et al. 2008), the AE from non-saline soil is given as:

$$AE = \frac{P_{sv} (RH_s - RH_a)}{Ra + Rs} \quad (3.03)$$

Where P_{sv} is the saturation vapour pressure at a given temperature (kPa); RH_s is the RH of soil pore air given by the thermodynamic equation (equation 2.01) as a function of total suction at the soil surface (Edlefsen and Anderson 1943); RH_a is the RH of the air; Rs is the soil resistance (day/mm) to vapour diffusion from the evaporation front to the soil-atmosphere boundary (Van de Griend and Owe 1994) and; Ra is the aerodynamic resistance (day/mm) given when equation 2.19 is rearranged as:

$$Ra = \frac{P_{sv} (1 - RH_a)}{PE} \quad (3.04)$$

Where PE is the potential evaporation (mm/day). Combining equation 3.03 and equation 3.04 re-arranged for PE to define RE , we obtain:

$$RE = \frac{AE}{PE} = \left[\frac{(RH_s - RH_a)}{(1 - RH_a)} \right] \left[\frac{1}{\left(1 + \frac{Rs}{Ra}\right)} \right] \quad (3.05)$$

Figure 3.09. Profile total suctions in the top 1cm of the 10cm-thick soil column. Symbols at the 0mm mark on the depth axis are the total suctions extrapolated to the surface of columns from the total suction measured for the top 1cm sample using equation 3.02.

Figure 3.10. Relative evaporation measured for the 10cm-thick NS soil columns as a function of total suctions measured for bulk samples obtained in the top 1cm.

The left hand side of equation 3.05 is the Wilson et al. (1997) model previously given in equation 2.02 (with RHs given as a function of total suction at the soil surface-thermodynamic equation). Thus, the RE of a non-saline soil is defined by equation 3.05 as a function of both the total suction at the surface as well as the soil resistance to water vapour diffusion to the soil surface from the evaporation front. For the 10cm-thick NS soil, R_s was back-calculated using equation 3.03 from the corresponding measured AE and R_a estimated from measured PE using equation 3.04. The total suctions at the soil surface were extrapolated from values determined for the bulk sample in the top 1cm of the columns using equation 3.02, as previously described.

Predictions of RE thus obtained gave good agreement with experimental data for all 3 independent drying column experiments for the 10cm-thick NS soil under ambient laboratory and simulated wind top boundary condition (Figure 3.11). The validity of equation 3.05 for the NS soil columns was further assessed by conducting a drying test similar to the previous 3 independent tests, under a much lower evaporative demand. The drying test was carried out without wind simulation using a fan, resulting in PE ranging between 4-5mm/day (compared to PE of 14-20mm/day for the tests with wind simulation). Predictions of RE for the drying test using the same extrapolation procedure (and coefficients) as the tests where wind was simulated also agreed well with experimental data (Figure 3.12).

Figure 3.11. Relative evaporation measured from 10cm NS soil columns desiccating under simulated wind and predictions using equation 4.06 for three independent replicate drying experiments.

Figure 3.12. Relative evaporation measured from 10cm NS soil columns desiccating under ambient wind condition and predictions using equations 2.02 and 3.05.

Figure 3.13. Soil resistance (R_s) calculated for 10cm NS soil columns as a function of volumetric water content of the bulk sample in the top 1cm. Also fitted to the data is the Van de Griend and Owe curve.

The soil resistance, R_s , calculated using equation 3.03 as a function of the volumetric water content (VWC) measured in the top 1cm of the 10cm NS soil columns is presented in Figure 3.13. The soil resistance is shown to increase with decreasing VWC as the soil columns desiccated; indicative of increasing depth to the evaporation front over time. The exponential relationship between R_s and VWC is similar to the data obtained from fast-air circulation chamber for a fine sandy loam soil (Van de Griend and Owe, 1994). Bittelli et al. (2008) assessed other empirical functions relating R_s as a linear (Camillo and Gurney 1986) and power (Fen Sun 1982) functions of the volumetric water content against the exponential function of Van de Griend and Owe (1994) and concluded that the exponential function is the most accurate. The exponential relationship of Van de Griend and Owe (1994) is also fitted to the data points in Figure 3.13 for comparison.

A drying column test was conducted for the 10cm-thick treated soil columns (LS, S and HS) to characterize the profile total suction within the top 1cm. Total suctions of samples of the treated soil columns obtained (using a spatula) at 2mm intervals of the top 1cm of soil were determined. Profiles of total suctions obtained for the LS, S and HS soil columns as shown in Figure 3.14 are linear in shape, with the total suctions measured in the top 1cm being representative of corresponding average values. Thus, the total suction measured for the bulk sample in the top 1cm of treated soil columns were used to predict RE. In the same way, total suction measured for the bulk sample in the top 1cm was used to predict RE for the thickened tailings columns tested in Chapter

Figure 3.14. Profiles of total suction within the top 1cm of; (a) LS, (b) S, and (c) HS soil columns. Open symbols are the respective total suctions for the top 1cm of soil columns.

5. Also, for the treated soil columns and thickened tailings columns (in Chapters 4 and 5, respectively), the exponential relationship (Figure 3.13) was used to calculate R_s from the corresponding VWC in the top 1cm. R_a was calculated from the corresponding daily PE data as previously discussed. RE was then predicted from R_a , R_s , measured total suction in the top 1cm and measured weather data using equation 3.05. The predicted RE was thereafter compared to experimental data for both the treated soil columns and thickened tailings columns. To be clear, equation 3.02 was used to extrapolate the total suction at the soil surface from the total suction value measured for the bulk sample in the top 1cm only for the non-saline soil columns in Chapters 4 and 5. For the treated soil columns (Non- saline; Saline and Hyper-saline) as well as the thickened tailings columns in Chapters 4 and 5, the value for the bulk top 1cm sample was used in equation 3.05 without extrapolation. This was based on the curvilinear and linear total suction profiles observed for the desiccating non-saline and saline soil columns as presented in Figures 3.09 and 3.14, respectively.

3.2 Numerical Modeling of Evaporative Fluxes in Desiccating Saline Soil and Thickened Tailings

3.2.1 Introduction

Following the experimental characterization of the 1D transport of pore-water solute and the relationship to evaporative fluxes in desiccating saline soil and thickened tailings, the numerical prediction of fluxes was undertaken. The goal was to, based on

the understanding gained from the experimental programme undertaken for this thesis, improve on the current capacity for predicting evaporative fluxes from saline thickened tailings stack. This is important for mine tailings operators to improve the effectiveness of using numerical tools to aid in deposition planning and management. A commercial unsaturated flow code, SVFlux (SoilVision Systems Ltd, Saskatoon, SK) was chosen and used as the numerical platform. The following sections describe how the unsaturated flow code was employed to model the evaporative behaviour of the soil and thickened tailings tested in this thesis. A description of how the numerical framework for accounting for solute transport in modeling evaporative behaviour of soil and tailings proposed in this thesis was implemented in SVFlux is also provided. In Chapter 6 of this thesis, the surface accumulation of salt in desiccating thickened tailings columns was modelled using a commercial 1D solute transport numerical code (ChemFlux) coupled to SVFlux. ChemFlux is from the same proprietor as, and compatible with, SVFlux. Details about the solute transport numerical code and its implementation are also provided in the following section.

3.2.2 SVFlux

SVFlux is a commercial 1-dimensional finite element (FEM) code that is capable of transient unsaturated flow analysis. For unsaturated soil conditions such as the case for this thesis, SVFlux models the 1D flux of water flow (in both liquid and vapour forms)

assuming isothermal soil conditions. The flow of liquid water in soil or tailings is governed by the generalized Darcy's Law (Bear 1972) given as:

$$V^w = -K^w(\psi) \frac{\partial h}{\partial z} \quad (3.06)$$

Where V^w is the liquid pore-water velocity (m/s); $K^w(\psi)$ is the hydraulic conductivity (m/s) as a function of matric suction, ψ (kPa); h is the hydraulic head (m); and z is the elevation (m).

Water vapour flow in unsaturated soil or tailings is governed by the modified Fick's Law (Philip and de Vries 1957; Fredlund and Dakshanamurthy 1982), given by:

$$V^v = -K^v \frac{1}{\gamma} \frac{\partial \psi}{\partial z} \quad (3.07)$$

Where V^v is the pore water vapour velocity (m/s); K^v is the pore water vapour conductivity (m/s) in the air phase as a function of matric suction, ψ (kPa) ; and γ is the unit weight of water.

By combining equations 3.06 and 3.07 for liquid water and vapour fluxes and writing the continuity equation for a representative elemental volume (REV), the h-based

formulation of the partial differential equation (PDE) for 1D transient unsaturated water flow is given as:

$$\frac{\partial}{\partial z} \left[(K^w(\psi) + K^v(\psi)) \frac{\partial h}{\partial z} - K^v(\psi) \right] = -\gamma m^w \frac{\partial h}{\partial t} \quad (3.08)$$

Where t is time (s); and m^w is the derivative of the SWCC with respect to matric suction or the slope of the consolidation curve in the positive pore-water pressure region. K^w , K^v and m^w vary with matric suction and this accounts for the non-linear behaviour exhibited by unsaturated soil or tailings.

SVFlux implements a generic FEM algorithm called FlexPDE™ that is versatile in handling the highly non-linear behaviour exhibited by unsaturated soil (SoilVision Systems Ltd 2008). The numerical code allows for fully-automated mesh generation and refinement, adaptive time stepping as well as automated generation and control of time steps. The FlexPDE™ algorithm employs the Newton-Raphson iteration scheme for convergence and implements a fully-implicit approach to ensure convergence using the diagonal-block inverse matrix as a pre-conditioner (SoilVision 2008). SVFlux can implement either the h-based or mixed based formulation of the PDE to be solved, depending on the choice of the user.

3.2.3 Predicting Evaporative Fluxes in Saline Soil and Thickened Tailings Using SVFlux

In setting up the numerical models for predicting evaporative fluxes from the saline soil and thickened tailings in SVFlux, the following general procedures were followed in this thesis:

(a) *Set up the Model Parameters:* The h-based formulation was specified as well as the start and end times, which were set to the duration for which the soil or tailings column or stack was left to desiccate in the respective laboratory drying experiment. Though the flow code has an in-built capacity for adaptive time stepping and automatic mesh generation and refinement, a minimum time step and mesh size of 30 minutes and 0.001m were specified, respectively. The default spatial and temporal convergence error limit of 0.0001 for 1D analysis was specified.

(b) *Specify the Domain Geometry:* The geometry of the domain for the desiccating soil or thickened tailings was specified according to the experimental set up. For the single-layer soil and thickened tailings columns, only one region was specified in the code. In the case of the multi-layer tailings deposits, several regions, each corresponding to an individual tailings layer, was specified in the simulation. A second-order (quadratic) interpolation of nodal values of the field variable (hydraulic head for SVFlux; concentration for ChemFlux) was specified for all simulations.

(c) *Define Initial Conditions:* Both the soil and tailings tested in this thesis undergo initial settling when deposited at saturation. To account for this, the procedure of Fisseha et al. (2010) was followed: an average initial positive pore-water pressures of 2 and 3kPa as well as m^w values (equation 3.08) of 0.024 and 0.03kPa^{-1} were specified for the soil and thickened tailings, respectively. These parameters are chosen in order to force the numerical code to generate the same mass of water as would be generated by settling in reality. In modeling the multi-layer tailings tests, the final matric suction profile from the simulation of the older layer was used as its initial suction profile when modeling a new layer. For the new layer, an initial positive pore-water pressure distribution is specified, as previously described.

(d) *Specify the Boundary Condition:* A zero flux lower boundary condition was specified for all simulations, as there was no bottom drainage in all the desiccation tests. For the multi-layer deposits, no boundary condition was specified at the interface between two layers as they are assumed to be hydraulically continuous. For all simulations, a climatic boundary condition was specified at the top of the soil and tailings. The climatic boundary condition was determined as a function of the modelled total suction at the surface using the Wilson et al. (1997) model (equation 2.02). Fredlund et al. (2011) reported on the need to adjust the total suctions used in the Wilson et al. (1997) equation to

calculate AE in order to obtain of fit of experimental data with numerical predictions. The said authors introduced a “suction correction factor” that can be implemented in SVFlux, with values ranging from 0 to -2. For all simulations for the soil and thickened tailings undertaken in this thesis, a suction correction factor of -0.5 and -0.65 were used for column drying test conducted under ambient (AW) and simulated wind (SW), respectively. These values gave the best fit of experimental data (more details presented in Chapters 5 and 6). Daily values of PE determined from the soil and tailings desiccation tests were entered into the numerical code. The daily ambient RH and temperatures data recorded for the respective drying tests were also entered into SVFlux.

The numerical code was originally built with the option of the end-user specifying the osmotic suction at the surface of soil or tailings being modelled. This value of osmotic suction was assumed constant by the code throughout the simulation period. Given that advective transport of solute during evaporation causes temporal increase in osmotic suction at the surface, a framework that accounted for this temporal increase was explored. The proprietor of the commercial code was consulted and the capability to enter temporal data of osmotic suction was added to the numerical code. Consequently, temporal values of osmotic suction calculated from measured EC data using equation 3.01 were entered into the numerical code. The osmotic suction data entered for a given day is then added by the numerical code to the modelled matric suction at

the surface. The total suction obtained is then adjusted by the numerical code using the input suction correction factor in computing the AE from the soil or tailings from the input PE and climate data.

(e) *Define the Material Properties:* The drying SWCC of the soil and tailings (Figure 3.02) were entered into the numerical code and fitted with Fredlund and Xing (1994) equation. The saturated hydraulic conductivity (K_{sat}) of the soil and tailings (Table 3.01) were specified in the code. The hydraulic conductivity function, $K^w(\psi)$, of the soil was estimated by the code from the input K_{sat} and fitted SWCC using the indirect method of Fredlund et al. (1994). For the tailings, $K^w(\psi)$ was estimated by the indirect method of Mualem-Van Genutchen (Van Genutchen 1980) using the SWCC that accounted for shrinkage of the tailings as per Fisseha et al. (2010) - more details can be found in Simms et al. (2007). In modeling the multi-layer tailings deposits, the SWCC of the old layer is modified to reflect its permanent volume change when initially dried as per Fisseha et al. (2010). The $K^w(\psi)$ of this old layer was then estimated from the K_{sat} and the modified SWCC fitted with the Fredlund and Xing (1994) curve using the Fredlund et al. (1994) method.

(f) *Specify the desired output format for post-processing analysis and visualization:* The desired output plots of AE, RE, profile and temporal GWC and matric suction were specified in the numerical code prior to running the numerical simulation.

This was done to facilitate easy visualization and post-processing analysis of model results.

The numerical results obtained following the above procedures were thereafter compared to experimental data for the soil and thickened tailings desiccation tests.

3.2.4 ChemFlux

ChemFlux is a commercial 1-dimensional finite element (FEM) solute transport numerical code from the same proprietor as SVFlux that can be used for transient problems. ChemFlux uses the same solver algorithm (FlexPDE) as SVFlux, and can be coupled to the latter to predict 1D solute transport and surface salt accumulation from desiccating saline soil and thickened tailings. ChemFlux solves the transient form of the PDE for 1D transport of pore-water solute in desiccating soil and tailings previously given in equation 2.24. Full coupling of ChemFlux to SVFlux allows the two PDEs (equations 2.24 and 3.08, respectively) to be solved simultaneously, with the numerical solution of the time derivative of head (velocity) in the latter input into ChemFlux to solve for solute concentration.

ChemFlux, coupled to SVFlux, was used in Chapter 6 of this thesis to model the solute transport and salt accumulation at the surface of desiccating thickened tailings columns. For the coupled model, the same model parameters, time-stepping and mesh-

refinement schemes, as well as domain geometry specified for the corresponding SVFlux simulation was adopted in ChemFlux. The simulation of solute transport using ChemFlux requires that an initial uniformly-distributed solute concentration be specified. The initial pore-water solute concentration estimated from the EC measured for the thickened tailings columns was specified. The boundary condition specified at both the top and bottom of the thickened tailings columns was zero flux, with dispersivity (equation 2.23) and diffusion coefficient (equation 2.22) of 0.001m and $3.25 \times 10^{-9} \text{ m}^2/\text{s}$, assigned, respectively. These values are typical for the scale of problem being solved for the column study conducted in the current thesis (Domenico and Schwartz, 1990; Fisseha et al. 2010). Solutions of concentration obtained from the numerical simulations were compared to experimental data. A schematic of the flowchart for numerical prediction using SVFlux and ChemFlux is presented in Figure 3.15.

3.3 Principle, Design and Prototype Testing of a New Matric Suction

Sensor

3.3.1 Introduction

The determination of matric suction in unsaturated soils and tailings is important for many geotechnical and geo-environmental applications (Fredlund and Rahardjo 1993; Vanapalli et al. 1996; Williams et al. 1997; Weeks and Wilson 2005; Newson and Fahey 2003; Simms et al. 2007). Therefore, an Improvement in the capacity of

Figure 3.15. Schematic of numerical simulations using SVFlux and ChemFlux.

practitioners to measure the wide range of matric suctions encountered in many engineering applications is desirable. The following sections provide details of the conception, operating principle, material selection, design and prototype testing of a new matric suction sensor.

The prototype matric suction sensor (hereafter referred to as “Poroelastic sensor”) consists of a porous material with high AEV (8000kPa) and hence, is not prone to cavitation for matric suction values below this AEV. The porous material is sufficiently “soft” enough to undergo measurable volume change as a result of change in pore-water pressure, but stiff enough to be used as a robust sensor in soil. The resulting

volume change was correlated to the change in positive or negative pore-water pressure by poroelasticity theory, which is described in the following section.

3.3.2 Poroelasticity: Theory of Pore-water Pressure-Induced Volume Change of a

Linearly-elastic Porous Material

The pore fluid of a porous material interacts with its bulk material as a result of both “fluid-to-solid” and “solid-to-fluid” couplings. The “fluid-to-solid coupling” arises when a change in the pore pressure (fluid pressure) results in a change in the volume of the porous material. “Solid-to-fluid coupling” exists when the pore pressure is affected by a change in the stress applied to the bulk solid of the porous material (Wang 2000). The pore-pressure induced change in volume of the porous material (poroelasticity) is analogous to, and governed by the same constitutive equations as thermal-induced change in volume of an elastic material (thermoelasticity).

According to Biot’s theory (1941) for a porous material containing a fluid under isotropic applied stress, σ , there are two equations governing the elastic behaviour of a Poroelastic material. The first equation is simplified as the sum of changes in applied stress and pore pressure of a poroelastic material leads to a fractional change in its volume, given as:

$$\epsilon = a_1\sigma + a_2P \quad (3.09)$$

The second equation explains that total changes in applied stress and pore pressure of a porous material requires that fluid be added to, or removed from the amount of fluid stored within the material (Wang 2000), and is also given in a linear form as:

$$\zeta = a_3\sigma + a_4P \quad (3.10)$$

Where ϵ is the volumetric strain, given as $\delta V/V$; V is the bulk volume and δV is change in bulk volume of porous material; and ζ is the change in fluid content of porous material (positive if fluid is added and negative if removed from material).

The applied stress, σ , is positive if tensile and negative if compressive; P is the pore-fluid pressure (positive if more than atmospheric and negative if less than atmospheric), and; a_1 , a_2 , a_3 and a_4 are generic coefficients introduced to linearize these two constitutive equations (Wang 2000). The pore-fluid pressure, P , is typically assumed to be uniform throughout an isotropic homogenous medium (Endres 1997).

The “fluid-to-solid” and “solid-to-fluid” couplings for an incompressible fluid (such as water) are very significant, but negligible for a highly compressible fluid like air. Given that there is no applied external stress on a porous material, a uniform increase in pore-water pressure causes a uniform increase in imposed linear strain (Wang 2000).

Poroelasticity theory constitutes the basis for the design of the new Poroelastic sensor described in this thesis. Apart from potential soil-structure interaction with test material or overburden pressure when used at depths, no significant external stress is expected to be applied to the constituent material of the Poroelastic sensor. Therefore, it is a reasonable assumption that only “fluid-to-solid coupling” is significant for the application being considered and that a uniform change in pore-water pressure will cause a uniform change in volume of porous material (Endres 1997).

3.3.3 Choice and Preliminary Testing of Candidate Porous Material

A number of candidate porous materials were evaluated for designing the Poroelastic sensor. The selected material is a commercially-available open-cell porous glass, 2.76mm in diameter, with excellent absorption properties. The material has high mechanical strength, is chemically non-reactive and non-flaking. The porous glass has an internal surface area of $250\text{m}^2\text{g}^{-1}$, an approximate dry specific gravity of 1.5, porosity and void ratio of 45.8% and 0.845, respectively (as determined in our laboratory). The candidate material has an average pore diameter of 4 millimicrons, dielectric constant of 3.1 at 25°C and 100Hz, and an electrical impedance of 500 ohms in KCl.

Also, the AEV of the candidate material was estimated from its average pore-size distribution to be approximately 8000kPa. The Young Modulus (E) and Poisson ratio (μ) of bulk material from which the candidate material was made are 65GPa and 0.24,

respectively (Bentz et al. 1998). Previous authors (Yates 1954; Scherer 1986; Bentz et al. 1998) have either previously used or characterized the candidate porous material. The pore-water pressure-induced change in strain of porous material has been previously described by linear elastic equations similar to equations 3.09 and 3.10 (Amberg and McIntosh 1952; Scherer 1986). The candidate material was therefore an excellent choice for designing the Poroelastic sensor as it conforms to the basic assumptions of the poroelasticity theory.

A rough evaluation of the candidate porous material was initially conducted by observing its linear strain when saturated. This was done by full immersion of a length of material in distilled water, while applying vacuum (-0.9 atm gauge) for 24 hours in order to dislodge air pockets trapped in its void spaces. Prior to saturation, the material was prepared by rapidly wiping with gauze soaked in isopropyl alcohol, with the excess alcohol dried with absorbent Kleenex. Following the application of vacuum, the porous material was left submerged under water for 5 hours until no further change in its mass was detected. The final length of the saturated material was thereafter determined using digital callipers. Based on the mass of water absorbed by the dry porous material relative to its oven-dried mass, a 98% degree of saturation was achieved by this procedure.

From the initial (dry) and final (saturated) lengths of the porous material, the linear strain resulting from saturation was determined as:

$$\epsilon = \frac{\Delta l}{l} \quad (3.11)$$

Where Δl is change in length (mm) and l is the initial length of porous material (mm) and ϵ is strain (microstrains, $\mu\epsilon$). A strain of 200 $\mu\epsilon$ was measured using this rough procedure, hence demonstrating the suitability of the candidate porous material in designing the new Poroelastic sensor.

3.3.4 Assembly of Poroelastic Sensor

In order to accurately measure the strain on the porous material, a SR-4 general-purpose electrical resistivity strain gage (Vishay Micromasurements, Raleigh, NC) was mounted on the candidate porous material. The strain gage has a grid resistance of $120.0 \pm 0.2 \Omega$, with a gage factor of $2.01 \pm 1.0\%$ at 24°C . The temperature coefficient (TC) and transverse sensitivity of the gage are $+1.2 \pm 0.2\% / 100^\circ\text{C}$ and $+1.6 \pm 0.2\%$, respectively. The porous material was prepared by degreasing using clean gauze dipped in GC-6 isopropyl alcohol, followed by repeated scrubbing with M-Prep. Conditioner A (Intertechnology, Don Mills, ON) and clean gauze until gauze was no longer discoloured. The porous material was wiped dry with a single slow stroke of the gauze to avoid re-

contamination. The surface of porous material was then reconditioned to an optimum pH of 7.0 – 7.5 by liberal application of M-Prep Neutralizer 5A (Intertechnology, Don Mills, ON), and wiped dry with a single slow stroke of the gauze sponge.

The electrical resistivity strain gage was mounted as soon as the porous material was prepared, keeping the working area clean to avoid re-contamination and poor bonding of strain gage to the porous material. The porous material was then secured on a piece of wood with adhesive tape to facilitate easy strain gage installation. The strain gage was placed on a clean piece of glass, with its foil (unbounded) surface facing up. A PCT-2M gage installation tape (Vishay Micro-measurements, Raleigh, NC) was stretched across the surface of strain gage, exerting slight thumb pressure to ensure the installation tape holds the strain gage well when lifted. The tape was carefully lifted at about 45° angle from the piece of glass, without doubling the tape, in order to prevent the strain gage from being stretched and damaged. The installation tape, with the strain gage, was then placed on the surface of porous material and pressed firmly with thumb pressure. One end of tape was thereafter pulled back gently at an angle of about 45°, lifting up the strain gage with it. M-Bond 200 Adhesive catalyst C (Vishay Micro-measurements, Raleigh, NC) was applied sparingly onto the bonding surface of the strain gage. To ensure limited application of catalyst, excess catalyst was removed from brush by wiping brush against the tip of the bottle six times before smearing the bonding surface of the strain gage. Two drops of M-Bond 200 adhesive (Vishay Micro-measurements, Raleigh, NC) was placed onto the two edges of installation tape, about

1cm away from one end of the strain gage. The gage installation tape was immediately stretched back onto the surface of porous material, the strain gage pressed down in the process, with a firm thumb pressure maintained for at least 1 minute to ensure proper bonding. The installation tape was then pulled away from the surface of porous material, leaving the bonded strain gage to cure for about 1 hour before the attachment of lead wires.

Two thin enamel-coated tin wires were soldered onto the terminals of the strain gage, with the gage foil protected from heat using masking tape and a tiny piece of paper. Soldering was done by placing some solder directly on a hot soldering iron, placing the tin wire with uncoated end on the terminal of strain gage, and placing the iron on top of both terminal and wire, with the application of moderate pressure. The other two ends of the attached lead wires were soldered onto tabs previously mounted on a cap pre-installed on one end of porous material (for easy handling of the Poroelastic sensor). To the adjacent ends of the tab were soldered a length of wire for connection to a strain indicator. The exposed surface of bonded strain gage was then water-proofed by applying a thin and even layer of molten M-coat microcrystalline wax (Vishay Micro-measurements, Raleigh, NC). The installed strain gage was thereafter tested to ensure proper installation using Model 1300 gage installation tester (Intertechnology, Don Mills, ON). The Poroelastic sensor (Figure 3.16) was connected to a 3800 Wide-Range strain indicator ((Vishay Measurements Group, Raleigh, NC), setting the gage factor to that of the mounted strain gage, and properly zeroing the strain indicator.

3.3.5 Stability and Sensitivity of Poroelastic Sensor to Ambient Environmental Conditions

The sensitivity of the Poroelastic sensor to ambient boundary conditions was tested after it was assembled. This was done by placing the Poroelastic sensor, connected to the strain indicator, inside an empty desiccator bottle with some distilled water at the base. The desiccator bottle was then sealed and left to stand at room temperature for 3.5 hours, while the time series of changes in strain of Poroelastic sensor was monitored. This allowed the Poroelastic sensor to respond to gradual changes in relative humidity inside the desiccator (caused by increasing water vapour pressure as the water at the base of desiccator evaporated).

Figure 3.16. Schematic of Poroelastic sensor showing position of bonded strain gage.

The result of the sensitivity test (Figure 3.17) showed that the Poroelastic sensor is sensitive to change in ambient RH. As the prototype sensor was initially conceived to be inserted into the soil surface, it became necessary to isolate the portion of the Poroelastic sensor that would be exposed to ambient air. Thus, the exposed portion of sensor material was coated with a water-restricting M-Coat B Nitrile rubber (Measurement Group Inc. Raleigh, NC) to minimize sensor's fluctuations in response to variations in ambient R.H. The tip of the Poroelastic sensor that was to be inserted in test material was left uncoated (Figure 3.16).

Figure 3.17. Response of Poroelastic sensor over time to increasing ambient relative humidity when its constituent porous material was left uncoated.

The Poroelastic sensor may also undergo some deformations due to fluctuations in ambient temperature. Therefore, the stability of the coated Poroelastic sensor was tested by saturating the Poroelastic sensor, leaving it under ambient conditions and monitoring its response over a 5-hour period. The result showed that once the Poroelastic sensor was coated, it became stable under ambient conditions after equilibration with the ambient RH (Figure 3.18). The temperature in the laboratory varied between 20 and 23 °C during the period of the test. Therefore, the Poroelastic sensor's response seemed stable and insensitive to this scale of temperature variation.

Figure 3.18. Response of previously-saturated Poroelastic sensor over time after coating exposed portion of its constituent porous material with water-restrictive rubber.

3.3.6 Poroelastic Sensor Testing: Saturation, Drying and Re-saturation Test

To evaluate the repeatability of Poroelastic sensor measurements over time, the prototype was initially saturated in a vacuum desiccator as previously described, and subsequently subjected to repeated cycles of drying and wetting. “Wetting” involved sticking the tip of Poroelastic sensor inside distilled water in a beaker and monitoring the change in strain over time until no further change in strain was observed. The Poroelastic sensor was then taken out of water and left to stand under ambient condition while change in strain was also monitored until no further change in strain was observed. This wetting and drying test was repeated over three cycles.

Figure 3.19 presents the response of the Poroelastic sensor during the wet/dry cycles, both in terms of strain and matric suction calculated using the poroelasticity equations as discussed in the next section. It was promising to note that the Poroelastic sensor returned to the same reference strain when rewetted and showed no evidence of hysteresis for the observed range of matric suctions, which are well below the AEV of the porous material. It is also interesting to note the decrease in the rate of drying as the calculated matric suction approached 4000 kPa. This value of suction corresponds to when the RH at the surface of the Poroelastic sensor would begin to drop and Stage II evaporation would have commenced (Wilson et al. 1997; Fisseha et al. 2010).

Figure 3.19. Response of Poroelastic sensor during three cycles of wetting and drying in terms of (a) strain and (b) matrix suction.

3.3.7 Poroelasticity Equations for Converting Strain to Matric Suction

In order to compare values obtained from Poroelastic sensor to matric suctions obtained from other measuring devices or techniques, the poroelasticity equation was used to convert strain measurements to matric suction. Mackenzie (1950) showed that the linear strain, ϵ , for a linearly-elastic porous material that is partially saturated is related to its capillary (matric) suction by:

$$\epsilon = \frac{SP}{3} \left[\frac{1}{K} - \frac{1}{K_s} \right] \quad (3.12)$$

Where S is the degree of saturation; P is the capillary pressure (kPa) in the pore fluid of porous material; K is the bulk modulus of porous solid and K_s is the bulk modulus of material that makes up the solid frame of porous material. Equation 3.12 is known to be accurate for degrees of saturation of 80% or greater (Bentz et al. 1998). Given that the AEV of constituent porous material of the sensor is very high (8000kPa), it was anticipated that for matric suctions lower than 8000kPa, equation 3.12 will be accurate.

The other parameters in equation 3.12 (K_s and K) were calculated from basic poroelasticity equations.

K_s is given by:

$$K_s = \frac{E_s}{3(1-2\mu)} \quad (3.13)$$

Where E_s and μ are the Young Modulus (kPa) and Poisson ratio of solid backbone of the porous material from which the Poroelastic sensor was made, respectively, with values previously given.

K was also calculated using equation 3.13, but may be alternately determined from the properties of the solid phase of the bulk material if the pores are assumed spherical (Christensen 1991) as:

$$K = K_s \left(1 - \frac{(3K_s + 4G_s) n}{4G_s} \right) \quad (3.14)$$

Where n is the porosity of the porous material and G_s is the shear modulus of the solid backbone of the porous material. G_s is given by:

$$G_s = \frac{E_s}{2(1+\mu)} \quad (3.15)$$

The Young Modulus of elasticity, E , of the assembled Poroelastic sensor was determined by tracking the strain observed when a given load is placed on the sensor

when saturated (Figure 3.20). The Poroelastic sensor was inverted and held in place by means of a clamp system attached about 2cm below the attached strain gage. 30g weight was placed on top of the free end of the Poroelastic sensor and the strain was recorded. E was calculated from:

$$E \text{ (kPa)} = \frac{\text{Axial Stress}}{\text{Axial Strain}} \quad (3.16)$$

Where stress is the load (in N m^{-2}) and strain was obtained from the strain indicator. Using this procedure, repeatable values of E within 5% of the mean were obtained. It was observed that using this experimental value of E to calculate K directly (from equation 3.13) rather than calculating K from K_s and E_s (from equation 3.14) gave more accurate predictions. This is probably because the perfect alignment of the strain gage with the axial axis of the porous material is impossible. Therefore, all conversions of strain measurements to matric suction, using equation 3.12 was done using the measured value of E for the assembled Poroelastic sensor.

The strain gage measures the axial strain on porous material, which is of more interest in the application under consideration as the diameter of porous material is small enough (2.76 mm) compared to its length (8cm) such that volumetric strain may not be significantly different from axial strain. Also, the transverse sensitivity of the

attached strain gage is small ($+1.6 \pm 0.2\%$) and since this is a transducer application, the gage is deemed adequate for 1D measurement of strain (Wu 1962).

Figure 3.20. Experimental set up for the determination of Young Modulus, E , of the assembled Poroelastic sensor.

3.3.8 Shrinkage Curve and Estimated SWCC of the Porous Material

The shrinkage curve of the porous material was determined by tracking the changes in water content of previously-saturated Poroelastic sensor as well as the associated strains as it dried on a weighing scale (Figure 3.21). Assuming that volume change of the porous material is isotropic, void ratio was calculated. Strain measurements were converted to matric suctions using equation 3.12 to generate an estimated SWCC

(Figure 3.22). It was observed that some desaturation of the porous material occurred before the theoretical AEV (8000kPa), down to $S \sim 0.7$. Two SWCCs (in terms of S versus matric suction) are shown: one with $S=1$ in equation 1.12 and the other using the value of S calculated as the porous material dried. There was no discrepancy between the two matric suction curves obtained by the two approaches until matric suction values in excess of 6000kPa were recorded (Figure 3.22).

Figure 3.21. Shrinkage curve of the porous material used in designing Poroelastic sensor.

Also, the difference in terms of calculating matric suction became increasingly important as the matric suction increased: S is 0.96 at 1000kPa; 0.9 at 3000kPa and; 0.85 at 5000kPa. To verify that this decline in S before the theoretical AEV was not a result of imperfections in the constituent porous material that may vary from one sensor to another, a repeat test using another replicate sensor was conducted. Results from the replicate Poroelastic sensor also showed similar pattern (Figure 3.22).

Figure 3.22. Replicate soil water characteristic curves of porous material used in designing the Poroelastic sensor.

3.3.9 Poroelastic Sensor Testing: Comparison to Tensiometer, Heat-Dissipation Sensor, Axis-Translation Technique and Relative Humidity Sensor in Soil and Thickened Tailings

Having established the Poroelastic sensor's stability, as well as capacity for repeatable wetting, drying and re-saturation, the sensor was deployed in measuring the matric suction of two test materials. The test materials chosen are the silt and thickened gold tailings that were tested throughout this thesis, which had been previously described (Section 3.1.2). For the tests involving the silt, it was prepared at an initial GWC of 30% ($S \sim 100\%$) using distilled water and placed inside an open aluminum container with dimensions as shown in Figure 3.23. The Poroelastic sensor and a previously-saturated T5 Tensiometer (UMS) were both inserted to same depth (3cm) inside the soil, with the Tensiometer connected to a multi-meter for reading the matric suction of test material (Figure 3.23). The silt was left to desiccate under ambient laboratory conditions, with a no flow bottom boundary condition. The strain on the Poroelastic sensor and Tensiometer readings were concurrently data logged over time until the latter failed and cavitation was observed. The strain readings from the Poroelastic sensor were converted to matric suction and compared to matric suction measurements from the Tensiometer.

