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Stress-strain behaviour of unsaturated compacted coal rejects and tailings

Olivier Buzzi[1*], *Jianping* Li[2], *Jubert* Pineda[1], *Daniel* Payne[2], *Kaiwen* Ouyang[1], and *Jinbiao* Wu[1]

[1]Priority Research Centre for Geotechnical Science and Engineering, University of Newcastle, Callaghan, 2308, NSW.
[2]BHP, Moranbah, Queensland, 4744, Australia

Abstract. The paper presents the results of an experimental study aimed at evaluating the stress-strain response of unsaturated tailings (Mixed Plant Reject and Dewatered Tailings) from a mine in Queensland, Australia, which can be applied to further optimise current tailings disposal strategies of the mine. Triaxial tests at constant gravimetric water content were performed on specimens prepared at different compaction states using dynamic and static methods, to determine their shear strength. The dynamically compacted specimens display a higher strength than that statically compacted ones, which highlights the significance of stress history for tailings strength. As-compacted and post-testing suction measurements, performed using a high-capacity tensiometer, showed a reduction in matric suction irrespective of the material type, which is caused by mechanical wetting. The strength envelope was found to be non-linear, partly because of suction changes during testing. Post-testing suction measurement showed spatial variability within each specimen, with the central part of the samples experiencing the maximum suction reduction. The paper concludes with a discussion on the interpretation of such results.

1 Introduction

Tailings are a fine-grained waste product of the mining industry and their composition depends on the resource being mined and the geological environment. Tailing management practice has been progressively widened from tailing dams, or tailing storage facilities, to co-disposal strategies in spoil piles [1].

(a)

(b)

(c)

(d)

Fig. 1. Examples of tailings disposal solutions. (a): tailings disposed in a cell; (b): desiccated tailings, 8 months after disposal in a cell (from [2]). (c) co-disposal of mixed plant reject (MPR) from a tiphead (from [2]); (d): paddock tipping amongst waste rock (from [3]).

Dewatered tailings can be disposed in cells within a spoil pile (Figure 1a and 1b) or mixed with coarse rejects, a product referred to as mixed plant reject (MPR), and tipped on the batter of a spoil pile (Figure 1c). MPR can also be co-disposed with waste rock in paddocks (Figure 1d). Regardless of the disposal solution, given that tailings are incorporated in spoil piles, it is essential to adequately assess their shear

* Corresponding author: Olivier.Buzzi@newcastle.edu.au

strength under saturated and unsaturated conditions, and account for their presence in the spoil pile stability analyses [2]. The shear strength of waste rock, both saturated and unsaturated, has received significant attention [4-8] and so have saturated tailings (e.g. [9]), largely in the context of tailings storage facilities. In contrast, it seems that testing of tailings under unsaturated conditions is fairly recent and not many results are reported in the literature [11-13]. Vo and co-workers [14] specify that this is particularly the case for coal tailings. This paper presents the results of triaxial tests on unsaturated compacted coal tailings retrieved from a disposal cell in a spoil pile of a Queensland mine, which can be used in the future for further optimising current co-disposal strategies implemented at this particular mine.

