Proceedings of the 4th International Conference on Unsaturated Soils, ASCE, Carefree, Arizona, April 2-6, Vol. 1, pp. 883-893. 2006

Unsaturated Properties of Mixtures of Waste Rock and Tailings

B.E. Wickland[1], G.W. Wilson[1], D.G. Fredlund[2], and D. Wijewickreme[3]

[1]Mining Engineering Department, University of British Columbia, 6350 Stores Road, Vancouver BC, V6T 1Z4; PH (604)-822-6781; FAX (604)-822-5599; website: http://www.wilson.mining.ubc.ca/

[2] Department of Civil and Geological Engineering, University of Saskatchewan, Saskatoon, S7N 5A9, Canada, PH (306) 261-8629; email: unsaturatedsoil@yahoo.com

[3]Department of Civil Engineering, University of British Columbia, 6250 Applied Science Lane, Vancouver, BC, Canada V6T 1Z4; PH (604) 822-5112; FAX (604) 822-6901; e-mail: dwije@civil.ubc.ca

Abstract:

Mixtures of mine waste rock and tailings, tailings alone, and waste rock alone were examined for soil-water characteristic curves (SWCC's) along the drying path. Laboratory data were compared with matric suction measurements and observations from a two year meso-scale column study of self-weight consolidation under free drainage. Waste rock alone had a near zero air-entry value and reached residual water content at low matric suctions. The mixture remained saturated relative to waste rock alone, a finding that was attributed to the presence of a fine-grained tailings matrix. The tailings had a high air-entry value, but also had significant volume change with increasing matric suction. The mixture had less total volume change than tailings for a given change in matric suction. The lower total volume change of mixtures was attributed to the presence of an internal "waste rock skeleton." Both the mixture, and tailings alone had SWCC's with a change in slope that was dominated by changes in volume, rather than a distinct air entry value (AEV), and a volume change correction was required to accurately determine the SWCC. Under prolonged drainage and/or high matric suctions, the mixture developed cracks within the tailings matrix. In general, the results indicate that mixtures can remain tension saturated for long periods of time relative to waste rock alone. Mixing for disposal therefore has the potential to limit the rate of acid rock drainage, particularly for wet climates.

Introduction

Problems associated with conventional methods of mine waste disposal have lead to an increasing interest in alternative disposal methods. Conventional disposal methods involve end dumping of waste rock in large piles and the impoundment of slurried tailings. The porous, open structure of waste rock piles allows convective flow of oxygen and has resulted in the problem of acid rock drainage (ARD). The semi-fluid structure of tailings in impoundments has, in combination with the upstream method of construction, resulted in catastrophic failures involving loss of life and environmental damages. Both ARD and potential for liquefaction failure are long term liabilities.

Mixing mine waste rock and tailings is an alternative disposal practice with the potential to limit the production of acid rock drainage (ARD) by maintaining a water saturated void space. This paper compares the soil-water characteristic curves (SWCC's) of a mixture of waste rock and tailings with waste rock alone, and with tailings alone. The laboratory derived SWCC's are also compared with results from a meso-scale column test described in Wickland and Wilson (2005).

Methods

Soil-water characteristic curves (SWCCs) for specimens of Carbon in Pulp (CIP) tailings and for a mixture of waste rock and tailings were obtained by Tempe Cell test. The mixture material was sampled during construction of a field scale experiment described by Wickland and Wilson (2005), and tested in a 150 mm diameter Tempe cell, shown in Figure 1.

