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Investigation of Shear Strength and Breakdown of Mine Waste Rock

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ABSTRACT: To investigate the shear strength of mine waste rock, large-scale laboratory direct shear tests were carried out on Breccia, Weathered Shale, Breccia on Weathered Shale, and Weathered Shale on compacted clay, under applied normal stresses of 250 kPa, 500 kPa or 1000 kPa. The Breccia, Weathered Shale and Breccia on Weathered Shale samples were loosely-placed and tested dry, representing the bulk of the waste rock dump volume in the field. The Weathered Shale on compacted clay was tested under both dry and wet (the worst case) conditions to represent the interface between Weathered Shale and compacted clay liners within waste rock dumps. The peak shear and normal stresses were corrected for area reduction and plotted to provide the shear strength envelopes, from which shear strength parameters were recommended. To assess the potential for breakdown of the waste rock on wetting, particle size distribution curves were obtained by dry and wet sieving. Also, slake durability indices were obtained for Breccia and Weathered Shale by carrying out slake durability tests. Overall, the results indicated negligible potential for breakdown of the Breccia and Weathered Shale on wetting.

1. INTRODUCTION

As a part of the mining of metalliferous ores, excavated overburden needs to be dumped in a nearby storage, usually a surface waste rock dump. The side slopes of a surface waste rock dump form at the angle of repose of the mine wastes, which is typically in the range from 35° to 40° (Williams, 2001, 2014, and 2015). Such slopes are normally not compacted and are subjected to rainfall, making the geotechnical stability of loose-dumped waste rock slopes a significant concern for mining and geotechnical engineers. Figure 1 shows a photograph of a slope formed by end-dumping mine waste rock from a truck.

Fig. 1. End-dumping mine waste rock from a truck.

The angle of repose of a dump is often simply adopted as the friction angle of the mine waste. However, the angle of repose represents the loosest possible packing under virtually no normal stress or the friction angle at the critical state (Williams 1996). The waste rock would be expected to have a friction angle of typically 4° to 6° higher than the angle of repose of the material on loose-dumping, due to the effects of overburden stress (Williams, 2015). At angle of repose of the mine waste, the dumps are generally geotechnically stable, at least in the short-term. In the long-term, however, water and weathering of the material are the major causes of slope instability, and it has been found that subsequent failures are generally rainfall-related (Chowdhury and Nguyen, 1987; Fourie, 1996; Williams, 2015). It is also well documented that the shear strength of dry material is higher than that of saturated or submerged samples (Kjaernsli and Sande, 1963; Fredlund et al., 1978). In waste rock dump slopes, the shear strength decreases significantly with decreasing matric suction associated with increasing moisture content caused by rainfall infiltration (Fredlund and Rahardjo 1993). Therefore, when the dumps regularly experience high infiltration rates due to prolonged rainfall events over the wet season, failures will be more likely to occur. Rainfall-induced slope failures in waste rock dumps are common hazards in the wetter regions of the world.

Therefore, the determination of the shear strength parameters of loose-dumped mine waste rock is essential for the design and for stability analyses to ensure the stability and safety of waste rock dumps. Shear strength parameters of soils are traditionally determined by carrying out conventional small direct shear box test in the laboratory. However, depending on the scale of the direct shear box, waste rock samples typically need to be scalped; i.e., particles larger than a nominal maximum of five times the height of the box are removed. Scalping ensures that there are sufficient particles over the height of the specimen to generate shear along the interface between the two halves of the direct shear box. However, given that scalping can easily reduce the friction angle of a material by several degrees compared with the full-scale specimen (Williams, 2015), large-scale direct shear box testing is preferred over small-scale direct shear box testing when dealing with coarse-grained soils (Vallerga et al. 1957; Cerato and Lutenegger 2006; Wu et al. 2008; Ueda et al. 2011; Wang et al. 2013).

In this paper, large-scale direct shear box tests were carried out on mine waste rock to recommend the shear strength parameters for dump stability analyses. In addition, dry and wet sieving, as well as slake durability tests, were carried out to assess the potential for breakdown of the waste rock on wetting.

