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Desiccation and Shrinkage of Low Plasticity Tailings: Testing and Preliminary Modeling

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ABSTRACT
This paper presents experimental results from free and restrained shrinkage tests conducted on tailings. The laboratory technique used here has been recently developed to assess the desiccation of tailings from hard rock mines. Sample results obtained with this testing procedure are presented and compared with results from a pressure plate extractor test performed on the same tailings. Comparison between experimental data and numerical simulation results is also used to analyze the unsaturated behaviour of tailings subjected to desiccation.

RÉSUMÉ
Ce papier présente des résultats expérimentaux issus d'essais de retrait libre et contraint réalisés sur des échantillons de résidus miniers. La technique de laboratoire utilisée ici a été récemment développée pour évaluer la dessiccation de résidus de mines en roche dure. Quelques résultats sont présentés et comparés à ceux d'un essai en cellule de pression réalisé sur les mêmes résidus. Une comparaison entre les résultats expérimentaux et ceux de simulations numériques sert aussi à analyser la réponse non saturée des résidus miniers en phase de dessiccation.

1 INTRODUCTION

Surface impoundments are commonly used in the mining industry to dispose of mill tailings. Problems associated with conventional methods of tailings disposal have lead to an increasing interest in alternative disposal methods for base and precious metals mines (Bussière, 2007). Such is the case with surface paste tailings deposition, where each layer of densified tailings is placed and allowed to dry before the next layer is put in place. This technique was applied at the Bulyanhulu mine (Barrick Gold, Tanzania), where paste tailings deposition is cycled between different towers in the impoundment (Martin et al., 2006).

Deposition of paste tailings at Bulyanhulu has been ongoing since 2001. On location, it has been observed that the optimum desiccation condition can be obtained with a 5-day deposition cycle, using a layer thickness of about 30 cm (Theriault et al., 2003; Fisseha et al., 2010). The tailings can then densify and gain significant strength through shrinkage and desiccation, leading to the development of stable stacks. In the presence of reactive minerals, the operator must however minimise tailings desaturation and cracking with the timely placement of the next layer, to avoid an increased acid production (Martin et al., 2006, 2010).

When exposed to surface conditions, tailings can be subjected to large matric suctions during dry spells, which favors shrinkage. The volumetric straining in turn affects their hydro-geotechnical behaviour in various ways. Such fine-grained material exposed to evaporation and/or drainage may become unsaturated upon drying. During this process, negative pore water pressure (i.e. suction) develops in the porous medium (e.g. Nahlawi and Kodikara, 2006). This may induce a volumetric contraction (Mbonimpa et al., 2006) that can lead to various problems. The effect of desiccation can become more problematic when shrinkage is restrained and cracks appear at the surface of fine-grained materials (Konrad and Ayad, 1997; Péron et al., 2006).

Analyzing tailings behaviour for such conditions is challenging because the processes involved are not yet well understood and characterized. A better knowledge of tailings desiccation is required to assess their *in situ* behaviour in order to further improve the disposal strategy.

This paper presents a laboratory technique recently developed to evaluate the shrinkage of tailings from hard rock mines; the procedure can also be applied to low plasticity silty soils. Sample results obtained on the Bulyanhulu mine tailings with this testing procedure are presented and compared with those obtained from a pressure plate test performed on the same material. Together, these two types of test can be used to evaluate the hydro-geotechnical response of unsaturated tailings naturally exposed to various levels of suction. This paper also presents early results on restrained desiccation (and cracking) tests conducted on the same low plasticity tailings. The results from laboratory tests are compared with preliminary numerical simulation results on the unsaturated response of the tailings.

2 MATERIALS AND TESTING PROCEDURE

2.1 Basic properties

Tests were performed on tailings from the Bulyanhulu gold mine, prepared as a paste, with a pulp density P of about 72%. According to the Unified Soil Classification System, USCS (e.g. McCarthy, 2007), these tailings are classified as a sandy silt (ML), based on their grain-size curve and (lack of) plasticity. Some basic geotechnical properties of the tailings are shown in Table 1. The free and restrained desiccation experiments were carried out in a room where the temperature and relative humidity were monitored.