The drying silt was also monitored for matric suction using both the Poroelastic sensor and WP4-T Dewpoint PotentiaMeter (Decagon Devices Inc., Pullman WA). The silt was prepared at a GWC of 33% at the start of the drying test and left to desiccate under

ambient laboratory conditions. The experimental set-up for the drying test was similar to that previously described (Figure 3.23), except that at each sampling event, about 5g soil sample was taken for determination of matric suction using the WP4 (RH sensor). The drying test was continued for several days until the theoretical AEV of the Poroelastic sensor was exceeded, after which the sensor was grossly under-predicting the matric suction of test material in comparison to the RH sensor. Though the RH sensor measures total suction, the measurements for the silt is matric suction as there was no osmotic suction for the silt since it was prepared with deionised water. The time series of matric suctions for the silt obtained from the two devices were compared at the end of the drying test.

Also, the evolution of matric suctions in desiccating gold thickened tailings with an initial GWC of 38% was monitored using the Poroelastic sensor and compared to concurrent determinations using a heat-dissipation (HD) sensor. As shown in Figure 3.24, the Poroelastic and HD sensors were placed side by side, within the top 3cm of the desiccating thickened tailings. The thickened tailings were allowed to desiccate under ambient conditions, but with wind simulated by means of a fan. The bottom boundary condition of the desiccating thickened tailings was no flow. The strain and HD measurements were automatically recorded every half-hour using a data acquisition system. This desiccation experiment was repeated with the HD sensor replaced with a previously-saturated Tensiometer. For both thickened tailings drying tests, the

measured strains were converted to matric suction values and compared to matric suction determinations using the HD sensor and Tensiometer.

Figure 3.23. Schematic of experimental set-up for comparing Poroelastic sensor to Tensiometer and R.H sensor in drying silt.

The measurement of matric suction in the silt using the Poroelastic sensor was also compared with matric suctions established using the axis-translation technique. The axis translation experimental set up is similar to the one described in Oliveira and

Fernando (2006). Prepared at an initial GWC of 30% and void ratio of 0.8, the silt was placed inside air-tight axis-translation cell (AEV of ceramic disc being 500kPa). An initial air pressure of 50kPa was imposed on the sample and sustained until the air pressure is in equilibrium with the soil pore-water pressure. At equilibrium, the water level in a burette attached to ceramic disc of the axis-translation cell remained constant, indicating that the soil pore-air pressure was atmospheric. Thus, the matric suction of the soil is equal to the pore-water pressure (same as imposed air pressure) at equilibrium according to the principle of axis translation (Hilf 1956). The air pressure within the cell was then bled off, the top of the cell removed and the tip of Poroelastic sensor inserted into a 3cm-deep pilot hole inside the silt. Strain measurements were taken until a steady value was obtained as the Poroelastic sensor equilibrated with the soil. The silt was prevented from drying by covering with plastic when monitoring the Poroelastic sensor and taking the mass of the axis-translation cell including the test silt prior to, and immediately after taking readings. Also, back-flow of water from the water reservoir of the axis-translation set-up into the test silt was prevented by detaching the cell from reservoir before bleeding the air pressure within the cell and prior to matric suction determination using the Poroelastic sensor. This procedure was repeated for 50kPa increments of air pressure up to a maximum of 300kPa. The matric suction values of test silt determined from strain measurements using the Poroelastic sensor was compared with values from the axis translation technique.

Figure 3.24. Schematics of experimental set-up for comparing Poroelastic sensor to Heat-dissipation sensor and Tensiometer in desiccating thickened gold tailings.

In order to characterize the equilibration time for the Poroelastic sensor under applied air pressure, a time series of matric suctions recorded by the Poroelastic sensor was obtained at 50 and 200kPa applied air pressures. Once the test silt was equilibrated at a given applied air pressure, the Poroelastic sensor was inserted into the test silt, the cell was closed, the water reservoir re-attached and the given air pressure applied. The strain indicated by the Poroelastic sensor was then monitored and converted to matric

suction equivalents. The equilibration time for the Poroelastic sensor was found to be between 13 and 18 minutes (Figure 3.25).

Figure 3.25. Time series of equilibration of Poroelastic sensor with air pressure applied using axis-translation technique with silt at 50 and 200kPa.

The drying soil water characteristic curve (SWCC) of the 25-50 micron artificial silts was obtained using the Poroelastic sensor and WPT-4 Relative Humidity sensor (Decagon Devices Inc., Pullman, WA) (Figure 3.26). Even though the relative humidity sensor typically measures total suction of test material, the suction values of test material obtained in this study is matric since there is no osmotic component of total suction for the artificial silts. This is because the silt is a chemically-inert material under

the ambient conditions, and the initially dry sample was prepared using deionised water. The Soil Water Characteristic Curves obtained for both the Poroelastic sensor and R.H sensor were highly correlated, with a R^2 value of 0.821 (Figure 3.26). Compared to values obtained from R.H sensor, the Poroelastic sensor under-predicted the matric suction values of artificial silts at suction values lower than 400kPa, but slightly over-predicted the matric suction values at suction values between 400 and approximately 1200kPa (Figure 3.26). However, the accuracy of the R.H sensor is ± 0.1 MPa for total suction determinations ranging from 0 to 60MPa (Decagon Devices Inc., Pullman WA. The Poroelastic sensor was capable of predicting matric suction values as high as 5500kPa, but for matric suction values beyond its AEV (8000kPa), the sensor grossly under-predicted the matric suction of silt as determined using the R.H sensor (data not included). The Poroelastic sensor's capability for such high-range matric suction values is very promising as it can be potentially applied for test materials at high matric suction regimes, close to its AEV.

Figure 3.26. Soil Water Characteristic Curves obtained for artificial silt using Poroelastic and Relative Humidity Sensors.

CHAPTER 4: EFFECTS OF SALINITY AND SOLUTE TRANSPORT ON EVAPORATION FROM SILTY SOIL

ABSTRACT: Salinity in soils is known to suppress evaporation by at least three mechanisms: increase in albedo, changes in soil hydraulic properties due to salt precipitation, and increase in osmotic suction due to pore-water solute concentration at the soil surface. This paper investigated the relative importance of the last two mechanisms in an experimental study of solute transport and unsaturated flow in artificial silt-sized soil. Three sets of soil columns, identified as Low-saline (LS), Saline (S), and Hyper-saline (HS) treatments, were prepared with 5, 10 and 20% NaCl solutions, respectively, and were allowed to dry for 14 days. Each set contained multiple replicates that were destructively sampled on different days to obtain profiles of NaCl concentration, total suction, and gravimetric water content. Treatments with higher initial pore-water salinity had lower evaporation, with cumulative actual evaporation for the LS, S and HS soil columns being 36, 20 and 17% of the total potential evaporation for the entire drying period, respectively. The minimum relative evaporation was independent of the initial pore-water salinity, as the maximum total suction at the surface of all three treated soils was similar in all cases, and appears to be close to the value of osmotic suction corresponding to the concentration of NaCl at the solubility limit. Profiles of total suction with depth in the top 1cm of the soil become almost uniform by this point, implying that salt precipitation upon exceeding the solubility limit strongly reduces water transport near the surface almost immediately. Evaporation

rates predicted using total suction data from the top 1cm of soil columns agreed well with measured values for the LS soil, as well as for the first 1 and 3 days for the S and HS soil, respectively. Once the solubility limit of NaCl was exceeded for the S and HS soil, predictions of RE were generally higher than observations. Therefore, osmotic suction explained the reduction in evaporation up till the solubility limit of NaCl after which further reduction observed in this study can be attributed to the effect of salt precipitation.

4.1 Introduction

The one-dimensional (1D) transport of dissolved solutes in unsaturated media (such as soil and mine tailings) is of interest for many applications in agriculture and mine tailings management. These include the negative impacts of salinity on crop yields (Shimajima et al. 1996; Fujimaki et al. 2006) and reduction in the pace of successful reclamation of mine tailings disposal sites due to lowered rates of evaporation and shear strength gain (Rassam and Williams 1999a; Fujiyasu and Fahey 2000; Fisseha et al. 2010). The re-vegetation of decommissioned saline mine tailings facilities is also undermined by surface salt accumulation.

Evaporation is driven by the gradients in vapour pressures at the soil-atmosphere boundary, and proceeds in three stages as shown by Figure 4.01 (Gardner and Hillel 1962; Wilson et al. 1994; Bonsu 1997). In stage I, the actual evaporation (AE)

from saturated or near-saturated soil proceeds at the maximum (potential) rate for total suction (sum of matric and osmotic suctions) values less than about 3000kPa at the soil surface. At this stage, the rate of evaporation is only a function of climatic conditions, and water is transported within the soil as liquid. Total suction of the soil is functionally related to relative humidity (RH) of the soil pore air (Edlefsen and Anderson 1943). RH begins to significantly decrease for total suctions greater than 3000 kPa (Wilson et al. 1997), causing a reduction in the vapour pressure gradient as well as evaporation rate. This declining stage of evaporation is termed Stage II evaporation. During stage II evaporation, water transport within the soil occurs via a combination of liquid flow and water vapour diffusion. The total suction at the soil surface may continue to increase in Stage II until a new equilibrium between moisture supply and evaporation (Stage III) is reached when evaporation rate is low and constant (Gray 1970; Wilson et al. 1994). Water flow in soil at Stage III occurs via water vapour diffusion.

According to Wilson et al. (1997), the relative evaporation, RE (ratio of actual evaporation, AE to potential evaporation, PE) is known to be correlated to the total suction at the soil surface, and is given as:

$$RE = \frac{AE}{PE} = \left[\frac{e^{-\left(\frac{\psi g W_p}{RT}\right) - h_a}}{1 - h_a} \right] \quad (4.01)$$

Where ψ = total suction at the soil surface (m); W_v = the molecular weight of water (0.0186 kg/mol); g = gravitational acceleration (9.81m/s^2); R =universal gas constant (8.314 J/mol.K); T = temperature of air above soil surface (K) and h_a = relative humidity of air above soil surface (expressed as a fraction). This relationship has been shown to be valid, independent of the particle size distribution, water content and drying time of the soil, with the model validated for clay, silt and sandy soils (Wilson et al. 1997) under certain conditions (considering thin samples and controlled relative humidity environment).

Figure 4.01. Variation in relative evaporation with total suction and water content of unsaturated soil (Modified from Wilson et al. 1994).

Apart from total suction at the soil surface, soil resistance is another empirical approach to describing the evaporative behaviour of the soil (Camillo and Gurney 1986; Van de Griend and Owe 1994; Alvenäs and Jansson 1997; Bittelli et al. 2008). Two types of resistances are generally identified: the soil resistance (R_s) to water vapour diffusion to the surface from the evaporation front and the aerodynamic resistance (R_a) to the movement of vapour away from the evaporating soil surface. R_s increases with desiccation as the evaporation front recedes deeper and water vapour is transported over longer distance to the soil surface. The computation of R_s using different equations (Camillo and Gurney 1986; Kondo et al. 1990; Van de Griend and Owe 1994) and subsequent application for predicting evaporation tend to give different results as these equations are specific for a given soil (Bittelli et al. 2008).

Solute transport is coupled to evaporation in unsaturated soils (Chen 1992; Nassar and Horton 1999; Fujimaki et al. 2006). Evaporation drives the upward flux of pore-water solutes, while the accumulation of solutes /salts at the soil surface lowers the rate of evaporation. Reduction in PE by as much as 90% for saline soil (Chen 1992; Newson and Fahey 1997) as well as evaporation being completely shut down in surface-deposited thickened tailings after three weeks of deposition has been reported (Simms et al. 2007). Better understanding of the mechanisms by which salts reduce evaporation continues to be an area of interest to researchers, with the objective of improving the current capacity for predicting evaporation in saline soil and tailings.

The three mechanisms of salinity reducing evaporation in soil are: surface albedo, osmotic suction, and salt precipitation. Previous work have focussed on the effect of albedo (Malek et al. 1990; Newson and Fahey 2003; Simms et al. 2007), osmotic suction (Noborio et al. 1996; Yakirevich et al. 1997) or salt crust (Fujiyasu and Fahey 2000; Fujimaki et al. 2003; Fujimaki et al. 2006). However, the relative importance of these three mechanisms in suppressing evaporation is not well understood.

Fujiyasu and Fahey (2000) tested saline mine tailings and concluded that while osmotic suction was a contributing factor, surface albedo and salt crust were the most significant factors causing reduction in evaporation. Newson and Fahey (2003) conducted a series of field and laboratory trials on saline mine tailings deposits and concluded that pore-water salinity caused a significant reduction in the rate of evaporation, both before and after the formation of a salt crust. Simms et al. (2007) reported that although albedo was a significant factor affecting evaporation from dewatered mine tailings deposits, it was not sufficient to explain the scale of reductions in evaporation observed in both the laboratory and the field. Simms et al. (2007) suspected that one or both of the other two factors may be relatively more important. For the current paper, the effect of albedo was excluded by conducting all column drying experiments under ambient laboratory lighting. In the current study, evaporation was solely driven by wind generated by an oscillating fan.

The capacity of currently-available numerical codes for predicting evaporative fluxes from saline soils and mine tailings is limited by their inability to accurately account for the effect of pore-water salinity (Fujiyasu and Fahey 2000; Simms et al. 2007; Fisseha et al. 2010). Therefore, an improved understanding of the feedback between 1D solute transport and unsaturated flow is important for better predictions of evaporative fluxes from saline soils and mine tailings. Specifically, the current paper investigated the relative contribution of osmotic suction and salt precipitation to reduction in evaporation from silt. Using a modified wax column technique, solute transport and evaporative fluxes from three sets of treated soil columns were monitored.

4.2 Materials and Methods

4.2.1 Modified Wax-Column Technique for Studying Solute Transport and Unsaturated Water Flow in Soil

The petroleum jelly wax-column technique of Khasawneh and Solileau (1969) was modified and employed to investigate the 1D solute transport and unsaturated water flow in the current study. This technique is conventionally used for fertilizer diffusion studies in soil (Khasawneh et al. 1974; Akinremi and Cho 1991; Kumaragamage et al. 2004; Olatuyi et al. 2009) as it allows for preparation of soil columns that can be sectioned into profile samples as thin as 5mm. A molten mixture of petroleum jelly (1 part by mass) and paraffin wax (2.5 parts) was poured and solidified to form a mould with a cylindrical cavity that could be used to pack, dry and destructively sample soil.

The cavity was created by placing a cylindrical aluminum can inside an empty milk carton, pouring the molten petroleum jelly-wax mixture inside the milk carton and allowing the pour to set for 24 hours. Figure 4.02 shows the schematic and dimensions of the modified wax column used for the current study.

The test soil used in this study was silt-sized spherical glass micro-beads (Potter Industries Inc. LaPrairie, QC, Canada) with geotechnical properties as shown in Table 4.01. The particle size distribution, as determined by the hydrometer method, is presented in Figure 4.03.

Figure 4.02. Schematic of petroleum jelly-wax column used for soil column experiment.

Table 4.01. Geotechnical properties of silts used for preparing soil columns

Property	Value
Specific Gravity	2.48
D ₁₀ , D ₅₀ , D ₆₀ (microns)	1, 31, 41
Cu (D ₆₀ /D ₁₀)	41
Liquid limit (%)	19
Plastic limit (%)	13
Saturated hydraulic conductivity (m/s)*	1.7×10^{-6}

*The value of saturated hydraulic conductivity for the silt was determined using falling head test at a void ratio of 0.8 as per Fisseha et al (2007).

Figure 4.03. Particle-size distribution (PSD) of test silt determined by the hydrometer method.

For all laboratory experiments presented in this paper, prior to packing inside replicate wax columns, the silt was prepared using NaCl solutions of different concentrations, and thoroughly homogenized using a mechanical mixer. To remove any large air pockets, each packed column was gently tapped three times immediately after pouring the soil slurry into the wax column.

The total mass and volume of each replicate packed soil column was recorded at the onset of the drying experiment after which the soil columns were left to dry under ambient laboratory conditions and simulated wind. At each sampling event, one replicate soil column was destructively sampled by sectioning into 1cm thin slices using a hacksaw and mitre box. The soil from each slice was kept inside sealed Ziploc plastic bag and thoroughly homogenized by hand before conducting different soil analyses on subsamples. Therefore, the soil parameters determined and recorded for each profile sample is the average value for the respective 1cm thick profile depth of the soil.

4.2.2 Preparation of Soil Columns at Varying Initial Pore-water Salinities

In order to study the effect of initial conditions on 1D solute transport and implications for unsaturated flow in soil, three levels of pore-water salinities were investigated. Solutions of reagent-grade NaCl (Lot # 8J9286; Purity > 99.0%; BioShop Canada Inc., Burlington, ON) containing 5, 10, and 20% (mass of salt / mass of solution) were used in preparing the soil to a homogenous pore-water concentration. Three sets

of soil column experiments were conducted in succession, one each with the 5, 10 and 20% NaCl solution. The 5, 10, and 20% NaCl pore-water concentration treatments are hereafter referred to as Low-saline (LS), Saline (S) and Hyper-saline (HS) treatments, respectively. For the LS and HS experiments, the initial gravimetric water content (G.W.C), expressed as the mass of NaCl solution per mass of dry soil, was 30%, while for the S treatment, it was 33%. The initial GWC alternately expressed as the mass of water per mass of dry soil, was 28.5, 29.7, and 24% for the LS, S and HS treatments, respectively. Initial void ratios varied between 0.86 and 0.83, giving degrees of saturation (volume of water / pore volume) between 72 and 83%. However, the soil samples would settle significantly within 2 hours after deposition, to void ratios between 0.78 and 0.73, giving degrees of saturation between 96 and 81%. These degrees of saturation fall within the range where the air phase for a porous material can be considered discontinuous (Ng and Menzies 2007). A non-saline soil column (NS) prepared with deionised water was also set up to serve as control for each soil salinity treatment.

4.2.3 Experimental Conditions and Sample Analyses

The packed soil columns were left to dry under ambient lighting and simulated wind. The potential evaporation rate (PE), as determined from concurrent measurements of evaporation from a wax column filled with distilled water, was between 8 and 12 mm/day for both the LS and HS treatments and between 14 and

18mm/day for the S treatment. The difference in PE was due to variation in the laboratory ambient temperature and RH, both of which were dictated by the building's centrally-operated climate control system. The ambient temperature and RH were monitored throughout the drying experiments using a USB-502 RH / Temperature Data Logger (Measurement Computing, Norton, MA). The data for the LS, S and HS treatments are presented in Figures 4a, b and c, respectively. One soil column per treatment was destructively sampled as previously described on days 2, 3, 4, 5, 7, 9, 11 and 14.

The soil samples obtained from column slices were analyzed for electrical conductivity (EC), NaCl concentration, G.W.C and total suction. For the EC analysis, 1 part homogenized soil sample was mixed with 4 parts de-ionized water, shaken using an orbital shaker (175 rpm for 30 minutes), and centrifuged at 3000 rpm ($1000 \times g$) for 2.5 minutes. The resulting supernatant was analyzed for EC using a Traceable Conductivity Meter (VWR International, Friendswood, TX). The EC data was thereafter used to determine the NaCl concentration in the supernatant by means of a calibration curve (Figure 4.05) established using standard NaCl solutions (Fisher Scientific, Ottawa ON). It is important to note that the NaCl dissolved in the supernatant contained both NaCl dissolved in the pore-water and NaCl that would have been originally precipitated in the soil sample, but was re-dissolved by the addition of water while preparing the supernatant. Using the dilution factor, the NaCl is reported in concentration of mass of solute per volume of pore water (as parts per thousand, ppt). In addition, using the USDA (1954) approximation, the osmotic suction of the supernatant was calculated

Figure 4.04. Ambient relative humidity and temperature during the drying experiment for Low-saline (a), Saline (b) and Hyper-saline (c) treatment soil columns.

Figure 4.05. Calibration curve of electrical conductivity (EC) against pore-water NaCl concentration.

from the EC measurements. Since the supernatant contained both the precipitated and dissolved solute, the osmotic suction calculated from the EC data is expected to be higher than osmotic suction due to pore-water solute alone. The G.W.C of soil samples was determined by oven-drying at 105⁰C for 24 hours. The total suction of the homogenized soil samples was determined immediately after sampling by means of a WP4-T Dewpoint PotentiaMeter (Decagon Devices Inc., Pullman, WA). The WP4-T measures the sum of the osmotic suction (due to solute dissolved in the soil liquid phase) and the matric suction (due to net capillary force of the soil air phase on the liquid-solid soil matrix) of the soil samples (Leong et al. 2003). Hence, the osmotic suction included in the total suction measurements is entirely due to soil pore-water

dissolved solute and is therefore expected to be less than the osmotic suction calculated from the EC data.

4.2.4 Soil Water Characteristic Curves for Soil with Different Initial Pore-water Salinities

To investigate whether the initial pore-water salinity of the soils would influence the water retention properties of the soil, the soil water characteristic curves (SWCC) of the LS, S, HS and non-saline soils were determined for remoulded samples. Soil samples were prepared at several gravimetric water contents using NaCl solutions prepared at the three pore-water salinities of the LS, S and HS treatments. The matric suctions at the various G.W.Cs were determined with a T5X Tensiometer (UMS München, Germany) having a suction range up to 200kPa. Matric suction determinations involved sticking the tensiometers into test samples, ensuring good contact between the porous tip and the test material, and allowing equilibration of the tensiometer with test sample before taking a final reading. Evaporative water loss from samples during equilibration was prevented by covering the samples with parafilm; the lack of water loss was confirmed by weighing the sample before and after matric suction determination. As a result of remoulding, these SWCC's will not necessarily be the same as the drying SWCC's of the treated soil columns. Despite this limitation, the SWCCs should provide some insights into the potential influence of pore-water salinity on the water retention properties of the test soil. The same determination was made for the non-saline soil. The SWCCs

obtained are presented in Figure 4.06. As can be seen, the influence of initial pore-water salinity on the SWCC was minimal.

4.2.5 Measurement and Prediction of Evaporation Rates from Saline Soil Columns

A wax column filled with distilled water was set up at the beginning of each soil column drying experiment for PE determinations throughout the drying period. At the start of each sampling event, the daily PE as well as the daily AE from treated (LS, S and HS) and corresponding non-saline soil columns (NS) were determined by mass difference over a 24 hour period. The RE was determined for the treated and NS soil columns from the corresponding AE and PE data.

Figure 4.06. Soil water characteristic curves for remoulded Low-saline (LS), Saline (S), Hyper-saline (HS) and Non-saline (NS) soils.

The Wilson et al. (1997) model (equation 4.01) was derived based on the assumption that the air, water and soil are approximately at the same temperature. This assumption was validated for the present study and the results presented in Appendix A1. The model was tested for three replicate drying experiments for the non-saline soil columns. Predictions of RE from equation 4.01 using total suction data in the top 1cm of the 10 cm-high NS soil columns and corresponding weather data did not agree with experimental data (Figure 4.07). For one of the three independent replicate drying experiments, using total suction data obtained in the top 2mm of the soil column still gave predictions of RE that were not in agreement with measurements (Appendix A2). Wilson et al. (1997) proposed and validated Equation 4.01 for sand, silt and clay soils with sample thicknesses ranging from 0.2 to 0.7mm under controlled RH and temperature. Thin samples were deliberately chosen by Wilson et al. (1997) in order to correlate a property at the "soil surface" with evaporative fluxes. Any other mechanism(s) below the soil surface that influences the rate of water supply to feed evaporative demand at the soil surface was intentionally excluded.

A validation test of the Wilson et al. (1997) model (equation 4.01) was conducted for the NS soil by conducting three independent replicate experiments for 2mm-thick soil samples drying under simulated wind. In each drying experiment, several replicate samples of the NS soil contained inside total suction sampling cups (1.5cm high, 4.2cm i.d) were concurrently dried over a 4-hour period. AE was determined from change in mass of replicate soil samples and PE was simultaneously determined from similar

sampling cups containing distilled water. The RE of the desiccating soil samples was determined from the measured AE and PE values. After the determination of AE from a replicate soil sample, its total suction was measured using the WP4-T device. The ambient RH and temperature were monitored throughout the drying experiment, and along with the measured total suction, were used to predict RE using equation 4.01. Predictions of RE were in better agreement with measured values for the 2mm-thick samples (Figure 4.08) compared to using the total suction values either in the top 1cm or 2mm of the 10cm-thick columns (Figure 4.07 and Appendix A3). Therefore, it was clear that other transport process(es) below the soil surface was driving evaporative fluxes for the 10cm-thick NS soil, in addition total suction at the soil surface.

Once the supply of water to the soil surface becomes limited (starting from the beginning of Stage II evaporation and afterwards), the rate of evaporation is known to be affected by the diffusion of water vapour from the evaporation front to the soil surface (Van de Griend and Owe 1994). For the thin samples tested in Wilson et al. (1997) and the 2mm soil samples tested for the current paper, the samples were thin enough such that the evaporation front was more or else right at the soil surface. Thus, the distance for water vapour to travel from the evaporation front to the soil surface was negligible. Hence, total suction at the soil surface mainly controlled evaporative fluxes. In contrast, for the 10cm-thick NS soil columns, the depth to evaporation front increases with time, resulting in an increase in soil resistance to water vapour diffusion as the soil columns continued to dry. Thus, in addition to total suction at the soil surface,

Figure 4.07. Relative evaporation (RE) measured from 10cm-thick Non-saline (NS) soil columns and predictions from total suction in the top 1cm of desiccating column using equation 4.01. Results shown are for three independent replicate drying experiments.

Figure 4.08. Relative evaporation measured from 2mm-thick soil samples and predictions from total suction using equation 4.01. Results of 3 independent replicate drying experiments are shown.

soil resistance to water vapour diffusion is expected to control the rate of evaporation for the 10cm-thick NS soil columns. Therefore, an empirical model that accounts for both the total suction at the soil surface as well as additional soil resistance to water vapour transport was required to predict evaporative fluxes from the 10cm-thick NS soil columns.

An ancillary drying experiment for the NS 10cm-thick soil column was conducted to determine the profiles of total suction within the top 1cm over time. Profile samples at 2mm intervals were obtained by means of a spatula and the total suction determined with the WP4-T. The profiles of total suction within the top 1cm of the 10cm-thick NS soil columns revealed a generally curvilinear shape (Figure 4.09). This implied that the total suction “at the surface” of the soil columns will be higher than the corresponding average values measured for the top 1cm. As a result, it was necessary to approximate the total suction “at the surface” of the NS soil columns by extrapolating from the total suction measured in the top 1cm. Fitting trendlines to Figure 4.09 showed that a power function consistently gave the best correlation (Appendix A2), with R^2 values ranging from 0.89-0.98. Three regions were identified from the curves of measured RE as a function of total suctions determined in the top 1cm of two independent sets of the desiccating soil columns (Figure 4.10) as follows:

$0 < \psi < 3\text{MPa}$; Region 1

$3 < \psi < 15\text{ MPa}$; Region 2

$\psi > 15 \text{ MPa}$; Stage Region 3

Where ψ is the total suction of the bulk top 1cm sample of the NS soil column.

Figure 4.09. Profile total suctions in the top 1cm of the 10cm-thick soil column. Symbols at the 0mm mark on the depth axis are the total suctions extrapolated to the surface of columns from the total suction measured for the top 1cm sample using equation 4.02.

Therefore, an extrapolation function for the total suction at the surface of the NS soil column ψ_e , is defined as:

$$\psi_e = \psi^a \quad (4.02)$$

Where “a” is an extrapolation coefficient specified, based on the region of the RE versus total suction curve (Figure 4.10), as:

$a=1.35$, 1.2 , and 1.1 for Region 1, 2, and 3, respectively. As shown in Figure 4.09, the above extrapolation procedure gave reasonable values of total suctions at the surface of the desiccating 10cm-thick NS soil columns. This is in line with previous work by Alvenäs and Jansson (1997) that reported the need to extrapolate the average total suction measured for the top layer of a desiccating sandy loam soil in order to accurately determine the value of the total suction “at the soil surface”.

Figure 4.10. Relative evaporation measured for the 10cm-thick NS soil columns as a function of total suctions in the top 1cm. Results shown for 2 independent replicate drying experiments.

The bulk transfer equation (Noborio et al. 1996; Bittelli et al. 2008) gives the AE from non-saline soil as a function of soil resistance as:

$$AE = \frac{P_{vs} (RH_s - RH_a)}{Ra + Rs} \quad (4.03)$$

Where P_{vs} is the saturation vapour pressure at a given temperature (kPa); RH_s is the RH of soil pore air given by the thermodynamic equation as a function of total suction at the soil surface (Edlefsen and Anderson 1943) as:

$$RH = e^{-\frac{\psi_g w_v}{RT}} \quad (4.04)$$

Rs is the soil resistance (day/mm) to vapour diffusion from evaporation front to the soil-atmosphere boundary (Van de Griend and Owe 1994) and; Ra is the aerodynamic resistance (day/mm) which can be back-calculated from PE (Fujiyasu and Fahey 2000) as:

$$Ra = \frac{P_{sv} (1 - RH_a)}{PE} \quad (4.05)$$

Where RH_a is the RH of air above the soil surface.

A combination of equation 4.03 and a rearrangement of equation 4.05 (for PE) in defining RE gives:

$$RE = \frac{AE}{PE} = \left[\frac{(RH_s - RH_a)}{(1 - RH_a)} \right] \left[\frac{1}{\left(1 + \frac{R_s}{Ra}\right)} \right] \quad (4.06)$$

The first part of the right side of equation 4.06 is the Wilson et al. (1997) model previously given in equation 4.01 (with RHs expressed as a function of total suction at the soil surface as per equation 4.04). Hence, equation 4.06 defines the RE from non-saline soil as a function of both the total suction at the soil surface and the soil resistance to water vapour diffusion from the evaporation front to the soil surface. The RE for the 10cm-thick NS soil columns was re-calculated using equation 4.06, with R_s back-calculated from the AE measured from the soil columns (using equation 4.03). R_a was back-calculated from the corresponding measured PE (using equation 4.05). The total suctions at the surface of the soil columns were extrapolated from the values measured in the top 1cm using equation 4.02 as previously described. The predictions of RE thereby obtained gave a good fit to the experimental data for all 3 independent column experiments for NS soil drying under simulated wind (Figure 4.11). To test the validity of equation 4.06 for the NS soil columns under a lower evaporative demand (PE of 4-5mm/day) compared to the previous 3 independent drying tests (PE of 14-20mm/day), a similar test was conducted without wind simulation. Using the same

Figure 4.11. Relative evaporation measured from 10cm NS soil columns desiccating under simulated wind and predictions using equation 4.06 for three independent replicate drying experiments.

extrapolation procedure (and coefficients) as the columns drying under simulated wind, predictions of RE using equation 4.06 also gave reasonable agreement with experimental data (Figure 4.12). In fact, the agreement was further improved when slightly lower extrapolation coefficients, a , were used for Regions I and II of the RE versus total suction curve ($a=1.1$ and 1.05), respectively (Figure 4.12).

Figure 4.12. Relative evaporation measured from 10cm NS soil columns desiccating under low evaporative (ambient wind) condition and predictions using equations 4.01 and 4.06. Predictions using equation 4.06 with the same values of “ a ” as the NS soil columns under high evaporative demand (simulated wind) is compared to predictions with $a = 1.1, 1.05, 1.1$).

The soil resistance, R_s , calculated for the 2 replicate drying experiments using a rearrangement of equation 4.03 is expressed as a function of the volumetric water content (VWC) measured in the top 1cm as shown in Figure 4.13. R_s increases with the reduction in VWC in the top 1cm as the NS soil columns dried. This trend is indicative of the increase in the depth to evaporation front as the soil desiccated, and is similar to the data obtained from fast-air circulation chamber for a fine sandy loam soil (Van de Griend and Owe 1994). During Stage I when the soil is saturated and has a high VWC, the evaporation front is right at the surface and R_s is low. Beginning from stage II however, as the soil desaturates, VWC decreases and the depth to evaporation front increases, causing a corresponding increase in R_s .

Figure 4.13. Soil resistance (R_s) calculated for the 10cm NS soil columns as a function of volumetric water content in the top 1cm.

A separate soil column drying test for the LS, S and HS treatments was conducted to characterize the profile total suction in the top 1cm of the 10-cm-thick columns. Profiles of total suction and GWC at 2mm intervals in the top 1cm of the 10cm-thick treated soil columns were determined from samples taken using a spatula. The profile evolution of total suctions in the top 1cm of the LS, S and HS soil columns are presented in Figure 4.14. The profile total suctions for the treated soil columns are linear in shape, with the measured total suctions for the top 1cm samples being representative of the corresponding average values (Figure 4.14). Thus, the total suction data measured in the top 1cm of the treated soil columns were used to predict RE. The exponential correlation (Figure 4.13) was used to calculate R_s for the LS, S and HS soil columns from the corresponding VWC measured in the top 1cm. R_a was back-calculated from the corresponding measured daily PE data. Therefore, RE was predicted from the total suction data along with the calculated R_a and R_s as well as the measured weather data using equation 4.06. The values of RE predicted over the duration of drying were then compared to experimental data for LS, S and HS soil columns.

Figure 4.14. Profiles of total suction within the top 1cm of; (a) LS, (b) S, and (c) HS soil columns. Open symbols are the respective total suctions for the top 1cm of soil columns.

4.3 Results and Discussion

4.3.1 Theoretical Prediction of Evaporative Fluxes from Desiccating Non-saline Soil

Columns: Comparison to Literature

For non-saline soils, several theoretical formulations for predicting evaporative fluxes during the different stages of evaporation exist in literature (Alvenäs and Jansson 1997; Wilson et al. 1997; Newson and Fahey 2003; Armstrong et al. 2008; Fredlund et al. 2011). The intent in the current paper is not to review these procedures, but rather to focus on one of these previous publications that relates directly to the approach proposed for theoretical prediction of fluxes from the NS soil columns in the current work. Fredlund et al. (2011) explored the theory and solutions of 3 different models that predict evaporation based on vapour pressure gradient under either isothermal or non-isothermal conditions. Whether a coupled or uncoupled numerical analysis is required depends on the assumptions made in calculating the vapour pressure at the soil surface (P_{vs}) from the saturation vapour pressure (P_{vo} ; which is a function of the temperature at the soil surface, T_s). For isothermal conditions, T_s is assumed to be the same as the temperature of the air directly overlying the soil (T_a); hence, an uncoupled numerical analysis is undertaken. For non-isothermal analysis, the solution for T_s from the heat flow partial differential equation (PDE) is coupled to the unsaturated flow PDE in order to calculate P_{vs} that is used to compute evaporation.

Apart from T_s , the quantification of total suction (ψ) is also required for the determination of P_{vs} . Fredlund et al. (2011) stressed the need to not ignore the osmotic component of the total suction in computing P_{vs} , which is consistent with the current work of fundamentally understanding the relative contribution of osmotic suction to reduction in vapour pressure gradient. One major similarity between Fredlund et al. (2011) and the current work is the acknowledgement of the need to adjust the suction value used for calculating P_{vs} in order to adequately estimate the total suction “at the surface”. For either coupled or uncoupled analyses, the authors extrapolated the suction value by raising it to an exponential function of an empirical “adjustment factor”. This ensured agreement between theoretical predictions and experimental data of evaporation. This is similar to the extrapolation of total suction measured in the top 1cm to the surface of the NS soil column as done in the current study.