2. TESTING EQUIPMENT AND PROGRAM

2.1. Large-scale direct shear testing machine

An advanced, large-scale direct shear device ADS-300 (manufactured by Wille Geotechnik of Germany), is available in the Geotechnical Laboratory at The University of Queensland (UQ; see Fig. 2). The shear box has a dimension of 300 mm by 300 mm by 200 mm, complying with ASTM 5321, and the sidewalls of the shear box are 20 mm thick. This machine is moderately stiff, with a load capacity of 100 kN in both horizontal and vertical directions (up to 1000 kPa).

The floating upper half of the shear box is designed to create a gap between upper and lower halves by means two compression springs, which avoid any metal on metal contact on which unwanted friction can develop. During the shearing process, the upper half of the shear box is fixed, and the shear load is transmitted by moving the lower half of the shear box. Four linear variable differential transformers (LVDTs) are installed at the four corners of the top of the loading plate, and the average value of the settlement is calculated based on these four measuring points.

The machine is able to automatically stop the test when the tilt of the loading plate exceeds 10% or any one of the four LVDTs exceeds 50 mm travel, avoiding erroneous results due to tilting. The machine sits in a tank that can be flooded for wet testing. Hence, the machine can carry out large-scale direct shear tests on specimens either at the as-sampled gravimetric moisture content (dry), or in a water bath (wet). In this study, when testing under wet conditions, the specimen was allowed to soak overnight in the water tank prior to the normal stress being applied the following day. Settlements are recorded during the application of the normal stress until settlement essentially ceases. During the subsequent shearing of the specimen, vertical displacement, shear displacement, and shear force are recorded.

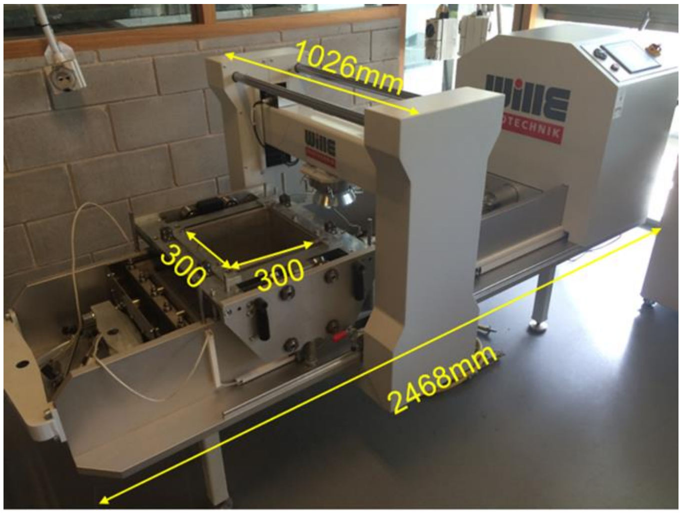


Fig. 2. UQ’s large-scale direct shear testing machine manufactured by Wille Geotechnik of Germany.

2.2. Large-scale direct shear testing program

Single-stage, large-scale (300 mm by 300 mm by 190 mm high) direct shear box tests were carried out on Breccia, Weathered Shale, Breccia on Weathered Shale, and Weathered Shale on compacted clay (see Table 1).

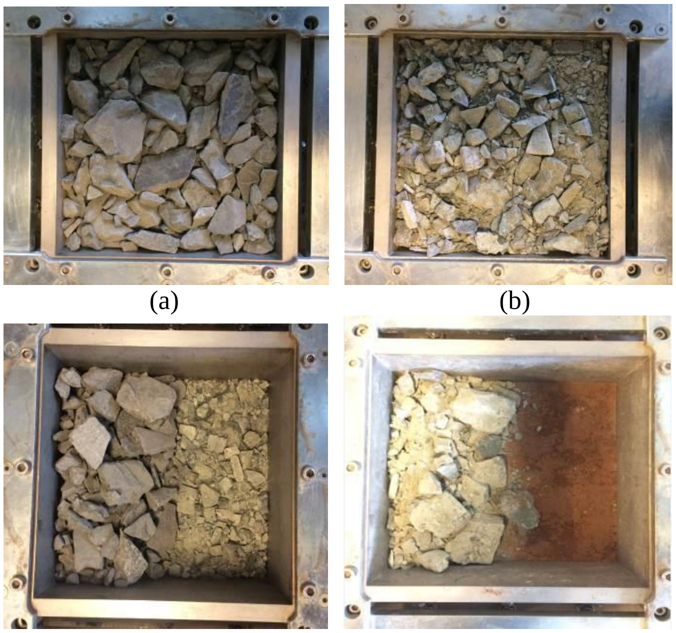
Table 1. Testing program and initial test conditions.