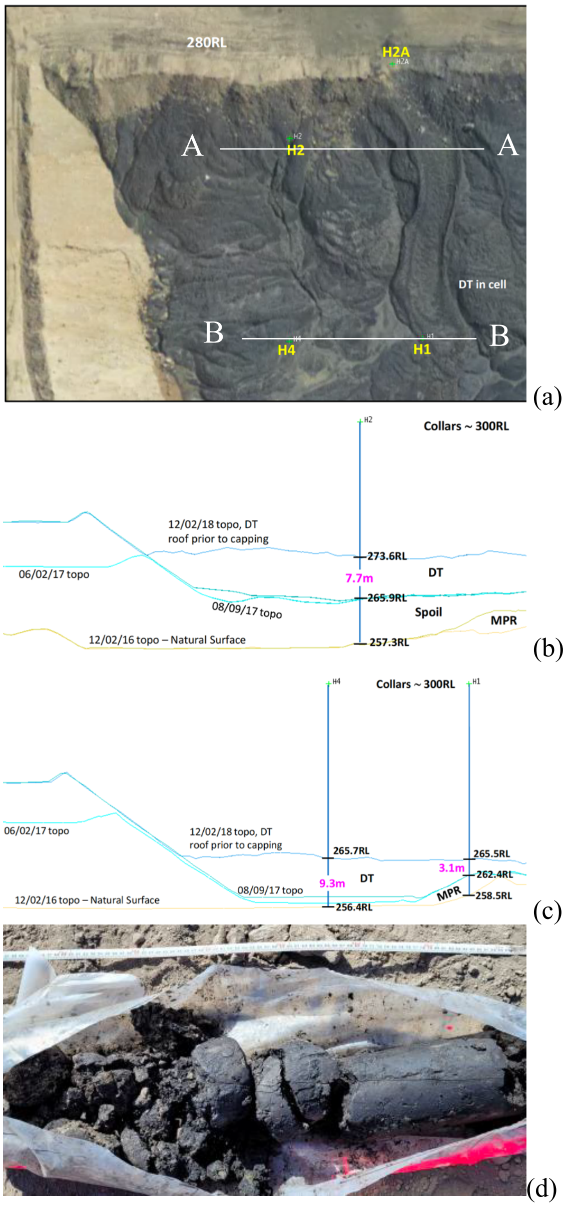

Fig. 2. (a): Aerial photograph of the disposal cell in which tailings were placed, showing location of cross sections AA and BB, boreholes H1, H2, H4. Cross sections AA (b) and BB (c). Example of specimen retrieved from borehole H2 (d).

2 Materials and specimen preparation

The tailings used in this study are dewatered tailings (DT) and mixed plant rejects (MPR) that were disposed in cells or on waste pail bench in a Queensland mine, as per [3] and Figure 2. At placement, the tailings had a moisture content of about 37% and were left exposed to the environment for about 6 months before being capped. The capping (waste rock) was about 35 m thick and sonic drilling (boreholes H1, H2, H4, see Figure 2) took place 4 years after capping.

Although the objective of this work was to retrieve intact specimens that could be tested for shear strength, the specimens were highly disturbed during the sonic drilling process. Consequently, after some initial measurements of bulk density, moisture content and suction on retrieved cores, all material from each borehole was crushed (to particles size < 2.36 mm) and homogenised prior to mechanical testing. Before crushing the MPR tailing (borehole H2), the large mineral particles were removed (because of size constraints on triaxial specimens) and as such, MPR H1 has a very similar particle size distribution to DT H2 and H4. The particle size distribution of homogenised materials was obtained by wet sieving [15] and is shown in Figure 3. After crushing the material retrieved from the boreholes, the crushed materials were water sprayed and left to equilibrate for several days to achieve a moisture content equal to the *in situ* moisture content (taken as the average value from all cores, for a given borehole). Two compaction techniques were used in this study: static compaction (at a rate of 1 mm/min) and dynamic compaction by hand using a 15 mm steel rod (to replicate a proctor compaction process). The specimens were compacted to the average *in situ* bulk density measured for each borehole. In both compaction methods, the tailings specimens (50 mm diameter, 100 m height) were compacted in five layers in a split mould.

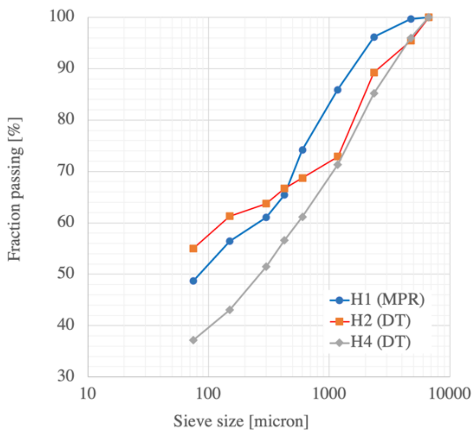

Fig. 3. Particle size distribution obtained by wet sieving for H1, H2, H4 homogenised tailings.

The initial conditions of the triaxial specimens post compaction are given in Table 1. The microstructure of the compacted H1, H2 and H4 specimens (quasi static compaction only), obtained by mercury intrusion porosimetry is shown in Figure 4 with the wetting branch of the water retention curve for all three materials. Interestingly, the curves are almost linear in the log scale rather than the conventional sigmoidal shape.

Table 1. Initial conditions of compacted specimens. Moisture content and saturation degree in %, suction in kPa, dry density in g/cm^3. A technical issue occurred during the measurement of suction for dynamically-compacted specimens and no suction data is available for those specimens.