In addition, Fredlund et al. (2011) revisited the Wilson et al. (1997) model (equation 4.01) and identified that for the sand column tested by Wilson (1990), the model over-predicted actual evaporation (AE) for the first 5 days of drying. The over-prediction was attributed to over-estimation of the RH at the surface given the low air-entry value (AEV) of the sand. Hence, the authors suggested that a “surface resistance” to evaporation be accounted for in the case of the sand column in order to better predict P_{vs} . This was again addressed by applying the correction factor, which value was reported to potentially vary for different soils. Hence, the foregoing work is also similar

to the modification of Wilson et al. (1997) model to account for the soil resistance in the desiccating NS soil columns as proposed and validated in the current study.

4.3.2 Desiccating Salinized Soil Columns

4.3.2.1 NaCl and Total Suction Profiles

Figure 4.15 shows the NaCl concentration profiles at various times for the LS, S and HS soil columns. There is a general pattern of NaCl accumulation in the top 1cm of the soil columns, irrespective of the initial pore-water salinity. The magnitude of NaCl build-up in the top 1cm increases with increasing initial pore-water salinity, consistent with evaporation driving advection of ions to the surface. The surface accumulation generally continued until day 11, after which the NaCl concentrations in the top 1cm dropped slightly. This drop in surface concentration has been previously attributed to “back diffusion”, i.e. the surface-accumulated salt creates a steep concentration gradient within the profile that drives diffusive solute transport in the direction opposite to water flow (Elrick et al. 1994; Fujimaki et al. 2006; Fisseha et al. 2010).

As expected, NaCl concentrations at depths were lower compared to the surface, with mass balance calculations confirming mass conservation in all treated soil columns (Figure 4.16). Similar pattern of surface salt accumulation has been previously made for soil and mine tailings in both field and laboratory studies (Newson and Fahey 2003; Fujimaki et al. 2006). The reader is reminded that the NaCl concentration profiles were

Figure 4.15. Profile NaCl concentration over time for Low-saline (a), Saline (b) and Hyper-saline (c) soil columns.

Figure 4.16. Mass balance of the recovery of NaCl in the soil extracts for the Low-saline, Saline and Hyper-saline soil columns.

obtained from the E.C of slurried profile samples. Hence, the concentration profiles represent both dissolved and precipitated mass of NaCl per volume of pore fluid.

The profile evolution of total suction over time for all treated columns is presented in Figure 4.17. The general trend was the development of high total suctions in the top 1-2cm of the soil columns. In the top 1cm, total suction increased rapidly until day 11, 11, and 9 for the LS, S, and HS treatments, respectively, and subsequently decreased by day 14. This pattern is similar to the previous observation from NaCl concentration data. It is interesting that irrespective of the initial pore-water salinity, the maximum total suction values at the top 1cm of soil columns were similar (about 39MPa). The NaCl concentrations exceeded the solubility limit (~370 ppt) by days 11, 5,

Figure 4.17. Profile evolution of total suction over time for Low-saline (a), Saline (b) and Hyper-saline (c) soil columns and for Non-saline soil column on day 14.

and 3 in the LS, S and HS soil columns, respectively. Using a variety of methods (USDA 1954; Robinson and Stokes 1955; Campbell 1985; Abedi-Koupai and Mehdizadeh 2008) to calculate the equivalent osmotic suction from EC or NaCl concentration data, a range of osmotic suctions from 10 to 39 MPa was generated. However, these methods are based upon broad empirical correlations that have limitations at high ionic concentrations. It is likely that the upper limit of total suction observed in the current study was controlled by the solubility limit of NaCl. A maximum value of osmotic suction implies an upper limit to the suppression of evaporation by osmotic effects. Such a limit, irrespective of the initial pore-water solute concentration, has also been observed in mine tailings deposits and saline soil (Newson and Fahey 1997; Fujimaki et al. 2006).

Due to a lower RE in the HS treatment, temporal changes in the total suction profiles at depths below 2cm were generally smaller compared to the LS and S treatments. The final total suction profiles for the non-saline soil columns for all treatments were similar, and with the exception of the top 1cm of the soil columns, the values were small compared to those of the corresponding treated soil columns (Figure 4.17). These suction values for the NS soil are matric since there was no osmotic component to the total suction. The G.W.Cs at the surface of the treated columns on the last day of sampling were high compared to the NS columns (Figure 4.18), corresponding to very low matric suctions as per the SWCC of remoulded samples (Figure 4.06). This implies that the high total suctions in the top 1-2cm of all treated soil columns can be entirely attributed to osmotic suction.

Figure 4.18. Profile gravimetric water content at the end of experiment for Low-saline (LS) and the Non-saline (LS_NS), Saline (S) and the Non-saline (S_NS), and Hyper-saline (HS) and the Non-saline (HS_NS) soil columns.

As secondary evidence, osmotic suctions estimated from the EC data from the treated soil columns using the USDA (1954) equation were on the order of the measured total suction values for the top 1cm (Figure 4.19). In Figure 4.19, estimated osmotic suction exceeding measured total suction (i.e. after day 3 in the HS treatment and after day 11 in the S treatment) is due to re-dissolution of precipitated NaCl prior to EC determination. These values of osmotic suction included contributions from both pore-water solute and precipitated salt. Nevertheless, this pattern is consistent with previous observation regarding the solubility limit of NaCl being exceeded by days 11, 5 and 3 in the top 1cm of the LS, S and HS soil columns, respectively.

Figure 4.19. Osmotic suctions in the top 1cm of treated soil column expressed as a percentage of corresponding total suctions. Osmotic suctions were calculated from the EC of supernatants obtained by dissolving precipitated salts and diluting pore-water solute using the USDA (1954) approximation. Osmotic suction was therefore contributed by both pore-water solute and precipitated salt.

4.3.2.2 Measured and Predicted Evaporation Rates for Desiccating Treated Soil

Columns

The measured and predicted RE for the three salinity treatments, as well as measured values for the non-saline soil columns are presented in Figure 4.20. With the exception of past the first 6 days of drying for the S columns, measured RE for treated soil columns were consistently lower compared to the corresponding NS soil columns. Over the first few days of drying, the magnitude of the difference in RE between the treated and NS soil columns depended on the initial pore-water salinity. For the S and HS treatments, after just 24 hours of drying, RE was reduced to a fraction of the

Figure 4.20. Relative evaporation (RE) measured and predicted for Low-saline (LS), Saline (S) and Hyper-saline (HS) soil columns and measured for corresponding Non-saline soil columns.

corresponding values for the NS soil. In the case of the LS soil column, RE values for the first two days of drying were close to those of the NS soil, but steadily decreased below the latter afterwards. This pattern in RE for different initial pore-water salinities is generally similar to observations for mine tailings made by Fujiyasu and Fahey (2000). Starting from day 7, RE in the S treatment and NS control were both extremely low due to the high evaporative demand during this experiment, as previously mentioned. For the LS and HS soil columns, the RE values for the corresponding NS soil column were higher than the equivalent salinity-treated soil columns throughout the drying period.

RE values predicted from the total suction data were in agreement with values measured experimentally for the LS treatment. This implied that osmotic suction alone explained the reduction in evaporative fluxes observed for the LS soil columns. The shapes of the predicted RE vs. time curves for the S and HS treatments were similar to that of the measured curves during the first two days, although the magnitude of measured RE values were much smaller than predictions. The disparity between the predicted and measured RE values after day 0 and 2 for the S and HS soil columns, respectively, can be attributed to additional contribution (apart from osmotic suction) from salt precipitates to salinity-induced reduction in evaporation. The first visual appearance of salt crust at the top of LS, S and HS columns was on day 9, 3 and 1, respectively. In fact, for both S and HS soil columns, the extent by which RE was over-predicted was observed to increase with salt accumulation per unit cross-sectional area of the top 1cm of soil columns (Figure 4.21). The slope of the correlation between the

extent of over-prediction of RE and amount of accumulated salt for the S treatment was higher compared to the HS soil (Figure 4.21), consistent with the higher evaporative demand for the latter. Also, the predictions of RE for the S and HS soil columns falling until day 5 and 2 and remaining constant afterwards is consistent with the solubility limits of NaCl having being exceeded by day 5 and 3 in the respective soil columns. In other words, once the solubility limit of NaCl was reached, osmotic suction attained a maximum value and no further osmotic-induced reduction in evaporative fluxes occurred. Therefore, additional reduction in evaporation can be attributed to salt precipitation.

It is interesting that over time, profiles of total suction within the top 1 cm of the treated soil columns became more uniform (Figure 4.14), implying that osmotic suction became more uniform, keeping water transport and evaporative fluxes low. The corresponding profile G.W.C data within the top 1cm on day 14 for the treated soil columns were also high (4.84-5.93% for LS; 5.43-6.75% for S; 6.83-7.99% for HS), keeping the contribution from matric suction to total suction relatively low. Thus, for the duration of drying the treated soil columns considered in this study, osmotic suction was the main contributor to reduction in evaporative fluxes up till the solubility limit. Once the solubility limit was exceeded (as in the case with the S and HS soil columns), further reduction in evaporation can be attributed to salt precipitation at the soil surface. Therefore, a combination of osmotic suction and salt precipitates seemed to lock in

moisture within the soil columns and subsequently kept evaporative fluxes low, with the upper limit of contribution from osmotic suction defined by the solubility limit of NaCl.

Figure 4.21. Ratio of predicted to measured Relative Evaporation (RE) plotted against the mass of NaCl precipitated per unit area of the top 1cm of the Saline and Hyper-saline soil columns.

4.3.2.3 Salinized Soil Columns: Comparison of Results with Other Studies

The pattern of prediction of evaporation for the S and HS soil columns is similar to observations by Fujimaki et al. (2006) for loamy sand prepared with various salt solutions. Fujimaki et al. (2006) reported that numerical predictions without accounting for salt crusts consistently over-predicted evaporative fluxes. For the combinations of

soil textures and salt solutions considered, Fujimaki et al. (2006) observed evaporation rates that decreased for 2–4 days and then became relatively constant. They concluded that an increase in osmotic suction alone was not sufficient to explain the reduction in evaporation due to salinity. One difference between the Fujimaki et al. (2006) study and the current study is that in the former, the soil columns were kept nearly saturated throughout the evaporation experiment. This meant that the contribution of matric suction to total suction would have been lower compared to the current study. However, osmotic suctions in the current study were shown to be the main component of total suction and were able to solely explain reduction in fluxes for the first 1-2 days in the S and HS soil columns, similar to observations by Fujimaki et al. (2006).

Nassar and Horton (1999) conducted a soil column evaporation experiment under non-isothermal conditions, considering the effect of compaction and salinity on evaporation and water / solute distributions within the soil profile. Pore-water salinity was observed to reduce cumulative evaporation from soil columns, with evaporation rates decreasing with higher salinity level. This was attributed to salinity lowering the vapour pressure and increasing total suction. The contribution of osmotic suction to reduction in evaporation decreased over time for the upper 5cm of the soil columns, coinciding with solute accumulation for the non-compacted soil columns at the same depth. Also, the GWC at the top of the saline soil columns were generally higher compared to the non-saline soil columns. These observations are generally in line with those in the current study, despite the isothermal conditions for the current study.

The larger extent of over-prediction for the S (compared to the HS) soil columns may be due to the higher evaporative demand during the former. This is in line with observation by Fujiyasu and Fahey (2000) that high evaporative demand increases the extent of reduction in evaporation due to salt precipitation for saline mine tailings deposit. In fact, for the current study, the contribution of salt precipitation to reduction in evaporation for the S soil column is larger compared to HS soil column, as depicted by the higher slope of the correlation plots for S columns in Figure 4.21.

4.3.2.4 Cumulative Evaporation from Treated Soil Columns

Figure 4.22 shows the cumulative AE and PE for the LS, S and HS soil columns. The cumulative AE fell below the cumulative PE, starting from around day 3, 2 and 1 for the LS, S and HS soil column, respectively, with the divergence increasing over time in all cases. The cumulative AE over the entire 14 days of drying was 36, 20 and 17% of the corresponding cumulative PE for the LS, S and HS soil columns, respectively. Similar significant reduction in evaporative fluxes due to salinity has been reported for both soil (Chen 1992; Fujimaki et al. 2006) and mine tailings (Fujiyasu and Fahey 2000; Simms et al. 2007). The higher cumulative evaporation from the S soil column (Figure 4.22) is due to the lower ambient RH during its drying compared to the LS and HS soil columns (Figure 4.04). A repeat experiment where LS, S and HS soil columns were all prepared at an initial GWC of 30% and concurrently dried also gave similar scales of reduction in cumulative evaporation (22, 19 and 10%, respectively) as presented in Appendix A4.

Figure 4.22. Cumulative actual and potential evaporation from Low-saline (a), Saline (b) and Hyper-saline (c) soil columns.

4.3.2.5 Gravimetric Water Content Profiles

The average G.W.Cs in the treated and non-saline soil columns conform to the observed cumulative evaporation rates for each test. Of particular interest is the occurrence of higher G.W.Cs in the top 1 cm than at slightly deeper depths at certain times, including the end of the experiments, for the LS and S soil columns (Figures 4.18 and 4.23). This behaviour may be due to water transport by chemical osmosis that occurs simultaneously with back-diffusion (Barbour and Fredlund 1989) or as a result of osmotic gradient. Scotter (1974) observed an increase in water content at the salinized end of a sealed column of an initially wet soil drying under isothermal conditions, and attributed this to water transport by osmotic effects. This hypothesis is supported by observations in the current study that the LS and S soil columns showed the largest extent of back-diffusion (Figures 4.15 and 4.17).

The overall rate of decline in GWC profiles over time was most rapid for the LS soil columns (Figure 4.23), consistent with its lowest percentage reduction in cumulative AE (Figure 4.22). For all three treatments, the final GWC at all depths were still high (Figure 4.23), the suppression of evaporation due to salinity. The general trend was the soil columns being relatively drier at the surface compared to at depths. It is interesting to observe that the spread in profile GWC within the soil columns generally increased over time and decreased with increasing initial pore-water salinity (Figure 4.23). Therefore, salinity suppressed evaporative fluxes from the treated soil columns, despite the presence of a “reservoir” of water at depths within the soil.

Figure 4.23. Gravimetric water contents over time at different depths of the Low-saline (a), Saline (b) and Hyper-saline (c) soil columns.

4.4 Practical Relevance of Research Findings

The observations on the feedback between solute transport and unsaturated flow from the current paper have both agricultural and geotechnical / geo-environmental implications. This thesis research ultimately seeks to improve current capability for accurate prediction of evaporation in saline thickened mine tailings stacks given the initial and site-specific boundary conditions. Better understanding of the relative contributions from mechanisms by which salinity lowers evaporation, as provided in the current study is the first step in this direction. The accumulation of salts within the crops' rooting zone, as shown in this study, pose a high risk to crop growth under arid or semi-arid agricultural production systems.

In mine tailings management, the goal is to optimize deposition such that the time lag between deposition cycles is long enough to permit strength gain of stacks, but short enough to keep up with turnover of fresh mine tailings. It is generally desirable that tailings stacks have a uniformly drying profile required to provide the bearing capacity needed to ensure the geotechnical stability of a newly-deposited stack. Achieving this goal might be complicated when salts accumulate at the surface and keeps the deeper portions of the stack wet while the top few centimetres appear dry. This is of great consequence especially in arid and semi-arid areas where a combination of hyper-saline tailings storages and high evaporative demand (Newson and Fahey 1997; Fujiyasu and Fahey 2000) makes site closure, reclamation and rehabilitation difficult.

On a positive note, in the case of sulphide-mineral containing mine tailings, the accumulation of salts at the surface may restrict oxidation to the top few centimetres of the stack, thereby reducing the risk for acid mine drainage from disposal sites. Finally, observation from the current study that up till the solubility limit, osmotic suction alone can explain the reduction in evaporation due to salinity is significant. This implies that numerical modeling of evaporation from saline soil and mine tailings should account for the temporal increases in osmotic suction during desiccation.

4.5 Summary and Conclusion

Irrespective of the initial pore-water salinity of the soil, there was surface salt accumulation and similar maximum total suctions were measured in the top 1cm of treated columns. This is likely due to solubility limit on the maximum pore-water solute concentration, which may define the upper limit of suppression of evaporation by osmotic suction. While it was expected that matric suctions would continue to increase with evaporation, and therefore higher total suctions would be observed past the onset of salt precipitation, this did not in fact occur. Under the isothermal conditions of the current study and with effects of albedo exempted, osmotic suction was mainly responsible for the reduction in evaporative fluxes due to pore-water salinity up till the solubility limit of NaCl. Past the solubility limit, additional reduction in evaporative fluxes was attributable to salt precipitation changing the hydraulic properties of the soil. Therefore, the accuracy of predictions of evaporative fluxes in saline soil and mine

tailings is expected to be improved when the temporal increase in osmotic suction due to surface salt accumulation is accounted for. Future research considering the effects of non-isothermal conditions, wet-dry-wet cycles and inter-layer transfer of water on solute transport and associated reduction in evaporative fluxes is warranted.

CHAPTER 5: PREDICTING SALINITY-INDUCED REDUCTION IN EVAPORATIVE DENSIFICATION OF SILT AND THICKENED MINE TAILINGS

ABSTRACT: The capacity of current unsaturated flow codes to accurately predict evaporative fluxes from saline soil and mine tailings deposits is undermined by pore-water salinity. Presented are results from a laboratory column study relating 1D solute transport to evaporation in soil prepared with 10% NaCl solution and acid-generating thickened tailings both desiccating under ambient (AW) and simulated (SW) wind conditions. Replicate soil and tailings columns were left to desiccate for 14 days and profiles of electrical conductivity, salt concentration, gravimetric water content and total suctions were obtained at 1cm intervals of 10cm-high columns and related to measured evaporative fluxes. Salt accumulation was observed in the top 1cm of both soil and tailings columns, with the rate of drying and salt accumulation higher for the SW compared to the AW column. The maximum total suction observed for the AW and SW soil columns was similar, likely limited by the solubility limit of NaCl. Osmotic suction was the main component of measured total suction in all columns, and was sufficient in explaining reductions in evaporation up to the solubility limit, with further reduction attributed to salt precipitation. Numerical predictions of cumulative evaporation, total suction and profile gravimetric water content using a commercial 1D unsaturated flow code that accounted for temporal increase in osmotic suction at the surface generally agreed well with experimental data.

5.1 Introduction

Many researchers and practitioners in the fields of agriculture, hydrology, geo-environmental and geotechnical engineering routinely use numerical methods to predict evaporation from soil and mine tailings. The end goals may be diverse, ranging from irrigation planning (Kandelous and Šimůnek 2010) to regional water budgeting, as well as from tailings deposition planning (Fujiyasu et al. 2000; Simms et al. 2007) to slope stability analyses (Rassam and Williams 1999a). While the numerical prediction of evaporative fluxes from non-saline soil or mine tailings is relatively straightforward, predictions for saline soil and mine tailings is complicated by the effect of salinity (Gran et al. 2011). In most cases, for saline soil and mine tailings, numerical predictions of evaporation begin to significantly diverge from observations following salt precipitation at the surface (Fujimaki et al. 2006; Simms et al. 2007; Fisseha et al. 2010).

The mechanisms by which salinity reduces evaporation from soil (albedo, salt precipitation and osmotic suction) are well documented in literature (Chen 1992; Newson and Fahey 1997; Fujiyasu and Fahey 2000; Fujimaki et al. 2003; Simms et al. 2007). However, the extent to which each or a combination of these mechanisms contributes to reduction in evaporation from saline soil or mine tailings is not well understood. A better understanding of the relative contributions from these mechanisms is important for improving numerical prediction of evaporation from saline

soil and tailings. Considerable focus in literature has been on improving the prediction of evaporation from saline soil and mine tailings.

Yakirevich (1997) presented a 1D numerical model that couples moisture flow and heat transport to an atmospheric boundary layer model at the surface to predict evaporation from an enclosed saline soil with a thermal gradient applied at the ends. The model accounted for osmotic suction in solving the moisture flow equation assuming non-isothermal conditions, and without considering the effects of albedo and salt precipitation. Prediction of water flow and solute transport showed sufficient agreement with experimental data, except at the cold ends of the sealed saline soil columns. When the model was tested for an evaporating saline soil using synthetic soil parameters, cumulative evaporation was found to be inversely correlated to the initial osmotic suction. However, the model was not validated with experimental data to test how well it can predict evaporative fluxes from saline soil under evaporative top boundary conditions.

Unlike Yakirevich et al. (1997), Fujimaki et al. (2006) incorporated the effect of salt precipitation in predicting evaporation from salinized loamy sand and sand columns drying under isothermal conditions. The matric suction at the surface of the drying soil columns was kept low by keeping the soil columns wet by means of a constant head of NaCl or KCl solution applied through the base. The bulk transfer equation was modified

to include an additional salt crust resistance term (R_{sc}) and used to predict evaporation from the soil columns. It was observed that evaporation rates from the soil columns were substantially over-predicted when R_{sc} was ignored. Although better prediction of evaporation was obtained with the inclusion of R_{sc} , the model still over-predicted fluxes, especially for the loamy sand column treated with KCl solution. Also, the model was not evaluated for the common case of evaporation under net water deficit.

Fisseha et al. (2010) conducted laboratory-scale multi-layer drying tests on acid-generating mine tailings under isothermal and ambient radiation conditions. Crack formation, matric suction, gravimetric water content (GWC) and osmotic suction were measured alongside evaporation rates during the experiment. Two numerical codes that simulate liquid water and water vapour fluxes under either isothermal or non-isothermal condition were used to predict evaporation. Predictions of evaporation were in agreement with measured values prior to rewetting the second layer of tailings, after which the numerical codes consistently over-predicted fluxes. This was attributed to salinity shutting down evaporation. The authors underscored the need for future framework to incorporate solute transport and salt precipitation into numerical predictions of evaporation from surface-deposited mine tailings.

Based on the foregoing, better understanding of the relative contributions of the mechanisms of salinity-induced reduction in evaporation is warranted, with the goal of

improving current capability for numerical prediction in saline soil and mine tailings. Hence, the current paper characterized the 1D solute transport in desiccating saline soil and mine tailings, and related this to observed evaporative fluxes. The empirical model of Wilson et al. (1997) was modified and used to evaluate the relative contribution of osmotic suction and salt precipitation to observed reduction in evaporative fluxes. Based on experimental observations, a numerical framework that accounts for the temporal increase in osmotic suction in predicting evaporative fluxes from desiccating saline soil and mine tailings is proposed. Using a commercial 1D finite element unsaturated flow code, the numerical framework was implemented and evaluated. Some discussion of the practical relevance of the findings from this paper is provided at the end.

5.2 Background Theory of Evaporation from Soil and Mine Tailings

The rate of evaporation from soil or mine tailings is driven by the vapour pressure gradient at the soil-atmosphere boundary. The vapour pressure is related to the relative humidity (RH) at the soil surface, which is in turn a function of the total suction at the soil or tailings surface according to the thermodynamic relationship (Eldefsen and Anderson 1943) given as:

$$RH = e^{-\frac{\psi g w_v}{RT}} \quad (5.01)$$

Where ψ is the total suction at the soil surface (m); g is the gravitational acceleration (m/s^2); W_v is the molecular weight of water vapour (0.018016 kg/mole); R is the universal gas constant (8.314 J/mole.K); and T is the absolute temperature (K).

Evaporation from soil or tailings proceeds in 3 stages, starting with Stage I when evaporation from saturated material occurs at the potential rate, and is controlled only by climatic conditions. Stage II begins when the soil is sufficiently desaturated such that evaporation rate begins to fall below the potential rate (PE) and evaporation rate becomes a function of both climatic conditions and material properties. A new equilibrium between the soil and atmospheric conditions is eventually reached (Stage III) whereby evaporative fluxes stay low and constant (Gray 1970; Wilson et al. 1994).

Wilson et al. (1997) proposed an empirical model that relates relative evaporation, RE (actual evaporation / potential evaporation) to the total suction at the soil surface, given as:

$$RE = \frac{AE}{PE} = \left[\frac{e^{-\left(\frac{\psi g W_v}{RT}\right)} - h_a}{1 - h_a} \right] \quad (5.02)$$

Where h_a = relative humidity of the air above soil or tailings surface (expressed as a fraction) and all other parameters as previously defined in equation 5.01. Based on the

fit of equation 5.02 to experimental data, RE was found to be approximately 1 during Stage I, declined rapidly during Stage II until the soil reached Stage III when it stayed low and constant (Wilson et al. 1997). The model was validated for thin samples (thicknesses of between 0.2 and 0.7mm) of sand, silt and clay soils under constant ambient temperature and RH, and was shown to be independent of the water content and particle size distribution of the soil.

Apart from predicting evaporation from the total suction at the soil surface, evaporation from unsaturated soil has also been predicted using the soil resistance to water transport (Camillo and Gurney 1986; Van de Griend and Owe 1994; Bittelli et al. 2008). This approach identifies two types of resistances that control the gradient in vapour pressure at the soil-atmosphere interface. The efficiency with which water vapour is transported away from the evaporating surface is depicted as aerodynamic resistance (R_a), which is a function of the wind velocity and surface roughness (Gray 1970; Wilson et al. 1994). The soil resistance, R_s , describes the efficiency with which water vapour diffuses from the evaporation front, through the soil matrix, to the evaporating surface, and varies inversely with water content. A number of empirical equations have been proposed expressing R_s as various functions of the soil water content (Camillo and Gurney 1986; Kondo et al. 1990; Van de Griend and Owe 1994). The computed value of R_s is then combined with the corresponding value of R_a in order to estimate evaporation from soil.

5.3 Materials and Methods

5.3.1 Test Materials and Preparation of Soil and Tailings Columns

The materials tested in this paper are 25-50 micron silt-sized spherical glass beads (Potter Industries Inc. LaPrairie, QC, Canada) and dewatered gold mine tailings received in 2006 from Bulyhanhulu gold mine in Tanzania. The silt and mine tailings were chosen as candidate materials for testing due to their similar geotechnical properties (Table 5.01) and particle-size distributions (Figure 5.01). The soil water characteristic curves (SWCC) for the silt and mine tailings, as determined by axis-translation technique in a pressure-plate apparatus, are also similar (Figure 5.02). The solid-phase and pore-water composition of the mine tailings is detailed in Fisseha et al. (2010). Wax column moulds were prepared from molten mixture of 1 part (by mass) of petroleum jelly and 2.5 parts of paraffin wax following the procedure of Khasawneh and Solileau (1969). The wax column mould is shown in Figure 5.03, with a cylindrical cavity that was used to pack, dry and destructively sample the test soil and mine tailings at 1cm intervals.

The test soil was prepared with 10% NaCl solution (mass of salt/mass of solution) to an initial gravimetric water content (GWC) of 33% (mass of solution / mass of dry silt) and thoroughly homogenized using a mechanical mixer. Alternately expressed as mass of water per unit mass of dry silt, the initial GWC of the salinized silt was 29.7%. The salinized soil slurry was packed in the 12cm-high wax columns (Figure 5.03), but would

Table 5.01. Geotechnical properties of mine tailings and silt tested

Parameter	Mine Tailings	Silt
Specific Gravity	2.9	2.48
D ₁₀ , D ₅₀ , D ₆₀ (microns)	2, 35, 55	1, 31, 41
Cu (D ₆₀ /D ₁₀)	27.5	41
Liquid limit (%)	20	19
Plastic limit (%)	19	13
Saturated hydraulic conductivity (m/s)*	2.0E-7	1.7E-6

*Saturated hydraulic conductivity values were determined by falling head tests at void ratio of 0.8 as per Fisseha et al. (2007) and Fisseha et al. (2010).

Figure 5.01. Particle size distributions of silt (determined by hydrometer method) and mine tailings (determined by hydrometer and sieve analyses).

Figure 5.02. Soil water characteristic curves (SWCC) for silt and mine tailings obtained using the axis-translation technique in a pressure plate apparatus. (See Sections 2.10.2.2 and 3.3.9 for more details).

settle within a few hours after packing to about 10cm. The mine tailings was pumped at the mine site at a GWC of 38%, but would settle during shipping to the laboratory. The mine tailings was shipped in sealed plastic containers kept and covered with process water inside 5-gallon plastic buckets to prevent evaporation and oxidation of constituent sulphide minerals during transit. Hence, prior to packing the mine tailings inside the wax columns, it was mechanically homogenized to the initial pumping GWC using the bleed water contained inside the sealed plastic container alone. Similar to the salinized soil, the mine tailings was packed in 12cm-high wax columns, but would also settle within a few hours of packing to about 10cm. Immediately after packing, the wax columns for both salinized soil and mine tailings were gently tapped three times on a work bench to ensure uniform packing and eliminate any entrapped air pockets.

5.3.2 Experimental Conditions, Column Sampling and Sample Analyses

All the salinized soil and mine tailings column drying experiments were conducted under laboratory conditions, with ambient lighting to exclude the effect of albedo on evaporation rate. Two contrasting top boundary conditions were imposed on the soil and tailings columns: ambient wind (AW) with no oscillating fan to drive evaporation, and simulated wind (SW) with an oscillating fan to drive evaporation from the columns. This resulted in difference in evaporative demand for the AW and SW columns, with the potential evaporation (PE) rates of between 3-6 and 12-20 mm/day measured for the columns dried under the respective boundary condition. The AW and SW column drying experiments for each of the soil and mine tailings were conducted in sequence. The bottom boundary condition for all soil and tailings columns was a no-flow boundary. The ambient temperature and relative humidity (RH) throughout the column drying experiments were recorded by means of a USB-502 RH/Temperature Data Logger (Measurement Computing, Norton, MA). The ambient temperature and RH data are presented in Figure 5.04.

A number of replicate columns (9) were prepared at the beginning of each column desiccation experiment, with the initial mass of each replicate column recorded. The columns were left to desiccate for 14 days under the specified boundary conditions. For each batch of desiccation experiment, a similar wax column, filled with distilled water was also set up for PE determination. One replicate soil or tailings column was destructively sampled at pre-determined intervals after the mass of the column had

been measured to calculate daily actual evaporation (AE) rate. The columns were destructively sampled by obtaining 1cm-thick soil or tailings sections with the aid of an adjustable hacksaw and a Jobmate plastic mitre box used as guide to ensure uniform slices. The profile soil or tailings samples were kept inside sealable Ziploc bags and manually homogenized prior to taking subsamples for analyses. Hence, the parameters determined for each profile depth would represent the average for the respective 1cm depth. Special caution was taken to prevent cross contamination of samples when sampling the soil or tailings columns.

Figure 5.03. Schematic diagram of wax column used for packing, drying and destructively sampling salinized silt and acid-generating mine tailings.

Figure 5.04 Ambient temperature (Temp) and relative humidity (RH) during desiccation of salinized soil and acid-generating thickened mine tailings under ambient (AW) and simulated (SW) wind boundary conditions.

For both the salinized soil and tailings, the gravimetric water content (GWC), electrical conductivity (EC) and total suction of the profile samples were determined

immediately after destructive sampling. GWC was determined by mass difference after placement of samples in oven at 105°C over a period of 24 hours. EC analysis was conducted on the supernatant obtained from agitating a 1:5 (sample: sample + de-ionized water) slurry using an orbital shaker (Speed - 175rpm; duration - 30 minutes), followed by centrifugation at 3000rpm ($1000 \times g$) for 2.5 minutes. The EC of resulting supernatant was determined by means of a previously-calibrated Traceable Conductivity Meter (VWR International, Friendswood, TX). Total suction (matric + osmotic suctions) analysis was conducted on profile samples using a WP4-T Dewpoint Potential Meter (Decagon Devices Inc., Pullman, WA). For the salinized soil columns, NaCl concentrations of sample extracts were estimated from the corresponding EC value using a calibration curve (Figure 5.05) previously obtained for standard NaCl solutions (Fisher Scientific, Ottawa ON). The profile NaCl concentrations are reported as mass of solute per volume of pore solution (as parts per thousand, ppt), after accounting for the dilution of the pore solution during sample extraction. It is to be noted that as NaCl concentrations were calculated using the EC of the soil extracts, value obtained would include both the pore-solution NaCl as well as the salt that may have precipitated out of the pore solution, which was re-dissolved.

5.3.3 Measurement and Prediction of Evaporation from Desiccating Salinized Soil and Mine Tailings Columns

The daily AE from replicate soil or tailings columns was determined by mass difference over a period of 24 hours. The corresponding PE was concurrently

determined from identical wax columns filled with distilled water. The Wilson equation (equation 5.02) was tested in 10cm-high non-saline (NS) silt columns, similarly prepared as the salinized soil columns, but with the silt mixed with distilled water to an initial GWC of 30%. This initial GWC was chosen to match the initial value of the salinized soil (expressed in terms of percent water per dry silt). Daily RE values from the NS soil columns were determined over a period of 14 days, and total suction data in the top 1cm of the soil columns was obtained as previously described. RE values were then predicted from the total suction and weather data obtained during the desiccation experiment using equation 5.02. The Wilson et al. (1997) model was derived based on the premise that the temperatures at the surface of evaporating water and soil, as well as the directly-overlying air are approximately the same. This assumption was validated for the desiccating NS soil columns (Appendix A1). A comparison of experimental and

Figure 5.05. Calibration curve of NaCl concentration against electrical conductivity (EC) for NaCl standard solutions.

predicted values of RE for three independent trial experiments (Figure 5.06) showed no agreement between observations and predictions. Even when the total suction data measured in the top 2mm of the desiccating soil columns in one of the independent trials was used to predict RE, there was still no agreement between predictions and observations (Appendix A3). Equation 5.02 was proposed and validated by Wilson et al. (1997) for thicknesses of clay, silt and sand ranging from 0.2 to 0.7mm desiccating under controlled temperature and RH. The main objective in Wilson et al. (1997) was to define a property at the “soil surface” that controlled evaporation, hence the choice of extremely thin soil samples. Thus, the influence of any other soil property below the soil surface on the rate at which water is supplied to satisfy evaporative demand was deliberately excluded.

The non-fit of the data by Wilson et al. (1997) model was addressed by conducting three independent trial experiments for the NS soil using samples of 2mm thickness desiccating under simulated wind. Each trial consisted of several replicate samples of the NS soil prepared at an initial GWC of 30% drying inside sampling cups (1.5cm high and 4.2cm i.d) for a duration of 4 hours. The AE from the desiccating soils samples was calculated from change in mass of the replicate soil samples, with the PE concurrently determined from change in mass of similar sample cup containing distilled water. RE was then calculated from corresponding AE and PE values. Immediately following the determination of AE from a replicate soil sample, its total suction was measured using the WP4-T total suction device. Ambient temperature and RH were also

Figure 5.06. Relative evaporation (RE) measured from 10cm-high Non-saline (NS) soil columns and predictions from total suction in the top 1cm of desiccating column using equation 5.02. Results shown are for three independent trial experiments.

measured during the desiccation experiment, and used along with total suction data to predict RE using equation 5.02. Better agreement between predictions and experimental values of RE was obtained for the 2mm-thick NS soil (Figure 5.07) in comparison to the predictions obtained from total suction values measured in the top 1cm or 2mm of the 10cm-high NS soil columns (Figure 5.06 and Appendix A3). It was then inferred from the foregoing that apart from total suction at the NS soil surface, another soil property below the surface was influencing surface evaporation for the 10 cm-high NS soil columns.