Table 1. Basic properties of Bulyanhulu tailings

Parameter	Value
D_{10} (mm)	3×10^{-3}
D_{60} (mm)	3.8×10^{-2}
C_U (-)	12.7
D_r (-)	2.93
k_{sat} (m/s)	$10^{-7(*)}$

(*) k_{sat} (saturated hydraulic conductivity) for a void ratio of about 0.65 (from Martin et al. 2006)

2.2 Experimental methods

2.2.1 Testing equipment

One of the goals for these tests is to provide relatively simple conditions for the results assessment. The tests are conducted in perspex moulds with a rectangular cross section. The testing set-up and procedure are fairly similar to those developed for clayey slurries by Péron et al. (2006). Modifications were implemented to take into account the specific properties of hard rock mine tailings, which show little cohesion (when saturated) and a larger frictional strength when compared with most clayey soils (Saleh-Mbemba et al., 2010). During the tests, the base and sides of the specimen are covered with a thin, flexible plastic film. The rectangular mould opening that laterally confines the tailing specimen in each hollow plate (12 mm thick) is 200 mm in length and 30 mm in width (Figure 1). Various specimen thicknesses can be tested by superposing more than one plate.

A digital camera is mounted on top of the set up to capture and save the images of the tested specimens.

2.2.2 Specimen preparation and free shrinkage test procedure

Prior to the experiment, the tailings are thoroughly and uniformly mixed. The samples tested here were prepared at a water content w = 38.5% (pulp density P ≈ 72%). The tailings specimen is gently placed into the mould up to the required thickness using a flat spoon. When the mould is filled, the excess material is removed from the top using a steel bar and the surface level is smoothed. The thin, flexible plastic film below and on the sides of the specimen reduces the shear resistance that could prevent free deformation during drying, while at the same time creating a 1D evaporative flux condition (from the top surface only). Tests were conducted on specimens having different thicknesses; results on the 36 mm specimens are mainly presented here.

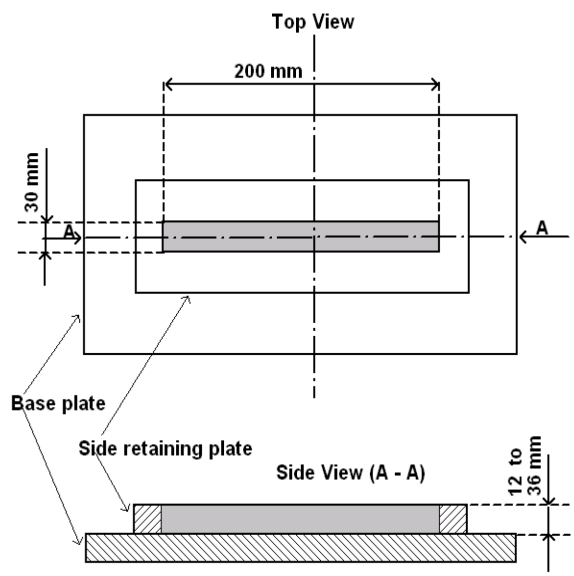

Figure 1. Schematic views of the testing set –up

While drying from evaporation, the tailings specimens are monitored for gravimetric water content and volume changes at regular time intervals. The total mass and average water content are recorded by weighing. Strains (in three directions) are measured using a precision vernier calliper. The settlement of the sample is obtained from the variation of the sample height upon drying. This height is measured at five locations using the vernier, which is fixed to the support; the average value of height is used to determine the volume of the specimen at each stage of drying. The lateral and longitudinal shrinkage strains are also computed from the direct size measurements. The experiment is stopped when the specimen mass stabilizes, i.e. when the dehydration process is completed.