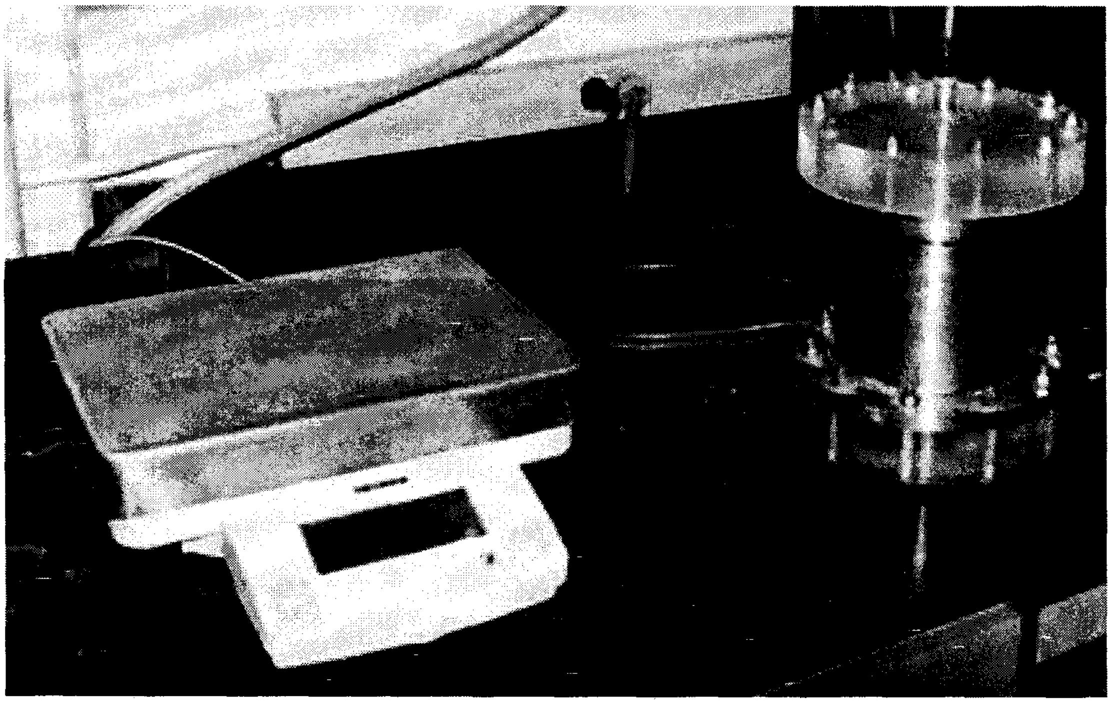

Figure 1. Large diameter Tempe cell with scale.

The tailings were taken from a mill circuit, thickened using a flocculant, and then tested in a standard Tempe cell ring. For both tests, specimen dimensions were measured to determine specimen volumes at the end of each pressure interval. The mixture specimen was constructed using altered sedimentary waste rock and tailings slurry. The SWCC of the altered sedimentary waste rock was not tested in this study but the SWCC for a similar rock type, a black sedimentary waste rock, was previously determined and is included for comparison purposes. Both rock types were taken from the same open pit and had similar particle size distributions. It is noted that the altered sedimentary waste rock was slightly more competent and less friable than the black sedimentary rock.

Particle size distribution was determined for a duplicate specimen of the mixture material by using a washed sieve analysis and for a tailings specimen by hydrometer and wet sieve analysis. The tailings were tested for liquid and plastic limits following ASTM D4318-84. The shrinkage limit of the tailings was also determined by placing tailings in a metal ring, drying at room temperature and in an oven, then coating the specimen in wax to determine final dried volume.

Results

Particle Size Distributions

Particle size distributions of the mixture, source materials, and the black sedimentary rock, are shown in Figure 2.