Mine waste rock tested	Initial moisture content (%)	Initial dry density (t/m^3)
Breccia	0.4 (Dry)	1.769
Weathered Shale	1.1 (Dry)	1.624
Breccia on Weathered Shale	1.1 (Dry)	1.632
Weathered Shale on compacted Clay	1.7/13.6 (Dry)	1.783/1.850
	Near-saturated (Wet)	1.783/1.850

The tests were carried out under dry or wet conditions, under nominal initial applied normal stresses of 250 kPa, 500 kPa or 1000 kPa, representing waste rock dump heights of about 14 m, 28 m, and 56 m, respectively (assuming a wet unit weight of 18 kN/m^3). Settlements were recorded during the application of the normal stress until settlement essentially ceases (after about 24 hours), but these results are not reported herein. Shearing was carried out at a rate of 0.1 mm/min to a nominal 10% shear strain (30 mm displacement) to avoid excessive distortion of the top cap, so that shearing took 5 hours in total for each specimen. Settlement and shear force were recorded at nominal 2 min time intervals throughout the shearing, resulting in 150 data points.

2.3. *Sample preparation*

Initial Breccia and Weathered Shale specimens were near dry and had a pre-scalped maximum particle size of about 75 mm. As mine waste rock dumps are commonly formed at the angle of repose of the material by end-dumping, the Breccia and Weathered Shale were loosely-placed in the shear box to model loose-dumping in the field. The Breccia, Weathered Shale, and Breccia on Weathered Shale specimens were tested air-dry, representing the bulk of the waste rock dump volume in the field. The Weathered Shale on compacted clay was tested under both dry and wet conditions, representing the interface between Weathered Shale and compacted clay liners within the waste rock dump. In this study, dry tests were carried out at the as-sampled moisture state of the waste rock, while wet tests were carried out by immersing the large shear box in a water bath and testing the specimen wet, which is generally the worst case. The clay was compacted in the lower half of the shear box with loosely-placed Weathered Shale filling the top half of the shear box. Figure 3 shows photographs of sample preparation for the direct shear tests carried out in this study.

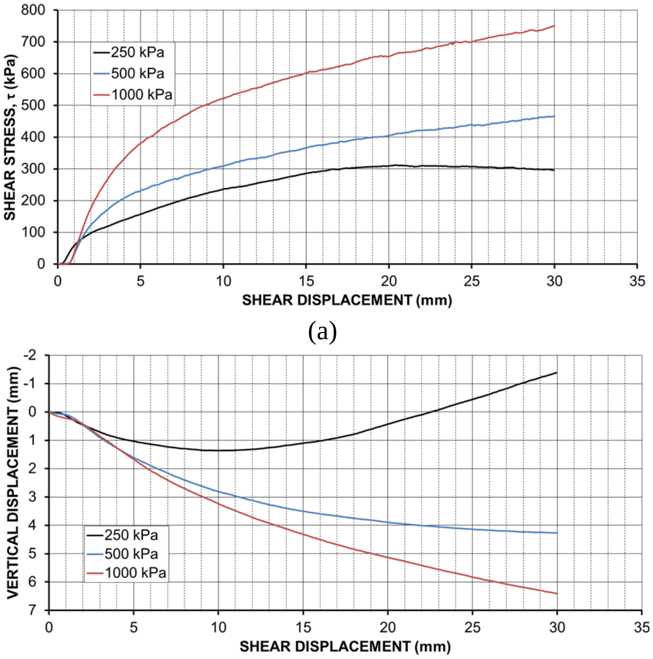

(a) (b)

(c) (d)

Fig. 3. Sample preparation of: (a) Breccia, (b) Weathered Shale, (c) Breccia on Weathered Shale, and (d) Weathered Shale on compacted clay.