The experiments were performed at 22℃ (± 1.5℃) with an average relative humidity RH varying between 31 and 54%. The average pan (potential) evaporation PE is 2.16 mm/day. Cracks did not appear during testing as shrinkage can freely develop (unrestrained). The initial and final water content are determined using oven drying. At the end of the experiment, the specimens are oven-dried at 40℃ for 48 hours to obtain their final volume without changing the material structure, and then at 105℃ for 24 hours to measure the mass of solids M_S.

2.2.3 Restrained testing procedure

Laboratory experimentation on desiccation cracking is also carried out to examine the relationship between strain and water content at crack initiation, with the other prevailing conditions. For the restrained desiccation tests, only the 36 mm thick mould is used, as it is considered the most representative for the purpose of this investigation. Tests are carried out using the same moulds, in which a wire mesh is placed at the bottom, as shown in Figure 2. The aim of this modification is to restrain shrinkage and thus induce cracks by limiting horizontal displacement at the base of the specimen undergoing drying.

Each specimen is prepared at the same initial water content as for the free desiccation tests. It is placed into the mould using the same procedure and left to dry until the appearance of the first crack.

Figure 2. Modified set-up for restrained shrinkage; a wire mesh is seen at the base of the mould opening.

Figure 3. Characterization of crack appearance using a magnifying stereoscope.

Crack initiation is characterized using a magnifying stereoscope, as shown on Figure 3. The time for crack initiation is established from frequent measurements and observations (typically four per hour). Once the first crack is initiated, the mould is weighed to obtain the humid mass $M_{h\text{-}cr}$ of the specimen. This gives the water content w_{cr} at the onset of crack initiation:

$$w_{Cr} = \left(M_{h-Cr} - M_S\right)/M_S \qquad [1]$$

where M_S is the weight of the oven dried specimen.

As will be shown below, the water retention curve (WRC) can then be used to estimate the critical suction ψ_{ca} for crack appearance.

2.2.4 Pressure plate extractor tests

Pressure plate tests are performed for comparative purposes and to obtain additional information. The pressure plate tests are conducted following the standard testing procedure ASTM D3152. The saturated tailings specimens are held in individual soft (flexible) plastic rings which are placed directly on the saturated porous cellulose membrane in the pressure chamber. Eight duplicate specimens can be tested simultaneously. To obtain more representative results, two series of tests are performed on the same material, at the same average initial water content (of 38.5%), by applying several pressure levels up to about 4000 kPa.

The volume of one of the specimens is determined at the end of each matric suction increment, through size measurements. A vernier is used to measure sample thickness. The area of the specimens is determined from a numerical image using the ImageJ software (Girish and Vijayalakshmi, 2004). The method consists in digitizing the picture, and converting the number of image pixels into an area (Saleh-Mbemba et al., 2010).

The volumetric water content corresponding to each applied matric suction level during the pressure plate test is calculated from the following relationship:

$$\theta = wD_r/\left(1+e\right) \qquad [2]$$

where θ is the volumetric water content (which depends on the applied matric suction ψ); w is the gravimetric water content, D_r is the relative density of the solid grains, and e the void ratio.

3 TESTS RESULTS AND INTERPRETATION

3.1 Shrinkage curve

Shrinkage is usually characterized from the curve that relates the void ratio e to the water content w (e.g. Bardet 1997). Figure 4 shows the shrinkage curve obtained on the Bulyanhulu tailings. The void ratio, determined from the specimen volume at each stage, is plotted against the corresponding water content.

Figure 4 shows that the shrinkage curve initially follows a linear progression, along the so called the “load line” (e.g. Sposito, 1973) or “one-to-one relationship” (Croney and Coleman, 1953; McGarry, 1988). As the specimen remains saturated during this first stage, the volume lost is directly related to the amount of water being removed (Bronskwijk, 1989; Mitchell, 1991;

Fredlund and Rahardjo, 1993; Head, 2006). When the water content reaches the air entry value condition (w_{AEV}), the largest pores start to drain (Brooks and Corey, 1964; Mbonimpa et al., 2006). This is followed by the residual shrinkage stage, where the removal of water exceeds the specimen volume reduction. In terms of void ratio reduction, this stage is very short for the low plasticity tailings, so the onset of desaturation is close to the shrinkage limit w_S.

