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Settling and consolidation behaviour of coal tailings slurry under continuous loading

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ABSTRACT

Tailings are generated as the fine-grained wastes on the washing of run-of-mine coal to meet market specifications. Coal tailings are typically sand-sized and finer, and are pumped as an aqueous slurry at a solids concentration of typically 25% solids by mass, conventionally to a surface tailings storage facility. The physical processes that coal tailings undergo on sub-aerial disposal to a surface tailings storage facility include beaching, hydraulic sorting, settling, self-weight consolidation and desiccation. The settling and consolidation of coal tailings, the topic of this paper, have the most profound effect on the volume that the deposited tailings occupy. These processes are particularly important where the rate of rise is rapid and/or deposition is under water. Settling occurs in the upper part of the recently deposited tailings layer, while consolidation occurs simultaneously towards the base of the layer. The two processes of settling and consolidation are conventionally tested separately in the laboratory; settling in a column and consolidation in a consolidometer. This paper describes a purpose-built, large, slurry consolidometer, in which coal tailings slurry is added in three layers at a nominal 25% solids by mass, allowed to settle between layers, and consolidated under three different continuous loading sequences. Thus the two processes of settling and consolidation are carried out in the same testing apparatus, from an initial consistency representative of field conditions.

Keywords: coal tailings, consolidation, continuous loading, settling, slurry consolidometer

1 INTRODUCTION

Coal tailings from the processing of run-of-mine coal to meet market specifications are typically sand-sized or finer (<1 mm), although modern coal preparation plants or washeries separate coal down to <0.125 mm and the resulting tailings are correspondingly fine-grained. The tailings are typically thickened to a solids concentration of about 25% by mass (mass of solids/total mass, expressed as a percentage), and delivered by centrifugal pumps to a tailings storage facility (TSF). Surface TSFs are the most common, although tailings can also be stored in dis-used open pits or in underground workings. This paper relates to coal tailings deposition in surface TSFs by sub-aerial deposition. In practice, the tailings are disposed from a single point or multiple perimeter discharge points, resulting in the formation of an upper exposed tailings beach with a shallow slope (typically about 1%) to the decant pond, where the supernatant water collects and can be returned to the processing plant.

The physical processes that all tailings undergo on sub-aerial deposition to a surface TSF are beaching, hydraulic sorting of particles according to their size and specific gravity, settling, self-weight consolidation and desiccation on exposure to drying by solar and wind action (Williams 2005). All of these processes affect the geotechnical engineering behaviour and parameters of the resulting tailings deposit, and hence affect the volume that the stored tailings occupy. The settling and consolidation of tailings have the most profound effect on the volume that the deposited tailings occupy. They are particularly important where the rate of rise is rapid and/or deposition is under water.

The initial settling of tailings from a slurry involves a rapid and very dramatic reduction in solids volume, with limited particle contact, and essentially no development of excess pore water pressure or effective stress within the solids. As the tailings settle to form a sediment, particles come into contact, excess pore water pressures develop and, on drainage and consolidation, these transfer to effective stress. The magnitude of consolidation is far less than the reduction in volume on settling, and consolidation is a far slower process than settling.

The settling and consolidation behaviour of tailings are among the key factors used to estimate the storage volume required to accommodate the production of tailings from a given processing plant, which is crucial in the design of the TSF. However, the accuracy of such estimates relies upon the availability of reliable settling and consolidation test data (Morris *et al.* 2000). In the laboratory, settling and consolidation testing of tailings are conventionally carried out in quite separate apparatus, with no over-lap between them.

A laboratory settling column test, carried out in a graduated 1,000 cc measuring cylinder, is typically used to estimate the settling behaviour of a given tailings slurry from a relatively low solids concentration. However, this test suffers from interaction with the wall of the measuring cylinder (Williams and Morris 1988). In reality, the “wall” is so distant in a TSF that it has no effect. The wall effect in a settling column test is a function of the wall surface area to volume ratio, increasing with increasing area to volume ratio. The presence of the wall increases the rate of particle settling due to the enhanced flow of water up the wall, and decreases the rate of consolidation in the soil-like sediment that forms at the base of the column due to increasing wall friction as effective stresses increase. In addition, the sediment that forms cannot be transferred to a consolidometer for subsequent consolidation testing.