Starting from stage II, the rate of evaporation is known to be controlled by the diffusion of water vapour from the evaporation front to the soil surface (Van de Griend and Owe 1994). The thin samples tested in Wilson et al. (1997) and the 2mm-thick samples tested in the current paper were sufficiently thin for the evaporation front to be located close to the soil surface, and the distance over which water vapour diffusion would take place was negligible. Thus, total suction at the soil surface mainly controlled evaporative fluxes for the 2mm samples in this paper and the samples tested in Wilson et al. (1997). The desiccating 10cm-high NS soil columns tested in this paper would have the evaporation front recede deeper within the profile over time, increasing the resistance of the soil to water vapour diffusion to the soil surface. Thus, for the 10cm-high soil columns, soil resistance to water vapour diffusion would influence the rate of evaporation, in addition to total suction at the soil surface. As a result, Wilson et al.

Figure 5.07. Relative evaporation measured from 2mm-thick NS soil samples and predictions from total suction using equation 5.02. Results of 3 independent trial drying experiments are shown.

(1997) model would be applicable to the 10cm-high NS soil columns only if the effect of soil resistance to water vapour transport to the soil surface is accounted for.

A supplemental desiccation experiment was conducted for the 10cm-high NS soil columns to profile the total suction at 2mm intervals in the top 1cm of the columns. Using a spatula, samples at 2mm intervals were obtained for the NS soil columns desiccating over 14 days, and the total suctions were determined as previously described. Temporal profiles of total suctions obtained generally showed a curvilinear shape (Figure 5.08). Thus, the total suction at the soil surface would be expected to be higher than the corresponding average values determined for bulk sample obtained in the top 1cm of the soil column. Consequently, an approximation of the total suction at the soil surface was undertaken by extrapolation of the value measured for the bulk sample obtained in the top 1cm of the soil columns. A series of trendlines fitted to Figure 5.08 revealed that a power function gave the best correlation with R^2 values of between 0.89 and 0.98 (Appendix A2). From the curves of experimental RE and total suctions measured for the bulk sample in the top 1cm of the soil columns (Figure 5.09), three regions were delineated as follows:

$0 < \psi < 3000$ kPa; Region 1

$3000 < \psi < 15000$ kPa; Region 2

$\psi > 15000$ kPa; Region 3

Where ψ is the total suction measured for the bulk sample obtained in the top 1cm of the NS soil column.

Figure 5.08. Temporal profiles of total suction at 2mm intervals of the top 1cm of the 10cm-high NS soil columns. Symbols at the 0mm mark on the depth axis are the total suctions extrapolated to the surface of columns from the total suction of the bulk sample in the top 1cm using equation 5.03.

Thus, an extrapolation function is defined for estimating the total suction at the surface of the soil column (ψ_e) from the total suction measured for the bulk sample in the top 1cm (ψ) as:

$$\psi_e = \psi^a \quad (5.03)$$

Where “a” is an extrapolation coefficient based on the region under the RE versus total suction curve (Figure 5.09), specified as:

$a=1.35$, 1.2 , and 1.1 for Region I, II, and III, respectively. Using this extrapolation procedure to obtain approximate total suctions at the soil surface gave reasonable values relative to the profiles of total suctions measured at 2mm intervals within the top 1cm of the NS soil columns (Figure 5.08).

Figure 5.09. Relative evaporation measured for the 10cm-high NS soil columns as a function of the total suctions for the bulk sample obtained in the top 1cm. Results shown for 2 independent drying experiments.

According to the bulk transfer equation (Noborio et al. 1996; Bittelli et al. 2008), the AE from a non-saline soil is given as:

$$AE = \frac{P_{sv} (RH_s - RH_a)}{Ra + R_s} \quad (5.04)$$

Where P_{sv} is the saturation vapour pressure at a given temperature (kPa); RH_s is the RH of soil pore air given by the thermodynamic equation as a function of total suction (equation 5.01); RH_a is the RH of the air above the soil surface; Ra is the aerodynamic resistance (day/mm) which is a function of the wind profile and surface roughness (Wilson et al. 1994) and can be backcalculated from PE (Fujiyasu and Fahey 2000) using:

$$Ra = \frac{P_{sv} (1 - RH_a)}{PE} \quad (5.05)$$

By re-arranging equation 5.05 to define PE and defining RE from AE (equation 5.04) and PE, we have:

$$RE = \frac{AE}{PE} = \left[\frac{(RH_s - RH_a)}{(1 - RH_a)} \right] \left[\frac{1}{\left(1 + \frac{R_s}{Ra}\right)} \right] \quad (5.06)$$

The first portion of the right hand part of equation 5.06 is the same as the Wilson et al. (1997) model given in equation 5.02, with RH_s defined as per equation 5.01. Thus, equation 5.06 incorporates the soil resistance to water vapour diffusion in

defining RE for the soil columns, in addition to the total suction at the soil surface. Equation 5.06 was then used to re-calculate the RE for the desiccating 10cm-high NS soil columns. R_a and R_s were back-calculated from the measured values of PE (from equation 5.05) and AE (from equation 5.04), respectively. Total suctions at the soil surface were estimated from values measured for the bulk sample in the top 1cm using equation 5.03 as previously described. The predictions of RE obtained using equation 5.06 agreed well with experimental data for all 3 independent column drying experiments as shown in Figure 5.10. The validity of equation 5.06 was further tested for 10cm-thick NS soil columns drying under a much lower evaporative demand. The columns were prepared similar to the 3 previous tests (with high evaporative demands- PE of 14-20mm/day) but allowed to desiccate under low evaporative demand (no wind was simulated, hence PE of only 4-5mm/day). The same extrapolation procedure (and coefficients) was used as the high PE columns, resulting in predictions of RE that agreed well with laboratory data (Figure 5.11). Using slightly different values of "a" ($a=1.1$ and 1.05 for Region I and II in the RE versus total suction curve, respectively) for the soil columns desiccating under low evaporative demand even gave better agreement with experimental observations (Figure 5.11).

The soil resistance (R_s) calculated for replicate drying experiments 1 and 3 using equation 5.04 is expressed in Figure 5.12 as a function of the volumetric water content (VWC) measured for bulk samples in the top 1cm of the NS soil columns. R_s is shown to exponentially increase with reductions in VWC as the soil columns desiccated. This

Figure 5.10. Relative evaporation measured from desiccating 10cm-high NS soil columns and predictions using equation 5.06 for three independent replicate drying experiments.

Figure 5.11. Relative evaporation measured from 10cm NS soil columns desiccating under low evaporative demand (ambient wind-PE=4-5mm/day) and predictions using equations 5.02 and 5.06. Predictions using the same extrapolation coefficients ($a=1.35, 1.2, 1.1$) as the soil columns desiccating under high evaporative demand (simulated wind) are compared to predictions using values of $a=1.1, 1.05, 1.1$ for Stage I, II and III evaporation, respectively.

pattern indicated that the depth to evaporation front increased as the soil dried, causing R_s to increase. Previous authors have proposed empirical equations describing R_s as linear (Camillo and Gurney 1986); power (Fen Sun 1982) or exponential (Van de Griend and Owe 1994) function of VWC. Bittelli et al. (2008) evaluated these empirical relationships and concluded that the exponential equation gave the best fit to experimental data given that it implies an upper limit for the R_s value at the soil's

residual water content. The exponential relationship between R_s and VWC as shown in Figure 5.12 is similar to the empirical curve fitted to data obtained by Van de Griend and Owe (1994) for a desiccating fine sandy loam using a fast-air circulation chamber. This exponential relationship was used to calculate R_s for the salinized soil and tailings columns from the corresponding VWC data determined for bulk sample obtained in the top 1cm. Also, for each replicate salinized soil and tailings column sampled during the desiccation experiment, R_a was back-calculated from the measured daily PE.

Figure 5.12. Soil resistance (R_s) calculated for the 10cm NS soil columns as a function of the volumetric water content measured for the top 1cm bulk sample.

Similar to the NS soil columns, a separate drying column test was conducted for the salinized soil and tailings in order to characterize the profiles of total suction in the

top 1cm over time. Total suctions of profile samples obtained at 2mm intervals of the salinized soil and tailings columns were determined, and the results are shown in Figure 5.13. The profiles of total suction for both the salinized soil and the tailings were generally linear in shape. Also, with the exception of day 12 for the tailings columns, the total suction measured for the bulk top 1cm sample was representative of the respective average total suctions (Figure 5.13). Therefore, the total suction values of the bulk top 1cm samples were used to predict RE for both the salinized soil and tailings columns. The values of R_a , R_s , total suction and weather data obtained throughout the 14 days of drying the salinized soil and tailings columns were used to predict RE using equation 5.06. The predicted values of RE were thereafter compared to experimental data over the 14-day period of the desiccation experiment.

5.3.4 Numerical Modeling of Evaporation from Desiccating Salinized Soil and Tailings Columns

Evaporative fluxes from the salinized soil and tailings columns were modelled with a 1D Finite Element code, SVFlux, a commercial product from SoilVision Systems Ltd (Saskatoon, SK). The numerical algorithm solves the governing partial differential equation (PDE) for the 1D flux of both liquid water and water vapor under isothermal conditions given as:

$$\frac{\partial}{\partial z} \left[(K^w(\psi) + K^v(\psi)) \frac{\partial h}{\partial z} - K^v(\psi) \right] = -\gamma m^w \frac{\partial h}{\partial t} \quad (5.07)$$

Figure 5.13. Temporal profiles of total suctions at 2mm intervals in the top 1cm of the desiccating salinized soil and tailings columns. Data at the 10mm depth axis are corresponding total suction measured for the bulk sample obtained in the top 1cm of column.

Where z is the elevation (m) above a datum; $K^w(\psi)$ is the hydraulic conductivity (m/s) as a function of matric suction, ψ (kPa); h is the hydraulic head (m); $K^v(\psi)$ is pore-water vapour conductivity in the air phase as a function of matric suction; γ is the unit weight of water; t is time (s); and m^w is the derivative of the soil water characteristic curve (SWCC) with respect to matric suction or the derivative of consolidation curve with respect to positive pore-water pressure.

In modeling the tailings columns, $K^w(\psi)$ was estimated with the indirect method of Mualem-Van Genuchten (Van Genuchten 1980) using the drying SWCC that accounted for the shrinkage of the tailings as per Fisseha et al. (2010). The estimated $K^w(\psi)$ and saturated hydraulic conductivity (K_{sat}) of the tailings (Table 5.01) were input into SVFlux, which is presented as relative hydraulic conductivity function in Appendix B1. The $K^w(\psi)$ for the salinized soil columns was automatically estimated by the numerical code from the input K_{sat} (Table 5.01) and drying SWCC (Figure 5.02) using the Fredlund and Xing (1994) equation. $K^v(\psi)$ is a function of the molecular diffusivity of water vapor in air (D^v) and the tortuosity factor (α) of the soil. SVFlux computes D^v using the equation in Kimball et al. (1976) and assumes value of α after Ebrahimi-B et al. (2004). The initial settling by the tailings and soil was accounted for in the numerical code by following the procedure in Fisseha et al. (2010): an average initial positive pore-water pressure of 3kPa and m^w value (equation 1) of 0.03 kPa^{-1} was specified for simulating the tailings columns. For the salinized soil columns, 2kPa and 0.024 kPa^{-1} were chosen for the initial pore-water pressure and m^w , respectively. Specifying an initial positive

pore-water pressure in the simulations forces the model to generate an equivalent mass of bleed water resulting from settling.

The numerical code has an in-built capacity for adaptive time stepping as well as automatic mesh generation and refinement. However, an initial time step of 30 minutes and mesh size of 0.001m was specified for all simulations. The geometry of the soil and tailings columns was specified as per Figure 5.03. Climatic and zero flux boundary condition was specified at the top and bottom of the soil and tailings columns, respectively. The climatic boundary condition was specified in the code by the Wilson et al. (1997) model (equation 5.02), with evaporative flux being a function of the modelled total suction at the soil or tailings surface. For the coupled soil-atmospheric numerical model (SVFlux), the steep total suction gradient created at the soil surface by the vaporization of liquid water is accounted for by a surface suction correction factor. SVFlux implements this correction factor by raising the suction originally modelled by solving the unsaturated flow PDE (Equation 5.07) to an exponential function, given by Fredlund et al. (2011) as:

$$\psi_a = \psi_o \times 10^{-c} \quad (5.08)$$

Where ψ_a is the adjusted suction that is used by SVFlux in equation 5.02; ψ_o is the original suction value obtained from the numerical solution of equation 5.07; and c is the correction factor.

This surface suction correction is implemented in SVFlux in order to ensure numerical stability and improve the agreement between numerical solutions of evaporative fluxes and experimental data (Fredlund et al. 2011). The values of ' c ' ranges from 0 to -2 in SVFlux and is expected to be dependent on the type of soil being analysed with coarse-grained soils having the most negative value (Fredlund et al. 2011). The correction factor chosen for modeling both the salinized soil and tailings columns was -0.5 and -0.65 for the AW and SW boundary conditions, respectively. These values gave the closest fit between predictions of evaporative fluxes and experimental observations for both the soil and tailings columns. Predictions from SVFlux using the correction factor was undertaken for one of the three independent drying experiments for the Non-saline silt columns with data previously presented in Figures 5.10. Figure 5.14 shows similarity between RE predictions from SVFlux and predictions using the Wilson + Soil resistance approach (equation 5.06) as previously described. The slight under-prediction of RE by SVFlux starting from around day 2 results from the application of the correction factor (c in equation 5.08) to total suctions modelled at the surface by SVFlux. As shown in Figure 5.15, the total suctions at the surface of the soil columns predicted by SVFlux is comparable to the values extrapolated from measurements for the bulk top 1cm (using equation 5.03). However, the application of the correction

factor to the former by SVFlux in computing RE resulted in substantially higher values of total suction, thereby causing predictions of RE to be slightly lower.

Figure 5.14. RE measurements from NS soil columns desiccating under SW and predictions by SVFlux and using Wilson et al. + Soil Resistance model (equation 5.06).

The numerical code calculates the daily AE from the columns from input daily PE, weather data measured from the respective AW and SW laboratory column drying experiment and modelled total suction at the surface. The osmotic suctions in the top 1cm of the salinized soil and tailings columns over time, estimated from the measured EC data using the USDA (1954) approximation, was also input into the numerical code. In order to account for the maximum contribution of osmotic suction to total suction for

Figure 5.15. Total suctions measured for the bulk top 1cm of NS SW soil column and extrapolated to the surface using equation 5.03 and corresponding predictions of total suctions at the surface by SVFlux prior and after the “c” parameter was applied. Values are presented in logarithm (a) and linear (b) scales.

the salinized soil columns, the osmotic suction at which estimated NaCl concentration reaches the solubility limit was set as the peak value for the remaining days in the

simulation. In the case of the tailings columns, the calculated osmotic suction when the EC started to decrease after sustained increase in EC was set as the upper limit of osmotic suction and maintained the same for each of the remaining days of the simulation. This maximum EC for the desiccating tailings was chosen as a proxy for the point where the pore-water solute saturation concentration had been reached. The simulation was run for 14 days for both the salinized soil and tailings columns desiccating under AW and SW top boundary conditions. An alternate simulation for each of the salinized soil and tailings columns was set up for the AW and SW boundary conditions, but without the inclusion of temporal values of osmotic suction over the duration of the desiccation. As previously mentioned, the parameters measured for each profile depth for the soil and tailings columns represents the average value for the depth. Therefore, the average of the numerical solutions of GWC at x and $x-1$ centimetres were taken for each depth (e.g. the value of GWC at 5cm depth was obtained as the average of GWC at 4 and 5cm). Numerical predictions of cumulative evaporation and profile GWC were compared to corresponding laboratory measurements.

5.4 Results and Discussion

5.4.1 Profile Pore-water Solute Transport in Desiccating Soil and Tailings Columns

The profiles of NaCl concentrations for the salinized soil columns under AW and SW boundary conditions are presented in Figure 5.16. Salt rapidly accumulated in the

top 1cm of the soil columns under both AW and SW boundary conditions, with a higher rate and magnitude of accumulation observed in the latter. This pattern is consistent with the higher evaporative demand for the SW boundary condition translating into faster rate of advective transport of pore-water solute. While the NaCl in the top 1cm continued to increase until the last day of drying for the AW soil columns, concentration peaked on day 11, and slightly declined on day 14 for the SW columns. This drop in salt concentration may be due to back-diffusion of precipitated salt in response to a sharp concentration gradient as observed in other studies (Fujimaki et al. 1997; Fujimaki et al. 2006). The concentration of NaCl in the top 1cm of the AW and SW soil columns had exceeded the solubility limit (~ 370 ppt) by days 9 and 5, respectively.

Figure 5.17 shows the EC at different depths for the tailings columns desiccating under AW and SW boundary conditions. For the AW tailings columns, increases in EC values were strictly restricted to the top 1cm of the columns. The SW tailings columns showed significant increases in the EC in the top 1cm as well as some increase beyond the as-deposited value at other depths after day 9 of drying. The rate of increase and magnitude of EC values in the top 1cm of the SW tailings columns was generally higher compared to AW columns. This pattern is also consistent with the higher evaporative demand and more rapid solute advection for the SW compared to the AW columns. The osmotic suctions corresponding to the maximum EC in the top 1cm of the AW and SW tailings columns estimated using the USDA (1954) equation are 4.94 and 25.29 MPa, respectively. Such maximum values of osmotic suction would delineate an upper limit to

Figure 5.16. NaCl concentrations over time at different depths of salinized soil columns drying under ambient (AW) and simulated (SW) wind boundary conditions.

the contribution of osmotic suction to salinity-induced reduction in evaporation from the desiccating tailings over the 14-day drying period. Hence, the higher maximum osmotic suction for the SW tailings column is expected to translate into a relatively higher suppression of evaporation compared to the AW tailings columns. Unlike the soil

Figure 5.17. Electrical conductivity (EC) of pore extracts over time at different depths of tailings columns drying under ambient (AW) and simulated (SW) wind boundary conditions.

columns, there was no evidence of back diffusion in both the AW and SW tailings columns (Figure 5.17) over the 14-day period.

5.4.2 Profile Evolution of Total Suction in Desiccating Soil and Tailings Columns

The profiles of total suction over time for the AW and SW salinized soil columns are shown with significant increase in total suction, especially in the top 2cm (Figure 5.18). Total suction increases in the top 1cm of the SW soil columns were very rapid compared to the AW soil columns. Similar to profile NaCl concentration, a slight drop in total suction was observed in the top 1cm of both AW and SW soil columns by day 14. The profiles of total suctions for both AW and SW soil columns were non-uniform. Despite the contrasting evaporative demands for both AW and SW soil columns, the maximum value of total suction in the top 1cm was the same (about 39MPa). This maximum total suction is within the range of equivalent osmotic suction values calculated from the EC or NaCl concentration at the solubility limit of NaCl (~370ppt) using different empirical correlations (USDA 1954; Campbell 1985; Abedi-Koupai and Mehdizadeh 2008). Thus, the upper limit of total suction observed for both AW and SW soil columns is most likely imposed by the solubility limit of NaCl.

Figure 5.19 presents the evolution of total suction for the AW and SW tailings columns. With the exception of day 14 for the SW column, the profiles of total suction for the tailings columns were generally low in comparison to the salinized soil columns (Figure 5.18). This is due to the significantly lower pore-water salinity of the tailings compared to the salinized soil: the initial pore-extract EC were 0.78 and 9.95 mS/cm, respectively. Significantly higher rates and values of total suctions were recorded for the SW compared to the AW tailings columns, consistent with its higher evaporative demand.

The highest total suctions were consistently observed in the top 1cm of the desiccating tailings columns. With the exception of the top 3-4cm for the SW columns, total suction was uniformly distributed throughout the profile for both AW and SW columns.

Figure 5.18. Total suction profiles over time for salinized soil columns drying under ambient (AW) and simulated (SW) wind boundary conditions.

Figure 5.19. Total suction profiles over time for tailings columns drying under ambient (AW) and simulated (SW) wind boundary conditions.

5.4.3 Desiccation Behaviour of Salinized Soil and Tailings Columns

The profiles of GWC for the salinized soil columns (AW and SW) are shown in Figure 5.20. Though the rate of profile dewatering in the first 7 days for the SW was higher compared to the AW soil columns, the final profile GWC in both cases were

similar. This is consistent with the same maximum total suction recorded for both SW and AW columns. With few exceptions, the top few centimeters of the soil columns were the driest for both SW and AW soil columns. Beyond day 7, further profile drying of the SW columns was minimal in contrast to the AW columns where significant drying continued to take place past day 7. This pattern is consistent with the exceedance of solubility limit of NaCl by day 5 and 9 for the SW and AW soil columns, respectively.

The lowest GWC measured at the end of drying the salinized soil columns (~8%) is not sufficiently low to warrant considerable contribution of matric suction to total suction. In fact, the lowest GWC in the top 1cm (12%) on day 14 for both SW and AW soil columns translates to an equivalent matric suction of ~150kPa, which is insignificant compared to the total suction (~39MPa) observed at the same depth on the same day. This implies that osmotic suction was the major contributor to the high total suctions recorded for the salinized soil columns, explaining the same upper limit to total suction recorded for both AW and SW soil columns as imposed by the solubility limit.

Figure 5.21 presents the temporal profiles of GWC for the desiccating tailings columns. Significantly rapid profile drying was observed for the SW tailings, with greater than 70% of total reduction in as-deposited GWC occurring in just 5 days, a pattern consistent with the high PE for the column. The AW tailings columns exhibited a lower rate of profile desiccation. Unlike the saline soil columns, the final profile GWC for the

Figure 5.20. Gravimetric water contents over time at different depths of salinized soil columns drying under ambient (AW) and simulated (SW) wind boundary conditions.

AW and SW tailings columns were significantly different, with the latter being within the residual range for the tailings. Thus, the contribution of matric suction to total suction for the SW tailings column (Figure 5.19) was relatively significant in comparison to the salinized soil columns. In fact, the equivalent matric suction in the top 1cm of the SW

Figure 5.21. Gravimetric water contents over time at different depths of tailings columns drying under ambient (AW) and simulated (SW) wind boundary conditions.

tailings column on day 14 was approximately 9,000kPa, being about 42% of the total suction measured at the same depth (21,340kPa) on same day. This contribution from matric suction may explain the continued increase in total suction for the tailings columns unlike the salinized soil columns (Figure 5.18). However, similar to the soil

columns, osmotic suction still constituted a more significant component of total suction for the tailings columns.

5.4.4 Measurement and Empirical Predictions of Evaporation Rates from Desiccating Salinized Soil and Tailings Columns

The evaporative fluxes from the salinized soil columns are presented as Relative Evaporation, RE (AE normalized by corresponding PE) in Figure 5.22. RE measured for the first 2 days of drying the AW soil column was more or less constant and high, followed by a decline until around day 10 after which RE remained low and somewhat constant. RE was only high for the SW soil columns at the onset of drying (Figure 5.22), with rapid decline beginning from day 1 till day 4 after which RE remained constant. Hence, the salinity-induced reduction in evaporation for SW soil column was more rapid and pronounced than the AW soil, in line with its higher evaporation-driven advection.

As shown in Figure 5.23, the AW tailings column was mostly at Stage I evaporation throughout the experiment, consistent with the maximum total suction in the top 1cm being less than 1500kPa (Figure 5.19). For the SW tailings columns, RE was high only for the first 2 days after which it began to steadily decrease until day 8 and remained low and constant afterwards. This evaporative behavior is explained by the high total suctions recorded in the top 1cm of the SW tailings columns (Figure 5.19). Thus, the desiccation behavior of the tailings was similar to that of the salinized soil

Figure 5.22. Relative evaporation measured from desiccating salinized soil columns and predictions from total suction in the top 1cm using equation 5.06. Data for columns drying under ambient (AW) and simulated wind (SW) boundary conditions shown.

columns, with the magnitude of reduction in fluxes for the latter being larger due to its higher initial pore-water salinity. The foregoing demonstrates that evaporative demand dictates the extent of suppression of evaporative densification by pore-water salinity.

Predictions of RE for the AW and SW soil columns (Figure 5.22) showed reasonable agreement with data for the first 4 days of drying the former. Beginning from day 5, predictions began to diverge from observations for the AW column, with the magnitude of divergence increasing over time. For the SW soil columns, agreement between predicted and measured RE values was restricted to only the first day past which RE was increasingly over-predicted. Over-prediction of RE would indicate that other factor(s), in addition to osmotic suction, was contributing to the reduction in evaporation for the soil columns.

Predictions of RE for the SW tailings column were in general agreement with observations (Figure 5.23), consistent with its low PE and total suctions. For the SW tailings columns, predictions of RE were in agreement with data up to day 2, after which RE was increasingly over-predicted till day 10 following which predictions again matched data (Figure 5.23). As previously observed, the maximum osmotic suction in the top 1cm of the SW tailings columns is more than 5 times the equivalent for the AW columns. Hence, the maximum contribution of osmotic suction to reduction in evaporation was not attained for the AW columns unlike the case for the SW tailings columns.

It was previously noted that osmotic suction was the main component of total suctions in the top 1cm of the salinized soil columns, and the total suctions were used to predict RE. Thus, the reasonable prediction of RE for the first 4 days of drying the AW

Figure 5.23. Relative evaporation measured from desiccating tailings columns and predictions from total suction in the top 1cm using equation 5.06. Data for columns drying under ambient (AW) and simulated wind (SW) shown.

soil columns demonstrates that osmotic suction was the main contributing mechanism to reduction in evaporation. Having excluded the effect of surface albedo in the current study, over-prediction of RE after day 4 and 0 for the AW and SW soil columns, respectively, could be attributed to additional contribution of salt precipitation. This interpretation is supported by two points. First, the concentration of NaCl in the top

1cm of the SW and AW soil columns had exceeded the solubility limit earlier on (by day 5) and later (by day 9) during the respective drying experiment. Hence, the maximum contribution of osmotic suction to reduction in fluxes was reached early and towards the end of the respective desiccation experiment. Secondly, previous research has shown that the extent of the contribution of salt precipitation to suppression of evaporation is enhanced by high evaporative demand (Fujimaki et al. 2006). Hence, the over-prediction of RE for SW soil column starting right from day 1 can be attributed to early precipitation of NaCl contributing to additional reduction in evaporation. Therefore, it can be concluded that osmotic suction alone explained the reduction in evaporation up till the solubility limit of NaCl beyond which additional reduction in fluxes is attributed to salt precipitation.

Also, the evaporative behaviour exhibited by the thickened tailings columns is similar to observation from saline mine tailings by Fujiyasu and Fahey (2000) that a higher PE increases the contribution from salt precipitates to reduction in fluxes. Osmotic suction exclusively explained the reduction in evaporative fluxes throughout the desiccation period for the AW tailings column in contrast with the SW tailings column. For the latter, beyond day 2, additional contribution from salt precipitation became increasingly higher consistent with increasing over-prediction of RE. Thus, similar to the salinized soil columns, over-prediction of RE for the SW tailings columns is consistent with its high evaporative demand.

Therefore, from the experimental observations made in the current study, the contribution of osmotic suction to reduction in evaporation was limited by the solute saturation concentration. Past the saturation concentration, the contribution of salt precipitates became increasingly more prominent, accounting for additional reduction in fluxes. The rate at which the saturation concentration is reached is a function of the prevalent evaporative demand as exemplified by the earlier observation of salt precipitation for the SW compared to the AW boundary condition.

5.4.5 Numerical Predictions for Desiccating Salinized Soil and Tailings Columns

Previous authors (e.g. Fisseha et al. 2010 and Fredlund et al. 2011) have expressed the need for a framework that accounts for 1D solute transport and osmotic suction in predicting unsaturated flow and evaporation. This is deemed necessary in order to improve the accuracy of numerical predictions of evaporative fluxes in saline soil and tailings. Based on the relative significance of osmotic suction in explaining reduction in evaporation as observed in the current study, a numerical framework that accounts for temporal increase in osmotic suction at the surface was evaluated. The following compares numerical predictions of evaporative fluxes, total suction and GWC for the soil and tailings columns to data based on the proposed numerical framework.

5.4.5.1 Cumulative Actual Evaporation

Numerical predictions of cumulative AE are compared to experimental data for the AW and SW soil columns as presented in Figure 5.24. Good agreement was obtained for the AW soil columns when the temporal increase in osmotic suction was accounted for, otherwise cumulative AE was significantly over-predicted. In the SW soil column, predicted cumulative AE correlated well with observations only up to day 3, after which the numerical code increasingly over-predicted evaporation (Figure 5.24). When osmotic suction was ignored, over-prediction of cumulative AE was immediate from day 1.

As shown in Figure 5.25, numerical predictions of cumulative AE agreed well with observations for both the AW and SW tailings columns. Without accounting for osmotic suction, cumulative AE was slightly over-predicted. However, unlike the case for the salinized soil columns, predictions of AE were not significantly sensitive to accounting for osmotic suction. This is due to the initial pore-extract EC for the tailings columns being about 13 times less compared to the soil columns, resulting in lower values of osmotic suctions recorded and input into SVFlux to predict evaporation (Appendix B2). For the SW tailings column, the observation that matric suction significantly contributed to the high total suctions recorded in the top 1cm was confirmed by numerical predictions irrespective of whether or not osmotic suction was accounted for (Appendix B3). Thus, osmotic suctions input into the numerical code were not sufficiently high to cause substantial difference in modelled total suctions to such an extent as to force predictions of AE to be sensitive to osmotic suction (Appendix B3) as was the case for

the salinized soil. In other words, the initial pore-water salinity of the tailings was relatively low such that temporal increase in osmotic suction was not as significant as for the saline soil columns to cause substantial reduction in predictions of evaporation.

Figure 5.24. Cumulative actual evaporation measured and predicted for salinized soil columns desiccating under ambient (AW) and simulated wind (SW) boundary conditions. Predictions with and without accounting for temporal evolution of osmotic suction are shown in the dotted lines.

Figure 5.25. Cumulative actual evaporation measured and predicted for tailings columns desiccating under ambient (AW) and simulated wind (SW) boundary conditions. Predictions with and without accounting for temporal evolution of osmotic suction are shown in the dotted lines.

The peak osmotic suction for the AW and SW soil column was specified in SVFlux on day 9 and 4, respectively, and kept constant till the end of the simulation period (Appendix B2). These peaks represented when NaCl concentrations in the top 1cm of

soil column had exceeded the solubility limit, explaining why predictions of evaporation diverged from observations starting from day 4 and 10 for the SW and AW soil columns, respectively (Figure 5.24). It can be inferred from the foregoing that the magnitude of contribution from osmotic suction to reduction in evaporation for the soil and tailings columns was controlled by both the initial pore-water salinity and evaporative demand. The contrast between the salinized soil and tailings columns showed that initial salinity influenced the magnitude of temporal increases in osmotic suction that in turn suppressed evaporation. Evaporative demand controls the rate at which the solubility limit is reached and the peak contribution of osmotic suction to reduction in fluxes is mobilized as exemplified by the contrast between AW and SW boundary conditions.

5.4.5.2 Comparison of Predictions of Cumulative Actual Evaporation by SVFlux and Wilson + Soil Resistance Model (Equation 5.06)

The predictions of cumulative AE for the soil and tailings columns (AW and SW) using SVFlux and the Wilson + Soil Resistance model (equation 5.06) are compared in Figures 5.26 and 5.27. Numerical predictions by SVFlux accounted for osmotic suction at the surface, in addition to applying the surface correction factor. For both the SW soil and tailings, the empirical model is shown to over-predict cumulative AE in comparison to SVFlux (Figures 5.26 and 5.27). This is due to the total suctions predicted by SVFlux at the surface and adjusted using the correction factor being substantially higher compared to the total suctions measured in the top 1cm of the soil and tailings columns

Figure 5.26. Cumulative actual evaporation (AE) measured from salinized soil columns desiccating under ambient (AW) and simulated (SW) wind conditions and predictions using SVFlux and Wilson + Soil Resistance Model (Equation 5.06).

(Figures 5.28 and 5.29). Consistent with the discrepancies in the prediction of cumulative AE, the difference in the corrected modelled and measured total suctions in

the top 1cm of the soil and tailings columns is especially significant for the SW boundary condition. The reader is reminded that for the saline soil and tailings columns, based on the profiles of total suction in the top 1cm being linear (Figure 5.13), the bulk total suction measured in the top 1cm was used to predict evaporation using equation 5.06.

Figure 5.27. Cumulative actual evaporation (AE) measured from tailings columns desiccating under ambient (AW) and simulated (SW) wind conditions and predictions using SVFlux and Wilson + Soil Resistance Model (Equation 5.06).

Figure 5.28. Total suctions (Total) measured (D) from top 1cm of salinized soil columns desiccating under ambient (AW) and simulated (SW) wind conditions and numerical predictions (P) with the suction correction factor applied to total suction values modelled in the top 1cm by SVFlux. Also shown are the osmotic suctions (osmotic) computed from EC data in the top 1cm. The values are plotted on logarithm (a) and linear (b) scales.

Figure 5.29. Total suctions (Total) measured (D) from top 1cm of thickened tailings columns desiccating under ambient (AW) and simulated (SW) wind conditions and numerical predictions (P) with the suction correction factor applied to total suction values modelled in the top 1 cm by SVFlux. Also shown are the osmotic suctions (osmotic) computed from EC data in the top 1cm. The values are plotted on logarithm (a) and linear (b) scales.

On the other hand, SVFlux accounts for the steep gradient in total suction at the soil surface by applying a correction factor to the modelled suction values according to equation 5.08. This explains the discrepancy between predictions of total suction by SVFlux and values measured and used in equation 5.06 (Figures 5.28 and 5.29).

Prior to applying the correction factor to total suctions modelled at the surface (0cm) by SVFlux, better match of predictions to measured total suction in the top 1cm was obtained (Figures 5.30 and 5.31), especially for the salinized soil columns (Figure 5.30). The total suctions for the SW tailings columns were still over-predicted by SVFlux even prior to applying the correction factor (Figure 5.31) due to the high matric suctions predicted by the numerical code (Appendix B3), even though better agreement was obtained (Figure 5.31). The osmotic suction values presented in Figures 5.28 to 5.31 (and elsewhere in this thesis) are the raw values in the top 1cm of columns estimated from EC data using the USDA (1954) approximation. Hence, the plotted osmotic suctions represent contributions from both soil solution and precipitated salt, explaining why some values exceeded the corresponding total suction measured in the top 1cm of the soil or tailings column.

As secondary evidence, AE was predicted (equation 5.06) from total suction data for the soil and tailings columns after being adjusted using 'c' (in equation 5.08). AE for the AW soil and tailings was well predicted by both the numerical code and empirical

model (Figures 5.32 and 5.33). Also, the discrepancies between the numerical and empirical predictions of AE were generally lower, even though equation 5.06 still slightly

Figure 5.30. Total suctions measured in the top 1cm of salinized soil column desiccating under simulated wind (SW) condition and numerical predictions of total suctions at the surface (0cm) from SVFlux prior to, and after applying the suction correction factor. Also shown are the corresponding osmotic suctions in the top 1cm calculated from EC data. The values are presented in logarithm (a) and linear (b) scales.