The results obtained on tailings agree with those of Péron et al. (2006), who carried out shrinkage tests on silty soils. They reported that the shrinkage curve is almost bilinear, with the first part following the saturation line, and a second horizontal part with a constant void ratio equal to a limiting void ratio ($e_S = e_f$).

All measurements of the length to width ratios indicated that shrinkage of the specimens was isotropic along the two horizontal directions. This is not the case with the vertical shrinkage strain, which was typically larger.

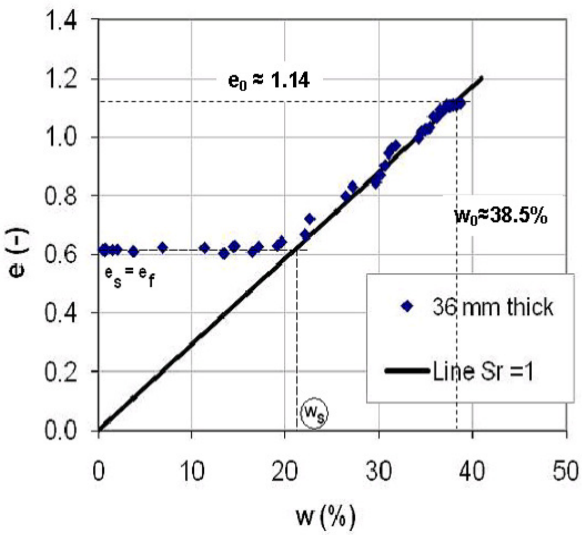

Figure 4. Shrinkage curve of the Bulyanhulu tailings

The values for the main parameters obtained from the e-w curve shown in Fig. 4 (and in Fig. 5 below) are:

- The water content at the air entry value (w_{AEV}) of the material, which is about 21.9%.
- The final void ratio e_f, which is close to 0.61.

The final void ratio e_f is of great importance for predictive purposes. Other experiments (not reported here) have shown that this value is not constant for a material as it is related to other factors, including the initial water content (Saleh-Mbemba, 2010).

The AEV of such compressible material can be assessed from the water retention curve (WRC) expressed from the relationship between the degree of saturation S_r and suction ψ. As shown in Figure 5c, the AEV of the Bulyanhulu tailings specimen is close to 65 kPa at the onset of desaturation; the AEV determination is further discussed below.

The shrinkage limit w_S of Bulyanhulu tailings was also determined from the shrinkage curve at 21.7%. It is interesting to note that the shrinkage limit value obtained from Figure 4 is the same as that obtained from the pressure plate extractor test, as shown on Figure 5b. As was also observed by Péron et al. (2006) on silty soils, it can be seen that the two values, w_{AEV} and w_S, are close to each other.

3.2 Fundamental relationships for deformable tailings

Figure 5 shows a representation of the fundamental relationships for the Bulyanhulu tailings in six planes, as obtained from the combined data of the free desiccation tests and pressure plate test. These plots show the void ratio e, degree of saturation S_r, and volumetric water content θ along the y axis, against suction Ψ (left) and gravimetric water content w (right) along the x axis. Among these relationships are the water retention curves (volumetric water content θ or degree of saturation S_r versus suction Ψ) and volumetric shrinkage curves (void ratio e versus gravimetric water content w or suction Ψ). Mbonimpa et al. (2006) discussed the significance of these relationships.