3. LARGE-SCALE DIRECT SHEAR TEST RESULTS AND DISCUSSION

Typical raw results (not area-corrected) for the large-scale direct shear testing of Breccia at its as-sampled gravimetric moisture content (dry) are presented in Fig. 4. Figure 4 (a) shows the shear stress increasing monotonically at a reducing rate with increasing shear strain to an ultimate (maximum) shear strength, with no apparent peak for initially loosely-placed, coarse-grained specimens. The higher the applied normal stress, the higher the shear stress achieved.



(a)

(b)

Fig. 4. Typical raw direct shear results for Breccia tested dry: (a) shear stress versus shear displacement, and (b) vertical displacement versus shear displacement.

Figure 4(b) shows that the specimens are generally “contractive” (settling on shearing, settlement being shown as positive). The higher the applied normal stress, the more the specimens settle during shearing. The test results of Weathered Shale, Breccia on Weathered Shale, and Weathered Shale on compacted clay, showed a similar pattern. It was found that the Weathered Shale on compacted clay specimen tested under wet condition under an applied normal stress of 1000 kPa underwent significantly larger settlement. The vertical displacement was monitored throughout the tests and the final dry densities were calculated, as given in Table 2 and illustrated in Fig. 5. It can readily be readily seen that the higher the applied normal stress, the higher the dry density achieved, in turn resulting in a higher shear strength. This compensates for an expected slower increase in shear stress at failure with increasing applied normal stress, resulting in an approximately linear shear strength failure envelope.

The results of all the tests carried out are summarized in Table 2. The shear stresses at failure (or at 10% shear strain, whichever occurs first) and the corresponding applied normal stresses were corrected for area reduction and plotted to determine the failure envelopes, as shown in Fig. 6. It should be noted that the actual normal stress at failure after area correction is slightly higher than the initial applied normal stresses, as listed in Table 2.

Table 2. Summary of all large-scale direct shear results.

Material tested		Initial dry density (t/m^3)	Final dry density (t/m^3)	Normal stress at failure (kPa)	Shear stress at failure (kPa)
Breccia (Dry)		1.769	1.834 1.837 1.884	272 556 1111	336 518 834
Weathered Shale (Dry)		1.624	1.743 1.776 1.796	278 556 1111	281 542 821
Breccia on Weathered Shale (Dry)		1.632	1.704 1.727 1.759	272 555 1108	253 486 819
Weathered Shale on compacted clay	Dry	1.850/1.783	1.837 1.888 1.955	277 556 1110	199 362 730
	Wet	1.850/1.784	1.996 2.044 2.132	278 556 1111	167 330 662

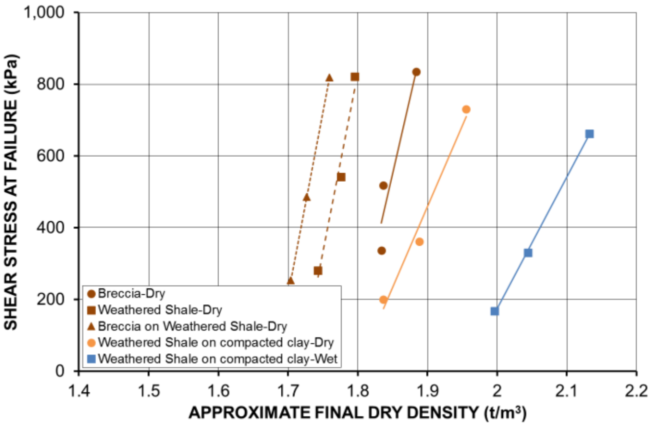


Fig. 5. Shear stress at failure versus approximate final dry density.

