Proceedings Tailings and Mine Waste 2014 | Keystone, Colorado, USA | October 5-8, 2014

Settlement and collapse behaviour of coal mine spoil and washery wastes

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ABSTRACT: In order to reduce their environmental impacts, there are increasing demands being placed on open cut coal mine operators in Australia to seek alternative methods of disposing of washery wastes. The washery wastes include coarse-grained coarse reject and fine-grained tailings generated on the processing of run-of-mine coal. Attention is focusing on the possible incorporation of the washery wastes within the spoil piles formed on open cut coal mining. The contrasting characteristics of coal mine spoil and washery wastes are somewhat complimentary, making the co-disposal of washery wastes within spoil piles geotechnically feasible and environmentally attractive. Laboratory compression testing was undertaken on coal mine spoil, coarse reject, tailings, and blended coarse reject and tailings at different dry mass ratios. In the paper, the results of the laboratory testing program are compared and the likely effects of disposing of washery wastes within spoil piles are discussed. The laboratory compression of the different waste streams is found to be similar and complimentary.

1 INRODUCTION

Coal mining operations are generally associated with the production of three types of wastes; overburden spoil, and coarse reject and tailings generated on processing of the run-of-mine coal. Coal mine spoil is generated on the excavation of overburden to access the coal and is generally highly heterogeneous due to the combination of different types of materials, usually of sedimentary origin (Fityus *et al.* 2008). Coal mine spoil covers a wide range of particle sizes from boulders in excess up to about 2 m in size to sub-micron-sized clays. These materials are relatively easy to handle and are typically dealt with by loose dumping in in-pit or out-of-pit piles using a dragline or haul truck. Coal mine spoil piles settle over time, initially due to the self-weight of the spoil, followed by collapse on wetting-up, and longer-term physical and chemical degradation of the material. Spoil piles slopes may undergo geotechnical instability and are likely to undergo erosion due to surface runoff (Williams 2012). Spoil piles may also cause environmental problems where sulfides are present, including acid rock drainage (ARD), and spontaneous combustion.

Coarse reject, the coarse-grained waste product generated on the processing of run-of-mine coal, is typically in the size range from about 1 to 50 mm. Coarse reject is typically loose dumped in piles in a similar manner to spoil using haul trucks. The loose dumping of coal mine spoil and coarse reject facilitates oxygen entry, which may lead to ARD, spontaneous combustion, and material degradation.

Tailings, the fine-grained waste product generated from the processing of run-of-mine coal, are generally less than 1 mm in size. Their fine-grained nature makes them expensive to dewater to allow mechanical transportation (by truck or conveyor). Thus, tailings are generally thickened to about 25% solids by mass and pumped as a slurry from the process plant to the tailings storage facility, which is typically in the form of a surface containment or dis-used pit. The physical processes tailings undergo on sub-aerial disposal include beaching, hydraulic particle sorting according to particle size and specific gravity, sedimentation, self-weight consolidation, desiccation, and loading due to the placement of a capping prior to rehabilitation (Williams & Kuganathan 1992).

"Co-disposal" of washery wastes and spoil materials in one integrated disposal facility can be achieved by co-placement (i.e. a tailings facility contained by a containment dam constructed using spoil), by co-deposition (i.e. the co-placement of the coarse reject and tailings into a spoil pile, usually in separate layers), and by co-mingling (i.e. blended mixtures dumped in a storage facility; Gowan *et al.* 2010). Co-disposal is an advantageous alternative to the more common method of disposing the individual waste streams separately, as the complementing characteristics of the different waste streams can improve the overall particle size distribution and engineering behaviour. The addition of the fine-grained tailings can fill the pore space between coarse-grained coarse reject and spoil, restricting the infiltration of water and air through the mixture and consequently improving its geotechnical parameters and geotechnical and environmental behaviour.

However, the geotechnical characterisations of the spoil and washery wastes have a key role in the selection of the most appropriate co-disposal method, and in devising a practical co-disposal method. In order to have a better understanding of the co-disposed coal mine waste materials and highlight their differences, a series of laboratory tests was carried out. These included basic characterisation testing and compression testing of two different spoil materials and of mixtures of coarse reject and tailings with various dry mass ratios, including coarse reject only, and coarse reject to tailings (CR:T) dry mass ratios of 9:1, 6:1, and 3:1.