Two other complementary relationships shown in Figure 5 are not used as regularly, although these can also be useful to describe the hydrogeotechnical behaviour of unsaturated deformable materials. These are the degree of saturation S_r versus gravimetric water content w (Figure 5d) and the volumetric water content θ versus gravimetric water content w (Figure 5f). The former relationship has been described and used by Fleureau et al. (1993), while the latter was used by Saleh-Mbemba et al. (2010) who showed that, for the Bulyanhulu tailings, θ tends to vary bilinearly with w along two regimes with different slopes. The average slope of the two straight lines changes fairly abruptly from slope α_1 to slope α_2 at the shrinkage limit w_S.

One can also see on Figures 5b, 5d, and 5f the good agreement between the different experimental data obtained with the shrinkage tests and pressure plate test.

The dotted lines on these figures indicate the location of the air entry value (AEV) and related states for the six graphical relationships. It should be noted that the AEV used in this study is taken at the onset of desaturation, as shown by the dotted lines on Figure 5c; this point is also clearly identified on the S_r - w plot (Fig. 5d). If the commonly used tangent method (on the S_r – Ψ plot) was applied to assess the AEV, a value greater than 65 kPa would be obtained. This could lead to an overestimation of the predicted critical air entry time that is used in the shrinkage analysis presented below.

4. SHRINKAGE ANALYSIS

4.1 Critical air entry time (t_{cr-AE})

The time corresponding to the onset of desaturation (at w_{AEV}) is called here the critical air entry time (t_{cr-AE}). This parameter may be used when assessing material desaturation. The w_{AEV} has been obtained from Fig. 5d.

4.1.1 Experimental determination

The time required for air entry into the sample can be obtained from a w versus t plot. A practical mean to determine the critical time $t_{cr\text{-}AE}$ is to use a polynomial regression equation, as presented in Figure 6. From these results, it is inferred that the time required to reach the water content w_{AEV} of 21.9% is about 3.7 days. This time would be critical if there is a need to prevent air entering into the material layer, to avoid desaturation of the tailings under the corresponding exposure conditions. The value of $t_{cr\text{–}AE}$ obtained will be compared in the following section to numerical results.

The water content evolution shown in Figure 6 also shows that the time needed to reach complete dehydration is about 17 days for a specimen thickness of 36 mm tested in the laboratory.