Compaction	Average initial condition	H1	H2	H4
Quasi static	Moisture content	12.0	19.2	15.2
	Dry density	1.55	1.51	1.56
	Saturation degree	60	90	75
	Suction	1072	129	261
Dynamic	Moisture content	11.6	19.6	13.5
	Dry density	1.55	1.49	1.54
	Saturation degree	58	90	63

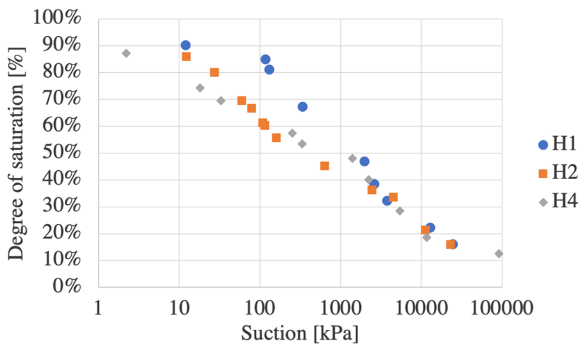

Fig. 4. Wetting branch (at constant dry density values of Table 1) of the water retention curves for tailings H1, H2, H4.

Despite being compacted fine grained materials, the air entry value of the tailings is very low (less than 1 kPa), which is consistent with coal tailings [16]. Also, the suctions and saturation degrees of Table 1 are consistent with those of Figure 4 for tailings H1 and H4 but there is an inconsistency for H2, which is an issue of experimental error at high saturation degree and very low suction.

3 Testing methods

For the retention curve, the air-dried crushed tailings were first wetted by spraying to a target moisture content and then, the material was compacted by quasi static compaction to the dry density of Table 1, with a high-capacity tensiometer placed in the loading cap and measuring suction under final load, as per [17]. For values of suction above 1500 kPa, the compacted specimens were unloaded and tested in a dewpoint potentiameter (WP4C, Decagon). Constant gravimetric water content triaxial tests were conducted at a shearing rate of 1 mm/min and all tests were terminated at an axial strain of 20%. Confining stresses of 50, 200, 350, 500 and 1000 kPa were applied. Confinement was applied at a rate of 10kPa/min and shearing started as soon as the target confinement was attained. Note that given that the specimens were unsaturated, some volume change was possible following the application of both isotropic stress and deviatoric stress. The initial suction of the compacted triaxial specimens was measured with high capacity tensiometer (accuracy +/- 7kPa) on the top and bottom faces of the specimen. Post testing, three slices (~20 mm in thickness) were cut from the specimen (close to the ends and in the centre) to allow measurement of density and suction (via a high capacity tensiometer). Offcuts were used to measure moisture content. Three consolidated undrained triaxial tests were conducted on saturated specimens of H1, H2 and H4 prepared by quasi-static compaction at dry density reported in Table 1 and under an initial effective confining stress of 50kPa. The objective of these tests is to highlight the effect of non-saturation of the deviatoric stress at failure.

4 Results

4.1 Effect of compaction method on deviatoric stress at failure

In Figure 5, one can compare the deviatoric stress at failure for the dynamically compacted specimens (q_D) to that of quasi-statically compacted specimens (q_{QS}). The dynamic preparation process consistently yields higher deviatoric stress, i.e. shear strength, and this effect seems to be exacerbated for low values of saturation degree (i.e. H1 compared to H2).

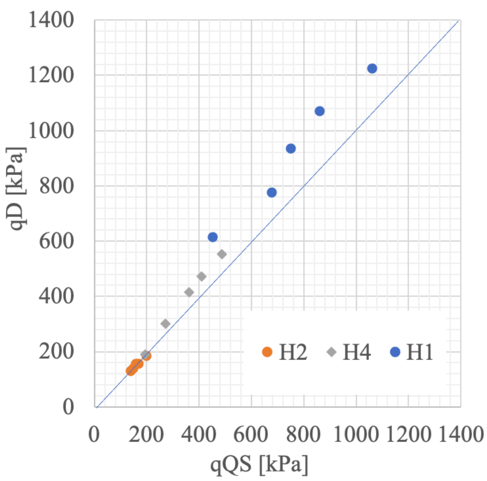

Fig. 5. Deviatoric stress at failure for dynamically compacted specimens (q_D) v. deviatoric stress at failure for quasi-statically compacted specimens (q_{QS}) for tailings H1, H2 and H4. The line has a 1:1 gradient.