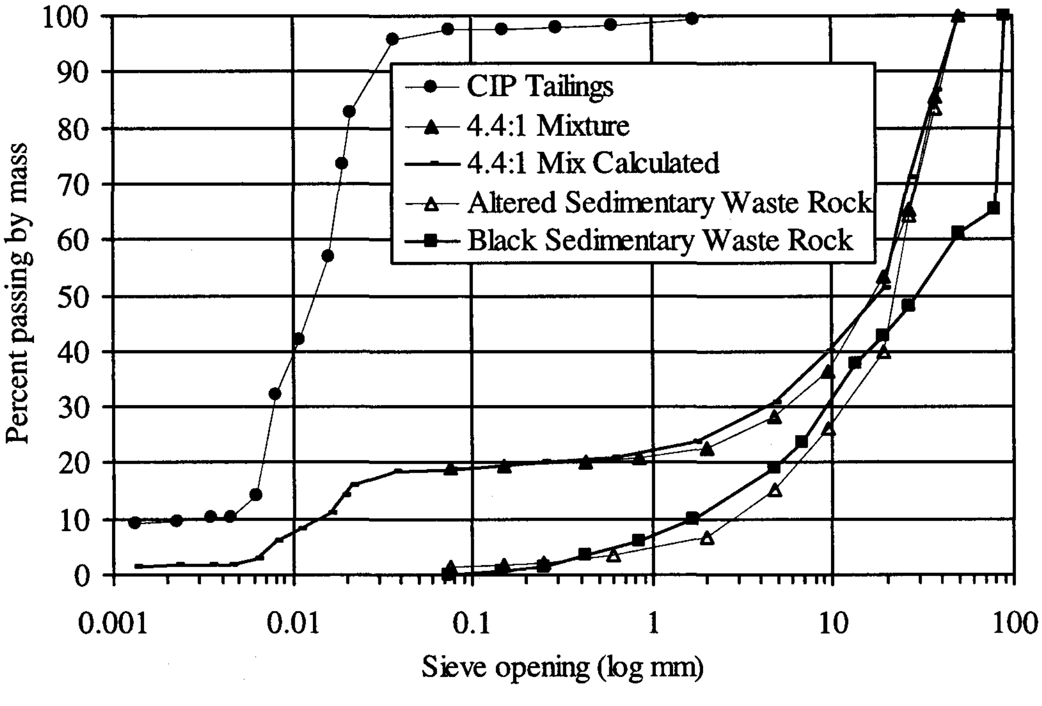

Figure 2. Particle size distributions.

The mixture ratio for the mixed specimen was 4.4:1 waste rock to tailings by dry mass. The mixture was constructed with the same CIP tailings. The tailings, mixture and waste rock specimens had 97%, 19%, and less than 2% passing the 75μm sieve, respectively. The tailings are considered to be fine-grained relative to other types of tailings. The particle size distribution of the black sedimentary rock was similar to the altered sedimentary waste rock used as a source for the 4.4:1 mixture, shown in Figure 2. On the basis of similar particle size distributions, the SWCC's for the black sedimentary waste rock and altered sedimentary waste rock used to construct the mixture are also expected to be similar.

Soil-Water Characteristic Curves

SWCC's for the mixture, tailings, and black sedimentary rock are shown in Figure 3. Data for the mixture and tailings are corrected for volume change and waste rock data are uncorrected for volume change. Values of volumetric water content for the oven-dried condition are assumed to be zero corresponding to a matric suction of 1,000,000 kPa.