2 TESTING METHODOLOGY

2.1 *Sampling*

Spoil samples were collected from a number of Eastern Australian coal mines including Jeebropilly Coal Mine (New Hope Australia Coal) in the Ipswich Coalfields, Queensland, and Mt Arthur Coal Mine (BHP Billiton) in the Hunter Coalfields of New South Wales. The sampling procedure is detailed in Williams (2012) and involved the passing of the spoil materials through a 19 mm sieve, and weighing both the >19 mm and <19 mm fractions. The >19 mm spoil materials were photographed for the estimation of their particle size using Split Desktop (www.spliteng.com), as detailed in Kho & Williams (2012). The <19 mm scalped samples were collected for subsequent laboratory testing, which necessarily restricted the maximum particle size that could be tested. The coal mine spoil materials sampled represent a range from the clay mineral-rich Jeebropilly weathered rock, which is prone to slaking and dispersion on wetting, to durable Mt Arthur 3-month old sandstone. The Jeebropilly weathered rock spoil and Mt Arthur 3-month old sandstone spoil hence represent extremes in terms of shear strength, durability and compressibility. Coarse reject and tailings washery waste samples were collected from Jeebropilly Coal Mine.

2.2 *Characterisation testing*

Characterisation testing was carried out on the two <19 mm spoil samples, on the coarse reject and tailings samples individually, and on mixtures of the washery wastes. The testing included the determination of the as-sampled gravimetric moisture content, Atterberg limit testing, specific gravity testing, dry and wet sieving analysis for particle size distribution, and Standard compaction testing, as appropriate. The characterisation testing was performed essentially in accordance with AS 1289, apart from the specific gravity testing, which was performed according to ASTM D 5550-00.

2.3 *Compression testing*

The laboratory compression testing was undertaken in a standard 76 mm diameter oedometer apparatus, requiring further scalping of the coarse-grained samples to <2.36 mm due to the height of the oedometer specimen being limited to about 20 mm. The two spoil samples were air-dried and dry-sieved through 2.36 mm, to avoid any degradation that might occur on wet sieving. The coarse reject was received wet and hence was wet-sieved through 2.36 mm.

Oedometer testing was undertaken on the scalped spoil samples, the wet-scalped coarse reject sample, and on mixtures of the wet-scalped coarse reject and tailings at dry mass CR:T ratios of 9:1, 6:1 and 3:1. The tailings were not subjected to oedometer testing since their settled state did not support even the weight of the oedometer top cap without material squeezing out. The spoil specimens were tested at their as-sampled moisture content (termed "dry") and in a water bath (termed "wet"). For the tests on the washery wastes, the coarse reject was added at its as-sampled gravimetric moisture content of 14.5% and the tailings were added at their settled gravimetric moisture content of 150% (settled to 40% solids by mass). No further water was added prior to testing of the washery wastes, but the washery waste samples became near saturated after the application of the initial normal stress.

Each test was carried out on loosely-placed specimens, to simulate the loose dumping of the waste materials in the field, and each increment of normal loading was applied for 24 hours or until settlement had essentially ceased. Seven increments of normal stress were applied to the spoil materials in a geometric series from 20 to 1,000 kPa. Ten increments of normal stress were applied to the coarse reject only and the washery waste mixtures in a geometric series from 4 to 1,000 kPa.

3 RESULTS OF CHARACTERISATION TESTING

3.1 *Gravimetric moisture content, Atterberg limits, and specific gravity*

Table 1 summarises the results of the characterisation testing of the spoil and washery waste materials tested. The gravimetric moisture content of the Jeebropilly weathered rock spoil is similar to that of the Jeebropilly coarse reject, while the Mt Arthur 3-month old sandstone spoil is relatively dry. The clay mineral-rich Jeebropilly weathered rock is highly plastic, while the Mt Arthur 3-month old sandstone has only slight plasticity. The Jeebropilly coarse reject is non-plastic, since the plastic clay minerals report to the fine-grained tailings, making them reasonably plastic. The specific gravity of the Mt Arthur 3-month old sandstone is highest, followed by that of the Jeebropilly weathered rock spoil and coarse reject, with the Jeebropilly tailings having by far the lowest specific gravity due to a relatively high content of carbonaceous material.