The difference in stress-strain-suction response is associated with the stress history of the specimens, as the dynamic and quasi static compaction would not generate the same stress or excess pore pressure in the specimen. Unfortunately, those stresses were not measured during the compaction. It is also expected that for specimens H4, the lower initial saturation degree (and hence higher suction) of dynamically compacted specimens contributes to a higher deviatoric stress. From a spoil pile stability perspective, it is important to prepare the specimens using a method that is both as representative as *in situ* conditions as possible, and conservative. As such, the quasi-static compaction method was deemed more suitable than the dynamic one and was used in the rest of this study.

4.2 Effect of non-saturation on deviatoric stress at failure

Figure 6 shows the difference in deviatoric stress at failure for saturate and unsaturated specimens, for the same dry density (or void ratio) and same total confining stress. The figure shows a clear contribution of suction to the shear strength of the materials: the drier the unsaturated specimen, the more exacerbated the difference of shear strength between the saturated and non-saturated specimens. For specimen H1, the deviatoric stress reduces by a factor 7, when the specimen is saturated compared to an initial saturation degree of ~60%. Because the results are expressed in terms of deviatoric stress, this reduction is only due to suction, not to the generation of positive excess pore pressure during shearing. Figure 6 clearly highlights the relevance of testing tailings both saturated and unsaturated, if one needs to adequately and comprehensively characterise their shear strength.

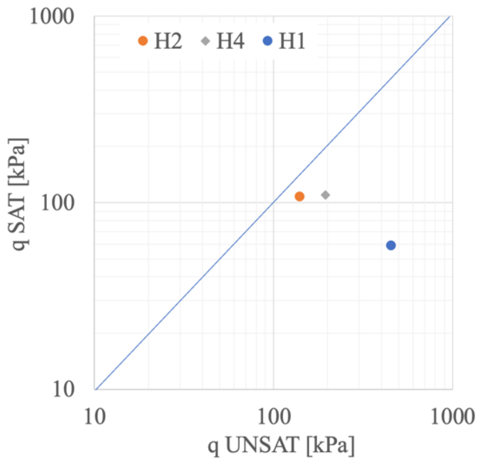

Fig. 6. Deviatoric stress at failure for saturated specimens (q_{SAT}) v. deviatoric stress at failure for unsaturated specimens (q_{UNSAT}) for tailings H1, H2 and H4. All specimens are compacted quasi-statically. Total confining stress applied is 50kPa. The line has a 1:1 gradient.

4.3 Response of specimens prepared by quasi-static compaction

Figure 7a shows the evolution of deviatoric stress with axial strain for the five tests conducted on specimens H1, prepared by quasi-static compaction. The response is mostly ductile, with only a slight peak visible under 50kPa and 200 kPa of confining stress. Under 1000kPa, a slight hardening is visible. All H2 and H4 specimens displayed a ductile hardening-type response (Figures 7b, 7c). For all materials, the higher the confining pressure, the higher the deviatoric stress. Figure 8 shows the two types of failure patterns observed in this study. For most specimens, no shear band developed and the specimens deformed as a "barrel". Specimen H1 tested under 50 kPa is the only one to have displayed a clear shear band.

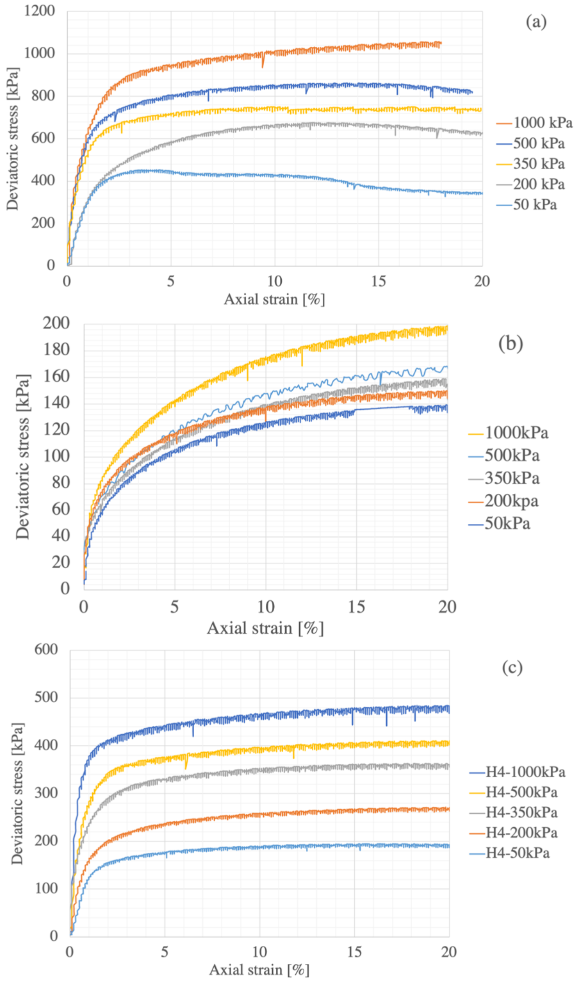

Fig. 7. Evolution of deviatoric stress with axial strain for H1 (a), H2 (b), H4 (c) specimens (quasi-static compaction).