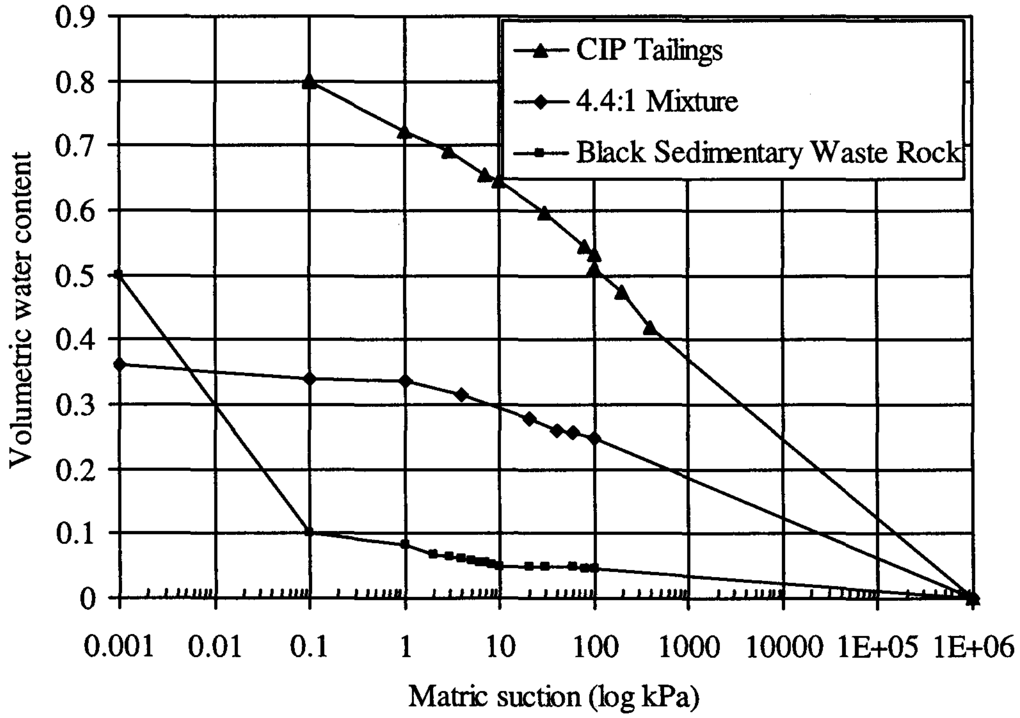

Figure 3. SWCC for tailings, mixture, and waste rock.

The data in Figure 3 indicate the tailings, mixture, and waste rock had initial volumetric water contents of 0.8, 0.36, and 0.50, respectively. At matric suctions greater than approximately 0.1 kPa, the mixture had slightly less than half the volumetric water content of the tailings and more than three times that of the waste rock.

The waste rock had an air entry value (AEV) of less than 1 kPa matric suction with a residual volumetric water content of approximately 0.05 (or 5%) at 10 kPa. The values of AEV for the mixture and tailings are not immediately apparent from Figure 3 because most of the change in volumetric water content was due to volume change or specimen shrinkage rather than de-saturation. According to measurements of specimen volume, the data presented in Figure 3 do not define an AEV or residual water contents for the waste rock, or for the tailings. The difficulty in determining AEV and residual suction is partly due to the limited range of suctions tested, but also due to shrinkage of specimens during the test.

The SWCC data for the tailings and mixture in Figure 3 are corrected for changes in volume during the test as recommended by Fredlund (1999). The volumetric water content corresponding to each applied matric suction during the Tempe cell test was calculated using:

1) $\theta(\psi) = [w(\psi)G_s] / [1+e(w(\psi))]$, where

θ is volumetric water content, ψ is matric suction, w gravimetric water content, G_s is specific gravity, and e is void ratio (Fredlund 1999). More simply, the specimen volume was determined at the end of each matric suction increment in order to calculate volumetric water content. Specimen volumes were calculated with the assumption that the mixture and tailings specimens remained saturated for the duration of the test (excluding the 1,000,000 kPa matric suction – oven dry condition). The assumption that the specimens remained saturated is valid for suctions to at least 40 kPa, and was made on the basis of shrinkage curve data. The value of G_s of the tailings was taken as 2.89

Shrinkage Curves

The specimen dimensions of mixture and tailings specimens were recorded at the end of each matric suction interval during the Tempe cell test. The tailings changed in volume by 53% for an increase in matric suction of 0 kPa to 100 kPa. The mixture changed in volume by 15% for an increase in matric suction of 0 kPa to 100 kPa. Changes in waste rock volume were not measured, but were quite small. Specimen volumes and void ratios were determined from specimen dimensions for the mixture and tailings specimens and are plotted as shrinkage curves in Figures 4 and 5, respectively.