Figure 5.31. Total suctions measured in the top 1cm of thickened tailings column desiccating under simulated wind (SW) condition and numerical predictions of total suctions at the surface (0cm) from SVFlux prior to, and after applying the suction correction factor. Also shown are the corresponding osmotic suctions in the top 1cm calculated from EC data. The values are presented in logarithm (a) and linear (b) scales.

under-predicted AE relative to SVFlux for the SW soil column due its high measured total suctions. For the SW tailings columns, equation 5.06 over-predicted fluxes relative to SVFlux due the latter over-predicting total suctions measured in the top 1cm (Figure 5.31). On balance, SVFlux still gave generally better agreement between predictions and measurements of cumulative AE for both soil and tailings columns. Equation 5.06 was still not comparable to SVFlux even when the predictions were based on extrapolated total suctions at the surface of the soil and tailings columns (using 'a' in equation 5.03) as presented in Appendices B4 and B5. Therefore, it can be inferred that accounting for osmotic suction at the surface and using a single correction factor in SVFlux was sufficient to predict fluxes from the salinized soil and tailings columns, giving better agreement with observations compared to the proposed empirical model. However, the proposed empirical model gave better predictions of evaporation compared to SVFlux for the non-saline soil columns (Figure 5.14).

5.4.5.3 Profile Gravimetric Water Contents

As shown in Figure 5.34, on average, the numerical code gave reasonable predictions of profiles of GWC for the AW soil column, with even better agreement when temporal evolution of GWC at select depths was considered (Appendix B6). The only difference is that the numerical solution gave uniform profiles of GWC in contrast with observations, especially as desiccation progressed. The good prediction of GWC for

Figure 5.32. Cumulative actual evaporation (AE) measured from salinized soil columns desiccating under ambient (AW) and simulated (SW) wind conditions and predictions using SVFlux and Wilson + Soil Resistance Model (Equation 5.06). The total suction used in equation 5.06 are values measured in the top 1cm of columns corrected using the surface correction factors used in SVFlux ($c=-0.5$ and -0.65 in equation 5.08 for AW and SW, respectively).

Figure 5.33. Cumulative actual evaporation (AE) measured from tailings columns desiccating under ambient (AW) and simulated (SW) wind conditions and predictions using SVFlux and Wilson + Soil Resistance Model (Equation 5.06). The total suction used in equation 5.06 are values measured in the top 1cm of columns corrected using the surface correction factors used in SVFlux ($c=-0.5$ and -0.65 in equation 5.08 for AW and SW, respectively).

Figure 5.34. Profiles of gravimetric water contents measured (D) and predicted (P) on select days for the salinized soil columns desiccating under ambient (AW) and simulated (SW) wind condition.

the AW soil columns aligns with the good prediction of cumulative AE as previously observed (Figure 5.24). Predictions of profile GWC for the SW columns did not generally agree with data (Figure 5.34 and Appendix B7), with consistent under-prediction by the numerical code, apart from day 5. As was the case with predictions of cumulative AE

(Figure 5.24), agreement between predicted and measured GWC was generally restricted to the first 2-5 days of drying the SW soil columns for all 3 select depths considered (Appendix B7), with increasing trend of under-prediction after day 2 or 5. This pattern is in line with increasing over-prediction of cumulative AE observed starting from day 4 for the SW soil columns (Figure 5.24).

The numerical predictions of profile GWC on select days for the AW and SW tailings columns are compared to experimental data as presented in Figure 5.35, with comparisons at select depths also shown in Appendix B8. On average, numerical predictions for the AW tailings columns agreed well with data on all select days (Figure 5.35) and for all 3 depths (Appendix B8) similar to the predictions of cumulative AE (Figure 5.25). However, for the SW tailings columns, numerical predictions agreed with data mostly on days 5 and 9 (Figure 5.35-based on profile average) and only at the 5cm depth (Appendix B8).

5.4.5.4 Optimization of Numerical Predictions of Evaporation, Total Suction and Profile Gravimetric Water Contents

To optimize numerical predictions of evaporation and total suctions, a series of simulations with and without accounting for osmotic suction and / or applying the surface correction factor was undertaken for the SW tailings column. The comparison of predicted to measured AE and total suctions (in the top 1cm of column) is presented in Figure 5.36. It is shown that the best prediction of both AE and total suction is obtained

when both the temporal evolution of osmotic suction at the surface of the tailings columns is accounted for and the surface suction correction factor is applied in the simulation.

Figure 5.35. Profiles of gravimetric water contents measured (D) and predicted (P) on select days for the tailings columns desiccating under ambient (AW) and simulated (SW) wind condition.

Figure 5.36. Comparison of SVFlux predictions of actual evaporation and total suctions in the top 1cm of the SW tailings column to experimental observations (Data). Numerical results for simulations with (Osmotic) and without (No Osmotic) accounting for osmotic suction and with and without using the surface suction correction factor (Correction factor-CF; No correction factor-NCF) are shown. Osmotic suctions in the top 1cm calculated from EC data also shown. Suction values plotted in logarithm (b) and linear (c) scales.

The corresponding predictions of the profiles of GWC on select days and time series of GWC at select depths are compared to data in Figure 5.37 and Appendix B9, respectively. Considering both the profiles (Figure 5.37) and time series (Appendix B9) of GWC, with the exception of 9cm depth, the predictions of GWC that applied the correction factor and also accounted for or did not account for osmotic suction gave the closest fit to experimental data. Overall, discrepancies between numerical predictions of GWC and laboratory data were observed on day 11 (Figure 5.37) as well as starting from day 3 at 1cm and day 5 at 3 and 9cm depths (Appendix B9).

Figure 5.37. Profiles of gravimetric water content predicted by SVFlux for the SW tailings column on days 5 and 11 compared to experimental observations (Data). Numerical results for simulations with (Osm) and without (NOsm) accounting for osmotic suction and with and without using the surface suction correction factor (Correction factor-CF; No correction factor-NCF) are shown.

To this end, a supplemental numerical analysis for the SW tailings column was conducted to optimize the numerical solutions for evaporation, total suction as well as profile GWC. The surface correction factor (c in equation 5.08) was varied, while the K_{sat} value input into the numerical code was increased by 1 order of magnitude (to 2×10^{-6} m/s). The hydraulic conductivity function $K(\Psi)$ was adjusted accordingly to reflect the increase in K_{sat} value. The results for 3 values of c (-0.98; -0.65; -0.33), being 1.5, 1 and 0.5 multiples of the value of c that has been previously used are presented in terms of evaporation, total suction in the top 1cm and profile GWC in Figure 5.38. The total suction data in Figure 5.38 are presented on linear scale in Appendix B10. Reducing the suction correction factor by half, accounting for osmotic suction, and increasing the saturated hydraulic conductivity value by 1 order of magnitude seemed to give the optimum solution for all 3 parameters. The impact of accounting for osmotic suction was also more distinct compared to prior numerical results for the SW tailings column (Figure 5.25).

From the foregoing, in addition to experimental evidence, numerical analyses showed that osmotic suction was sufficient to explain the reduction in evaporation observed for the salinized soil and tailings column, at least up to the solute saturation concentration. Also, the numerical analysis confirmed the moderating effect of initial pore-water salinity and evaporative demand on the contribution of osmotic suction to suppression of evaporation. It was also demonstrated through the numerical analysis that evaporative demand had an overriding effect on pore-water salinity. Despite the

Figure 5.38. Comparison of data with numerical predictions of; (a) actual evaporation; (b) total and osmotic suctions in the top 1cm; and (c) mean absolute deviation of predicted average profile GWC from data for both days 5 and 11 for the SW thickened tailings columns. The value of K_{sat} used in all simulations is 1 order of magnitude higher than the value determined from falling head test.

same initially high pore-water salinity for the AW and SW salinized soil columns, osmotic suction was a significant contributor to reduction in evaporation for almost the entire desiccation period in the former, in contrast to the latter. Therefore, an indirect interpretation of the numerical result would be that the contribution of salt precipitation to reduction in evaporation from the soil and tailings tested in the current study increased with increase in initial pore-water salinity and evaporative demand. This would be similar to conclusions in Fujimaki et al. (2006) and Fujiyasu and Fahey (2000) for saline soil and saline tailings, respectively. The major difference from the current study is that both studies investigated saline soil and tailings, respectively, desiccating under both simulated radiation and wind, and hence introduced the effect of albedo in addition to osmotic suction and salt precipitation. Also, for Fujimaki et al. (2006) the saline soil desiccated under very low matric suction conditions and would not be representative of jurisdictions where net water deficit causes the soil to be unsaturated for a considerable period of the year.

5.5 Summary and Conclusion

The current paper investigated the relative contribution of osmotic suction and salt precipitation to reduction in evaporation from desiccating saline soil and thickened gold tailings, exempting the effect of surface albedo. Salt accumulation was observed in the top 1cm of soil and tailings columns drying under both low and high evaporative demands, with the magnitude and rate of accumulation higher for the latter. Osmotic

suction significantly contributed to the high total suctions measured in the top 1cm of the salinized soil and tailings columns drying under either boundary condition. The maximum total suctions in the top 1cm of soil columns were similar irrespective of the evaporative demand, indicative of the solubility limit of NaCl setting the upper limit of contribution of osmotic suction to total suction. Thus, the peak contribution of osmotic suction to reduction in evaporation from the soil and tailings columns was limited to the solubility limit, beyond which salt precipitation occurs. Additional reduction in evaporation past this upper limit was attributed to salt precipitation. The rate at which this upper limit is reached was found to be a function of evaporative demand. The magnitude of the contribution of osmotic suction to reduction in evaporation was also found to be a function of the initial-pore water salinity.

Numerical predictions of cumulative evaporation, total suction and GWC using an unsaturated flow code that accounted for the temporal increase in osmotic suction at the surface of the salinized soil and tailings generally matched experimental data. Using the surface correction factor to adjust the total suction used to calculate evaporation and accounting for osmotic suction at the surface was sufficient to predict both evaporation and total suction, but not necessarily the GWC. The best match between predictions and experimental measurement of evaporative fluxes, total suctions and GWC was obtained when osmotic suction was accounted for, the correction factor was halved, and the K_{sat} value was increased by 1 order of magnitude.

The findings in the current paper have a number of practical implications for tailings deposition management. The goal in any tailings deposition scheme is to ensure the uniform profile evolution of matric suction (and shear strength) within the tailings stack such that the bearing capacity required to support fresh layers and / or ensure trafficability during site reclamation is sufficiently mobilized. While the column study undertaken in the current study may not be the most representative of field conditions, the results has demonstrated that if the tailings stack is thin enough, the goal may be achievable, irrespective of the prevalent evaporative demand. This is in line with the conclusion from numerical modeling by Simms et al. (2009) that evaporative densification is a significant contributor to shear strength gain of surface-deposited tailings stack, irrespective of the climatic condition. However, while the uniform profile drying of tailings stack may have desirable geotechnical implication, there may be an inevitable and un-intended geo-environmental consequence. For sulphide-mineral containing mine tailings, maintaining a degree of saturation sufficiently high to form a hydraulic barrier against oxygen ingress and subsequent oxidation and acid mine drainage is important. Hence, as demonstrated in the current paper, uniform profile drying due to evaporative densification may permit oxygen diffusion into the tailings stack, acting as a precursor for acid mine drainage, especially in humid climates where precipitation may accelerate the sulphide oxidation process.

Also, as shown in this paper, incorporating the increase in osmotic suction at the surface of tailings stacks over time can significantly improve the accuracy of predictions

of evaporative densification in saline mine tailings. This observation is a direct response to the need for a framework that incorporates the effects of solute transport and osmotic suction in improving the accuracy of predicting evaporation in saline soil and mine tailings (Fisseha et al. 2010; Fredlund et al. 2011). Lastly, the observation in the current paper that the contribution of osmotic suction to salinity-induced reduction in evaporative densification is limited by the pore-water solute saturation concentration is important. This solubility limit depicts the upper range of the contribution of osmotic suction to salinity-driven reduction in evaporation. It will be beneficial for future numerical formulation aimed at predicting the extent of reduction in evaporation due to salinity to incorporate this. A numerical framework that accounts for the additional contribution from salt precipitates, once the solubility limit is exceeded, may further improve predictions of evaporation, especially for hyper-saline mine tailings. Further investigations considering non-isothermal conditions, multi-layer tailings deposits as well as wet and dry cycles is warranted to more accurately mimic field conditions.

CHAPTER 6: NUMERICAL PREDICTION OF EVAPORATIVE FLUXES FROM SALINE THICKENED TAILINGS STACKS

ABSTRACT: Predicting evaporation from saline mine tailings is complicated by the suppression of fluxes due to pore-water salinity. This paper proposes a numerical framework that incorporates osmotic suction in predicting evaporation from saline thickened gold tailings. Series of column drying experiments were conducted to mimic field conditions, namely; varying evaporative demands, wet-dry-wet cycle and multi-layer deposition. Evaporation from the tailings columns were monitored along with profiles of total suction, electrical conductivity and gravimetric water contents. Solute accumulation was observed in the top 2cm of the tailings stacks over time. Predictions of evaporation and profile gravimetric water contents generally agreed with experimental data when the temporal increase in osmotic suction at the surface of the tailings was accounted for. Predictions of evaporation were sensitive to initial deposit thickness and saturated hydraulic conductivity of tailings, with the onset of Stage II evaporation delayed with either a high K_{sat} value or thicker deposit, associated with a significantly higher rate of profile dewatering of tailings. The overall drying time was substantially reduced when multiple (5) thin lifts (20cm) were deposited as opposed to an equivalent single deep (1m) deposit. Numerical analyses showed that placing a saturated sand capillary barrier between two fresh lifts may be effective in reducing surface salt accumulation and consequently prolong the time available for stack to efficiently harvest evaporative energy.

6.1 Introduction

The surface deposition of thickened mine tailings is increasingly being adopted by mine tailings disposal facility operators around the world, replacing conventional deposition of tailings slurries behind containment dams (Newman 2003), due to the potential risk of catastrophic dam failure associated with the latter (ICOLD 2001). Thickened tailings deposition also improves the geotechnical stability and trafficability of stacks, facilitating easy mine site closure and reclamation. Surface-deposited thickened tailings densify and gain shear strength through mechanisms such as self-weight consolidation, hindered settling and desiccation (Simms et al. 2009). Desiccation has been shown to contribute significantly to the development of shear strength and bearing capacity of such stacks (Rassam and Williams 1999a; Fujiyasu and Fahey 2000; Simms et al. 2009).

An important aspect of tailings deposition management is the capability to predict the rate of desiccation from fresh deposits. It is desirable to optimize deposition operations in a way that minimizes the time lag between deposition cycles but ensures stacks are stable enough to support fresh layers and / or traffic. Numerical modeling provides an important planning tool to aid in achieving such depositional objective. However, the capacity of current unsaturated flow codes to reasonably predict evaporative densification in tailings deposits with high pore-water salinity is limited. It is often the case that the predictive accuracy of these numerical flow codes breaks down

following the accumulation and subsequent precipitation of salt at the surface of tailings deposit (Simms et al. 2007; Fisseha et al. 2010). This is because salinity impedes the rate of evaporation and subsequent shear strength gain of tailings stacks (Newson and Fahey 1997; Simms et al. 2007; Fisseha et al. 2010).

Previous efforts aimed at predicting evaporative fluxes from saline soil and tailings stack have shown some limitations. Fujimaki et al. (2006) predicted evaporation from wet loamy sand and sand soils amended with NaCl and KCl solutions desiccating under isothermal conditions. Numerical solutions of water flow and solute transport were obtained sequentially using the bulk transfer and the advection dispersion equation (ADE), respectively. Evaporation from the desiccating columns was found to be significantly over-predicted for both soil types. When the bulk transfer equation was modified to incorporate the resistance to water flow due to salt crust, better predictions of evaporation was obtained, but fluxes were still over-predicted. This discrepancy was attributed to the ADE over-estimating the backward diffusion of accumulated salt at the soil surface leading to under-prediction of surface salt accumulation.

Simms et al. (2007) compared laboratory and field data for acid-generating thickened tailings to numerical predictions using a 1D non-isothermal Finite Element code. Reasonable predictions of evaporative fluxes were obtained for the “small-scale” laboratory test when the hydraulic conductivity function was adjusted to reflect the volume change undergone by the tailings. Likewise, predictions of profile gravimetric

water content (GWC) agreed well with field measurements up till 3 weeks after deposition, when the precipitation of salt at the surface of deposit had begun to suppress evaporative fluxes. In the case of the “large-scale” laboratory drying test, predictions of profile matric suctions were found to over-estimate experimental measurements, especially after few days of drying. The authors identified the need for future research to incorporate the effect of pore-water salinity and multi-layer deposition in modeling evaporative fluxes from tailings stacks.

A study by Fisseha et al. (2010) investigated the effect of inter-layer water flow and salt accumulation on the desiccation of 2 successive lifts of thickened gold tailings. The multi-layer stack was modelled using both a 1D isothermal (SVFlux) and non-isothermal (SoilCover) unsaturated flow codes. Actual evaporation (AE) from the tailings stack was reasonably predicted by both codes up till after the multi-layer stack was re-saturated following which predictions of evaporation were significantly exaggerated. The over-prediction was attributed to the rapid surface accumulation of salts following re-wetting. The authors showed that hydraulic interaction between the old and fresh tailings layers caused matric suction within the underlying layer to dissipate. The authors also compared predictions of surface salt accumulation to data estimated from electrical conductivity (EC) of pore solution obtained by pore-squeeze technique. However, two limitations are noted in the study. First, the authors were unable to fully characterize the temporal evolution of osmotic suction at the surface of the stack due to the inability to obtain pore-squeeze samples beyond the first few days of deposition or rewetting.

Secondly, the temporal evolution of osmotic suction was not accounted for in predicting evaporative fluxes from the multi-layer stacks. Fisseha et al. (2010) recommended that a numerical framework that accounts for solute transport and salt accumulation in predicting evaporation from saline tailings stack be explored in the future.

Improved capacity for predicting evaporation from saline tailings deposit is important considering the prevalence of hyper-saline tailings facilities around the world (Newson and Fahey 1997; Fujiyasu and Fahey 2000; Stolberg and Williams 2006). Therefore, the current research characterizes the one-dimensional (1D) solute transport in desiccating acid-generating thickened gold tailings, and relates this to observed evaporative behaviour. Based on results, a numerical framework that accounts for the temporal increase in osmotic suction at the tailings surface is proposed and evaluated. The proposed framework was validated under contrasting boundary conditions, dry-wet-dry cycles as well as multi-layer deposition. The sensitivity of predictions to the saturated hydraulic conductivity of the tailings was assessed. Exploratory modelling to assess multiple thin lift deposition against deep stacking was also conducted. In addition, the use of a sand “capillary barrier” slow down surface salt accumulation was evaluated. A brief discussion of the practical implications of the results from the current study for mine tailings management is provided at the end of this paper.

6.2 Theoretical Background

Similar to soils, evaporation from tailings is known to proceed in 3 Stages (Wilson et al. 1994; Fujiyasu et al. 2000; Fisseha et al. 2010). During Stage I, evaporation rate is entirely controlled by climatic conditions (Gardner and Hillel 1962; Wilson et al. 1994; Simms et al. 2007), and can be predicted by the Modified Penman's equation (Penman 1948; Wilson 1990). The model combines the mass transfer equation to ground surface energy budget to give the Potential Evaporation rate, PE as:

$$PE = \frac{\Gamma Q + \gamma E_a}{\Gamma + A\gamma} \quad (6.01)$$

Where Q is the heat budget or all net radiation (mm/day); Γ is the slope of the saturation vapour pressure versus temperature curve at mean temperature of air (mm Hg^{°C}); γ is psychometric constant. E_a is given by the mass transfer equation as:

$$E_a = f(u) P_a (B - A) \quad (6.02)$$

Where $f(u)$ is an empirical function of the average wind speed (see Wilson et al. 1994 for expressions); P_a and B is the water vapour pressure (mm Hg) and the inverse of the relative humidity (RH) of the air immediately above the tailings surface, respectively; A is the inverse of the RH of the pore-air at the tailings surface.

During Stage II, the rate of evaporation becomes limited by water supply and the rate of evaporation becomes dependent on both the climatic conditions and material properties. Hence, coupled soil-atmosphere flux models (e.g. Schieldge et al. 1982; Passerat De Silans et al. 1989; Wilson et al. 1994) are commonly used for predicting stage II evaporation. Wilson (1990) developed one of such models that couples mass flux (using Darcy's and Fick's Laws for liquid water and vapour flow, respectively) and heat flux to calculate AE from soil. The tailings continue to desaturate until a new equilibrium between the relative humidities at the soil surface and air directly overlying it is established (Stage III), when evaporation rate becomes low and constant.

Evaporation from tailings is coupled to the total suction at the surface, which is in turn functionally related to the RH of the pore-air (Edlefsen and Anderson 1943). Thus, evaporation is driven by the gradient in vapour pressures at the soil-atmosphere interface. The ratio of AE to PE, called "Relative Evaporation (RE)" is related to the total suction at the tailings surface (Wilson et al. 1997) by:

$$RE = \frac{AE}{PE} = \left(\frac{e^{-\left(\frac{\psi W_v g}{RT}\right)} - h_a}{1 - h_a} \right) \quad (6.03)$$

Where ψ = total suction at the soil / tailings surface (m); W_v = the molecular weight of water (0.0186 kg/mol); g = gravitational acceleration (9.81m/s^2); R =universal gas constant (8.314 J/mol.K); T = temperature of air above soil / tailings column (K) and h_o = relative humidity of air above soil/ tailings column (expressed as a fraction).

Equation 6.03 follows from equation 6.02, assuming that the relative humidity at the surface is the only parameter needed to compute RE. This equation (6.03) was tested by measuring evaporation from very thin soil samples (ranging from 0.2 to 0.7mm) under controlled temperature and relative humidity conditions. The total suctions of the thin samples were determined from their SWCC and the measured GWC. Recent work by Fredlund et al. (2011) has shown that Equation 6.03, when incorporated into unsaturated flow codes, is not always able to accurately predict evaporation in soil column tests. The empirical model was found to require the application of an empirical correction factor to adjust the total suction (ψ) used for predicting RE. The need for this correction factor is paralleled in soil science literature by the use of a variable soil resistance term (Alvenäs and Jansson 1997). There are several empirical formulations of this term, all of which depend on the water content “near the surface” (Camillo and Gurney 1986; Van de Griend and Owe 1994; Bittelli et al. 2008). This empirical (resistance) approach involves describing the evaporative behaviour of the soil in terms of both the soil (R_s) and aerodynamic (R_a) resistances to water vapour flow within the soil and away from its surface. As shown in Chapter 5 of this thesis, an empirical approach that combines both the total suction and the soil resistance approaches in

predicting evaporation may be viable for non-saline and low to medium saline soil and tailings.

In saline soils and mine tailings, evaporation is coupled solute transport (Newson and Fahey 2003; Fujimaki et al. 2006). Solute transport causes surface salt accumulation and lowers evaporation rate, while evaporation-driven advection causes surface salt accumulation. Unsaturated flow in desaturating tailings occurs via a combination of liquid water and water vapour flow. Liquid water flow is governed by the generalized Darcy Law (Bear 1972), given as:

$$V^w = -K^w(\psi) \frac{\partial h}{\partial z} \quad (6.04)$$

Where V^w is liquid pore-water velocity (m/s); $K^w(\psi)$ is the hydraulic conductivity (m/s) as a function of matric suction, ψ (kPa); h is the hydraulic head (m); and z is the elevation (m). On the other hand, water vapour flow is governed by the modified Fick's Law (Philip and de Vries 1957; Fredlund and Dakshanamurthy 1982), written as:

$$V^v = -K^v(\psi) \frac{1}{\gamma} \frac{\partial \psi}{\partial z} \quad (6.05)$$

Where V^v is pore-water vapour velocity (m/s); $K^v(\psi)$ is pore-water vapour conductivity in the air phase as a function of matric suction; γ is the unit weight of water; and ψ is the negative pore-water pressure/matric suction (kPa).

By writing the continuity equation for a representative elemental volume (REV) of tailings, and substituting equations 6.04 and 6.05 for liquid water and water vapour flow, respectively, the h-based formulation of the partial differential equation (PDE) for 1D transient unsaturated flow is expressed as:

$$\frac{\partial}{\partial z} \left[(K^w(\psi) + K^v(\psi)) \frac{\partial h}{\partial z} - K^v(\psi) \right] = -\gamma m^w \frac{\partial h}{\partial t} \quad (6.06)$$

Where t is time (s); and m^w is the derivative of the soil water characteristic curve (SWCC) with respect to matric suction or the derivative of consolidation curve with respect to positive pore-water pressure.

Solute transport in mine tailings is governed by the advection-dispersion equation (ADE) (Elrick et al. 1994; Fujimaki et al. 2006). ADE combines the advection and dispersion (diffusion) equations, assuming mass conservation, with the 1D transient form given as:

$$D \frac{\partial^2 c}{\partial z^2} - V \frac{\partial c}{\partial z} - c \frac{\partial V}{\partial z} = \frac{\partial c}{\partial t} \quad (6.07)$$

Where D is the dispersion coefficient (sum of diffusion coefficient, D_d and mechanical dispersion coefficient, D_m) and c is the pore-water solute concentration. D_m is given as:

$$D_m = \lambda V \quad (6.08)$$

Where λ is the dispersivity (m).

In order to improve numerical prediction of evaporation in saline tailings, a framework that accounts for the unsaturated flow-solute transport coupling is required (Fisseha et al. 2010; Fredlund et al. 2011). The current paper proposed and validated such numerical framework.

6.3 Materials and Methodology

6.3.1 Test Material

The thickened tailings tested in this paper was shipped from the Bulyanhulu gold mine in Tanzania, operated by African Barrick Gold Plc. The thickened tailings was pumped from the mine site at an out-of-pipe gravimetric water content (GWC) of

around 38% and shipped to the laboratory in plastic bags that were placed inside sealed plastic buckets, during which settling occurred. Prior to column preparation, the tailings were mechanically homogenized to the as-deposited GWC using the bleed water contained in the plastic bags. The geotechnical properties and particle-size distribution of the thickened tailings is presented in Table 6.01 and Figure 6.01, respectively. The shrinkage curve (Figure 6.02) was determined from volume measurements using an ultra-sonic displacement sensor (Model Ultra-U from Senix Corporation) and GWC data obtained from oven-drying at 105°C. The soil water characteristic curve (SWCC) for the thickened tailings (from Simms et al. 2007) was fitted using the Fredlund and Xing (1994) equation, and is shown in Figure 6.03. The SWCC and geotechnical properties of the gold tailings were employed in modeling the transient 1D unsaturated flow as described later in this paper. Mineralogical analyses of the tailings showed a solid-phase composition made up of mostly silicates (80%), Pyrite (6%), Calcite (5%) and Ankerite (4%) (Golder 2005). The pore-water chemical composition of the thickened tailings is shown in Table 6.02, with gypsum (Calcium sulphate) being the predominant solute (Bryan 2008). The thickened tailings had been previously shown to be “net acid-generating” (Bryan 2008). Series of column and multi-layer desiccation experiments were conducted using the gold thickened tailings as described in the following sections.

Table 6.01. Geotechnical properties of thickened gold tailings

Property	Measured Value
Specific Gravity	2.9
D ₁₀ , D ₅₀ , D ₆₀ (microns)	2, 25, 40
Cu (D ₆₀ /D ₁₀)	20
Liquid limit (%)	23
Plastic limit (%)	20
Shrinkage Limit (%)	20
Saturated hydraulic conductivity (m/s)*	2.0E-7

*Saturated hydraulic conductivity was measured from falling head tests at a void ratio of 0.8, as per Simms et al. 2007.

Figure 6.01. Particle size distribution of gold thickened tailings as determined by a combination of hydrometer and sieve analyses.

Figure 6.02. Shrinkage curve of gold thickened tailings.

Figure 6.03. Soil water characteristic curve (SWCC) of gold thickened tailings (from Simms et al. 2007) shown fitted using Fredlund and Xing (1994) equation.

6.3.2 Column and Multi-layer Desiccation Tests for Thickened Tailings

6.3.2.1 Modified Petroleum Jelly Wax-column Technique for Studying Solute Transport and Unsaturated Flow in Desiccating Thickened Tailings

The petroleum jelly-wax column technique proposed by Khasawneh and Solileau (1969) was modified and used for the series of column tests undertaken in this paper. The columns were used for packing, drying and sampling the thickened tailings. The technique had been previously used in several ionic diffusion studies in unsaturated soil (Akinremi and Cho 1991; Hao et al. 2000; Olatuyi et al. 2009) as it affords a convenient way of preparing and handling soil columns such that sections as thin as 5mm can be obtained for various profile analyses. Each wax column is a rectangular mould with a cylindrical cavity with dimensions as shown in Figure 6.04, made from a molten mixture of petroleum jelly (1 part) and paraffin wax (2.5 parts). The cavity of the wax mould was created by placement of a cylindrical aluminum can inside an empty 1.89L milk or juice carton prior to pouring the molten mixture and allowing the pour to solidify for 24 hours. The can was thereafter removed by pouring hot water inside it.

6.3.2.2 Preparation, Desiccation and Sampling of Thickened Tailings Columns

Tailings columns were prepared by packing the cylindrical cavity of the wax columns with the thickened tailings homogenized to the as-deposited GWC of 38%. The initial mass of each replicate tailings column was recorded, and columns were then left to desiccate under ambient laboratory conditions, with either wind simulated by means

of an oscillatory fan placed at the central edge of the drying platform (SW) or with only ambient wind (AW) allowed to drive evaporation. The packed tailings columns generally settled within few hours to a height of about 15cm, leaving bleed water at the top.

Table 6.02. Pore-water chemical composition of thickened tailings (From Bryan 2008)

Ion	Concentration (mg / L)
SO ₄ ²⁻	2140
Ca ²⁺	545
Mg ²⁺	125
K	283
Al	<0.1
Cu	0.07
Fe	<0.3
Pb	<0.01
Mn	2.8
Si	5
Zn	0.8
pH	6.93
Saturated thickened EC (mS/cm)	4.25

One replicate tailings column was destructively sampled at predetermined intervals by obtaining 1cm thick sections using an adjustable hacksaw (Mastercraft Canada, Toronto ON) for cutting and a Jobmate plastic mitre box (Trileaf Distribution Canada, Toronto ON) used as a cutting guide to ensure uniformity of sections. The choice of 1cm thick profile samples from the tailings columns was to ensure sufficient quantity of material for the different analyses (total suction, GWC and EC) to be conducted. The profile samples were retrieved, kept in sealed plastic bags and manually homogenized prior to conducting the various analyses. Thus, the parameters determined for each profile tailings sample represents the average for the respective 1cm depth. Extra cares was taken to ensure samples were not cross-contaminated and were minimally disturbed during the destructive sampling.

6.3.2.3 Dry and Dry-Wet-Dry Cycles for Desiccating Thickened Tailings Columns

Two sets of column desiccation experiments were conducted for the thickened tailings- dry and dry-wet-dry cycles. The desiccation experiments were designed to simulate tailings stack exposed to periods of continuous drying and precipitation event(s) within a drying cycle, respectively. For the drying cycle, the packed tailings columns were desiccated under AW and SW boundary conditions (henceforth referred to as “DRY(SW)” and “DRY(AW)”, respectively). The column experiments for the contrasting boundary conditions were conducted sequentially. The dry-wet-dry cycle desiccation experiment (hereafter referred to as “REWET”) was conducted under

Figure 6.04. Schematic diagram showing dimensions of petroleum jelly wax column used for packing and drying thickened tailings.

simulated wind, but with the tailings column re-saturated on day 11 after the onset of drying. The desiccating replicate tailings columns were re-wet by instalment addition of 150 ml of distilled water over a period of 3.5 hours, to mimic a daily total precipitation event of 267mm. The high precipitation event was simulated to ensure that the desiccating tailings columns were sufficiently re-saturated. The re-saturated tailings columns were then left to dry for additional 14 days, during which destructive profile sampling was periodically conducted.

6.3.2.4 Multi-layer Desiccation Test for Thickened Tailings

In order to simulate the sequential deposition of thickened tailings stacks, two sets of multi-layer desiccation tests were conducted under SW boundary condition. The multi-layer drying tests comprised of the sequential deposition of 3 and 5 layers of 12cm-thick thickened tailings lifts inside plastic columns with dimensions as shown in Figure 6.05. The 3-layer drying test (henceforth referred to as 3-LAYER) was conducted inside a plastic container with height and internal diameter of 37 cm and 29cm, respectively. The height and i.d of the plastic container for the 5-layer drying test (henceforth referred to as 5-LAYER) was 75 and 33cm, respectively. At the start of the multi-layer drying test, a sampling core (12cm high, 7cm i.d) was placed inside the plastic container followed by pouring a 12cm-thick lift of fresh thickened tailings, with the bore of the core filled simultaneously. As was the case with the tailings columns, the fresh lift would settle to about 10cm after few hours of deposition. The plastic container, together with the sampling core and thickened tailings deposit were placed on an electronic scale to monitor the daily evaporation from the stack over the duration of the desiccation experiment. One oscillating fan each was placed at a height of 0.68 and 0.30m from the top of the container for the 3-LAYER and 5-LAYER desiccation test, respectively, to simulate wind for driving evaporation. Similar columns were filled with distilled water to comparable depths for concurrent determination of PE throughout the two multi-layer drying tests.

The sampling core was retrieved from the desiccated tailings layer once the GWC was below 12%, and the intact tailings core sample retrieved from the sampling core. The intact tailings core was destructively sampled immediately after retrieval to obtain 1cm-thick profile samples according to the procedure previously described for the tailings columns. Evaporative loss from the intact core was minimized by keeping samples inside sealed Ziploc bags and immediately processing the core samples as soon as they were extracted. Another empty sampling core was placed at a different location on top of the desiccated tailings layer and a fresh lift of tailings was poured on the old layer covering the sampling core. The cavity left from retrieval of the last sampling core from the old tailings layer was plugged with fresh material during the deposition of subsequent lift. The sequential deposition of multiple lifts of thickened tailings was continued until the last layer had dried and the final tailings core sample had been retrieved and destructively sampled. At the end of the multi-layer drying, the entire desiccated stack was sampled at depths of 0-5, 10-15, 15-20, 20-25 and 25-30cm for the 3-LAYER, and depths of 0-5, 10-15, 20-25, 30-35 and 40-45cm for the 5-LAYER tailings stack.