Table 1. Results of characterisation testing of spoil and washery waste materials.

Sample	Jeebropilly Weathered Rock	Mt Arthur 3-month old Sandstone	Jeebropilly Coarse Reject	Jeebropilly Tailings
Gravimetric moisture content (%)	14.9	3.1	14.5	150.0*
Liquid limit (%)	71.0	26.3	Non-plastic	41.2
Plastic limit (%)	21.0	22.6	Non-plastic	17.2
Plasticity Index (%)	50.0	3.7	Non-plastic	24.0
Specific gravity	2.60	2.79	2.53	1.90

*Based on the results of sedimentation column testing.

3.2 *Particle size distribution*

Figure 1 shows the similar "all-in" particle size distribution curves for the Jeebropilly weathered rock and Mt Arthur 3-month old sandstone spoil samples, obtained using Split Desktop analysis. Both spoil types can be classified using the Unified Soil Classification (AS 1289) as sandy cobbly gravel.

Figure 2 highlights the substantial breakdown on wet sieving, compared with dry sieving, of Jeebropilly weathered rock spoil, with the gravel-sized particles breaking down to sand-sized particles, but little change in the proportion of fines, which remain agglomerated. The effect of adding dispersant prior to wet sieving of the Jeebropilly weathered rock spoil is seen on Figure 2 to be relatively minor.

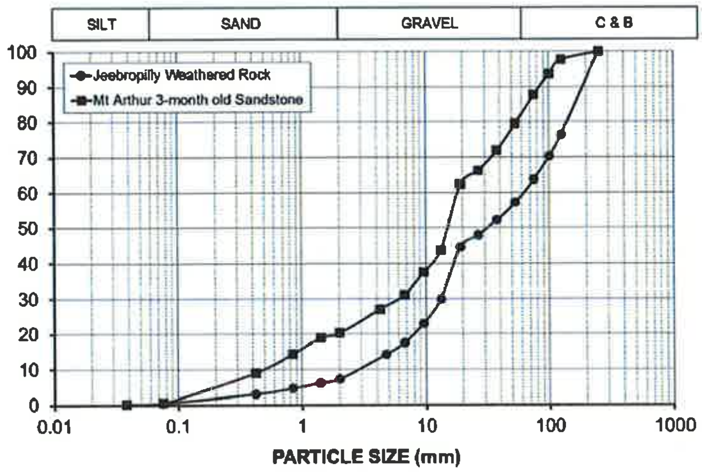

Figure 1. Particle size distribution curves of "all-in' spoil samples obtained using Split Desktop analysis.

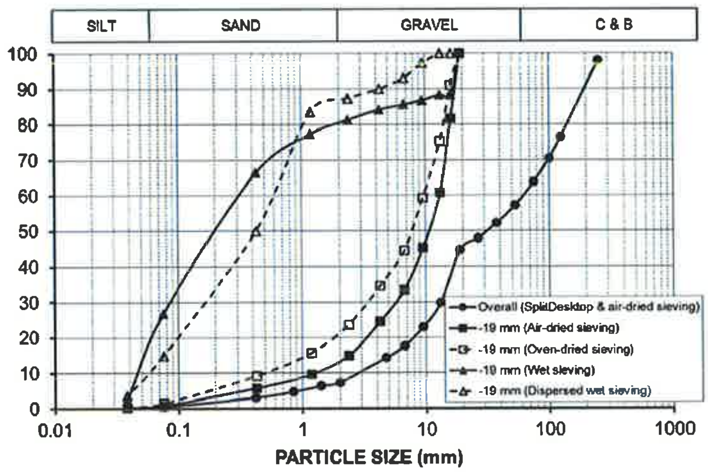

Figure 2. Results of dry and wet sieving of Jeebropilly weathered rock spoil.