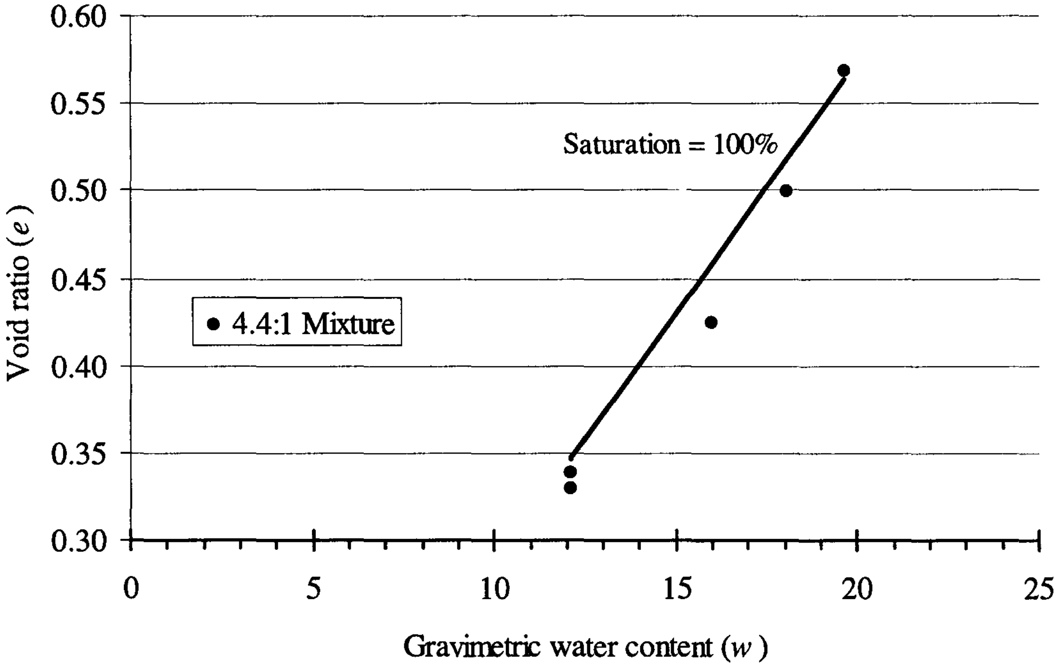

Figure 4. Shrinkage Curve for 4.4:1 Mixture.

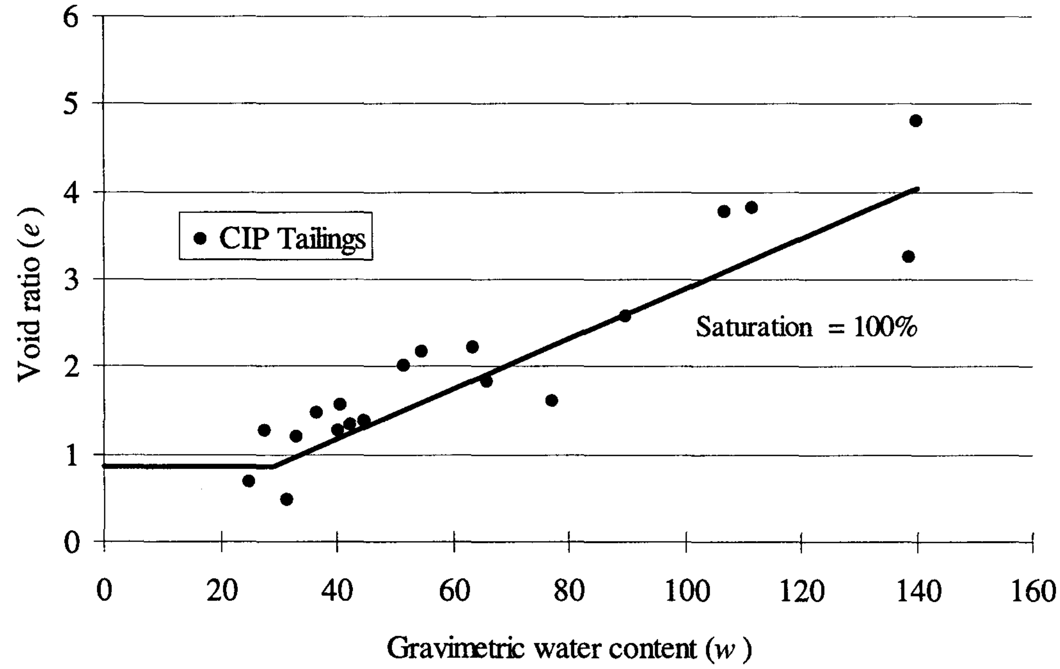

Figure 5. Shrinkage Curve for CIP Tailings.