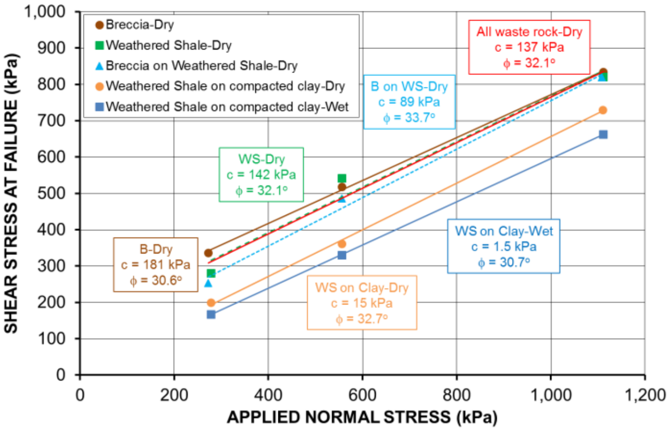


Fig. 6. Failure envelopes of all test results.

4. SHEAR STRENGTH PARAMETERS INTERPRETATIONS

4.1. Mohr-Coulomb Interpretation

The shear strength obtained from laboratory direct shear tests could be interpreted by the Mohr-Coulomb straight line failure criterion, according to the following equation:

$$\tau = c + \sigma_n \tan\phi \qquad (1)$$

where τ is the direct shear strength, c is the apparent cohesion, ϕ is the internal friction angle, and σ_n is the applied normal stress.

The shearing of the box results in a loss in contact area for the specimen, which is allowed for by applying an area correction to both the applied normal stress and the measured shear stress. Applying an area correction to the stresses for purely frictional materials has no impact on the resulting Mohr-Coulomb friction angle, since the failure point simply moves up the failure envelope. However, an area correction may change the cohesion intercept and friction angle when the cohesion is non-zero.

Figure 6 shows the Mohr-Coulomb failure envelopes of all the large-scale direct shear test results obtained in this study, and the resulting shear strength parameters are summarised in Table 3.

Table 3. Summary of calculated shear strength parameters.

Material tested		c (kPa)	ϕ (°)
Breccia (Dry)		181	30.6
Weathered Shale (Dry)		142	32.1
Breccia on Weathered Shale (Dry)		89	33.7
All waste rock (Dry)		137	32.1
Weathered Shale on compacted clay	Dry	15	32.7
	Wet	1.5	30.7

4.2. Alternative Interpretation

An alternative interpretation is to consider the shear strength simply in terms of secant friction angles at each applied normal stress for each material tested, which are the angles of the straight lines from each failure point drawn back to the origin. The secant friction angles calculated for all materials subjected to large-scale direct shear testing are plotted in Fig. 7. Also shown in Fig. 7 are the range of data from poor to good quality rock fill obtained from 200 mm diameter triaxial testing by Leps (1970), a typical angle of repose for loose-dumped waste rock of 37°, and an average applied stress of 900 kPa corresponding to about 50 m depth of waste rock. It can be seen from Fig. 7 that the better quality waste rock tested dry has secant friction angles within the range expected for rock fill and well above the angle of repose. The interface between waste rock and compacted clay, particularly when tested wet, have inferior secant friction angles.

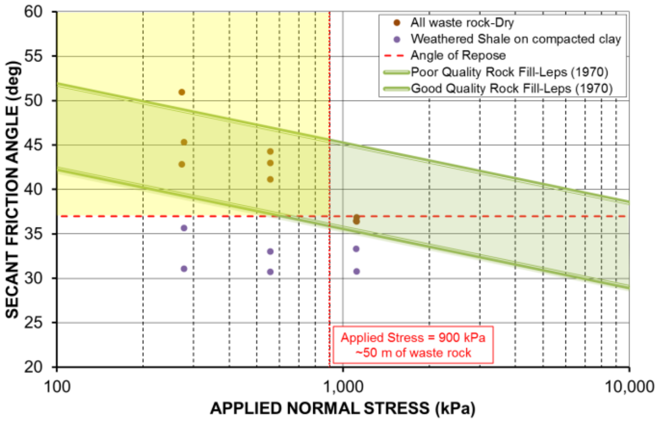


Fig. 7. Secant friction angle versus applied normal stress for direct shear test data, compared with data from Leps (1970).

5. BREAKDOWN ON WETTING

5.1. *Dry and wet sieving tests*

Both dry and wet sieving tests were carried out on Breccia and Weathered Shale samples to compare the change in the particle size distribution curves on wetting, compared with dry testing. It was found that there was negligible difference between the dry and wet sieving results for each sample, as shown in Fig. 8, indicating that there is little potential for breakdown of the materials on wetting.