6.3.2.5 Experimental Conditions, Sampling and Sample Analyses for Desiccating Thickened Tailings

The tailings column desiccation experiments (DRY(SW), DRY(AW) and REWET) each consisted of a total of 9 replicate columns prepared at the onset of the experiment. For each experiment, an additional wax column was filled with distilled

water for concurrent determination of daily PE. The replicate tailings and PE columns were left open to ambient temperature and lighting, but with and without simulated wind for the SW and AW boundary conditions, respectively. The ambient temperature and RH throughout the tailing column and multi-layer desiccation experiments were recorded using a USB-502 RH/Temperature Data Logger (Measurement Computing, Norton, MA). The ambient temperature and RH data are presented in Figure 6.06. During the desiccation experiments, potential evaporation (PE) rate ranged between 12 to 20 and 3 to 6 mm /day for the SW and AW boundary conditions, respectively. For all tailings column desiccation experiments (DRY(SW), DRY(AW) and REWET), one replicate

Figure 6.05. Schematic of multi-layer thickened tailings drying tests.

column was destructively sampled as previously described on select days for profile analyses. Prior to destructive sampling of a tailings column, the daily AE was determined by mass difference over the previous 24 hours. In the case of the multi-layer tailings desiccation tests, the intact tailings core retrieved at the end of the desiccation of an old layer was also destructively sampled for profile analyses. Similar to the tailings columns, AE and PE were determined by mass difference over 24 hour period of the columns containing tailings and distilled water, respectively. The PE recorded for the duration of the multi-layered desiccation tests was relatively lower compared to the DRY(SW) and REWET tailings column, with values ranging between 8 to 17 and 5 to 14mm/day for the 3-LAYER and 5-LAYER tests, respectively. The difference in evaporative demand can be attributed to the generally higher ambient RH for the multi-layer desiccation tests in comparison with the DRY(SW) and REWET tailings desiccation experiments (Figure 6.06).

Profile samples were kept and manually homogenized inside Ziploc plastic bags prior to analysis, with excess air expelled to minimize possible oxidation of constituent sulphide minerals. Subsamples of the homogenized tailings were taken for electrical conductivity (EC), GWC, and total suction analyses. EC analysis involved extracting 1 part of subsample with 4 parts of deionised water with an orbital shaker (175 rpm for 30 minutes), followed by centrifuging at 3000rpm ($1000 \times g$) for 2.5 minutes. The EC of the resulting supernatant was determined with a previously-calibrated Traceable Conductivity Meter (VWR International, Friendswood, TX). The EC of the tailings pore water was obtained by multiplying the EC of supernatant by the corresponding dilution

Figure 6.06. Ambient temperature and relative humidity for the DRY(AW and SW), REWET and multi-layer tailings desiccation tests.

factor that accounts for the GWC of the tailings profile sample. GWC of the profile samples were determined by difference in mass after oven drying at 105°C for 24 hours. The total suction of samples was determined with a WP4-T Dewpoint Potential Meter (Decagon Devices Inc., Pullman, WA). Also, the osmotic suction in the top 1cm of the tailings stack was calculated from the pore-water EC data using the USDA (1954) approximation given by:

$$\psi_o = 0.36 * EC * 101.325 \quad (6.09)$$

Where ψ_o is osmotic suction (kPa) and EC is the tailings pore-water electrical conductivity (mS/cm). The pore-water EC may be obtained from either the saturated extracts (such as was done for the current study) or the pore-squeeze extracts of the soil (using a pore squeezer to extract the natural pore fluid of a soil sample). Recent study (Abedi-Koupai and Mehdizadeh 2008) have shown that equation 6.09 may potentially over-estimate the osmotic suction of soil using the saturated extract method due to the somewhat non-linear correlation of EC with osmotic suction, especially for fine-grained soils (such as clay). On the other hand, the pore-squeeze extract method is known to give more accurate estimations of osmotic suction (Krahn and Fredlund 1972). However, the saturated extract method was chosen for the current study due to the inability to squeeze out sufficient pore solution from the limited profile sample sizes obtained from the tailings columns.

6.3.2.6 Numerical Predictions of Salinity-induced Reduction in Evaporation for Desiccating Thickened Tailings Columns and Multi-layer Deposits

Numerical modeling was undertaken to calibrate an unsaturated flow model that allows accounting for the effect of pore-water salinity on desiccation of tailings against laboratory data. The calibration was intended to evaluate how well the model can simulate evaporative densification in saline thickened tailings, and also for the purpose of using the numerical code for exploratory modeling as was done later in this paper. Evaporation from the desiccating thickened tailings (both columns and multi-layer deposits) was modelled using a commercial 1D finite element (FEM) code, SVFlux, from SoilVision Systems Ltd (Saskatoon, SK). The numerical code utilizes a generic FEM algorithm called FlexPDE™ that is capable of handling the highly non-linear behaviour characteristic of unsaturated soils. SVFlux models the 1D flux of water both in the liquid and vapour phases, assuming isothermal conditions. The FlexPDE™ algorithm solves the combined governing PDE for liquid water and water vapour fluxes, previously given in equation 6.06.

Though the numerical code has an in-built capacity for automatic mesh generation and refinement as well as adaptive time stepping, a minimum time step and mesh size of 30 minutes and 0.001m, respectively, was specified. A single domain was specified for the DRY(AW), DRY(SW) and REWET tailings columns for the entire duration corresponding to that of the respective desiccation experiments conducted in the laboratory. In contrast, for the multi-layer tests (3- and 5-LAYER), several domains

(regions), each being an equivalent of the individual stack layer, were specified in the simulations. The thickened tailings tested in this paper is known to undergo hindered settling just hours after deposition (Simms et al. 2007; Fisseha et al. 2010) to a minimum water content of around 34%. In order to generate an equivalent of this bleed water in the simulation, the procedure in Fisseha et al. (2010) was followed: an initial uniform positive pore-water pressure distribution and m^w values (equation 6.06) of 3kPa and 0.03kPa^{-1} were specified, respectively for a fresh layer. In the case of the multi-layer tests, the final matric suction profile for a desiccated layer was specified as the initial condition for the same layer when modeling the placement of a fresh layer. Though no bleed water was observed on top of stack during the placement of fresh tailings on a desiccated layer as a result of the inter-layer transmission of water, the bleed water was still simulated in the numerical code as previously described.

For all simulations, a zero flux lower boundary condition as well as a top climatic boundary condition was specified for all column and multi-layer tailings deposits. The climatic boundary condition models evaporation rate as a function of total suction at the tailings surface, as expressed in equation 6.03 (Wilson et al. 1997). The total suction at the surface of tailings modelled by SVFlux solving the unsaturated flow PDE (equation 6.06) is used in equation 6.03 to predict actual evaporation after being adjusted using a correction factor. The value of correction factor used for all simulations was -0.65, except for the DRY(AW) tailings column where a value of -0.5 was specified (please refer to Section 5.3.4 of Chapter 5 in this Thesis for more details). The correction factor is built

into SVFlux to ensure numerical stability and agreement between predictions of evaporation and laboratory data, with possible values ranging from 0 to -2 (Fredlund et al. 2011). The choice of -0.65 and -0.5 for the current study was to provide the closest agreement between predictions of evaporative fluxes and laboratory measurements for the tailings columns. No boundary condition was set between a desiccated tailings layer and a fresh tailings deposit in the case of the multi-layer desiccation tests as the two layers are not hydraulically isolated. Daily measurements of PE from corresponding column and multi-layer tailings desiccation experiment was entered into the numerical code in addition to the ambient RH and temperature recorded throughout the test.

The unsaturated flow code was initially set up by the proprietor such that the initial osmotic suction at the surface of tailings could be specified in a simulation. This input value of osmotic suction was assumed to be constant throughout the desiccation period and added to matric suction modelled at the surface to obtain the total suction used to predict RE. However, since evaporation-driven advective transport in the current tailings test is expected to lead to increase in osmotic suction at the surface over time, there was need to account for this temporal increase in osmotic suction. The proprietor of the numerical code was consulted and the capability to enter temporal osmotic suction data at the surface of tailings was added to SVFlux. Thus, the temporal osmotic suction data estimated from the pore-water EC data measured in the top 1cm of tailings column (using equation 6.09) were input into the numerical simulations. The maximum value of osmotic suction input into the numerical code was taken to be the

value at which measured pore-water E.C in the top 1cm began to decrease following a prior trend of sustained increase in EC. This maximum osmotic suction value was maintained for the remaining days of the simulation; beyond the solubility limit (when maximum osmotic suction is recorded), osmotic suction is expected to remain unchanged.

The soil water characteristic curve (SWCC) as presented in Figure 6.03 was entered into the numerical code, as well as the saturated hydraulic conductivity of the thickened tailings obtained from falling head test (Table 6.01). Upon rewetting a desiccated layer (by placement of a fresh lift of thickened tailings), the stack is unable to reach the initial GWC for fresh tailings due to permanent volume change. Thus, in modeling the desiccated layers for the multi-layer tests, the SWCC that accounts for permanent volume change was used for the old layer as per Fisseha et al. (2010). The hydraulic conductivity function, ($K^w(\psi)$) of the fresh tailings layer was estimated with the indirect method of Mualem-van Genutchen (Van Genutchen 1980) using the drying SWCC of the tailings that accounted for shrinkage during desiccation as per Fisseha et al. (2010). The generated hydraulic conductivity function (presented as relative hydraulic conductivity function in Appendix B1) was then manually input into SVFlux and applied for the fresh tailings layers. The $K^w(\psi)$ for the desiccated layer was estimated using the Fredlund et al. (1994) method from the K_{sat} and the modified SWCC that accounted for permanent volume change fitted with the Fredlund and Xing (1994) equation. More details of this procedure can be found in Simms et al. (2007).

6.4 Results and Discussion

6.4.1 Profiles of Electrical Conductivity and Total Suctions for Desiccating Tailings

Columns and Multi-layer Deposits

The temporal profiles of EC for the desiccating thickened tailings columns for all three treatments- DRY (AW), DRY (SW) and REWET are presented in Figures 6.07a, 6.08a and 6.09a, respectively. Relative to other depths, EC in the top 1cm of the columns increased rapidly for the DRY (AW), DRY (SW) and REWET treatments, with rate and magnitude of increase higher for the SW compared to AW column. The maximum EC for the DRY tailings columns was observed in the top 1cm on day 14 for both the AW and SW boundary conditions. The sharp decline in EC on day 15 for the SW tailings column can be attributed to back-diffusion, whereby surface-accumulated salt diffuses in the direction opposite to unsaturated water flow in response to a steep concentration gradient (Elrick et al. 1994; Fujimaki et al. 2006; Fisseha et al. 2010). The osmotic suctions corresponding to the maximum EC in the top 1cm of the DRY(AW) and DRY(SW) tailings columns estimated using the USDA (1954) equation are 2.88 and 34.50 MPa, respectively. If representative of the pore-solution's chemistry, such maximum value would delineate an upper limit to the contribution of osmotic suction to reduction in evaporation over the 15-day drying period. Hence, the significantly higher maximum osmotic suction for the DRY(SW) tailings column is expected to translate into a larger reduction in its evaporative densification.

Figure 6.07. Profiles of pore-water electrical conductivity (a), total suction (b) and gravimetric water content (c) over time for the DRY (AW) thickened tailings columns.

Figure 6.08. Profiles of pore-water electrical conductivity (a), total suction (b) and gravimetric water content (c) over time for the DRY (SW) thickened tailings columns.

Figure 6.09. Profiles of pore-water electrical conductivity (a), total suction (b) and gravimetric water content (c) over time for the REWET thickened tailings columns. Tailings columns were re-saturated on day 11 immediately after destructive sampling.

Similar trend of accumulation of salts at the surface was recorded for the REWET tailings columns (Figure 6.09a). Prior to and after re-saturating the tailings columns, modest increases in EC was observed at depths below 1cm, with increasing non-uniformity in profile EC as desiccation progressed, especially after rewetting. The EC dropped to the as-deposited value immediately after re-saturation, but the rate of increase in EC progressed more rapidly afterwards, faster than when the columns was initially drying, especially in the top 1cm. This pattern for the REWET tailings column is consistent with “precipitation” re-dissolving and pushing back salt previously accumulated at the surface, but not far down the profile enough such that the trend was quickly reversed by evaporation-driven advection. The peak EC in the top 1cm of the REWET columns prior to rewetting was higher compared to after rewetting, and the difference between EC in the top 1cm and the rest of the profile was also higher prior to rewetting (Appendix C1). Hence, it seemed that rewetting facilitated the redistribution of salt within the profile and reduced the maximum solute concentration at the surface of tailings column relative to the rest of the profile. Back-diffusion was also observed both prior to and after rewetting the tailings columns.

The highest EC was also recorded in the top 1cm of the multi-layer tailings stacks (Figures 6.10a and 6.11a), with generally smaller magnitudes compared to the DRY(SW) (Figure 6.08a). This can be attributed to the drier ambient conditions for the latter (average RH of 18%) compared to the former (Figure 6.06; average between 44-50%) translating into a higher evaporative demand and solute accumulation in the latter.

Figure 6.10. Profiles of pore-water electrical conductivity (a), total suction (b) and gravimetric water content (c) over time for the 3-LAYER thickened tailings stack.

Figure 6.11. Profiles of pore-water electrical conductivity (a), total suction (b) and gravimetric water content (c) over time for the 5-LAYER thickened tailings stack.

Similar to the REWET tailings columns, the difference between the EC in the top 1cm and corresponding values at depths below 1cm consistently reduced with subsequent deposition of fresh layer (Appendix C2). Hence, deposition of fresh lifts of tailings on an older stack had a similar effect as rewetting desiccated tailings columns. In contrast to the pattern of salt accumulation in the top 1cm of the multi-layer stacks, sampling the entire stack at the end of the desiccation experiment showed a more uniform solute distribution throughout the entire profile, especially for the 5-LAYER stack (Appendix C3). This is because the EC values in Appendix C3 represent the respective averages for the 5cm-thick profile bulk samples obtained from the entire stack at end of drying.

The periodic profiles of total suctions for the DRY(AW), DRY(SW) and REWET tailings columns (Figures 6.07b, 6.08b and 6.09b) generally corroborated the observations made with respect to the EC data. The maximum total suction observed on day 14 for the DRY(SW) column (49.92MPa) was mostly contributed by osmotic suction (accounting for about 75% of total suction measured). In fact, for the most part, osmotic suction contributed the more significant proportion of the high total suction values measured in the top 1cm of the DRY(SW) and REWET tailings columns (Appendix C4). However, for the DRY(SW) and REWET tailings, the true contribution of osmotic suctions may be lower than values computed from EC data as these values for both the pore solution and precipitated salt. Hence, the contribution of matric suction to the total suction recorded for the DRY(SW) and REWET tailings columns may be higher than

suggested by the balance of the proportion accounted for by the osmotic suctions estimated from EC data.

The rate and magnitude of increases in total suction for the REWET tailings columns was higher after re-saturation compared to prior (Appendix C5). This pattern is consistent with the “pushing back” effect of infiltrating water on surface-accumulated salt and subsequent rapid reversal of the direction of solute transport due to evaporative pull. Similar trend of surface salt accumulation was observed for the multi-layer tailings stacks as shown by total suction profiles in Figures 6.10b and 6.11b. Similar to the REWET columns (Appendix C5), the magnitude of differences between the total suction in the top 1cm and values at depths increased after the placement of the second layer for both the 3-LAYER and 5-LAYER stacks (Appendix C6).

6.4.2 Profile Desiccation of Tailings Columns and Multi-layer Deposits

The profiles of gravimetric water contents (GWC) for the DRY(AW), DRY(SW) and REWET tailings columns (Figures 6.07c, 6.08c and 6.09c) showed a more rapid dewatering for the DRY(SW) compared to the DRY(AW) columns. There was about 75% reduction in the as-deposited GWC over the first 5 days of drying for the DRY(SW) tailings columns compared to correspondingly smaller (25%) reduction for the DRY(AW) columns. This pattern is consistent with the significantly higher evaporative demand during the desiccation of the DRY(SW) compared to the DRY(AW) tailings columns.

Considering that the GWC in the top 1cm of the DRY(SW) columns by day 11 were within the residual water range (Figure 6.03), the additional contribution from matric suction to the high total suctions recorded would be confirmed. The G.W.C in the top 1cm of the DRY(SW) column on days 11, 14 and 15 (2.08, 1.67 and 4.55%) corresponds to matric suction values of 7, 12.5 and 1.3MPa, amounting to 41, 25 and 17% of the corresponding total suctions. Despite these substantial contribution from matic suction, osmotic suction still constituted the major proportion of total suctions measured for the DRY(SW) tailings column.

Similar rapid profile dewatering (to DRY(SW)) was observed for the REWET tailings columns both prior and after re-wetting (Figure 6.09c). As was the case in DRY(SW), an increase in profile GWC on the last day of drying was observed for the REWET column, coinciding with the back-diffusion of pore-water solute on respective last days. This reverse pattern of GWC may be due to water transport by osmosis that has been previously associated with back-diffusion mechanism (Barbour and Fredlund 1989). In contrast to some non-uniformity in profile GWC for the DRY(SW) and DRY(AW) tailings columns, the REWET tailings columns exhibited uniform profile drying consistent with the solute re-distribution due to rewetting.

The profile GWCs measured for all layers of the 3-LAYER and 5-LAYER tailings columns just prior to fresh lift deposition are presented in Figures 6.10c and 6.11c, respectively. Drying occurred rapidly for the first layer for both multi-layer tests, with

similar scales of reduction in both tests. For the 3-LAYER, further profile drying was observed for both layers 2 and 3, while additional drying achieved by placement of layer 2 was reversed by subsequent lifts for the 5-LAYER stack. This reversal may be due to the somewhat decreasing duration of drying layers 1, 2, 3, 4 and 5 (10, 14, 7, 7 and 11 days) for the 5-LAYER tailings stack. The reader is reminded that a layer of desiccated tailings was destructively sampled when the GWC in the top 1cm was lower than 12%. The profiles of GWC were uniform for entire stack depth for all multi-layer tests (Figure 6.10c and 6.11c), similar to observations for the REWET column. Also, the profile GWC for the entire stack after desiccation for both multi-layer deposits were similar to the corresponding profile for the top 10 cm. These observations further strengthens the hypothesis that percolating water from fresh tailings deposit facilitates uniform solute distribution and uniform profile drying of the tailings stack.

6.4.3 Comparison of Measurements and Numerical Predictions of Evaporative Fluxes from Thickened Tailings Columns and Multi-layer Deposits

The numerical predictions and measurements of evaporation from the thickened tailings columns are presented in Figure 6.12, with higher fluxes recorded for the DRY(AW) compared to the DRY(SW) tailings columns. The DRY(AW) column showed small and gradual decrease in fluxes over time unlike the DRY(SW) that exhibited rapid drop in fluxes. The REWET columns also exhibited a rapid drop in AE, falling to a low and somewhat constant value in just 6 days of drying (Figure 6.12), after which AE picked up

Figure 6.12. Actual evaporation rates measured from DRY (AW), DRY (SW) and REWET thickened tailings columns and predictions from SVFlux with and without accounting for the temporal increase in osmotic suction in the top 1cm.

when the desiccated layer was rewetted. The AE rapidly dropped afterwards to a residual value similar to prior rewetting.

As shown in Figure 6.12, when the temporal increase in osmotic suction in the top 1cm of the tailings columns was accounted, numerical predictions of AE agreed well with observations, with the exception of between days 6 and 9 for the DRY(SW) column. This good prediction was replicated for both dry and dry-wet-dry cycles. Numerical predictions of AE were slightly over-predicted when osmotic suction was not accounted for. However, the predictions of AE were not substantially sensitive to osmotic suction due to the low initial salinity of the tailings, which in turn resulted in comparatively low osmotic suction values that were input into SVFlux (Appendix C7). As a result, matric suctions predicted at the surface were substantially high such that accounting for osmotic suction did not make such significant difference in predicted total suctions (Figures 6.13 and 6.14) as to force predicted AE to be substantially lower than when osmotic suction was not accounted for. This is in contrast to the salinized soil columns in Chapter 5 of this thesis, with higher initial pore-water salinity and osmotic suction values (Appendix B2), making AE predictions to be sensitive to osmotic suction (Figure 5.24, Chapter 5). Hence, accounting for temporal increases in osmotic suction at the surface of desiccating tailings becomes more important as the initial pore-water salinity increases. Nevertheless, it is worth noting that accounting for osmotic suction gave predictions of total suctions that generally better match experimental data (Figures 6.13 and 6.14).

Figure 6.13. Total suctions predicted at the surface (0cm) of desiccating DRY(SW) tailings column and input over time by SVFlux (before applying the suction correction factor) to predict evaporation for simulations with and without accounting for osmotic suction. Sum of matric suctions predicted at the surface of tailings column by SVFlux and osmotic suction estimated from EC data and input into SVFlux is shown for the simulation that accounted for osmotic suction. Only the matric suctions predicted for desiccating tailings by SVFlux is shown and used for prediction of evaporation by the simulation that did not account for osmotic suction. The raw osmotic suctions in the top 1cm of tailings column estimated from EC data-Data(osmotic) are also presented. Values are shown on (a) logarithm and (b) linear scales.

Figure 6.14. Total suctions predicted at the surface (0cm) of desiccating REWET tailings column and input over time by SVFlux (before applying the suction correction factor) to predict evaporation for simulations with and without accounting for osmotic suction. Sum of matric suctions predicted at the surface of tailings column by SVFlux and osmotic suction estimated from EC data and input into SVFlux is shown for the simulation that accounted for osmotic suction. Only the matric suctions predicted for desiccating tailings by SVFlux is shown and used for prediction of evaporation by the simulation that did not account for osmotic suction. The raw osmotic suctions in the top 1cm of tailings column calculated from EC data-Data(Osmotic) are also presented. Values are shown on (a) logarithm and (b) linear scales.

The trend in measured AE from the multi-layer tailings stacks showed that the rewetting of desiccated stack due to placement of fresh lift is well captured as shown in Figure 6.15. During the laboratory experiment, very small or no bleed water was recorded following the placement of a fresh lift on a desiccated layer, in contrast to bleed water persisting for 1-3 days when the first layer was placed. This behaviour is expected as the inter-layer transmission of water from the fresh to the desiccated layer. Numerical predictions of AE agreed well with data for both multi-layer deposits. Similar to the columns, predictions of AE were not sensitive to osmotic suction but better predictions of total suction were obtained when osmotic suction was incorporated.

As shown by the comparison of measured and predicted total suctions in the top 1cm of the DRY(AW), DRY(SW) and REWET tailings columns (Figure 6.16 and Appendix C8), using the correction factor, c , and accounting for osmotic suction ensured agreement. Hence, not only is the prediction of evaporation improved by incorporating osmotic suction and applying the suction correction factor, so also is the prediction of total suction in the top 1cm. This is in line with the work of Fredlund et al. (2011) which reported that without applying ' c ' to adjust the total suction used to predict AE in SVFlux using equation 6.03, predictions agreed poorly with data. Simms et al. (2007) also noted that despite its reasonable prediction of evaporation, a non-isothermal unsaturated flow code (SoilCover) qualitatively over-predicted matric suctions for a desiccating tailings deposit just few days after drying. The current study has demonstrated that using the surface suction correction in SVFlux as well as accounting for the increase in

osmotic suction due to evaporation-driven advection of pore- water solute ensured better agreement of predictions to measured evaporation and total suction.

Figure 6.15. Actual evaporation rates measured over time from the 3-LAYER and 5-LAYER thickened tailings deposits and corresponding numerical predictions from SVFlux with and without accounting for the temporal increase in osmotic suction in the top 1cm.

Figure 6.16. Total suctions measured in the top 1cm of the DRY(AW), DRY(SW) and REWET tailings columns with corresponding numerical predictions by SVFlux with and without applying a surface suction correction factor. Also shown are the raw osmotic suctions estimated for the top 1cm of columns from the EC data.

Therefore, it can be concluded that the proposed numerical framework predicted both evaporation and total suction at the surface of the desiccating saline thickened tailings well when the following were accounted for:

- (i) Self-weight consolidation of the thickened tailings after deposition of fresh layer;
- (ii) Temporal increase in osmotic suction due to salt accumulation at the surface of deposit as it dried;
- (iii) The hydraulic conductivity function obtained using a SWCC that accounted for the shrinkage of the thickened tailings layer as it desiccated was utilized;
- (iv) A correction factor was incorporated in SVFlux to adjust the total suction that is used to compute the relative humidity within the soil atmosphere at the surface.
- (v) In the case of multi-layer deposit, the permanent volume change of underlying layer was accounted for in modeling the placement of the new layer.

6.4.4 Comparison of Measurements and Numerical Predictions of Profile Gravimetric

Water Contents of Thickened Tailings Columns and Multi-layer Deposits

Measured and predicted profiles of GWC on select days and temporal trends at 3 depths of the DRY(SW) and DRY(AW) columns are shown in Figure 6.17 and Appendix C9, respectively. Predictions agreed with data on select days (Figure 6.17) and at all 3 depths (Appendix C9) of the DRY(AW) columns, consistent with results for evaporation (Figure 6.12) and total suction (Figure 6.16). The numerical code also predicted well the uniform distribution of profile GWC as per measurements (Figure 6.17). For the DRY(SW) columns, predictions of profile GWC did not agree with observations on selected days (Figure 6.17). Also, the observed uniform profiles of GWC were not well predicted. Agreement with observed reduction in GWC was restricted to the top 1cm only (Appendix C9), otherwise, GWC at depths below 1cm was over predicted (Figure 6.17 and Appendix C9). This over-prediction may be attributed to two reasons. One is the uncertainties associated with fitting SWCC using pedo-transfer functions, PTFs (Mingbin et al. 2010), especially at the residual water content range of the soil or tailings. Secondly, the numerical code assumes a very sharp gradient of matric suction at the tailings surface, given the high evaporative demand for the DRY(SW) columns. In coupled soil-atmospheric modeling, evaporation creates a steep suction gradient at the surface. SVFlux has the in-built option of using an empirical correction factor to adjust the total suction used to calculate the RH at the soil surface (SoilVision Systems Ltd 2008). Based on the matric suction predicted at the tailings' surface from the numerical

solution of the unsaturated flow equation (Equation 6.06) as well as the SWCC of the material fitted with a PTF, the GWC is then inferred.

Figure 6.17. Profiles of gravimetric water contents measured (D) and predicted by SVFlux (P) on select days for the DRY(AW) and DRY(SW) thickened tailings columns.

To this end, the REWET tailings column was simulated with and without using 'c' and the result is presented in Figure 6.18. The comparison of predictions to measurements is also presented as time series at select depths in Appendix C10. Without applying 'c', the predictions of profile GWC slightly agreed better with data- relative to predictions with 'c' applied, measured GWC is lower (Figure 6.18 and Appendix C10). However, predictions of AE were poorer agreement when 'c' was ignored (Appendix C11a). Hence, on balance, the best predictions of cumulative AE and total suction were obtained when 'c' was applied and osmotic suction was accounted for (Appendix C11a). On the other hand, the best predictions of profile GWC was observed when 'c' was excluded but the osmotic suction was accounted for (Appendix C12).

As shown by the profiles of GWC at the end of desiccating each layer for the multi-layer deposits (Figure 6.19), profiles of GWC were grossly under-predicted in the top few centimeters and over-predicted at depths. This under-prediction at the surface can be explained as per previous discussion, while the over-prediction is consistent with the under-prediction in the top of the stacks. However, when the GWCs were averaged over the entire profile, better overall agreement between predictions and laboratory data was obtained for both the 3-LAYER and 5-LAYER stacks (Appendix C13). This observation will be in sync with the predictions of evaporation from the multi-lift deposits being in good agreement with laboratory observations.

Figure 6.18. Profiles of gravimetric water contents measured (D) and predicted by SVFlux on select days for the REWET thickened tailings columns. Predictions with (CF) and without (NCF) using a surface suction correction factor are shown as solid and broken lines, respectively.

Based on the optimization of numerical predictions for the SW tailings column in Chapter 5 (Section 5.4.5.4), supplemental simulation of the 5-LAYER tailings deposit was run using half the value of suction correction factor ($c=-0.33$) and K_{sat} value that is 1 order of magnitude higher ($2 \times 10^{-6} \text{ m/s}$) than previously used. The results of the predictions of AE and profiles of GWC at the end of desiccation for each of the 5 layers are presented in Appendix C14. It is shown that the predictions of AE when osmotic suction is accounted for (Appendix C14a) is slightly, but not substantially different compared to when osmotic suction was not included - similar to result previously presented in Figure 6.12. However, the profiles of GWC seemed more uniform

Figure 6.19. Profiles of gravimetric water contents measured (D) and predicted (P) at the end of desiccation of a layer for the 3-LAYER and 5-LAYER thickened tailings deposits. Each layer is numbered (e.g. L1 and L2 designates Layer 1 and Layer 2, respectively) accordingly.

(Appendix C14b) when compared to the previous profiles of GWC (Figure 6.19). It is important to note that though using the different values of “c” and K_{sat} produced a more

uniform profile distribution of GWC, the predicted average profile GWC is not substantially affected (the mean absolute error for all 5 layers is 23 and 26% for the previous and supplemental simulation, respectively). Hence, accounting for osmotic suction and applying 'c' ensures good prediction of both AE and profile GWC for the multi-layer tailings deposits.

From the foregoing, implementing the proposed numerical framework within the unsaturated flow code (SVFlux) is shown to give good predictions of evaporative fluxes and total suction as well as reasonable prediction of profile GWC for the thickened tailings deposits over different lengths of desiccation period (15 – 50days). The robustness of the numerical code is demonstrated for different deposition scales (small wax column and “large” column tests), prevailing evaporative demand (AW and SW) and hypothetical field scenarios (dry and dry-wet-dry cycles as well as multi-layer deposition). Therefore, having calibrated the numerical code, exploratory modeling of different field deposition configurations (varying deposit thicknesses) and field deposition strategies (multiple thin lifts versus single deep deposit) was undertaken. Also, the sensitivity of numerical predictions to the specific material property of saturated hydraulic conductivity of the modelled thickened tailings was assessed. In addition, a preliminary evaluation of the effectiveness of the “capillary barrier” concept to slow down the rate of surface salt accumulation and reduce the extent of salinity-induced reduction in evaporative densification was conducted. The following section provides details of the exploratory modeling, as well as the results obtained.

6.4.5 Exploratory Numerical Modeling of Evaporative Densification of Thickened Tailings Deposit

The goal of the exploratory modeling was to simulate field conditions as well as evaluate the implications of various depositional management options on the rate of evaporative densification of saline thickened tailings deposits. In addition, a 1D transient FEM solute transport code coupled to the unsaturated flow code was calibrated with experimental data and used to assess the effectiveness of a sand capillary barrier in reducing the surface accumulation of salts in desiccating thickened tailings deposits.

6.4.5.1 Sensitivity of Numerical Prediction of Evaporative Densification to the Saturated Hydraulic Conductivity and Lift Thickness of Thickened Tailings Deposit

Numerical simulations of evaporative fluxes for the DRY(SW) and REWET tailings columns were conducted as previously described, but with two different K_{sat} values assigned for the thickened tailings. These were 2×10^{-9} and 2×10^{-5} m/s, being 2 orders of magnitude lower and higher, respectively, compared to the value (2×10^{-7} m/s) measured from laboratory falling head tests that had been used for previous simulations in this paper. The input unsaturated hydraulic conductivity function [$K^w(\psi)$ in equation 6.06] was adjusted accordingly to reflect these changes in K_{sat} values. The resulting predicted RE values compared in Figure 6.20 show that for both DRY(SW) and REWET columns, the lower K_{sat} resulted in an earlier prediction of the onset of Stage II evaporation compared to predictions with K_{sat} from falling head test. In contrast, a

Figure 6.20. Numerical predictions of Relative Evaporation for the DRY(SW) and REWET thickened tailings columns for varying saturated hydraulic conductivity values (Low- 2×10^{-9} m/s; Falling Head- 2×10^{-7} m/s; High- 2×10^{-5} m/s) and lift thicknesses (15 and 50cm).

higher K_{sat} resulted in the predicted onset of Stage II evaporation being delayed. The higher K_{sat} depicts a less restrictive ability of the tailings to deliver water needed for driving evaporation, prolonging Stage I evaporation and delaying the onset of Stage II compared to the low K_{sat} value. Hence, the lower the K_{sat} would imply a longer time for the deposit to reach a target water content and shear strength. A significantly higher rate of profile dewatering for the high K_{sat} compared to the low K_{sat} predictions (Appendix C15) was in fact predicted. This sensitivity of numerical predictions to the K_{sat} is similar to observations made by Simms et al. (2009). The observation from the current study further emphasizes the need for sufficient material characterization in better predicting evaporative densification of deposits under a given set of site, depositional and environmental conditions.

The sensitivity of numerical predictions of evaporation to deposit thickness is similar to that of K_{sat} , with a thicker deposit (50cm) prolonging Stage I and delaying the onset of Stage II evaporation (Figure 6.20). This thicker deposit presents a larger water reservoir per unit cross sectional area, and given the same K_{sat} and in the absence of surface or salt crust, water supply is sustained longer compared to a thinner (15cm) deposit. The implication is that the rate of profile dewatering for the thinner DRY(SW) tailings column is considerably higher compared to the thicker lift (Figure 6.21). Based on the profile averages of the simulated GWC for the 2 lift thicknesses (Appendix C16), it would take 25 days for the thicker deposit to attain the shrinkage limit (20%) for the thickened tailings compared to 5 days for the thinner deposit. Hence, it would take 5

Figure 6.21. Numerical predictions of profile gravimetric water contents for 15cm and 50cm lifts of the DRY(SW) thickened tailings over a period of 15 days.

times the cycle time required for a 15cm lift to achieve an equivalent target average profile water content if 3.3 times thicker (50cm) lift was deposited instead.

A supplemental numerical analysis was conducted to evaluate the effectiveness of placing multiple thin lifts of tailings as opposed to placing an equivalent thickness in a single lift. Placement of 5 successive lifts, each 20cm thick was simulated, drying each multi-layer to an average profile GWC that is approximately the shrinkage limit of the thickened tailings. An equivalent single lift of 100cm thick deposit was also simulated and allowed to dry until the average profile GWC reached the shrinkage limit. The results are presented in Figure 6.22, showing that it took a total of 26 days (5, 6, 5, 5 and 5 days for Layer 1, multi-layers 2, 3, 4 and 5, respectively) to achieve the shrinkage limit by thin-lift deposition, compared to more than 90 days for the 1m deep single deposit. This superior dewatering performance can be attributed to the shorter drainage path for evaporation as well as the enhancement of the dewatering of the fresh layer due to its hydraulic interaction with the older desiccated layer in line with observation by Fisseha et al. (2010). The foregoing underscores the significance of adopting an optimum lift thickness to reduce the cycle time between deposition operations for tailings facilities where meeting tonnage processing objectives is often one of the most (if not the most) important driver for deposition planning. This is particularly important when the primary mechanism relied on for densification is evaporative forcing. Also multi-layer deposition of thin lifts of thickened tailings is demonstrated to be better than deposition of a single deep deposit. Therefore, for tailings management facilities where operational logistics

for frequent placement of material into a deposition cell is not a constraint, thin-lift multi-layer deposition may be a viable alternative to reaching a shear strength target within the shortest drying time possible.

Figure 6.22. Numerical predictions of the profile gravimetric water contents for 5 successive lifts each 20cm thick as well as the profile of GWC for a single lift of 1m deposit. The respective time taken to dry each layer or multi-layer to an average profile GWC of 20% (shrinkage limit of thickened tailings) is indicated inside the text box.