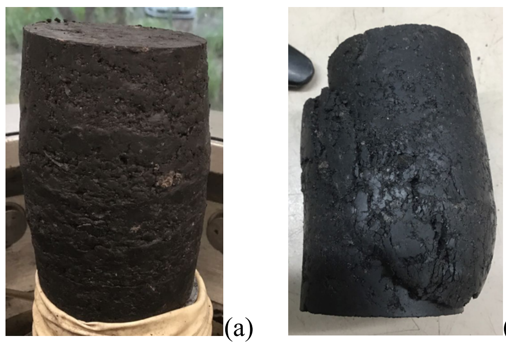
(a) (b)

Fig. 8. Photograph of H1 specimens after triaxial testing under confining stress of 1000kPa (a) and 50 kPa (b).

All specimens experienced a reduction in volume from the isotropic loading stage, leading to an increase of saturation degree (Sr) and reduction of suction (s) by

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mechanical wetting. This was also observed for spoil pile material by [18].

The final (post testing) average values of saturation degree and suction are shown in Figure 9. H2 was compacted close to saturation so the changes of Sr and s are marginal. However, for H1 and H4, the changes are significant. Under 1000kPa of confining pressure, suction in H1 and H4 specimens has reduced by about 400kPa and 46kPa (i.e. 36% and 37% of initial suction), respectively. Note that the values of average suction measured post testing differ from those of the SWRC, for the same saturation degree, because of the volume change that has occurred during testing.

Mechanical wetting results in suction reduction, and hence strength reduction, but also a progressive change of material's response, from drained to almost undrained. Figure 10 shows the Mohr circles (plotted in terms of total stress) for all tests. H2 specimens are very close to saturation (Sro~90%) and, with a friction angle of only 2°, the strength envelop is almost that of a saturated fine-grained soil under unconsolidated-undrained test.

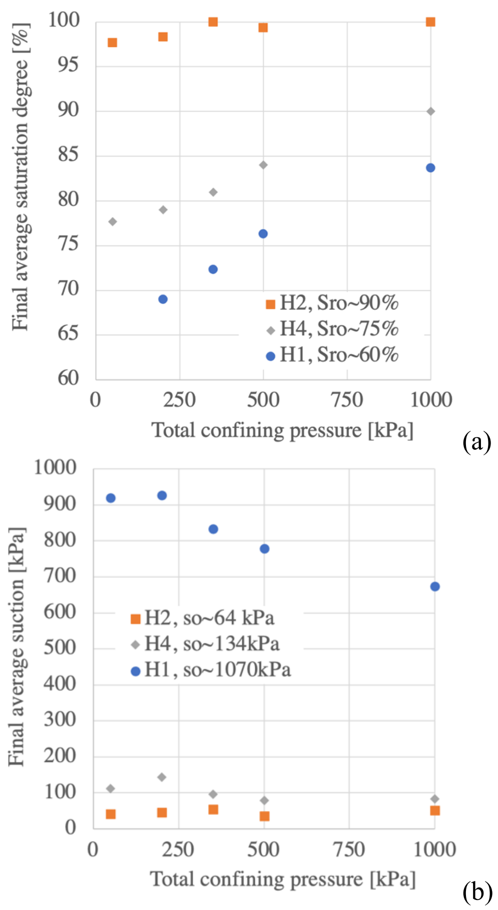

Fig. 9. Evolution of final average saturation degree (a) and suction (b) with total confining pressure for materials H1, H2 and H4.

In contrast, the strength envelope of materials H1 and H4 is not linear, and the friction angle (inferred to from linear fitting) reduces with increasing confining pressure. This is the effect of mechanical wetting whose effect is a combination of suction reduction and less effective confinement as the saturation degree increases. The shear strength parameters inferred from linear fitting of the strength envelopes (shown by the red lines in Figure 10) are given in Table 2.