Figure 3 shows that the Mt Arthur 3-month old sandstone spoil undergoes only limited breakdown on wet sieving, with a substantial increase in the proportion of fines generated. Figure 4 shows the particle size distribution curves obtained by dry and wet sieving of a sample of the whole coarse reject, and wet sieving of a sample of the whole tailings. The whole coarse reject sample can be classified using the Unified Soil Classification as a well-graded gravel

(GW), although wet sieving produces some gap-grading. The whole tailings sample can be classified using the Unified Soil Classification as a well-graded sand (SW). It is also notable, in Figure 4, that the whole tailings are about two orders of magnitude finer-grained than the coarse reject.

Air drying and oven drying followed by dry sieving of the whole coarse reject are seen in Figure 4 to produce similar particle size distribution curves. Wet sieving of the coarse reject, carried out without dispersant added, is seen to produce some breakdown of the fine gravel-sized particles to sand-sized particles. The breakdown seen in the Jeebropilly coarse reject sample is somewhat greater than that of the Mt Arthur 3-month old sandstone spoil, but substantially less than that of the Jeebropilly weathered rock spoil.

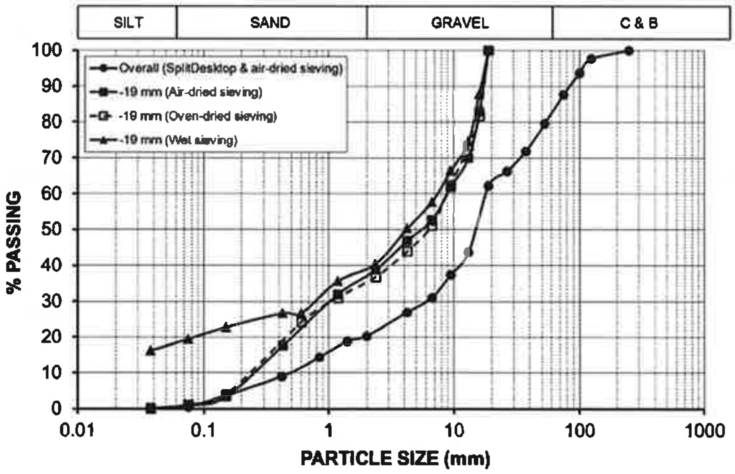

Figure 3. Results of dry and wet sieving of Mt Arthur 3-month old sandstone.

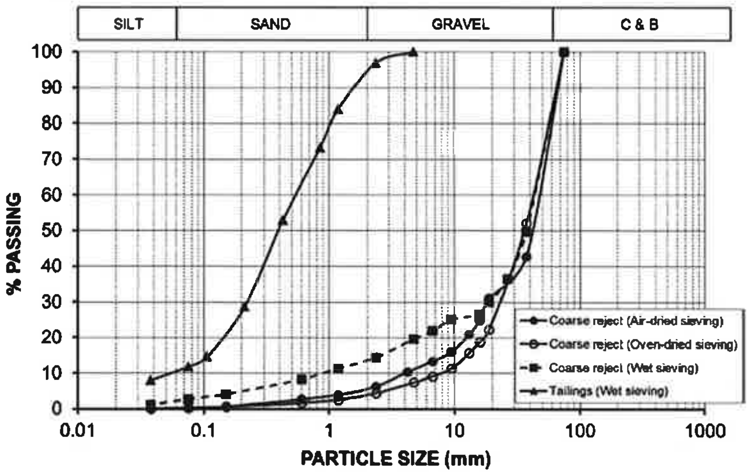

Figure 4. Particle size distribution curves from dry and wet sieving of Jeebropilly whole coarse reject and tailings.

3.3 *Standard compaction*

Standard compaction testing was carried out on <19 mm scalped spoil materials, <19 mm wet-scalped coarse reject, and on mixtures of <19 mm wet-scalped coarse reject and tailings with CR:T ratios of 9:1, 6:1 and 3:1. Table 2 presents the results of the Standard compaction testing, and shows that the maximum dry density (MDD) of the Jeebropilly washery waste mixtures is increasingly lower than that of the Jeebropilly spoil with decreasing CR:T dry mass ratio, due mainly to the much lower specific gravity of the Jeebropilly tailings. The MDD of the high specific gravity Mt Arthur 3-month old sandstone spoil is much higher than that of the Jeebropilly weathered rock spoil, and the optimum moisture content (OMC) is much lower for the Mt Arthur 3-month old sandstone spoil than the OMC values for the Jeebropilly wastes.