6.4.5.3 Numerical Evaluation of Effectiveness of Capillary Barrier to Slow down Surface Salt Accumulation in Saline Thickened Tailings Deposit

A commercial 1D solute transport numerical code (ChemFlux) from the same proprietor (SoilVision Systems Ltd) as SVFlux was used to predict the accumulation of salt for the DRY(SW) and REWET thickened tailings columns. Like SVFlux, ChemFlux is a transient 1D FEM that uses the same solver algorithm as the former (FlexPDE) to solve the PDE for solute transport for concentration, C (equation 6.07) in both temporal and spatial domains. ChemFlux is fully coupled to SVFlux, with the two PDEs (equations 6.06 and 6.07, respectively) being solved simultaneously. The coupled numerical simulation was set up with the same model parameters, time-stepping and mesh refining algorithms as well as domain geometry specified as previously described for SVFlux. The initial condition for the simulation using ChemFlux was specified as the equivalent initial pore-water solute concentration estimated from the EC data using a calibration curve obtained for standard NaCl solution (Figure 6.23). A zero flux boundary condition was specified at both the top and bottom of the tailings deposits, and dispersivity and diffusion coefficient of 0.001m and $3.25 \times 10^{-9} \text{ m}^2/\text{s}$, respectively, were assigned. These values are within the typical range for column studies of similar scales as the current study (Domenico and Schwartz 1990; Yakirevich et al. 1997; Fisseha et al. 2010). The average value of the numerical solutions of C in the top 2cm of the tailings deposits were compared to corresponding values calculated from measured EC using the calibration curve shown in Figure 6.23. The results are presented in Figures 6.24 and

6.25 for the DRY(SW) and REWET tailings columns, respectively, with ChemFlux generally giving reasonable predictions of solute concentrations.

The effectiveness of a capillary barrier in reducing the accumulation of salts at the surface of the thickened tailings deposit was assessed using ChemFlux. The configuration of the modelled tailings deposit is shown in Figure 6.26, with a 50cm thick sand capillary barrier sandwiched between two layers of thickened tailings deposits, each 75cm thick. The candidate sand used as a capillary barrier has a K_{sat} and specific gravity of 3×10^{-5} m/s and 2.67, respectively (Wilson et al. 1994), with the soil water characteristic curve (SWCC) relative to the thickened tailings presented in Figure 6.27. The numerical set up for the simulation using ChemFlux coupled to SVFlux was the same as previously discussed, with a few modifications.

A “no boundary” condition was specified in the interfaces between the tailings and the sand barrier as the entire column was assumed to be hydraulically continuous. All modeling parameters in SVFlux and ChemFlux were specified as previous for the tailings portion of Figure 6.26. In SVFlux, the initial head condition for the sand barrier was specified to be hydrostatic due to its negligible self-weight consolidation in comparison to the tailings. An alternate simulation was run assuming the sand barrier to be initially dry with an initial negative pore water pressure (10,000kPa), which is in excess of its AEV and within its residual matric suction range (Figure 6.27). The SWCC

data for the sand barrier from Wilson et al. (1994) was fitted with the Fredlund and Xing (1994) equation, while the hydraulic conductivity function was estimated from the fitted SWCC using the Fredlund et al. (1994) method. The sand barrier was assumed to have negligible initial solute concentration ($C_0 = 0 \text{ g/m}^3$), with the values of dispersivity and diffusion coefficient of 0.0005m and $7 \times 10^{-9} \text{ m}^2/\text{s}$ specified respectively. These values were assigned for the sand barrier as for a given solute, the dispersivity and diffusion coefficient for coarse-particle soil is known to be smaller and larger compared to a fine-particle soil, respectively (Vanderborght and Vereecken 2007; Hamamoto et al. 2009).

Figure 6.23. Calibration curve of electrical conductivity (EC) against pore-water NaCl concentration using a standard solution.

Figure 6.24. Pore-water solute concentration measured and predicted at 1cm and 2cm depths of the desiccating DRY(SW) tailings columns.

Figure 6.25. Pore-water solute concentration measured and predicted at 1cm and 2cm depths of the desiccating REWET tailings columns.

Figure 6.26. Configuration of two 0.75m-thick layers of the thickened tailings interlayered with a 50cm thick sand capillary barrier.

The numerical simulation was run for a total of 90 days with a constant PE, temperature and RH of 15mm/day, 25°C and 17.5% assigned, being the respective average value for the REWET tailings columns. The simulation was run for an extended period to allow the assessment of how a capillary barrier may influence surface salt accumulation for a deep thickened tailings deposit over a relatively long time frame. Also, the temporal osmotic suction data measured in the top 1cm of the REWET tailings column was input into SVFlux, with the peak value measured prior to re-saturating the columns assumed constant for the remaining period of the simulation. Another

simulation was also run without the sand layer as a barrier, but with just a single thickened tailings layer with an equivalent thickness of 1.5m.

Figure 6.27. Soil water characteristic curve (SWCC) of the candidate sand material used as capillary barrier (From Wilson et al. 1994) compared to the SWCC of the thickened tailings.

Numerical predictions of profile salt accumulation over time for the desiccating tailings deposits with and without the sand capillary barrier are shown in Figure 6.28, with cases where the sand was assumed to be initially hydrostatic versus dry presented. Results for the top 40cm of the tailings stacks are presented in Figure 6.28 for the purpose of clarity, while the results for the entire profile are presented in Appendix C17. The use of a sand capillary barrier is shown to have no significant impact on the pattern

of salt accumulation in the top 40cm of the tailings deposits over the 90-day period, except if the sand was placed saturated. In fact, placing the sand barrier dry increased the magnitude of salt accumulation at the top of the deposit (Figure 6.28A), relative to when the deposit had no sand barrier placed (Figure 6.28C). It is interesting to note that the magnitude of salt accumulation in the top few centimetres of the deposits were similar for the first 40 days of drying in all 3 depositional scenarios. In all cases, as previously observed from the tailings columns and multi-layer drying experiments, salt accumulation was restricted to the first few centimetres of the deposit.

When the entire profile of the deposits was considered (Appendix C17), a uniform profile salt distribution was observed at depths below ~20cm for the deposit with no capillary barrier. For the simulation where the capillary barrier was assumed to be placed initially dry, evidence of salt build up was observed within the sand barrier early on during the desiccation (up to ~ day 10), and the accumulated salt within the sand gradually got depleted as the tailings continued to dry (Appendix C17). On the other hand, the deposit where the sand barrier was placed saturated showed no salt accumulation within the sand layer initially, but slight salt accumulation occurred as time progressed, especially at the lower portion of the sand. Generally speaking, a retarded breakthrough of salt was observed for the configuration where the capillary layer was simulated to be placed saturated as opposed to dry. For the former configuration, at depths below 15cm of the top tailings layer, the mass of salt accumulated is shown to decrease over time, consistent with surface salt accumulation

Figure 6.28. Profiles of salt accumulated over time in the top 40cm of the desiccating tailings deposits with (A and B) and without (C) using sand capillary barrier. Results for the capillary barrier assumed to be placed initially dry (A) and saturated (B) are shown.

being mostly due to the upward advection of salt from the tailings layer overlying the sand layer. In contrast, the reduction in salt accumulation over time at depths below 15cm from the surface of the latter was marginal, with relatively more uniform profile salt distribution. This implies that the salt accumulated at the surface of the deposit with the initially-dry sand layer was due to advection from the entire profile of the tailings deposit.

Predicted profiles of GWC for the entire depth of the tailings deposits at select times are presented in Figure 6.29. For the deposit where the sand layer was placed dry, there was evidence of an upward flux of water in the top 35cm of the upper tailings layer contrasting with a downward flux into the sand layer in the lower ~35cm on day 1. On the same day, there was also an evidence of upward flux of water from the underlying tailings layer into the sand layer. Hence, there seems to be a combined process of downward drainage from the lower portion of the overlying tailings layer and capillary rise from the underlying tailings layer of saline pore-water into the sand layer right from day 1. On the same day 1, the deposit with the sand barrier placed saturated showed an evidence of the sand draining into the underlying tailings layer, with the top 12cm of the overlying tailings layer evaporating while the rest of its profile had relatively high but uniform GWC. Thus, the deposit where the sand barrier was simulated to be placed dry would have experienced a re-distribution of pore-water solute right from the start of desiccation. This would be consistent with this configuration exhibiting a more uniform solute distribution throughout the profile over the 90-day period, with the

exception of the top 20cm (Appendix C17). On the other hand, the deposit having the sand barrier placed saturated seemed to exhibit an “osmotic discontinuity” between the saline tailings layers overlying and underlying the sand layer (the reader is reminded that though a hydrostatic initial condition was simulated for the sand layer, its initial pore-water solute concentration was set as zero).

Figure 6.29. Profiles of predicted gravimetric water contents on days 1, 45 and 90 for the entire depths of the desiccating tailings deposits with capillary barrier placed dry (CBD), saturated (CBH) as well as without using sand capillary barrier (NCB).

By day 45, the deposit with the sand layer placed dry was showing a more uniform profile GWC within the tailings layers overlying and underlying the sand, as well

as within the sand layer itself compared to day 1. For the initially-saturated sand layer, the profile GWC in both the sand layer and the tailings underlying it was not uniform, but rather increasing with depth. This pattern of water distribution is indicative of the “gravimetric gradient” within the 2 layers being higher compared to day 1, which would be expected to facilitate the advective transport of pore-water solute from the underlying tailings layer, through the sand barrier, into the overlying tailings layer. However, as shown by the generally lower salt accumulation early on and at the upper portion of the sand layer (Appendix C17B), this was not the case. This steep “gravimetric gradient” is similar to the pattern for the tailings layer without the sand barrier on day 45 (Figure 6.29), with the latter showing expectedly higher salt accumulation at the surface due to evaporation-driven advection. This observation thus supports the previous hypothesis of the initially non-saline pore water for the wet sand barrier causing “osmotic discontinuity” between the saline layers of tailings on top of, and below it. The profile GWC for the tailings deposit where the sand layer was placed dry was consistently lower compared to either the deposit where the sand barrier was placed saturated or not placed at all (Figure 6.29). This pattern is also consistent with the higher surface salt accumulation for the former compared to the latter 2 deposits.

By day 90, the “gravimetric gradient” for the upper tailings layer for the deposit where the sand layer was initially dry had become much higher relative to the deposit where the capillary barrier was placed saturated. Similar to the trend prior to day 90, the profile GWC for the deposit with the sand layer placed dry was substantially lower

than the profiles for the deposit with the sand layer placed saturated or not placed at all. This depicts higher profile dewatering and is consistent with the highest magnitude of surface salt accumulation for the deposit with the sand layer placed dry in comparison to the other two depositional configurations.

Rooney et al. (1998) conducted a series of column tests to evaluate the effectiveness of placing variable thicknesses of gravel in-between a salinized clay at the base and a non-saline top soil. The gravel capillary barrier was placed initially saturated but was constantly drained to prevent water accumulation in it. One set of the columns was kept relatively moist by regular irrigation (WET), while the other set received lower applied moisture regimes (DRY). Soil columns without the capillary barrier exhibited significantly higher salt accumulation in the top soil, especially the DRY columns. The accumulation of salts in the top soil of the columns with varying thicknesses of capillary barrier were not significantly different and were substantially lower than the control soil columns. This observation by Rooney et al. (1998) is similar to the results of the numerical analysis in the current paper. However, there are a few differences between the aforementioned paper and the current study that are worth mentioning. One is the fact that both layers of tailings separated by the sand layer in the current paper are saline compared to only the salinized soil underlying the gravel barrier in Rooney et al. (1998). This implies that whether downward drainage from the overlying tailings layer or capillary rise of water from underlying tailings layer into the sand barrier in the current paper occurs, the potential for salinizing the barrier material exists. In contrast, the

potential for salinizing the gravel barrier in Rooney et al. (1998) would only result from capillary rise of water from the underlying salinized soil. Also, the gravel layer in Rooney et al. (1998) was frequently drained during the 130-day experiment, minimizing the hydraulic connection between the top soil and the underlying salinized soil as shown by the little or no downward drainage from both the top soil and the gravel layer into the salinized soil at the base of the columns. Hence, the risk of capillary rise of saline pore-water into the topsoil via the capillary barrier from the underlying salinized soil was minimal. Lastly, the operational and logistical feasibility of a scaled-up analogue where a drainage system would be installed and maintained functional in the capillary barrier layer was neither considered nor discussed by Rooney et al. (1998). On balance, the application considered by the said authors might be amenable to a drained capillary layer as only a single barrier layer was considered to isolate saline mine waste deposit prior to top soil placement and re-vegetation. Such constantly-drained capillary barrier might be challenging for the type of application considered in the current paper where the intent is to place sand layers in-between multiple lifts of saline tailings in order to minimize surface salt accumulation that can retard densification of the entire stack. The pattern of salt accumulation for the tailings deposit with and without the sand capillary barrier remained unchanged when the initial pore-water solute concentration was increased ~ 8-fold to mimic an “hyper-saline” tailings (from 13.37 to 100ppt) as shown in Appendix C18. The only difference is the commensurately higher magnitudes of salt accumulation for. Therefore, from the foregoing, for deep saline tailings deposits where evaporation-driven surface salt accumulation may be a concern, the placement of a

saturated capillary barrier of coarser-grained particles in-between tailings layers may be beneficial in reducing surface salt accumulation. This deposition strategy might be beneficial for saline tailings management where capillary barrier might prolong the time available for stacks to harvest evaporative energy before surface salt crust formation shuts down evaporative drying. However, the economic and logistical benefits of a capillary barrier in such case would need to be evaluated against potential gain in evaporative drying and shear strength enhancement.

6.5 Summary and Conclusion

This paper seeks to improve the prediction of evaporative densification in saline thickened tailings stack by characterizing its 1D solute transport and relating this to observed evaporative behaviour. Small column and multi-layer tailings columns undergoing dry and wet-dry-wet cycles were analysed and modelled with a 1D unsaturated flow code that accounts for the evolution of osmotic suction over time at the surface. The thickened tailings stacks showed evidence of salt accumulation in the top 2cm, with the magnitude and rate of accumulation higher for high evaporative boundary conditions. The majority of total suction measured in the top 1cm of stacks is due to contribution from osmotic suction. The deposition of multiple thin lifts (10cm each) of thickened tailings did not lead to significant salt accumulation at the surface of the topmost layer.

The proposed numerical framework (applying a surface suction correction factor and accounting for osmotic suction) gave the best predictions of both evaporation and total suction, and produced reasonable predictions of GWC. The robustness of the framework over a range of deposition scales (column versus 'bucket' tests), evaporative demands (AW and SW), multi-layer deposition schemes (3- and 5-layers) and hydrologic conditions (dry and dry-wet-dry cycles) was demonstrated. Predictions were found to be very sensitive to K_{sat} , with a lower value resulting in a significantly lower rate of profile dewatering compared to a higher K_{sat} value. Multiple thin-lift deposition significantly reduced the cycle time of deposit compared to a single equivalent deep stack. Placement of a saturated sand capillary barrier was shown to be effective in slowing down surface salt accumulation by osmotically isolating two layers of saline tailings.

The findings in the current paper have practical significance for tailings management. The accumulation of salts within the top 5cm of desiccating saline tailings stacks should be factored into tailings management operations aimed at efficiently harvesting available evaporative energy for atmospheric drying. As an illustration, mud-farming a saline stack once salts begin to accumulate at the surface (evident by white patches of salt at the top) may be beneficial. Also, the atmospheric boundary-dependence of the rate and magnitude of surface salt accumulation imply that any planned mud-farming activity can be best adjusted based on the season of the year. For example, surface farming such saline deposit in the fall season need not be as frequent as in the peak summer season. In addition, the placement of a fresh lift of saline tailings

(or rewetting) on a desiccated stack may temporarily help in re-mobilizing surface accumulated salts for the old layer and slightly facilitate the densification of entire stack.

In using numerical tools to aid saline tailings deposition planning and management, considerable effort should be devoted to material and pore-water chemistry characterization. The debate over what optimal thickness of fresh deposit can achieve a target shear strength within a given period is common-place for tailings facility operators, given the stringent regulatory and footprint requirements in many mining jurisdictions. Once the required characterization is done for a given site, unsaturated flow modeling can be an immensely-useful guide, in addition to operator's experience, in making the right call. Where evaporation is the primary driver for dewatering a stack, thin-lift deposition as opposed to deep stacking may significantly reduce the drying time needed to achieve a target water content or shear strength objective. Also, based on the preliminary numerical modeling in this paper, the deployment of a saturated sand capillary barrier in-between multiple lifts of saline thickened tailings may help reduce the rate of salt accumulation at the surface. Therefore, if deemed economically and operationally viable for a specific site, capillary barrier may prolong the time available for fresh saline tailings stack to harvest evaporative energy and shorten its cycle time. Additional empirical research into the effectiveness of capillary barrier in mitigating surface salt accumulation and consequent adverse effect on the rate of evaporative densification for saline tailings stacks is warranted.

CHAPTER 7: PRINCIPLE AND PROTOTYPE TESTING OF A NEW MATRIC SUCTION SENSOR

ABSTRACT: A new principle for matric suction measurement is proposed, based upon strain measurement of a contiguous porous material of high air-entry value (AEV). In theory, this allows for measurement of matric suction without the associated errors due to cavitation or hysteresis for suctions below the AEV. Results from testing a prototype sensor made from a deformable porous material with a high AEV ($S=0.85$ at 5 MPa) are presented. Deformation of the prototype was determined by means of attached electrical resistivity strain gauge. Matric suction is then inferred from the strain measurements using poroelasticity theory. Tests performed in a drying artificial silt show that matric suction values inferred using the prototype sensor showed reasonable agreement with corresponding values obtained using a tensiometer, a psychrometer, and with suctions established using axis-translation. Mean absolute errors of matric suction measurement were 8 kPa, 16 kPa, and 100 kPa for ranges of 0-150 kPa, 50-300 kPa, and 300-1200 kPa respectively. Also, matric suctions obtained using the prototype sensor over time for a desiccating acid-generating gold thickened tailings compared favourably to concurrent measurements made with a heat-dissipation sensor.

7.1 Introduction

Many geotechnical properties of soil are known to be dependent on matric or total suction (Fredlund and Rahardjo 1993). The coefficient of permeability and shear strength of unsaturated soils are dependent on the matric suction (Huang et al. 1998; Agus et al. 2003; Escario and Saez 1986; Vu and Fredlund 2004), while the evaporation rate is a function of total suction at the soil surface (Wilson et al. 1997). Values of soil suction are also useful in predicting the long-term stability of slopes (Feuerharmel et al. 2006), as well as in the evaluation of long-term performance of soil covers used for waste isolation (Williams et al. 1997; O’Kane et al. 1998; Weeks and Wilson 2005). In addition, soil suction data is important for the management of mine tailings disposal facilities, especially in arid or semi-arid climates (Newson and Fahey 2003; Simms et al. 2007).

Matric suction can be measured either directly or indirectly. The direct methods measure the negative pore-water pressure in the soil using a water reservoir connected to the pore-water through a material with a high AEV, while the indirect methods measure another property of the soil (such as relative humidity, thermal conductivity or electrical resistivity) which can be correlated to matric suction. Examples of devices commonly used to measure matric or total suction in unsaturated soils include the tensiometer, the heat-dissipation sensor, and the psychrometer. While a detailed review of the various techniques or devices is available in other sources (for example,

Rahardjo and Leong 2006), it is useful for the reader to appreciate the limitations of commonly-used sensors in the low suction range. Tensiometers offer fast and reliable readings for matric suctions less than the cavitation pressure. Some specialized tensiometers are able to measure up to 1500 kPa (Ridley et al. 2003; Tarantino and Mongiovì 2001) by eliminating cavitation nuclei in the water reservoir through the application of cycles of pressure and vacuum (Guan and Fredlund 1997). However, eventually, diffusion of air through the porous tip will induce cavitation. Heat-dissipation and electrical resistivity sensors offer increased range, but their accuracy is limited due to hysteresis in the water-retention curve of their porous bodies (Sattler and Fredlund 1989).

This paper introduces a new sensor to measure matric suction that potentially avoids the problems of cavitation and hysteresis, with a range up to several MPa. The proposed sensor infers matric suction of surrounding soils based upon volume change of a porous material with a high AEV, such that neither hysteresis nor cavitation will influence readings below this AEV. A prototype poroelastic sensor is described and its performance is evaluated by comparative suction measurements with tensiometers, heat-dissipation and relative humidity sensor in a drying soil and thickened tailings, and against matric suctions established in a soil using axis-translation.

7.2 Theory

The proposed sensor consists of an amorphous (glassy) porous solid with a contiguous solid phase of high AEV sufficiently “soft” such that it undergoes measurable volume change due to changes in pore-water pressure. Volume change in porous media due to changes in positive or negative pore pressure can be estimated by poroelasticity theory (Biot 1941). According to Mackenzie (1950), the change in matric suction of a linearly-elastic porous material that is saturated can be related to its linear strain using the following equation, for values of degree of saturation (S) for which there exists no continuous pathways of air in the porous medium, roughly $S > 0.8$:

$$\epsilon = \frac{SP}{3} \left[\frac{1}{K} - \frac{1}{K_s} \right] \quad (7.01)$$

Where ϵ is compressive strain, P is the negative capillary pressure or matric suction (kPa), K is the Bulk modulus of porous material, and K_s is the Bulk modulus of the solid frame of the porous material. The generality of $S \sim 0.8$ marking the limit between interconnected pathways of air and disconnected air pockets in various soils and other porous media is observed in studies on the diffusivity of gases through soils and rocks, for example, Aachib et al. (2004). K_s may be determined by (Biot 1941):

$$K_s = \frac{E_s}{3(1-2\mu)} \quad (7.02)$$

Where E_s and μ are the Young Modulus (kPa) and Poisson's ratio of the solid phase, respectively. The bulk modulus, K , may also be determined using Equation 7.02 given the Young's modulus, E , and the Poisson's ratio of the composite material. Alternatively, K may be determined from the properties of the solid phase if the pores are assumed to be spherical (Christensen 1991):

$$\frac{K}{K_s} = 1 - \frac{(3K_s + 4G_s)n}{4G_s} \quad (7.03)$$

Where n is the porosity of the material and G_s is the Shear Modulus of material given by:

$$G_s = \frac{E_s}{2(1+\mu)} \quad (7.04)$$

7.3 Materials and Methodology

7.3.1 Characteristics of the Porous Material

The porous material is a contiguous amorphous porous solid. It has an internal surface area of $250 \text{ m}^2\text{g}^{-1}$, an approximate bulk dry density of 1.5 g/cm^3 , porosity of

0.34, average pore diameter of 4 millimicrons and is opalescent in appearance. The AEV of the porous material was initially estimated from its average pore-size using the Young-Laplace equation to be about 8000 kPa. The Young Modulus and Poisson ratio of backbone material (solid phase) from which the porous material of poroelastic sensor is made are 65 GPa and 0.24, respectively. The Poisson's ratio of the composite porous material is reported by the manufacturer to be 0.17. Poisson's ratio of other porous materials is often lower than the Poisson's ratio for the solid phase material with zero porosity (Arnold et al. 1996). The specific gravity of the solid phase material is 2.15. The porous material can be formed into a variety of shapes. Thin rods of 3 mm diameter were selected, which were broken into various lengths ranging from 5-8 cm for use in the prototype sensor.

7.3.2 Assembly of the Prototype Poroelastic Sensor

The selected rod of porous material was first cleaned using isopropyl alcohol. The rod was then initially saturated through submersion in distilled water inside a vacuum desiccator, applying a vacuum (-0.9 atmospheres gauge) for 24 hours in order to dislodge air pockets trapped in the void spaces. After applying vacuum, the rod was left submerged under water for 5 hours. The degree of saturation achieved was calculated by determining the mass of water absorbed by the dry material, with comparison to the oven-dry mass. The volume of the saturated rod was calculated using digital caliper measurements of the length and diameter. Then the rod was wiped with tissue paper to

remove surface water and weighed immediately. The resulting degree of saturation was at least 98%.

An electrical resistivity strain gage was then bonded onto the porous rod using an adhesive and catalyst combination compatible with the strain gage. The attached strain gage was mounted so as to measure the axial strain of the porous material. The transverse sensitivity of strain gage used is small ($+1.6 \pm 0.2\%$). After curing for about 1 hour, two thin enamel-coated tin wires were soldered onto the terminals of the strain gage. The other two ends of attached lead wires were soldered onto tabs already mounted on a cap pre-installed on one end of porous material (for easy handling of the sensor). The exposed surface of the strain gage was then water-proofed by applying a thin and even layer of molten wax. Subsequently, the prototype sensor was water-sealed using a rubber-nitrile solution applied over the whole surface except within 3 cm of the tip. The strain gage was then tested in order to ensure proper installation using a Model 1300 gage installation tester (Intertechnology, Don Mills, ON). The poroelastic sensor prototype (Figure 7.01) was connected to a 3800 Wide Range strain indicator (Vishay Measurements Group, Raleigh, NC), setting the gage factor to that of the strain gage attached to poroelastic sensor and properly zeroing the strain indicator.

Figure 7.01. Schematic of prototype poroelastic sensor after assembly and coating.

7.3.3 Determination of Bulk Modulus

The Young's Modulus, E of the assembled prototype was measured by placing a known mass on top of the saturated prototype and observing the strain reported by the strain gage (Figure 7.02). For this measurement, the prototype was inverted and held level by a clamp, attached to the prototype about 2 cm below the strain gage. The mass used, placed on top of the free end of the prototype, was approximately 30 g. This method obtains repeatable values of Bulk Modulus within 5% of the mean. It was found that using this E to calculate K directly (from Equation 7.02) before substituting in Equation (7.01), rather than calculating K from K_s and E_s (from Equation 7.03) gave more accurate predictions, probably because perfect alignment of the strain gage with the

axial axis is not possible. All matric suction values presented in this paper were those calculated from strain measurements using this measured value of Young's modulus (E) for the fully-constructed sensor.

7.3.4 Shrinkage Curve and Estimated SWCC of the Porous Material

The shrinkage curve of the porous material in the prototype sensor was determined by tracking both the changes in water content of previously-saturated material as well as indicated strains as it dried on a weighing scale (Figure 7.03). To calculate the void ratio, volume change was assumed to be isotropic. Volume change measurements were converted to matric suctions using Equation 7.01 and assuming isotropic volume change to generate an estimated SWCC (Figure 7.04). It can be seen that some desaturation of the porous material occurs before the putative AEV (~ 8 MPa), down to $S \sim 0.7$. The degree of saturation curves are expressed in two ways, both using Equation 7.01 to predict matric suction from the measured linear strain, but one using the measured S in Equation 7.01, the other assuming $S=1$ in Equation 1. The difference, in terms of estimating matric suction, becomes increasingly important as suction increases: S is 0.96 at 1000 kPa, 0.9 at 3000 kPa, and 0.85 at 5000 kPa. To confirm that this decline in the degree of saturation before the AEV were not due to imperfections in the material that might significantly vary from sensor to sensor, a second test was performed on a different sensor, and as shown in Figure 7.04, the decrease in the degree of saturation was quite similar.

Figure 7.02. Schematic of setup used to determine the Young's Modulus of an assembled prototype poroelastic sensor. Prototype is inverted (not drawn to scale).

Figure 7.03. Shrinkage curve of porous material used in the prototype poroelastic sensor.

Figure 7.04. Replicate soil-water characteristic curves of the porous material used in the prototype poroelastic sensor.

7.3.5 Saturation, Drying and Resaturation Tests

To evaluate the stability and repeatability of the prototype, it was subjected to repeated wet/dry cycles. “Wetting” involved sticking the tip of the prototype sensor inside distilled water in a beaker and monitoring the change in strain with time until change in strain approached zero. The prototype poroelastic sensor was then taken out of water, left to stand in ambient air while the change in strain was monitored until the

rate of strain began to decrease significantly. Rewetting and subsequent drying were repeated for three cycles.

Figure 7.05 shows the behaviour of the prototype poroelastic sensor during the wet/dry cycles, both in terms of strain and matric suction calculated using the poroelasticity equations. It was promising to note that the prototype sensor returns to the same reference strain upon rewetting, showing no evidence of hysteresis for this range of matric suction.

Figure 7.05. Repeated wetting and drying cycles of prototype poroelastic sensor in terms of strain and inferred matric suction.

7.3.6 Comparative Measurements in Soil and Thickened Tailings using a Tensiometer, the Axis-Translation Technique, Heat Dissipation and Relative Humidity Sensors

Artificial silt-sized glass beads and acid-generating gold thickened tailings were used to test and compared the performance of the prototype sensor against well-established devices for measuring or establishing suction in unsaturated media. The “clean” silt was chosen in order to eliminate any potential interference in the performance of the prototype sensor due to osmotic suction. The thickened tailings was chosen to test the sensor’s performance in a medium with considerable pore-water salinity. The silt’s and thickened tailings geotechnical properties are shown in Table 7.01. Experimental procedures for testing and comparing the prototype sensor’s performance against tensiometer, axis-translation technique, heat-dissipation and relative humidity sensors are presented in the following subsections:

7.3.6.1 Comparison with Tensiometer

The artificial silt was prepared at a gravimetric water content (GWC) of 30% using distilled water and placed inside an open aluminum container with dimensions as shown in Figure 7.06. The soil was lightly packed by hand having an average void ratio of 0.8 and a degree of saturation of 0.93. The poroelastic sensor and a previously-saturated T5 tensiometer (UMS) were both inserted to same depth (3 cm) inside the artificial silt. A Type-T thermocouple was inserted to the same depth. There was no flow at the bottom of container and evaporation was allowed to occur under ambient conditions in the laboratory. The potential evaporation rate varied between 2 and 4 mm

per day, as estimated by evaporation from a 250 ml beaker. The poroelastic sensor, tensiometer and thermocouple outputs were concurrently recorded with a data logger.

Table 7.01. Geotechnical properties of thickened tailings and silt used for testing sensor

Parameter	Thickened Tailings	Silt
Specific Gravity	2.9	2.48
D ₁₀ , D ₅₀ , D ₆₀ (microns)	2, 35, 55	1, 31, 41
Cu (D ₆₀ /D ₁₀)	27.5	41
Liquid limit (%)	20	19
Plastic limit (%)	19	13
Saturated hydraulic conductivity (m/s)	2.0E-7	1.7E-6

7.3.6.2 Comparison with Matric Suctions Established with Axis-translation Technique

Measurements recorded by the prototype poroelastic sensor were also compared with matric suctions established using the axis-translation technique. Set up for the axis translation technique is similar to the one described in Oliveira and Fernando (2006). Starting from a GWC of about 30% and a void ratio of 0.8, matric suctions were imposed in increments of 50 kPa to a maximum value of 300 kPa. After equilibrium was achieved at a given stage, the air pressure was bled off, the top of the axis translation cell was removed, and the prototype poroelastic sensor was inserted into 3 cm deep pilot hole in the test silt. Strain readings from the prototype sensor were

recorded until a steady value was reached. Evaporation was prevented using a plastic film. The water content of the soil was maintained by detaching the axis-translation cell from its water reservoir before taking sensor readings.

Figure 7.06. Schematic of drying test for comparing prototype poroelastic sensor with tensiometer and Relative humidity sensor (Not drawn to scale).

7.3.6.3 Comparison with Heat Dissipation Sensor

The evolution of matric suctions in desiccating thickened tailings column deposited at an initial GWC of 38% was determined with the poroelastic sensor and

compared to concurrent determinations made using a heat-dissipation (HD) sensor. The set up of the drying test is shown in Figure 7.07, with the prototype and HD sensors placed side by side within the top 3cm of the desiccating thickened tailings. The desiccating tailings column was desiccated under ambient conditions with evaporation rates accelerated by means of wind provided with an oscillating table fan. No flow boundary was imposed at the bottom of the desiccating tailings column. A data acquisition system was used to record strain and HD measurements every half hour. The recorded strains were converted to matric suctions and compared to values recorded by HD sensor.

7.3.6.4 Comparison with Relative Humidity Sensor

Drying of the artificial silts was simultaneously monitored using both the poroelastic sensor and a WP4 Dewpoint PotentiaMeter (Decagon Devices Inc., Pullman WA). The artificial silt was prepared at a GWC of about 33% and a void ratio of ~ 0.8 , close to 100% saturation. The set-up for the drying test is similar to Figure 7.06, except that at each sampling event, about 5 g silt sample was taken for determination of matric suction using the Relative humidity (R.H) sensor. The GWC of the same soil sample was determined by difference in mass after oven-drying at 105°C for 24 hours. The drying test was continued under ambient evaporative conditions (no-flow boundary at bottom of container) for several days until the theoretical limit of the prototype poroelastic sensor (8000 kPa) was exceeded. Though the R.H sensor measures total suction,

measured suction values can be directly compared to matric suction as osmotic suction in the artificial silt is zero, as it is an inert material and the soil was prepared with distilled water.

Figure 7.07. Schematics of experimental set-up for comparing Poroelastic sensor to Heat-dissipation sensor in desiccating thickened gold tailings.

7.4 Results

As shown in Figure 7.08, the prototype poroelastic sensor and the tensiometer show reasonable agreement until the prototype records suction values in excess of 150 kPa. At this point, the steepness of suction with depth was likely high and small variations in depth of the sensors are significant enough to account for this difference. For values less than 150 kPa, the mean absolute error was less than 8 kPa. There is some variability in the poroelastic sensor's output, which may be due to temperature fluctuations. Temperature data from the thermocouple embedded in the soil is also presented in Figure 7.08. The maximum error in matric suction for values less than 150 kPa was 20 kPa.

Figure 7.08. Matric suction values inferred from the prototype poroelastic sensor and from a tensiometer in drying test using artificial silt.

When compared with matric suctions established using axis-translation, the mean absolute error (MAE) of the values reported by the prototype sensor was 16 kPa (Figure 7.09). Equilibration time varied with the level of suction in the soil, ranging between 5 and 20 minutes.

Figure 7.09. Comparison of matric suction values established by axis-translation and inferred by the prototype poroelastic sensor.

Figure 7.10 shows the matric suctions inferred by the Poroelastic suctions in comparison to values recorded by HD sensor when both were used to monitor a desiccating thickened tailings column. Over the duration of the desiccation test, with the exception of matric suctions between $\sim 4 - 10$ kPa, the matric suctions recorded by both

sensors are shown to compare well. Relative to the HD sensor, the prototype sensor under-predicted the matric suctions between 4 and ~ 10 kPa.

Figure 7.10. Matric suction values inferred from the prototype poroelastic sensor and from heat-dissipation sensor concurrently used in desiccating thickened tailings column.

A comparison of relatively high values of matric suctions measured in the artificial silt with total suction measurements from grab samples using the R.H sensor are shown in Figure 7.11. Matric suctions inferred from the poroelastic sensor are shown with and without incorporating the degree of saturation of the sensor in Equation 7.1. The prototype poroelastic sensor comparatively under-predicted suctions at values lower than 400 kPa, but slightly over predicted values between 400 and

approximately 1200 kPa. However, the accuracy of the R.H sensor is ± 0.1 MPa for total suction determinations ranging from 0 to 60 MPa. The absolute error between measurements from the two techniques is relatively low at the lower suctions, but increases as the measured values increase. Expressed as a percentage, the mean error for values less than the putative AEV of the sensor material (~ 8000 kPa) was 18%. Note that the highest suction measured below the putative AEV was 5500 kPa (Figure 7.11). For matric suction values greater than this value, the sensor grossly underpredicted the matric suction of silt as determined using the R.H sensor, which is not unexpected as these suctions exceed the expected range of the prototype poroelastic sensor. While the effect of incorporating the degree of saturation in the prototype matric suctions becomes visually apparent at higher suctions, there was no significant difference in the percentage mean error between either series of suction values inferred from the prototype poroelastic sensor and the suctions measured by the R.H sensor (Both at 18% mean error).