Laboratory consolidation testing of tailings is typically carried out in an oedometer or a Rowe cell, which generally require the specimen to be self-supporting; that is, soil-like rather than slurry-like. An oedometer specimen must initially be capable of supporting the mass of the top cap, so that the test can commence. Tailings settled underwater will have no strength, and hence no bearing capacity, at the surface of the sediment. Hence, an oedometer test can only start on a tailings specimen that has been pre-consolidated. Many tailings, particularly those that are clay mineral-rich, are too slurry-like to be suitable for oedometer testing, and their transitional behaviour between slurry- and soil-like cannot be captured in such an apparatus. In fact, tailings that do not settle well may never reach a soil-like consistency during deposition, and oedometer results would over-estimate their capacity to consolidate.

A Rowe cell applies stress hydraulically via a pressurised membrane, which makes it more amenable to testing slurry-like tailings. However, slurry-like tailings will undergo very large deformations on loading, stretching the membrane and causing the top porous disc above the specimen to deform. A Rowe cell will also have difficulty capturing the transitional behaviour of tailings between slurry- and soil-like consistencies. Both oedometers and Rowe cells are of limited height, making it impossible to model the settling of tailings from a slurry consistency.

This paper describes a purpose-built, large, slurry consolidometer, in which coal tailings slurry is added in three layers at a nominal 25% solids by mass, allowed to settle between layers, and consolidated under three different continuous loading sequences. Thus the two processes of settling and consolidation are carried out in the same testing apparatus, from an initial consistency representative of field conditions.

2 SLURRY CONSOLIDOMETER

The slurry consolidometer was purpose-built by Wille Geotechnik of Germany to a design specified by the Geotechnical Engineering Laboratory within The University of Queensland. The slurry consolidometer comprises a cell of internal diameter 150 mm and height of 410 mm instrumented with top and base load cells, and 1,000 kPa capacity mid-height and base pore pressure transducers; a 10 kN, electromagnetic load frame, and a 350 kPa pressure controller, as shown in Figure 1. The top load cell is connected to the loading piston to measure the applied stress, and the base load cell is imbedded in the base of the cell. The difference between the measured top and base loads give the combined piston and wall friction losses. The height of the cell allows tailings samples to be placed in a number of layers, and allowed to settle between layers, to form a test specimen of the order of 300 mm high. The specimen can be drained from the top or the base, or from both the top and the base, depending on the field conditions being simulated.

Figure 1: Slurry consolidometer cell and transducers, load frame and pressure controller.

3 TESTING

The purpose of the testing using the slurry consolidometer was to develop a testing methodology most appropriate for a particular coal tailings. The tailings tested and their sample preparation, the test methodology, and the simulation of the settling and consolidation processes, are described in the following sections.

3.1 Tailings tested and sample preparation

The tailings sample used in the study were coal tailings, flocculated and thickened to 25% solids by mass, collected from Jeebropilly Coal Mine, located in the Ipswich Coalfields of south-eastern Queensland, Australia. These tailings are nominally sand-sized (0.06 to 2 mm), with about 5% by dry mass gravel-sized (2 to 5 mm), about 5% silt-sized (0.001 to 0.06 mm), and about 5% clay-sized (<0.002 mm). However, the tailings are known to be smectite-rich, and are agglomerated both naturally and by virtue of the flocculant added to facilitate thickening. Their specific gravity was determined using a pycnometer with helium to be about 1.90, implying a coal content of about 55%, with the remainder comprising mainly smectite. The tailings were found to have a Liquid limit of 41% and a Plasticity Index of 24%, and they are classified as silty sand (SM) based on the Unified Soil Classification System.