The degree of saturation at the MDD and OMC of all waste materials tested is relatively low. The degree of saturation at MDD and OMC generally decreases with decreasing CR:T dry mass ratio of the Jeebropilly washery waste mixtures, despite there being an increasing proportion of tailings fines available to fill the pore spaces between the coarse reject particles.

Table 2. Results of standard compaction testing of spoil materials, coarse reject and mixture of coarse reject and tailings.

Sample (%)	Maximum Dry Density (Mg/m^3)	Optimum Moisture Content (%)	Degree of Saturation at MDD and OMC
Jeebropilly Weathered Rock	1.52	19.0	69
Mt Arthur 3-month old Sandstone	1.96	11.5	67
Coarse reject only	1.45	18.8	64
9:1 (CR:T)	1.42	19.3	65
6:1 (CR:T)	1.36	16.2	50
3:1 (CR:T)	1.31	18.5	55

4 RESULTS OF COMPRESSION TESTING

Figures 5 shows the compression test results for the <2.36 mm scalped Jeebropilly weathered rock and Mt Arthur 3-month old Sandstone spoil samples, tested under dry and wet conditions. Figure 6 presents the compression test results for the <2.36 mm wet-scalped washery waste samples, including coarse reject only, and mixtures of coarse reject and tailings, tested under wet conditions. Table 3 shows the values of the calculated compression indices C_c for the spoil and washery waste samples tested.

Table 3. Compression indices of spoil, coarse reject only, and coarse reject and tailings mixtures calculated from oedometer test results.

Sample	Compression Index (C_c)	
	Dry	Wet
Jeebropilly weathered rock	0.41	0.27
Mt Arthur 3-month old sandstone	0.17	0.21
Coarse reject only	-	0.52
9:1 (CR:T)	-	0.52
6:1 (CR:T)	-	0.33
3:1 (CR:T)	-	0.17

The Jeebropilly weathered rock spoil tested dry is seen in Figure 5 and Table 3 to be much more compressible than the Mt Arthur 3-month old sandstone spoil tested dry, but the two have more comparable copmpression indices on testing under wet conditions, due to the collapse of the Jeebropilly weathered rock spoil on initial wetting.

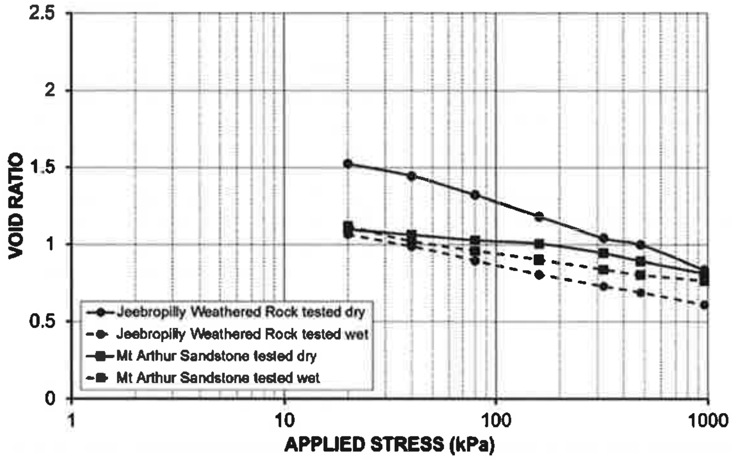

Figure 5. Results of dry and wet compression testing of <2.36 mm scalped Jeebropilly weathered rock and Mt Arthur 3-month old sandstone spoil materials.