The data in Figure 4 fall near the 100% saturation line, suggesting that the maximum applied matric suction of near 100 kPa (excluding the oven-dried condition of 1,000,000 kPa) did not exceed the AEV of the material. Small cracks were observed on the surface of the mixture specimen during tests at matric suctions greater than 40 kPa, corresponding to a gravimetric water content of 12%. The assumption that the specimens remained 100% saturated during the test is subject to interpretation. There is the possibility that there was some error in accurately determining specimen volume from dimensional measurements, particularly after the development of cracks. However, the assumption does not significantly change the shape of the SWCC, and provides a more accurate representation of behaviour than the assumption of zero volume change during the test.

The data presented in Figure 5 do not indicate a defined AEV for the tailings. The scatter in the data is attributed to errors in measuring specimen volume. Fredlund (1999) suggested using a correction for volume change based on the shrinkage limit. A shrinkage test was performed to determine final specimen volume for the oven-dried condition and results are illustrated in Figure 5 and included in Table 1. The measured shrinkage limit of 29% corresponds to a void ratio of 0.85, as illustrated in Figure 5. The shrinkage limit was also estimated from the Plasticity Index, and is included in Table 1.

Atterberg Limits

The liquid and plastic limits of the tailings were determined from laboratory testing, and are presented in Table 1. The shrinkage limit presented in Table 1 was estimated from the equation:

2) $SL = 20 \pm \Delta PI$, where

SL is the shrinkage limit, and ΔPI is the distance between the plasticity index and the A-line.

Table 1 Atterberg Limits for CIP Tailings.

CIP Tailings	Gravimetric Water Content (%)
Liquid Limit	50.2
Plastic Limit	33.2
Plasticity Index	17.0
Shrinkage Limit	
- measured	29.3
- estimated	25.0

Holtz and Kovacs (1981) provided a more detailed explanation of the method of estimation, and noted that the accuracy of such estimates is similar to the accuracy for actual laboratory shrinkage tests. The initial gravimetric water content of the slurry was near 110%.

Meso-Scale Column Study Results

Data from a meso-scale column study of the mixture material are presented here for comparison with laboratory results. The column study was described by Wickland and Wilson (2005), and involved loading three mixtures of waste rock and tailings into columns of 1 m diameter and 6 m in height, then monitoring for drainage, settlement, and pore water pressure response. A fourth column was loaded with waste rock only as a control. The columns were equipped with base drains and fitted with lids that allowed air flow but prevented influx of rainfall. Matric suctions measured for the mixture in Column 1, (a specimen of the same mixture is labelled "4.4:1 mixture" in this paper), are presented in Figure 6. Figure 6 includes measurements taken 125 days after column loading. A curve representing hydrostatic conditions with a water table at the base of the profile and matric suction measurements taken just prior to deconstruction are labelled "final."