In order to achieve a precise solids concentration and consistency between test specimens, samples were prepared for testing in the slurry consolidometer by first drying them in a 60°C oven (the temperature was limited to avoid combustion of the coal content), and then adding process water and stirring with a mechanical mixer, to achieve a solids concentration of 25% by mass, representing that achieved in the coal processing plant. The average electrical conductivity and the pH of the process water were 3,533 μs/cm and 8.7, respectively.

The test specimens were prepared in three layers. The volume of slurry and required mass of solids and water for each layer were calculated to fill about 200 mm height in the cell. Each batch of slurry was transferred to the cell using a funnel and tube, as a tremie to the base of the cell or top of the previously-placed and settled layer. Care was taken to minimise the amount of air mixed in with the specimen during placement, and the excess supernatant water from the previous layer was removed prior to the next layer being placed. Although the tailings slurry was prepared to 25% solids by mass, a small amount of extra water was required to wash out the tailings particles remaining in the funnel and tube, resulting in a reduction in the solids concentration to 22 to 23%. Each of the three layers of slurry was allowed to settle for about 2 hours, and the supernatant water was removed and weighed prior to the next layer of slurry being placed.

3.2 Test methodology

Three tests were carried out on settled specimens of Jeebropilly coal tailings using the slurry consolidometer, with top drainage only (and base pore water pressure measurement), and involving three different continuous loading sequences:

1. Constant rate of loading of 0.03 kPa/min, representing an actual rate of rise of about 1.3 m/year (assuming a settled and consolidated dry density of 12 kN/m^3), which was applied for about 7 days to achieve a final applied stress of 300 kPa, representing about 25 m height of settled and consolidated tailings. The specimen was allowed to settle further and consolidate under its self-weight overnight, before loading was commenced.
2. Geometrically increasing applied stress, inn 40 min time increments, starting from 0.05 kPa/min, then 0.1 kPa/min, 0.2 kPa/min, 0.4 kPa/min, 0.8 kPa/min, 1.6 kPa/min, and finally 3.2 kPa/min, for a total loading time of less than 5 hours to achieve a final applied stress of 259 kPa (short of 300 kPa due to the loading sequence adopted), allowing for the 5 kPa seating stress. The specimen was allowed to settle further and consolidate under its self-weight overnight, before loading was commenced.
3. Constant rate of loading of 0.2 kPa/min, representing an actual rate of rise of about 1.3 m/year (assuming a settled and consolidated dry density of 12 kN/m^3), which was applied for about 1 day to achieve a final applied stress of 300 kPa. The specimen was allowed to settle further and consolidate under its self-weight overnight, before loading was commenced.

The purpose of applying the three different continuous loading sequences was to adequately represent the rate of rise of tailings in the field, while minimising the total test duration.

3.3 Settling process

The degree of settling of each of the three layers was measured and the overall average settled % solids and settled height of the three specimens prepared for the different consolidation tests performed was determined, as summarised in Table 1. The greater settled height of the Test 3 specimen was due to settling and self-weight consolidation not being continued overnight.

Table 1: Settled solids concentration and height.

Test	Overall average settled solids concentration (%)	Overall settled height (mm)
1	47	280.0
2	49	258.0
3	49	258.5

3.4 Consolidation process

Continuous loading better represents the continuous deposition of tailings in the field than standard consolidation testing, which employs step-wise loading that is maintained until consolidation is complete. The standard loading duration is 24 hours, which extends the duration of the consolidation test to many days. Both in the field and under continuous loading in the laboratory, excess pore water pressures may not fully dissipate at the loading rate applied. For a laboratory continuous loading test to be representative of field conditions, the rate of loading and the rate of dissipation of excess pore water pressures should match, as closely as possible, the rates achieved in the field. The three continuous loading sequences tested using the slurry consolidometer were intended to represent typical tailings deposition rates in the field, accompanied by the generation and dissipation of excess pore water pressures and consequent consolidation settlement.