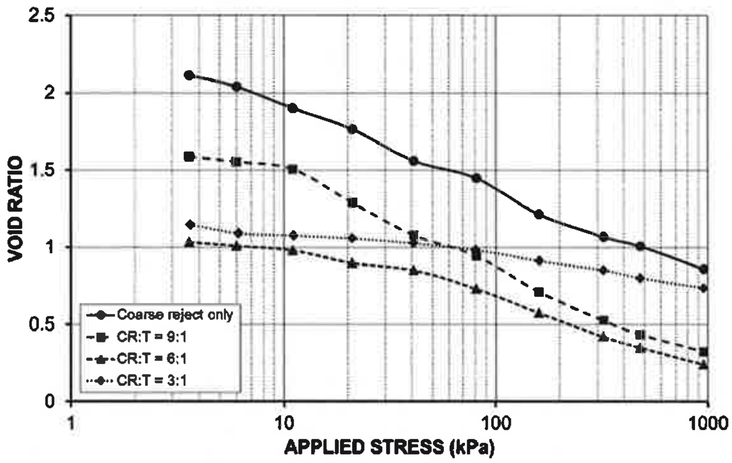

Figure 6. Results of wet compression testing of <2.36 mm wet-scalped washery wastes, including coarse reject only, and mixtures of coarse reject and tailings.

The compression index of Jeebropilly coarse reject tested under wet conditions is seen in Figures 5 and 6 and Table 3 to be far greater than that for Jeebropilly spoil, but the compressibility decreases with increasing proportion of tailings filling the pore space between the coarse reject particles (increasing CR:T dry mass ratio). This is likely due to the coarse reject particles being prone to crushing at point contacts, which is cushioned by the increasing presence of tailings.

5 DISCUSSION

Figure 7 compares the initial and final dry densities from the compression testing under wet conditions of all of the wastes tested, compared with their MDD values. Figure 7 shows that the final dry density of Jeebropilly weathered rock spoil and Jeebropilly washery waste mixtures exceeded their MDD values at 1,000 kPa applied stress (equivalent to about a 45 to 60 m high pile of the material, depending on its wet density), while Mt Arthur 3-month old sandstone only achieved about 80% of its MDD at 1,000 kPa applied stress.

The final dry densities for the Jeebropilly washery waste mixtures with CR:T dry mass ratios of 9:1 and 6:1 approached 2 Mg/m^3, much higher than for the other waste materials and mixtures tested. The final dry densities for Jeebropilly coarse reject only and for a Jeebropilly washery waste mixture with a CR:T dry mass ratios of 3:1, however, are significantly lower at about 1.35 Mg/m^3.

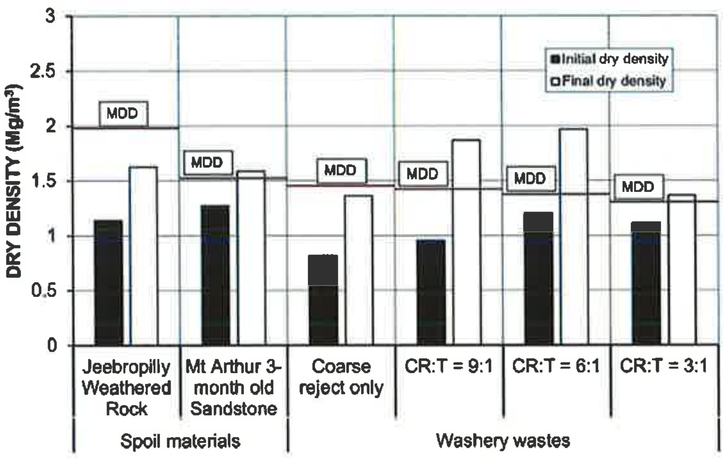

Figure 7. Comparison of initial and final dry densities of all materials subjected to compression testing under wet conditions.

The final void ratios for the Jeebropilly washery waste mixtures with CR:T dry mass ratios of 9:1 and 6:1 are in the range from 0.2 to 0.4. Williams *et al.* (2011) and Williams & Kho (2014) tested coal mine spoil under applied stresses up to 10 MPa and found the final void ratios to be about 0.3 for all samples tested, regardless of moisture state, scalping method and initial loading. On this evidence, the 9:1 and 6:1 CR:T dry mass ratio samples would not be expected to compress significantly more on loading above 1,000 kPa. This is attributed to the low crushing strength of the Jeebropilly washery wastes. The crushing strength of Jeebropilly weathered rock spoil is higher and that of Mt Arthur 3-month old sandstone is much higher still.