Note that there is a single point where the error between the prototype poroelastic sensor and the R.H sensor is the same magnitude as the measurement (Prototype reads 2000 kPa while R.H sensor reads 3500 kPa). This is likely attributable to the soil being near its residual water content, where slight changes in water content results in high changes in matric suction, Therefore, strictly speaking, the prototype poroelastic sensor only shows a reasonable comparison with the R.H sensor up to 1200 kPa, for which the MAE is 110 kPa, close to the accuracy of the R.H sensor.

Figure 7.11. Comparison of matric suction values inferred by the prototype poroelastic sensor and the R.H sensor (WP4).

7.4.1 Potential Limitations of Prototype Poroelastic Sensor

It is possible that soil-structure interaction may affect the measurements, especially if the sensor is placed relatively deeply into the soil: the response of the sensor in this condition is a function of effective stress and the relative stiffness of the sensor and the soil. However, this potential source error was not observed in the tests reported in this paper. Further tests will be undertaken to examine the susceptibility of the sensor to this potential problem. The effect of temperature under more variable climatic conditions may also influence deformation of this type of sensor. The range of temperatures in the laboratory for these tests ranged from 20 to 23 °C.

7.5 Conclusions

A new type of matric sensor is proposed, which works by inferring the matric suction of a surrounding soil by measuring deformation of a high AEV poroelastic material integral to the device. Tests of a prototype sensor in a drying silt show good agreement with a standard tensiometer, matric suction values established using axis-translation, and a relative humidity sensor (WP4 device). Mean absolute errors between matric suction values measured by these techniques and the prototype poroelastic sensor are 8 kPa, 16kPa, and 110 kPa; for ranges of 0-150 kPa, 0-500 kPa, and from 200 kPa-1200 kPa respectively. The sensor also compared well to HD sensor when used to monitor matric suctions over time in a desiccating thickened tailings.

CHAPTER 8: GENERAL DISCUSSION, CONCLUSION AND RECOMMENDATION

8.1 Challenges with Numerical Prediction of Evaporative Densification of Saline Mine Tailings

Numerical modeling of evaporative densification is an important planning tool for tailings facilities operators to keep pace with throughput pressure and increasingly-stringent regulatory environment in many mining jurisdictions. Saline and hyper-saline tailings storages are common in many mining operations either due to salinity in the source water used for mineral processing or salinity arising from chemical ore processing and /or recycling of process-affected water. Salinity complicates numerical prediction of evaporative densification in such saline deposit.

Current experience is that most unsaturated flow codes do a relatively poor job of predicting evaporative fluxes from saline soil and mine tailings deposits, especially following the surface salt precipitation. This has been attributed to the lack of a numerical framework for incorporating solute transport into routine unsaturated flow modeling. While the 3 mechanisms of salinity lowering evaporation fluxes are fairly well understood individually (particularly in soil), their relative contribution to reduction in fluxes from soil and thickened tailings is unclear. The current research aims at improving current understanding of the relative contribution of 2 of these mechanisms by

characterizing the 1D solute transport in desiccating saline soil and thickened tailings, and relating it to observed evaporative fluxes. A numerical framework that incorporates solute transport into the prediction of unsaturated flow in soil and thickened tailings was proposed and validated. The framework was tested for soil and thickened tailings columns under dry and dry-wet-dry cycles, as well as for multi-layer deposits. The framework was then used to assess the benefits of thin-lift multi-layer deposition as well as using capillary barrier to minimize surface salt accumulation of a deep thickened tailings deposit. The ultimate goal of this research is to improve numerical prediction of evaporative densification in saline thickened tailings stack. Discussion of the results obtained from the laboratory and numerical investigations conducted in this research are highlighted in the following subsections:

8.1.1 Experimental Investigation of Effects of Pore-water Salinity and 1D Solute

Transport on Evaporative Fluxes from Saline Soil

The 1D solute transport in soil columns prepared with 3 different initial concentrations of NaCl solution was characterized and related to observed evaporative fluxes. Excluding the effect of albedo, the relative contribution of osmotic suction and salt precipitation to the observed reduction in evaporative densification was evaluated. Salt accumulation was observed in the top 1cm of all treated soil columns, with early precipitation recorded for the higher initial salinity. Treated soil columns showed evidence of “back-diffusion” with a sharp drop in NaCl concentration at the end of the

column drying experiment following sustained surface accumulation. The model proposed by Wilson et al. (1997) had to be modified to account for soil resistance to vapour flow and sharp gradient in total suction in the top 1cm for predictions to match data. This modification is consistent with previous work by Alvenäs and Jansson (1997).

Pore-water salinity repressed evaporation from all treated soil columns, with the extent of reduction increasing with the initial pore-water salinity. The lower bound of evaporation was independent of the initial salinity, as the maximum total suction recorded for all three treatments was found to be the same within the timeframe (14 days) considered. This was attributed to NaCl solubility imposing a limit on the contribution of osmotic suction to reduction in fluxes as the total suction measured for all treatments were mostly osmotic. For the lowest initial salinity treatment, the relative evaporation (RE) predicted agreed well with experimental measurements, unlike for the higher salinity columns where RE were over-predicted once the solubility limit was exceeded and salt precipitation had commenced. Additional reduction in evaporation past this solubility limit was attributed to salt precipitation, with the extent by which RE was over-predicted observed to be directly proportional to the amount of precipitated salt per unit cross-sectional area of the top 1cm of soil columns.

8.1.2 Predicting Salinity-induced Reduction in Evaporative Densification of Silt and Thickened Mine Tailings

1D solute transport in salinized soil and acid-generating thickened tailings columns desiccating under contrasting evaporative conditions was characterized and related to observed fluxes. Salt was observed to accumulate at the surface of both salinized soil and tailings columns, the rate enhanced by higher evaporative demand. Reduction in evaporation due to salt accumulation was also enhanced by higher evaporative demand, associated with faster the rate of salt advection and accumulation at the surface. Irrespective of the prevalent evaporative demand, the maximum total suction recorded by the salinized soil columns was similar, likely constrained by the solubility limit of NaCl. The final profile GWC for the saline soil column was also similar for both high and low PE despite the initially higher rate of profile drying in the former.

The major component of total suction measured for all soil and tailings columns was osmotic, and up to the onset of salt precipitation, osmotic suction was sufficient to explain the reduction in evaporation rates in the desiccating columns. Additional reduction in evaporation past this point was attributed to increased resistance to water flow due to salt precipitation. The timing and magnitude of this additional contribution was accelerated and enhanced, respectively, by a high evaporative demand, consistent with previous observation from Fujimaki et al. (2006) and Fujiyasu and Fahey (2000).

Based on empirical results, a numerical framework that accounts for osmotic suction and steepness in gradient of matric suction at the surface was implemented to predict evaporation from the salinized soil and thickened tailings columns. The framework gave good predictions of evaporation and surface total suctions for the salinized soil and tailings columns desiccating under contrasting evaporative conditions. Specifying a peak osmotic suction past the solubility limit for the salinized soil resulted in sustained over-prediction of cumulative evaporation afterward, signifying additional contribution from salt precipitation. For the tailings column, predictions of AE was not substantially sensitive to osmotic suction, but accounting for osmotic suctions ensured better prediction of total suction in the top 1cm. On balance, accounting for osmotic suction and applying the suction correction factor gave the best fit of numerical predictions of evaporation and total suctions at the surface to experimental data, but not profile GWC. Predictions of evaporation, total suction and profile GWC was optimized by reducing the value of “c” parameter by half and increasing the value of K_{sat} input into the numerical code by 1 order of magnitude.

The relative contribution of osmotic suction to reduction in fluxes is enhanced by higher initial salinity, while a higher PE accelerates the pace at which solute advection causes the solubility limit to be reached and the contribution of osmotic suction is maxed out.

8.1.3 Numerical Prediction of Evaporative Fluxes from Saline Thickened Tailings

The versatility of a numerical framework that accounts for osmotic suction in prediction evaporation in single and multi-layer tailings deposits under various PE and hydrological conditions was assessed. Salt accumulation in all cases was restricted to the top 1cm of the tailings with total suctions at the surface mainly accounted for by osmotic suction. Predictions of both evaporation and total suction at the surface of all columns were adequate when the osmotic suction increases were accounted for and a correction factor was applied to adjust the total suction at the surface. Accounting for the osmotic suction is particularly important when the initial salinity is high.

Predictions were found to be sensitive to the value of K_{sat} and the lift thickness of tailings simulated, with a high K_{sat} and thin lift resulting in accelerated profile dewatering due to high water flux and shorter drainage path for evaporation, respectively. This trend is similar to observations made from numerical analyses by Simms et al. (2009), with the additional value of prior calibration of the unsaturated flow code with detailed data. Multiple depositions of 5 thin lifts, each 20cm thick, was shown to significantly reduce the cycling time to the tailings shrinkage limit (by ~70%) compared to deep-stacking a 1m lift at once. This was also attributed to a shorter “drainage path” for evaporation from thin lifts, as well as the dewatering effect of underlying desiccated layer on a fresh stack as per Fisseha et al. (2010).

After calibration with data, a 1D commercial FEM solute transport code was coupled to the unsaturated flow code and used to assess the effectiveness of using a candidate sand as capillary barrier placed between two thick tailings deposits to reduce surface salt accumulation. The capillary barrier was effective in reducing surface salt accumulation if placed saturated without periodic draining, by ensuring “osmotic discontinuity” between the two saline tailings layers. In fact, for the 90-day simulated, the saturated sand layer seemed to retard the osmotic breakthrough of salt from the underlying tailings layer, via the sand layer, to the overlying layer.

8.2 Challenges Associated with the Measurement of Suction in Soil and Tailings

The soil suction is an important parameter for describing the engineering behaviour of unsaturated soil (Fredlund and Rahardjo 1993) and is currently measured by various devices and techniques that are limited in certain ways. The current thesis also reports the conception, design and performance assessment of a new matric suction sensor that operates based on the direct correlation of the volume change of a linearly-elastic porous material to a change in capillary pressure of a test material at equilibrium. The following subsection briefly discusses the work and results from the prototype matric suction sensor.

8.2.1 Theory, Conception and Design of a New Matric Suction Sensor

This paper introduces a new prototype suction sensor that potentially avoids the dual problems of cavitation and hysteresis usually associated with Tensiometer and HD sensors, with demonstrated capability of suctions up to several MPa. The sensor infers the matric suction of a test material at equilibrium, from the volume change of the sensor's constituent porous material with a high AEV (8MPa), below which it is neither subject to hysteresis nor cavitation. The strain on the porous material is tracked by a mounted strain gage, and then converted to matric suction using the theory of poroelasticity. The sensor was shown to not be subjected to hysteresis and cavitation for matric suctions below its theoretical AEV.

8.2.2 Performance Testing of the New Matric Suction Sensor

When tested against Tensiometer, heat-dissipation sensor, relative humidity sensor and axis-translation technique, the prototype sensor was shown perform very well in soil and thickened tailings tested throughout this thesis. Equilibration time for the sensor ranged between 5 to 20 minutes. Matric suctions inferred by the sensor seemed to be insensitive to the degree of saturation (S) of the porous material down to a value of $S \sim 0.85$. As expected, suctions inferred by the sensor were grossly under-predicted for values in excess of its AEV.

8.3 General Discussion

The empirical model of Wilson et al. (1997) was proposed and verified based on the assumption that the temperature at the soil surface, of the air directly above it, as well as the water surface are similar, which was proven valid in the non-saline soil columns tested in this research (Appendix A1). The soils tested by Wilson et al. (1997) were deliberately constituted extremely thin to eliminate any other soil property below the soil surface, apart from total suction that may influence evaporation rate. This assumption did not hold for the 10cm NS soil columns tested in the thesis and will neither hold for most engineering applications. In these exempt cases, the evaporating front is typically located at some depths below the soil surface, and the resistance to water vapour diffusion would need to be accounted for, in addition to total suction at the surface. This fact was demonstrated in the current research and is in line with previous researchers who described the soil resistance as an important parameter for predicting evaporation from unsaturated soil (Camillo and Gurney 1986; Van de Griend and Owe 1994; Alvenäs and Jansson 1997; Bittelli et al. 2008).

In addition, conclusion from the current work is consistent with observation made by Fredlund et al. (2011) that using just the total suction at the soil surface to compute evaporation resulted in predictions that did not agree with experimental observations. Fredlund et al. (2011) reported that it was necessary to apply a correction to total suctions modelled at the surface for predictions to agree with data. The authors

justified this suction correction as a means to account for the soil exhibiting a “surface resistance” to evaporation. The current research has identified the total suction at the soil surface as well as the resistance of the soil to water vapour diffusion as two separate parameters needed to predict evaporative fluxes from soil. Hence, the use of the adjustment factor as proposed by Fredlund et al. (2011) could be regarded as an equivalent of accounting for the soil resistance posed by the soil.

The current research have contributed to an improved understanding of the mechanisms by which salinity lowers evaporative fluxes from saline soil and thickened tailings, building on existing literature. Without repeating similar observation from previous authors (Chen 1992; Newson and Fahey 1997; Fujiyasu and Fahey 2000; Fujimaki et al. 2006; Fisseha et al. 2010), the current research demonstrates the negative impact salinity can have on the evaporative densification and shear strength gain of soil and mine tailings. The current study also showed that the contribution of osmotic suction to reduction in evaporation is maxed out at the solubility limit of the solute, and additional reduction in fluxes can be attributed to salt precipitation.

In response to the need to define the relative contribution of osmotic suction and salt precipitation to reduction in fluxes as per Simms et al. (2007), the current work showed that osmotic suction alone is sufficient up till the solubility limit after which salt precipitation explain the additional reduction in evaporative fluxes. This conclusion is

also in sync with the work of Newson and Fahey (2003) from a series of field and laboratory observations. The pattern of salt accumulating at the surface of the saline soil and tailings from the current research is also consistent with previous observations by Fujiyasu and Fahey (2000), Newson and Fahey (2003), and Fujimaki et al. (2006). This surface salt accumulation in saline tailings deposits can potentially have negative implications for tailings facilities management and eventual site reclamation. One, evaporation-driven salt accumulation can significantly lower the rate of evaporative densification of tailings stacks, consequently impacting bearing capacity required during reclamation operations. Also, it can also limit the potential for establishing a vegetative cover during site rehabilitation. The common reclamation practice in arid jurisdictions (e.g. Western Australia) where tailings salinization poses a threat to successful site reclamation is to deploy a suitable soil cover (Newson and Fahey 2003) that can provide an adequate rooting depth for the vegetated plants. As shown through numerical analyses conducted in the current research, placement of layers of saturated sand in-between lifts of saline tailings may help slow down the surface build-up of salts and increase the ease of site closure and re-vegetation. However, the longer term sustainability and integrity of such soil covers in terms of eventual breakthrough and migration of salts to the surface may need to be assessed.

Also, the sensitivity of reduction in evaporation to evaporative demand as shown in the current research as well as by Simms et al. (2007) suggest managing salt crust formation on saline deposits (e.g by mud-farming) is best guided depending on the

season of the year. In addition, a numerical framework that accounts for solute transport in predicting evaporation from soil and tailings as advocated for by Fisseha et al. (2010) and Fredlund et al. 2011 was proposed and validated in the current research. The importance of adequate material and pore-water chemistry characterization to meaningful use of numerical modeling as a tool to aid in tailings deposition planning and management is demonstrated in the current research.

As shown through numerical analyses in this research, the placement of multiple thin lifts of saline thickened tailings as opposed to a one-time placement of an equivalent tonnage as a deep deposit may considerably reduce the cycle time for drying the stack to a target shear strength. Of course, for a specific site, the “optimum” lift thickness would need to be determined within the context of the prevalent environmental, operational and regulatory constraints. The benefit of reduction in total cycle time for a deep depositional tailings strategy will also need to be assessed against the operational cost of frequent tailings cycling using multiple thin lift deposition.

The capillary barrier concept involves taking advantage of the capillary break at the interface between two layers of materials having contrasting grain size distribution with the goal of limiting oxygen ingress and water infiltration into underlying acid-generating mine waste. While the concept has been previously applied for implementation of different types of soil covers over sulphidic mine wastes (e.g. O’Kane

et al. 1998; Bussière and Aubertin 1999; Bussière et al. 2007), the application of the concept to minimize surface salt accumulation in saline tailings deposit is limited. In the current research, the deployment of a layer of candidate sand between two lifts of saline tailings was shown to be effective in reducing the accumulation of salt at the surface of the stack if placed saturated. Therefore, if considered economically and logistically feasible, deploying a saturated layer of sand (e.g. by hydraulic placement of cyclone underflow) in-between lifts of saline thickened tailings may prolong the time for the deposit to harvest evaporative energy before salt accumulation shuts down evaporation.

The current research also documents the conception, design and testing of a new prototype sensor that demonstrates the application of poroelasticity principle to determine the matric suction in soil and tailings. The matric suction sensor was tested with desiccating soil and thickened tailings used throughout this research and compared to concurrent determinations using the current well-established devices and techniques. The sensor was shown to provide reasonable measurements of matric suctions for values below its theoretical AEV, and was not prone to either hysteresis or cavitation within this range of matric suctions. Based on the various performance tests conducted for the new sensor in this research, it was shown to give a reasonably wider range of matric suctions (up to around 5500kPa) compared to most currently-available devices. Future iterations and testing of the sensor should assess its robustness under more variable boundary conditions and higher effective stress applications.

8.4 Contributions of Research to Knowledge Base and State of Practice

The current research has made the following contributions to existing knowledge base and potentially, the state of practice:

- (a) The soil resistance to water vapour diffusion from the evaporation front to the soil surface needs to be incorporated in addition to the total suction at the surface in order to accurately predict evaporative fluxes from non-saline soil columns. The empirical model of Wilson et al. (1997) was modified to incorporate increasing resistance of the desiccating soil columns for predictions to match experimental observations.
- (b) In saline soil, osmotic suction is the predominant portion of total suction and significantly influences the evaporative behaviour of the soil. The upper limit of the contribution of osmotic suction to the reduction in the rate of evaporation from saline soil is set by the solubility limit of the pore-water solute.
- (c) When the surface albedo is not considered, the maximum limit of osmotic suction's contribution to salinity-induced reduction in evaporation for saline soil is independent of the initial pore-water solute concentration and evaporative demand. Rather, this upper limit of osmotic suction is set by the solubility limit of the pore-water solute. The rate at which this maximum osmotic suction is

reached is controlled by these 2 factors, with the limit attained more rapidly in the case of a higher initial salinity and higher evaporative demand.

- (d) With the exclusion of surface albedo, osmotic suction alone is sufficient to predict the reduction in evaporative fluxes due to pore-water salinity up till the solubility limit of the pore-water solute. Beyond the solubility limit, further reductions in evaporation can be attributed to salt precipitation at the soil or tailings surface changing the hydraulic properties.
- (e) The extent of the contribution of osmotic suction to reduction in evaporative fluxes from saline soil and mine tailings is controlled by the initial pore-water salinity. Increasing initial salinities shorten the time to the onset of salt precipitation when the contribution of osmotic suction to reduction in evaporation reaches a maximum.
- (f) Evaporative demand exerts a moderating effect on the contribution of osmotic suction to reduction in fluxes from desiccating saline soil and mine tailings. Given the same initial pore-water salinity, increasing the evaporative demand accelerates the rate of solute advection to the surface and shortens the time for the peak contribution from osmotic suction to reduction in fluxes to be reached. Hence, the duration for which osmotic suction alone can sufficiently explain reduction in fluxes is shortened with increasing evaporative demand for the same initial pore-water salinity.

- (g) A numerical framework that accounts for the temporal increase in osmotic suction gave good predictions of evaporative fluxes and total suctions at the surface of desiccating saline soil and thickened tailings. When the initial pore-water salinity is low, the contribution of osmotic suction did not make significant difference for predictions using the numerical framework due to low values of osmotic suction recorded at the tailings surface over time. However, accounting for osmotic suction resulted in better fit of predictions to measured total suctions at the surface of tailings. For high initial salinity, the numerical framework gave good predictions of evaporative fluxes under low evaporative demand where the duration to achieve the peak contribution of osmotic suction to flux reductions at the solubility limit was prolonged.
- (h) Applying the correction factor in the numerical code to correct for the total suction at the surface used to predict evaporation resulted in good agreement between predictions of evaporation and experimental data. Overall, the best fit of predictions to experimental observations of both evaporative fluxes and total suction at the surface was obtained when the correction factor was applied and the temporal increase in osmotic suction was accounted for.
- (i) Based on calibrating the numerical code with detailed profile solute transport characterization and evaporative fluxes data, predictions of evaporative fluxes was shown to be highly sensitive to the saturated hydraulic conductivity. If a high

K_{sat} value is used in the simulation, Stage I evaporation is substantially prolonged and the onset of Stage II is delayed. This is accompanied by a shorter time for the tailings profile to dewater to a target water content. Hence, the need for considerable effort to be committed to adequate material characterization in order to get the best value from using numerical prediction of evaporative densification of tailings deposits as a tool in tailings management and planning.

- (j) Based on the calibrated unsaturated flow code, thin-lift multi-layer deposition is shown to result in a significantly lower total cycle time required for dewatering to achieve an average profile GWC equal to the tailings shrinkage limit compared to a single deep deposit. This is attributed to a shorter drainage path for evaporative drying as well as enhanced dewatering of deposit resulting from the hydraulic interaction between the old desiccated and freshly-deposited thickened tailings layer. Hence, where operational logistics afford flexibility for thin layers of thickened tailings to be placed frequently in a single depositional cell, thin-lift deposition may offer superior performance by significantly reducing the cycle time required to achieve a shear strength target.
- (k) Based on a 1D FEM solute transport code coupled to the unsaturated flow code and calibrated with laboratory data for surface salt accumulation in the desiccating tailings columns, a sand capillary barrier placed between two saline tailings layers was shown to reduce surface salt accumulation if placed wet. Placing the sand barrier dry was shown to further increase the extent of salt

accumulation at the surface of the deposit compared to just placing the deposit without a layer of sand barrier.

- (l) The theory of poroelasticity was successfully adapted for the determination of matric suction in porous media-soil and thickened tailings. The principle involves the correlation of the change in negative pore-water pressure of a linearly-elastic porous material to a change in its volume (strain).
- (m) With the candidate porous material for the new matric suction sensor having a high AEV, for matric suction measurements below this AEV, there was no evidence of either hysteresis or cavitation.
- (n) The designed matric suction sensor compared well with tensiometers, HD sensor, axis-translation technique and RH sensor when used to characterize the matric suction development over time for desiccating soil and thickened tailings.

8.5 Recommendations for Future Research and Development

Despite the substantive research efforts and contributions made by the current research, the following gaps in knowledge base and suggested future research focus are identified:

- (a) More research is needed to empirically quantify the additional contribution of salt precipitation to salinity-induced reduction in evaporative fluxes once

past the solubility limit. The use of microscopic imaging techniques (e.g. Environmental Scanning Electron Microscopy, ESEM) to aid such investigation is recommended.

- (b) Based on results from such empirical research, a numerical platform for incorporating the additional contribution from salt precipitation to salinity-induced reduction in fluxes should be developed.
- (c) For cases where all 3 mechanisms of salinity-induced reduction in evaporative fluxes (albedo, osmotic effects and salt precipitation) are at play, better understanding of the relative contribution of each mechanism is warranted. Once this is done, developing a numerical framework that incorporates the relative contributions of these 3 mechanisms in predicting evaporative densification of saline soil and tailings deposits should be pursued. The current research represents the first step in the direction of developing a robust numerical tool for predicting evaporative fluxes from saline soil or tailings deposits, regardless of the level of pore-water salinity.
- (d) Further experimental investigation of the comparative dewatering potential of placing multiple thin lifts of saline thickened tailings as opposed to a single equivalent deep deposit would be beneficial for deposition planning in saline tailings facilities. Specifically, investigating the difference in the magnitude of surface salt accumulation for multiple thin-lifts versus deep-layer

depositional schemes and the resulting implications for profile dewatering is warranted.

- (e) Not much empirical evidence of the effectiveness of deploying a capillary barrier to mitigate the surface accumulation of salts from deep saline tailings deposits is available in literature. Therefore, future research into whether this depositional strategy can deliver on reducing surface salinization of tailings deposits, especially under arid and semi-arid climates where tailings salinization poses a serious challenge for mine site reclamation is warranted. Incorporating a cost-benefit analysis in such research and development efforts within the context of medium to long-term site reclamation costs will be valuable information for operators of saline tailings management facilities to make an informed decision based on the unique set of site conditions.
- (f) Future iterations of the poroelastic sensor should consider using alternate miniature strain gages (e.g. vibrating wire strain gage) that will not be subject to drift over the long run. The sensor should also be tested in a wider variety of soils and environmental conditions to further evaluate its robustness.
- (g) The sensitivity of the matric suction sensor to soil-structure interactions as well as temperature fluctuations should be investigated in the future. If found to be sensitive to these 2, the possibility of embedding the strain gage inside the porous material (as opposed to bonding onto it) should be

explored in the future. This will minimize possible mechanical interference or thermal effects on strain measurements recorded by the sensor.

8.6 General Conclusions and Recommendations

The soil resistance to water vapour diffusion and the steep gradient in “total suction at surface of desiccating NS soil column need to be accounted for in order to predict evaporation, in addition to soil suction at the surface. In order to improve the accuracy of numerical predictions of evaporation from saline soil and mine tailings, temporal increase in surface osmotic suction needs to be accounted for in addition to applying a suction correction factor. The upper limit of the contribution of osmotic suction to reduction in evaporation is the solubility limit of the pore-water solute. Once past this limit, further reductions in evaporative fluxes can be attributed to salt precipitation. The rate at which the solubility limit of the pore-water solute is reached was found to be a function of the prevalent evaporative demand.

Exploratory numerical modeling suggests that multiple thin-lift deposition dramatically reduces the total cycle time to achieve a given water content (or shear strength) compared to deep-stacking an equivalent tonnage of thickened tailings deposited. The placement of a saturated sand layer between lifts of saline thickened tailings may be beneficial in reducing the accumulation of salts at the deposits surface and mitigate negative impacts on evaporative drying.

A prototype sensor was designed and tested against conventional devices in quantifying the matric suctions in soil and thickened tailings. The sensor was proved to be capable of avoiding either cavitation or hysteresis at values up to a few MPas , as long as the high AEV of its porous material is not exceeded. The sensor infers the matric suction of a test material from the strain recorded by its porous material after equilibration with the negative pore water pressure of the test material. Future iterations of the sensor should investigate the potential effects of soil-structure interaction and temperature fluctuations on sensor performance and re-design sensor to minimize any observed impacts.

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10.0 APPENDICES

APPENDIX A1.

Temperatures at the surface of water and soil packed and drying inside wax columns under ambient laboratory condition with wind simulated with fan. The air temperature at 2cm height above the water and silt columns is also shown. Results presented are for 2 independent trials.

APPENDIX A2.

Profiles of total suction within the top 1cm of the 10cm-thick NS soil columns fitted with a power function at different intervals within a 14-day duration.

APPENDIX A3.

Relative evaporation (RE) measured from 10cm-thick Non-saline (NS) soil columns and predictions from total suctions measured at the top 1cm and 2mm of desiccating column using equation 4.01. Results shown are for one of three independent replicate drying experiments.

APPENDIX A4.

Cumulative evaporation from hyper-saline (HS), saline (S), low-saline (LS) and non-saline (control) soil columns prepared at same initial GWC (30%) and concurrently desiccating in the laboratory, as well as corresponding cumulative potential evaporation (PE).

APPENDIX B1.

Relative hydraulic conductivity function of thickened tailings input into SVFlux.

APPENDIX B2.

Osmotic suction values calculated from EC data over time for the salinized soil and tailings columns desiccating under ambient (AW) and simulated wind (SW). The values were entered into SVFlux to predict evaporation from the columns.

APPENDIX B3

Total suctions used over time by SVFlux (before applying the suction correction factor) to predict evaporation for simulations of SW tailings column with and without accounting for osmotic suction. Sum of matric suctions predicted at the surface (0cm) of the desiccating SW tailings column by SVFlux and osmotic suction estimated from EC data and input into SVFlux (Total_With Osmotic) is shown for the simulation that accounted for osmotic suction. The matric suction predicted at the surface is also shown (Matric_With Osmotic). Only the matric suctions predicted at the surface (0cm) of desiccating SW tailings by SVFlux is shown and used for prediction of evaporation by the simulation that did not account for osmotic suction. Measured values of total suction in the top 1cm of the tailings column are also shown (Data).

APPENDIX B4

Cumulative actual evaporation (AE) measured from salinized soil columns desiccating under ambient (AW) and simulated (SW) wind conditions and predictions using SVFlux and Wilson + Soil Resistance Model (Equation 5.06). The total suctions used in equation 5.06 were extrapolated from measured values using the extrapolation function in equation 5.03.

APPENDIX B5

Cumulative actual evaporation (AE) measured from tailings columns desiccating under ambient (AW) and simulated (SW) wind conditions and predictions using SVFlux and Wilson + Soil Resistance Model (Equation 5.06). The total suctions used in equation 5.06 were extrapolated from measured values using the extrapolation function in equation 5.03.

APPENDIX B6

Gravimetric water contents measured (D) and predicted (P) at 1, 5, and 9cm depths of the salinized soil columns desiccating under ambient (AW) and simulated (SW) wind condition.

APPENDIX B7

Gravimetric water contents measured (D) and predicted (P) at 1, 5, and 9cm depths of the tailings columns desiccating under ambient (AW) and simulated (SW) wind condition.

APPENDIX B9

Comparison of SVFlux predictions of gravimetric water content over time at 1, 3 and 9cm depths of the SW tailings column to experimental observations (Data). Numerical results for simulations with (Osmotic) and without (No Osmotic) accounting for osmotic suction and with and without using the surface suction correction factor (Correction factor-CF; No correction factor-NCF) are shown.

APPENDIX B10

Comparison of data with numerical predictions of total suction in the top 1cm of SW thickened tailings column. The value of K_{sat} used in all simulations is 1 order of magnitude higher than the value determined from falling head test. Solutions for variable values of "c" parameter (multiples of 0.5, 1 and 1.5 of previously used value of - 0.65) applied in simulations are shown.

APPENDIX C1.

Pore-water electrical conductivity at different depths over time for the REWET thickened tailings columns.

APPENDIX C2.

Pore-water electrical conductivity at different depths over time for the 3-LAYER and 5-LAYER multi-layer tailings deposits.

APPENDIX C3.

Profiles of pore-water electrical conductivity for different layers of the multi-layer tailings deposits (3-LAYER and 5-LAYER) and for the entire profile at the end of desiccation. Profile EC for 5cm-thick bulk samples (e.g 15-20cm) are shown at the end of the desiccation experiment.

APPENDIX C4

Plots of total suctions measured in the top 1cm of the desiccating tailings columns and corresponding osmotic suctions estimated from measured EC data using the USDA (1954) equation. The values of osmotic suctions exceeding corresponding total suctions at certain times is attributable to the dissolution of any precipitated salt prior to EC determination as well as uncertainties associated with the saturated extract method of osmotic suction estimation from EC data (as per discussion in Section 6.3.2.5).

APPENDIX C5.

Total suctions measured at different depths over time for the REWET tailings columns.

APPENDIX C6.

Profiles of total suctions measured at different depths over time for the 3-LAYER and 5-LAYER multi-layer tailings deposits.

APPENDIX C7.

Osmotic suction values calculated from EC data measured in the top 1cm over time for the desiccating DRY(AW), DRY(SW) and REWET tailings columns. The values were entered into SVFlux to predict evaporation from the columns.

APPENDIX C8

Total suctions measured in the top 1cm of the DRY(AW), DRY(SW) and REWET tailings columns with corresponding numerical predictions by SVFlux with and without applying a surface suction correction factor. Also shown are the osmotic suctions measured in the top 1cm of columns from the EC data.

APPENDIX C9.

Gravimetric water contents measured and predicted (from SVFlux) at depths of 1, 8, and 14cm of the DRY(SW) and DRY(AW) thickened tailings columns.

APPENDIX C10.

Gravimetric water contents measured and predicted (from SVFlux) at depths of 1, 8, and 14cm of the REWET thickened tailings columns. Predictions with and without using a surface suction correction factor are shown.

APPENDIX C11.

Comparison of SVFlux predictions of cumulative actual evaporation (a) and total suctions in the top 1cm (b) to measurements over time for the REWET tailings column. Numerical results for simulations with (Osmotic) and without (No Osmotic) accounting for osmotic suction as well as with and without using the surface suction correction factor (Correction factor-CF; No correction factor-NCF) are shown.

APPENDIX C12.

The profiles of gravimetric water content (GWC) measured (data) and predicted by SVFlux prior (Day 9) and after (Day 22) re-saturation for the REWET tailings column (a). Numerical results for simulations with (Osmotic) and without (No Osmotic) accounting for osmotic suction as well as with and without using the surface suction correction factor (Correction factor-CF; No correction factor-NCF) are shown. Also shown are the corresponding mean absolute errors of predicted average profile GWC relative to data for days 9 and 22 (b).

APPENDIX C13.

Average gravimetric water contents (GWC) measured and predicted for the entire profile for each desiccating layer of the 3-LAYER and 5-LAYER thickened tailings stacks.

APPENDIX C14.

Measured actual evaporation and predictions from SVFlux for the desiccating 5-LAYER tailings deposit with and without accounting for osmotic suction at the surface (a). The value of correction factor (c) and K_{sat} used in all simulations is half the value previously used (-0.33) and 1 order of magnitude higher than the value previously used, which was determined from falling head test, respectively. Profiles of gravimetric water contents measured (D) and predicted (P) at the end of desiccation of a layer for the 3-LAYER and 5-LAYER thickened tailings deposits. Each layer is numbered (e.g. L1 and L2 designates Layer 1 and Layer 2, respectively) accordingly.

APPENDIX C15.

Predictions of profile gravimetric water contents for the simulations using the low K_{sat} and high K_{sat} values for deposits of the DRY(SW) thickened tailings over a period of 15 days. The values for low and high K_{sat} were 2×10^{-9} and 2×10^{-5} m/s, respectively. The initial GWC (Day 0) for the tailings was 39%.

APPENDIX C16.

Comparison of the average profile gravimetric water contents simulated over time for a 15cm and 50cm lifts of the SW(DRY) thickened tailings. The average simulated profile GWC is fitted with an exponential function.

APPENDIX C17

Profiles of predicted mass of salt accumulated over time for the entire depth of the desiccating tailings deposits with (A and B) and without (C) using sand capillary barrier. Results for the capillary barrier assumed to be placed initially dry (A) and saturated (B) are shown.

APPENDIX C18

Predictions of profile salt accumulation over time in the top 40cm of a model desiccating "hyper-saline" tailings deposits with (A and B) and without (C) a sand capillary barrier. Results for the capillary barrier assumed to be placed initially dry (A) and saturated (B) are shown.

APPENDIX D. SAMPLE LABORATORY PICTURES

Tailings columns showing salt precipitates at the surface

Freshly prepared tailings columns. Also shown is the water column for PE determination.

Desiccating saline soil showing the salt precipitates at the surface.

Salt precipitates at the surface of the multi-layer deposits

Multi-layer deposit at the end of 5-LAYER deposit experiment