The slurry consolidometer has a set seating stress of 5 kPa, before readings are taken. In each test, the piston was advanced at a speed of 0.5 mm/min until the applied stress reached 5 kPa, when the slurry consolidometer was switched to stress control at the appropriate rate. Seating of the piston results in some loss of supernatant water and a minor loss of settled fines (about 5% of the total dry mass) from the top of the specimen around the piston, and associated settlement, since the piston incorporates an imperfect, low friction seal. This initial settlement is determined from the measured final height of the specimen minus the recorded settlement after seating. The fines initially extruded around the piston was also recovered and weighed.

4 TEST RESULTS

Figures 2 to 4 show the results of slurry consolidation Tests 1 to 3 carried out on the Jeebropilly coal tailings specimens, respectively. Figure 5 shows the results of all three tests plotted together for the purposes of comparison.

The values of pore water pressure plotted in Figures 2 to 4 include both excess and hydrostatic pore water pressures, with the latter accounting for about 2.5 kPa throughout the tests, due to the height of the settled slurry of about 250 mm. In all three tests, the excess pore water pressure initially increased in line with increasing applied stress and reached a maximum value of about 10 kPa, 20 kPa and 40 kPa in Tests 1, 2 and 3, respectively; thereafter dissipating rapidly. In Tests 1 and 3, the pore water pressure started to dissipate after about 50 min and about 200 min, respectively. The higher magnitude and longer dissipation time for pore water pressure in Test 3 compared to Test 1 can be attributed to its higher constant rate of loading. In Test 2, in which the rate of loading was doubled every 40 min, the pore water pressure continued to rise until the middle of the fourth loading increment, before starting to dissipate at a slow rate after about 130 min.

In the early parts of all of the slurry consolidometer tests, up until the dissipation of the pore water pressure, the stress measured at the base of the cell matched the applied stress, implying negligible piston and wall friction. However, after the dissipation of pore water pressures, only about 50% of the applied stress reached the base of the cell, indicating high wall friction losses due to the development of effective stresses in the specimen.