The percentage final compression relative to the initial height (ΔH_{final} / H_0) of all materials subjected to compression testing under wet conditions is shown in Figure 8. Jeebropilly coarse reject and washery waste mixtures with high CR:T dry mass ratios are seen in Figure 8 to compress most in relation to their initial loose heights. Jeebropilly weathered rock spoil shows intermediate compression relative to its initial loose height, and Mt Arthur 3-month old sandstone spoil and Jeebropilly washery waste mixture with a CR:T dry mass ratio of 3:1 compress least relative to their initial loose heights.

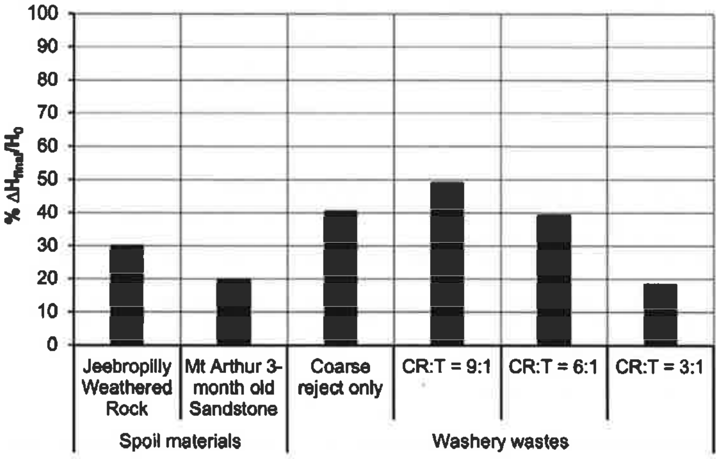

Figure 8. Comparison of final compression relative to initial loose height of all materials subjected to compression testing under wet conditions.

From these results it is apparent that, depending on the ratio of coarse reject to tailings generated on processing a given run-of-mine coal, it would be efficient in terms of optimising the available storage volume for the waste streams as a whole, to co-dispose washery wastes in spoil piles. Given the high dry densities achieved for combined washery wastes, it is likely that their shear strengths would also be acceptably high.

6 CONCLUSION

The paper describes characterisation and compression testing of a range of coal mine waste materials, including uncemented weathered spoil and cemented durable spoil materials, coarse reject, tailings, and mixtures of coarse rejects and tailings. It was found that washery waste mixtures of coarse reject and tailings with high CR:T dry mass ratios of 9:1 and 6:1 compressed 40 to 50% from their initial loose state under an applied stress of only 1,000 kPa. This is likely due to crushing at the weak point contacts between coarse reject particles. As the tailings content in the mixture increases further, the compression decreases to about 20%, which is comparable to that of durable spoil. The compression under 1,000 kPa applied stress of uncemented spoil was intermediate at about 30%.

It is apparent that, depending on the ratio of coarse reject to tailings generated on processing a given run-of-mine coal, the co-disposal of washery wastes is spoil piles would optimise the available storage volume for the waste streams as a whole. Given the high dry densities achieved for the loaded combined washery wastes, it is likely that their shear strengths would also be acceptably high.

7 AKNOWLEDGMENTS

The research on which this paper is based was funded under Australian Coal Association Research Program Project C19022. The management and staff of Jeebropilly Coal Mine, which is owned and operated by New Hope Corporation Australia, are acknowledged for providing spoil and washery waste samples for testing. The management and staff of Mt Arthur Coal Mine, which is owned and operated by BHP Billiton, are acknowledged for providing spoil samples for testing.

Masters student Bharat Yadav, and undergraduate Summer Research students Morgan Midgley, Mayla Martins, Nanae Kaneko and Nicholas Smith of the Geotechnical Engineering Centre within the School of Civil Engineering at The University of Queensland, are acknowledged for their assistance in carrying out the testing described in this paper.

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