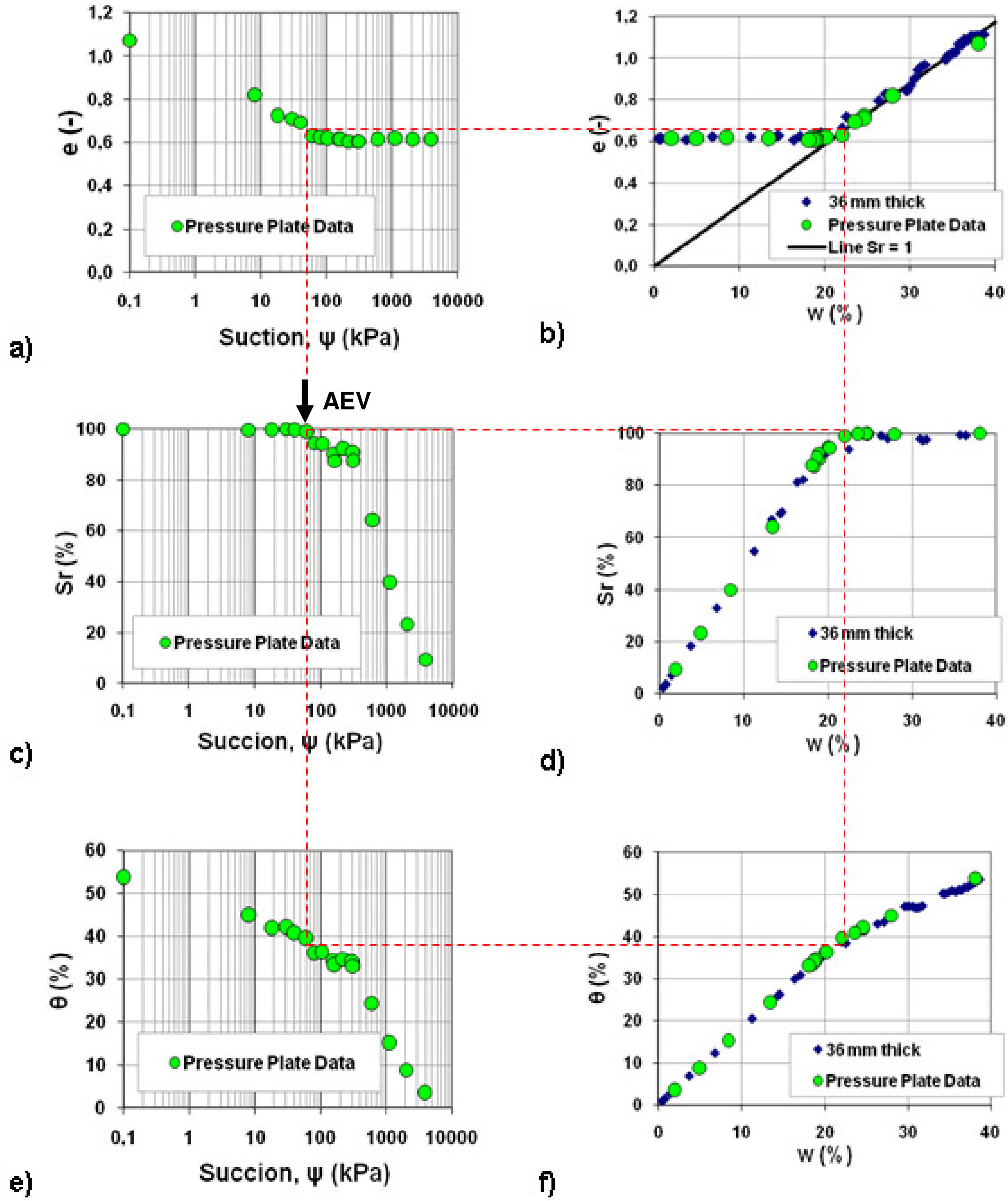

Figure 5. Different relationships for Bulyanhulu tailings; the dotted lines correspond to the air entry value and related states.

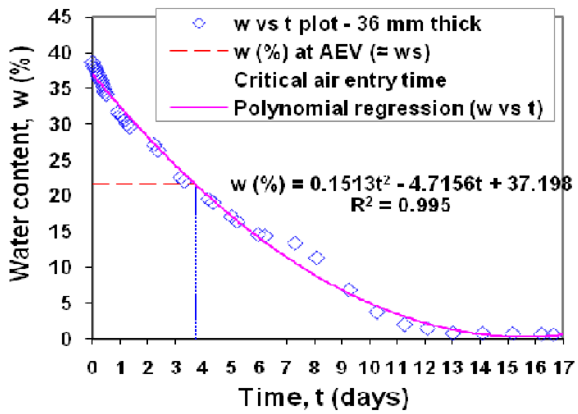

Figure 6. Evolution of the water content over time during the free desiccation test

4.1.2 Prediction of the critical air entry time

Additional work is underway to simulate the experimental tests, to better assess the results. The comparison with experimental results also serves to evaluate the reliability of the numerical model and our ability to predict the material response, including the critical air entry time for given a climatic condition and layer thickness.

Modelling approach

The numerical simulation of the drying process for the Bulyanhulu tailings specimen tested was undertaken using the finite element code Vadose/W (Geoslope International Ltd, 2007), which incorporates a coupled soil-atmosphere boundary condition at the surface. This code can simulate various situations including pore water pressure (suction) distribution under steady state and transient conditions. The finite element simulations were performed by discretizing the domain with rectangular elements.

In the simulations, the soil layer takes the dimensions and shape of the specimen used for the laboratory test (L = 200 mm and h = 36 mm). As this is a 2D code, the width is not taken into account in the calculations. The parameters required to apply the code include the water retention curve, which was obtained from the pressure plate test along a drainage path (Figure 5e), and the measured saturated hydraulic conductivity k_{sat}. The unsaturated hydraulic conductivity function was generated by the code using the Van Genuchten-Mualem model (Van Genuchten, 1980).