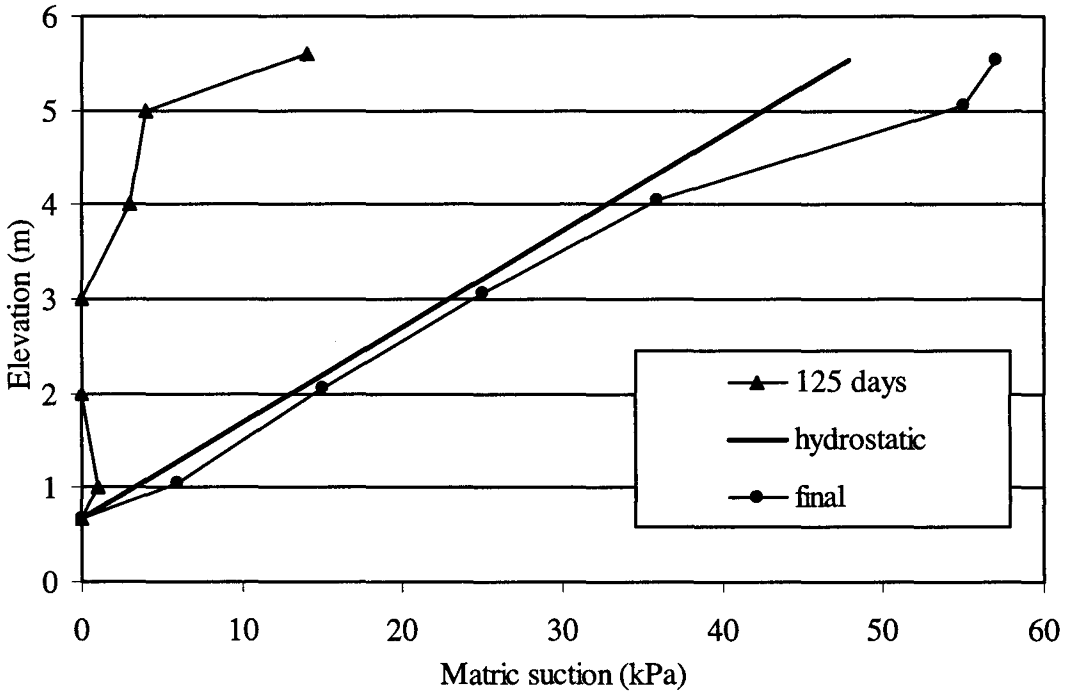

Figure 6. Mixture matric suction measurements from Meso-scale column study.

Immediately after placement of the fill the mixture profile was observed to undergo a phase of double drainage and ponding followed by a phase of single drainage with the development of negative pore-water pressures from the top down. Water exiting the surface of the specimen during the double drainage phase remained ponded on the surface of the profile until approximately 85 days after placement, leaving approximately 40 days of free drainage to develop the matric suction profile labelled "125 days" in Figure 6.

The column study was run for approximately two years and then dismantled. The profile was flooded six months prior to deconstruction, and then allowed to drain to the condition marked "final" in Figure 6. The final condition was close to the hydrostatic case with slightly higher matric suctions near surface. The maximum measured matric suction was 57 kPa. During final excavation and sampling of the Column 1 profile it was observed that mixture was drier near the surface, with the material becoming wetter with depth. Cracks and fissures were observed within the tailings matrix of the mixture above 4 m elevation. Material below the 3.5 m elevation was cohesive.

Analysis and Discussion

Analysis and discussion of results is divided into interpretation of laboratory results and relationship of laboratory testing results to the matric suction measurements and observations from the meso-scale column study.

Laboratory

Analysis of laboratory derived SWCC's for tailings, waste rock, and mixtures indicated the following:

1) Mixtures maintained water saturation upon application of matric suctions relative to waste rock alone due to the presence of a fine-grained tailings matrix. The air-entry values and residual matric suctions of the mixture and tailings specimens were not apparent from the range of matric suctions tested.
2) The waste rock had an air-entry value less than 1 kPa and reached residual water content at low matric suctions (near 10 kPa).
3) The tailings underwent a large volume change or shrinkage during the Tempe Cell test. From 0 kPa to 100 kPa matric suctions in the tailings specimen shrank by slightly more than 50% and the mixture shrank by 15%. The large degree of volume change was anticipated for slurried tailings. The volume change of the waste rock during the test was not measured but was quite small.
4) The limited volume change of the mixtures was attributed to the presence of a "waste rock skeleton." Tailings within the void space of the skeleton were observed to shrink and crack at higher suctions but the total volume of the mixture specimen did not change significantly. The phenomenon described is related to the construction of a mixture using tailings slurry with high water content.
5) Significant volume changes during de-saturation must be accounted for to accurately determine the SWCC; a finding which supports the conclusion of Fredlund (1999). Otherwise, the interpretation of the air-entry value for the SWCC will be inaccurate. Specimen volumes must be determined at the end of each matric suction interval and used to calculate volumetric water content, as in Equation 1. For the mixture and tailings specimens tested, the curved shapes of the SWCC's were due almost entirely to volume change associated with water loss from a saturated specimen rather than entry of air into the pore space.
6) Cracking upon de-saturation is, in some cases, more important than the air-entry value. The air-entry value (AEV) is defined as "...the matric suction value that must be exceeded before air recedes into the soil pores..." (Fredlund and Rahardjo 1993). If a saturated porous soil matrix is continuous,