Table 2. Strength parameters inferred from linear fitting of the Mohr Circles shown in Figure 10, for confining stresses in the range 50 to 1000kPa and the conditions of testing.

	Confining stress <500 kPa		Confining stress >500 kPa	
	Cohesion [kPa]	Friction angle [°]	Cohesion [kPa]	Friction angle [°]
H1	125	25	295	9
H2	64	2	64	2
H4	72	13	162	4

Although it is technically possible to interpret these tests in terms of cohesion and friction angle, without measurement or control of water pressure/suction, it is difficult to determine to what extent those tests are drained or undrained, to compute the values of effective stresses, and to interpret the results in an unsaturated soil mechanics framework. Additionally, the compressibility of the material will dictate the extent of mechanical wetting for a given applied stress, so care must be taken when using such results. As a minimum, suction should be measured during the triaxial test but, preferably tests with controlled suction should be performed given that suction is typically not uniform in the specimen, as shown in Figure 11 for specimen H1.

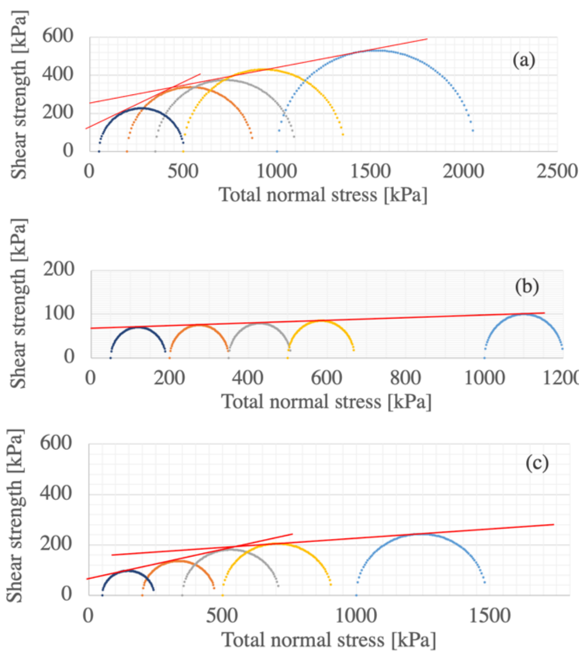

Fig. 10. Mohr circles at failure for all specimens tested (H1 (a), H2 (b), H4 (c)). The Mohr circles are plotted in terms of total stresses. The red lines are linear approximations of the strength envelope.

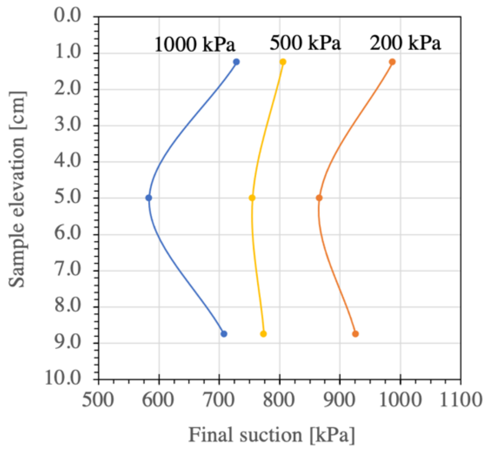

Fig. 11. Values of suction post-testing at different elevations of the H1 specimens tested under confining stress of 200kPa, 500kPa and 1000kPa.

5 Conclusions

A series of triaxial tests at constant gravimetric moisture content were conducted on tailings recovered from sonic drilling into a co-disposal cell and paddock bench from a Queensland mine. The objective of laboratory testing and data interpretation is to help the mine optimise the currently implemented co-disposal strategies. The unsaturated tailings specimens were compacted at a water content and density comparable to those measured on the specimens retrieved from coring. The tests have highlighted the contribution of suction, the significance of mechanical wetting on the strength envelope of the material. With waste rocks dumps now commonly exceeding 300 m in height, it is very important not only to think in terms of suction but also mechanical wetting and its consequence on stability. About 50m of overburden (i.e. ~1000kPa of overburden stress) is enough to increase the saturation degree from 75% to 90% (Figure 9). Depending on the initial saturation degree, and the degree of mechanical wetting, the friction angle can range from 2 º to 25º. Performing constant gravimetric moisture content tests is quite simple, and hence attractive to industry, but rigorously interpreting the test results can be challenging and triaxial tests under controlled suction should be performed.

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