Numerical simulations were performed under a transient coupled regime, for 17 days, using an adaptive time stepping scheme.

Boundary conditions

The boundary conditions applied at the tailings surface are the climatic conditions measured during the laboratory test. The Neumann boundary condition was applied initially at the surface, as the material was initially saturated (i.e. water table located at the top). A no flux boundary condition was applied at the base and on the sides of the modelled specimen. There is no infiltration, drainage and wind effect in these calculations.

Predicted suction and critical air entry time

Figure 7 shows the evolution of suction over time obtained from the simulation. It can be seen that suction values generated near the surface, middle and base of the specimen are the same for the first five days. Later, the suction varies with the position for the remainder of the test, because of the non uniformity of water distribution during drying. The suction generated at the surface of the specimen tends to become higher as the material close to the surface dries faster. The variation inside the specimen is however fairly small because of its limited thickness.

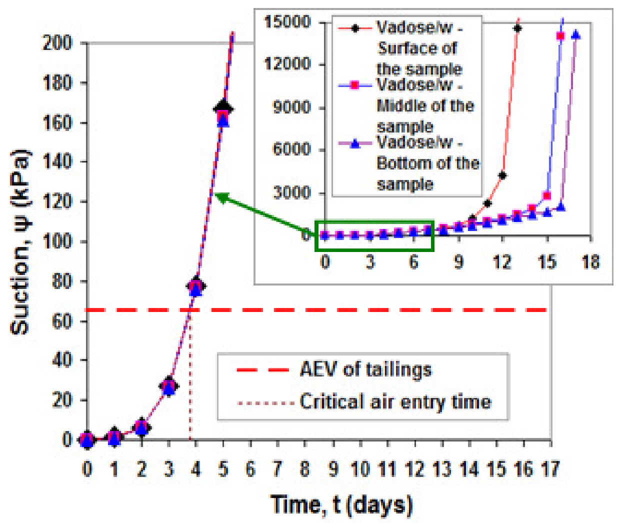

Figure 7. Predicted suction over time and air entry time

Figure 7 indicates that the critical time of air entry (to reach Ψ = AEV ≈ 65 kPa) is about 3.8 days. This corresponds well to the experimental results presented above.

4.1.3 Relationship between t_{cr-AE} and specimen thickness

Additional tests and simulations were performed to assess the relationship between the critical air entry time and the specimen thickness. The laboratory tests were conducted under the laboratory climatic conditions, on specimens with five different thicknesses (12, 24, 36, 48, and 60 mm). The numerical simulations were performed for the same climatic conditions, using thicknesses up to 1000 mm. Figure 8 shows the relationship between the critical air entry time and the specimen thickness for both the experimental and numerical model results. On this figure, one can see that the experimental data show a good agreement with the numerical results. One can also see that the critical air entry time seems to vary linearly with the specimen thickness up to 1000 mm.

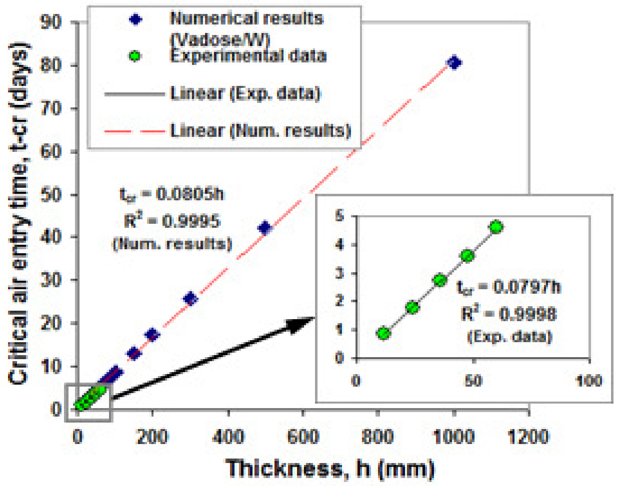

Figure 8. Critical air entry time versus specimen thickness; results from laboratory tests (close-up view on the bottom right) and from numerical simulations.