then the movement of air through the specimen will be limited to diffusive flow. If cracking occurs while the pores of the soil remain tension saturated, then there can be a significant increase in the air coefficient of permeability at matric suctions below the AEV. Air may flow through the cracks of the specimen while the pore space remains saturated. Air permeability will become a function of the size and connectivity of cracks dividing the saturated portions of the specimen.

Field Study

Comparison of laboratory SWCC's with matric suction measurements from a meso-scale column study indicated:

1. The column mixture profile maintained water saturation for prolonged periods of free drainage without access to water. The maximum matric suction measured in the column profile at 125 days after construction was near 15 kPa. The SWCC data indicated that the laboratory specimen was saturated, at 15 kPa. The laboratory test data and field observations imply that the column profile was saturated after 125 days of free drainage without access to water.
2. After a six-month period of free drainage without access to water, the maximum final measured matric suction was near hydrostatic with a maximum measured matric suction of near 60 kPa at the surface of the profile. The laboratory mixture specimen shrank and developed fine cracks within the tailings matrix at suctions greater than 40 kPa. During deconstruction of the column experiment, cracks and fissures were observed in the upper 1.5 m to 2 m of the column mixture profile, corresponding to measured matric suctions of greater than 40 kPa.
3. The control column with a waste rock only profile was initially unsaturated following construction, and remained unsaturated until flooded at day 13 of the test.

Summary and Conclusions

The soil-water characteristic curves, SWCCs, of tailings, waste rock, and a mixture of tailings and waste rock were presented and compared to results from a meso-scale column study. Key findings included:

1. Mixtures of waste rock and tailings remained saturated for significantly longer periods of time and at higher matric suctions than waste rock alone. The maintenance of saturation was attributed to the presence of a fine-grained tailings matrix. The result indicates that mixing waste rock and tailings for disposal has the potential to limit the production of acid rock drainage (ARD).
2. Mixtures had less volume change than tailings alone, a finding that was attributed to the presence of an internal "waste rock skeleton." Slurried tailings were observed to undergo a large degree of volume change or shrinkage upon application of matric suction. The large change in volume of the tailings was attributed to the high initial water content.

3. Under prolonged drainage without access to water the mixture material was observed to develop cracks through the tailings matrix. However, the mixture material was less prone to volume change and shrinkage upon drying than tailings alone. Instead, shrinkage cracking was observed within the tailings matrix while the total volume of the specimen was maintained. If mixtures are used as a mine waste disposal technique, then extreme drought and dry conditions have the potential to cause cracking and an increase in air and water coefficients of permeability. Consequently, the climate of a site and rainfall in particular should be considered in the application of mixing for disposal.
4. The findings of this study re-enforce the need to account for volume change when determining the soil-water characteristic curve, particularly for slurried specimens such as the tailings examined herein.

Acknowledgements

The authors would like to acknowledge the Natural Sciences and Engineering Research Council of Canada, Placer Dome Inc. and the Porgera Gold Mine for making this work possible.

References

Fredlund, D.G., and Rahardjo, H. (1993). *Soil Mechanics for Unsaturated Soils.* John Wiley and Sons Inc. New York.

Fredlund, M.D. (1999). The Role of Unsaturated Soil Property Functions in the Practice of Unsaturated Soil Mechanics, Ph.D. Thesis, University of Saskatchewan.

Holtz, R.D., and Kovacs, P.E. (1981). *An Introduction to Geotechnical Engineering*, Prentice-Hall, N.J.

Wickland, B.E., and Wilson, G.W. (2005). Self-weight consolidation of mixtures of mine waste rock and tailings. *Canadian Geotechnical Journal*, 42(2), 327-339.