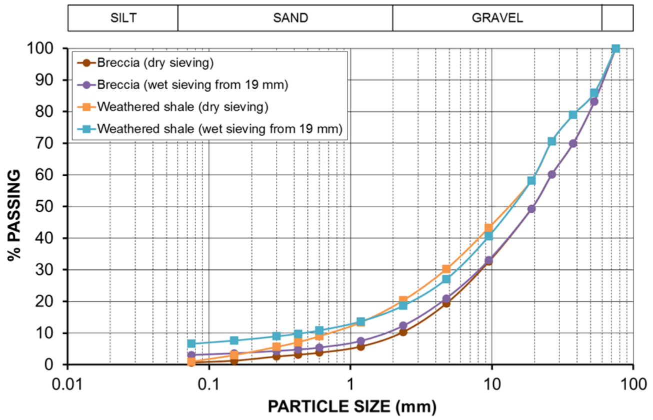


Fig. 8. Particle size distribution curves for Breccia and Weathered Shale subjected to dry and partial wet sieving.

5.2. *Slake durability tests*

Slake durability tests were carried out on Breccia and Weathered Shale samples in accordance with ASTM D4644 to determine their resistance to weakening and disintegration when subjected to two standard cycles of drying and wetting in water (see Fig. 9). The slake durability index $I_d(2)$ (2nd cycle) is calculated as a percentage ratio of the final to the initial dry sample mass as follows:

$$I_d(2) = \left[(W_F - C) / (B - C) \right] \times 100 \qquad (2)$$

where $I_d(2)$ is the slake durability index after the second cycle, B is the mass of the drum plus the oven-dried specimen before the first cycle, W_F is the mass of the drum plus the oven-dried specimen retained after the second cycle, and C is the mass of the drum.

(a)

(b)

Fig. 9. Slake durability testing: (a) rotation of drums, and (b) dry samples after second cycle.

From the calculated slake durability indices in Table 4 of $I_d(2)>98\%$, it is clear that samples remained virtually unchanged after two cycles (also see Fig. 9(b)). That is, the breakdown of the Breccia or Weathered Shale samples on wetting was negligible.

Table 4. Slake durability test results.

Sample	Initial moisture content (%)	C (g)	B (g)	W_F (g)	$I_d(2)$
Breccia	0 (Dry)	1258	1757	1748	98.2
	1.09 (Wet)	1261	1775	1768	98.7
Weathered Shale	0 (Dry)	1261	1719	1715	99.0
	4.16 (Wet)	1258	1749	1744	99.0

6. CONCLUSIONS

The main objective of this study was to investigate the shear strength parameters and the potential for breakdown of mine waste rock samples on wetting. It was found that waste rock and waste rock/compacted clay interfaces are largely frictional, but with a significant suction-induced apparent cohesion. Since the waste rock will be relatively free-draining, it is never likely to saturate, and suction-induced apparent cohesion can be relied upon. Being largely frictional, the depth of interest with respect to potential geotechnical slope instability is shallow (Williams, 2015).

Based on the dry and wet sieving, and the slake durability test results, the waste rock does not degrade significantly. Since it is likely that scalping to enable laboratory shear strength testing will reduce the friction angle of coarse-grained waste rock, the laboratory-derived friction angles are likely to be conservative by up to several degrees. It is worth noting that the angle of repose slopes formed by loose-dumping of waste rock are generally geotechnically stable. They are more susceptible to erosion on over-topping by rainfall runoff. Based on the shear strength test results reported herein, the recommended shear strength parameters of mine waste rock are:

- Near the surface:
  - Apparent cohesion = 50 ± 25 kPa
  - Friction angle = 40 ± 3°
- Within the waste rock:
  - Apparent cohesion = 100 ± 50 kPa
  - Friction angle = 35 ± 3°
- On waste rock/compacted clay interfaces:
  - Apparent cohesion = 20 ± 10 kPa
  - Friction angle = 33 ± 3°

It is recommended that these average and ranges of shear strength parameters be applied in sensitivity analyses of geotechnical slope stability of waste rock dumps comprising these materials.

7. ACKNOWLEDGEMENTS

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