These calculation results tend to indicate that the modelling approach used here can provide some useful information regarding desaturation of the material (despite the fact that the code does not take the volumetric changes into account).

4. 2 Evolution of void ratio and degree of saturation

Figure 9 presents the measured values of the void ratio and degree of saturation over time, for the 36 mm thick specimen tested in the laboratory. These results confirm that the time required for air entry into this specimen material is about 3.8 days. The limit void ratio of the material can also be assessed from figure 9 at e_f = 0.61.

These results also confirm that most of the volumetric strain takes place while the material is saturated ($t < t_{cr-AE}$). Rodriguez (2006) and Péron et al. (2006) made the same observations during their experiments on metallurgical wastes and silty soils respectively.

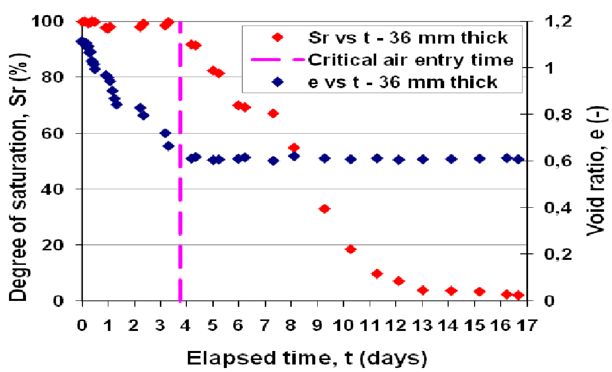

Figure 9. Degree of saturation and void ratio over time.

Such type of results may be used to predict the evolution of the degree of saturation, which is required when there is a need to prevent oxygen from entering reactive (acid generation) tailings. Numerical simulations similar to those shown above can then serve to complement the analysis, and to extend the results to representative *in situ* conditions.

4. 3 Suction induced cracking : early results

Finally, Figure 10 shows the appearance of the first crack during the restrained shrinkage test. This first crack was initiated at a critical water content w_{cr}=22.0% that corresponds to a critical suction Ψ_{CC}=62.9 kPa, a value near the AEV of material. This result is in agreement with the investigations of Péron et al. (2006, 2009) and Fleureau et al. (1993), who observed that cracks tend to appear near the onset of desaturation.

Figure 10. Crack on the tailings specimen during the restrained desiccation test on the Bulyanhulu tailings.

The time for crack initiation (t_{cr-cr}) is also a critical parameter to prevent fracturing, which leads to a modification of material properties. This time is needed when managing tailings deposition. Results shown here tend to indicate that t_{cr-cr} can be determined from a procedure similar to the one used for the critical air entry time. More tests to investigate this aspect further are being conducted.

5 CONCLUSION

The testing and interpretation procedure developed here seems appropriate to analyze the drying and shrinkage of tailings. The procedure has been used to assess the shrinkage curve from which one obtains the water content at the air entry value w_{AEV}, the final void ratio e_f and the shrinkage limit w_S of the material. The procedure also gives indications on the evolution of the water content, void ratio, and degree of saturation during drying.

The combination of the desiccation testing with the pressure plate test has also been used to establish some fundamental relationships for deformable fine-grained materials. The results can be used to evaluate the hydro-geotechnical response of unsaturated tailings exposed to various levels of suction. For instance, the procedure provides a means to obtain the critical air entry time for the exposure conditions and material properties of interest. A variant of this procedure has been used to assess the critical suction for crack initiation.

Numerical simulations have been used to predict the critical air entry time for different specimen thicknesses. These simulations have shown that the critical air entry time is a function of the layer thickness.

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