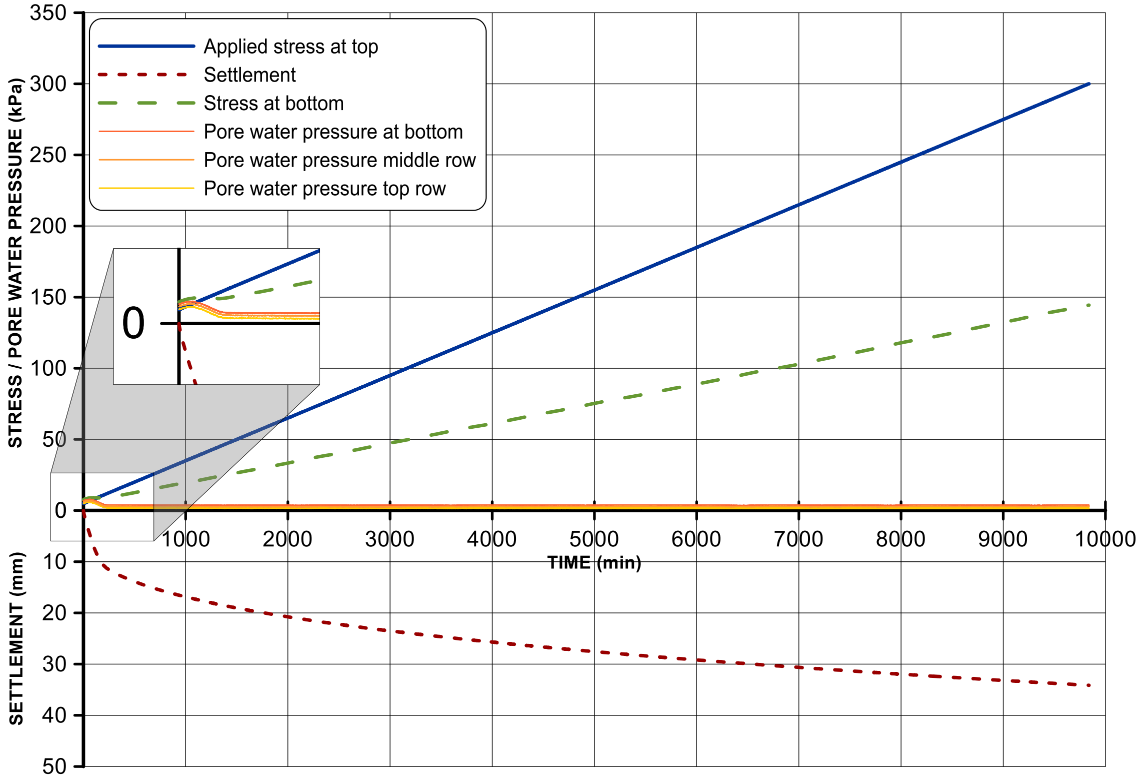


Figure 2: Results of slurry consolidation Test 1.

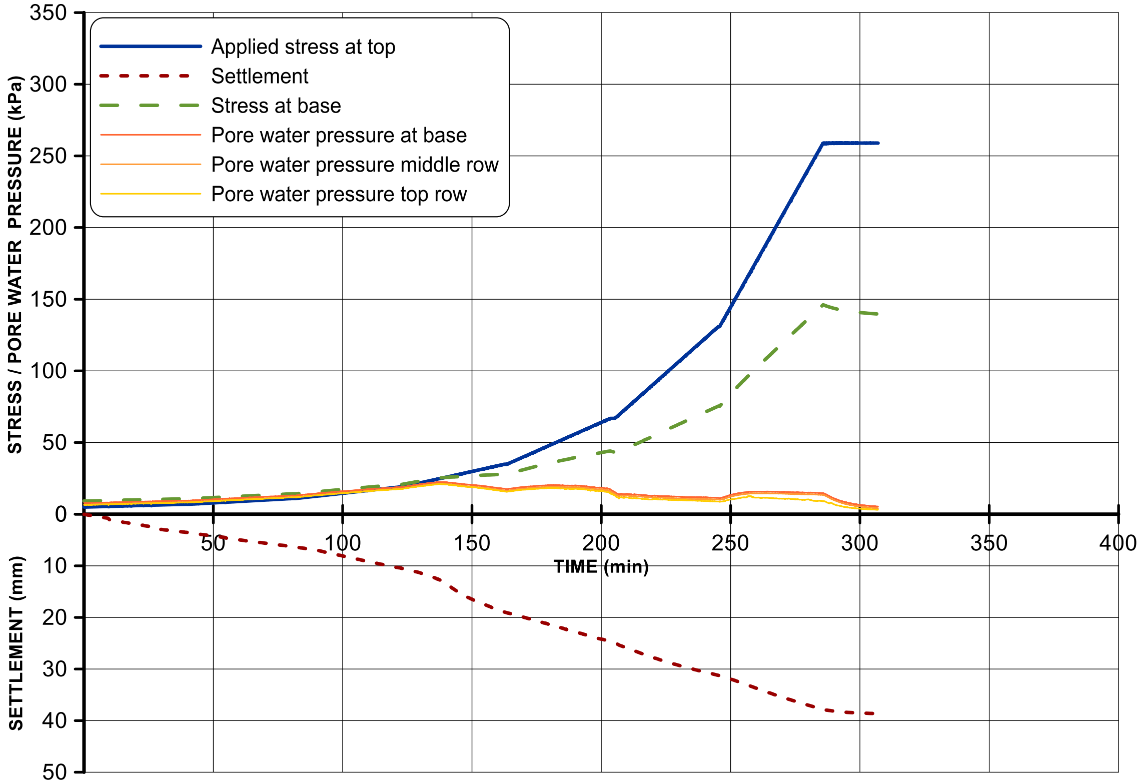


Figure 3: Results of slurry consolidation Test 2.

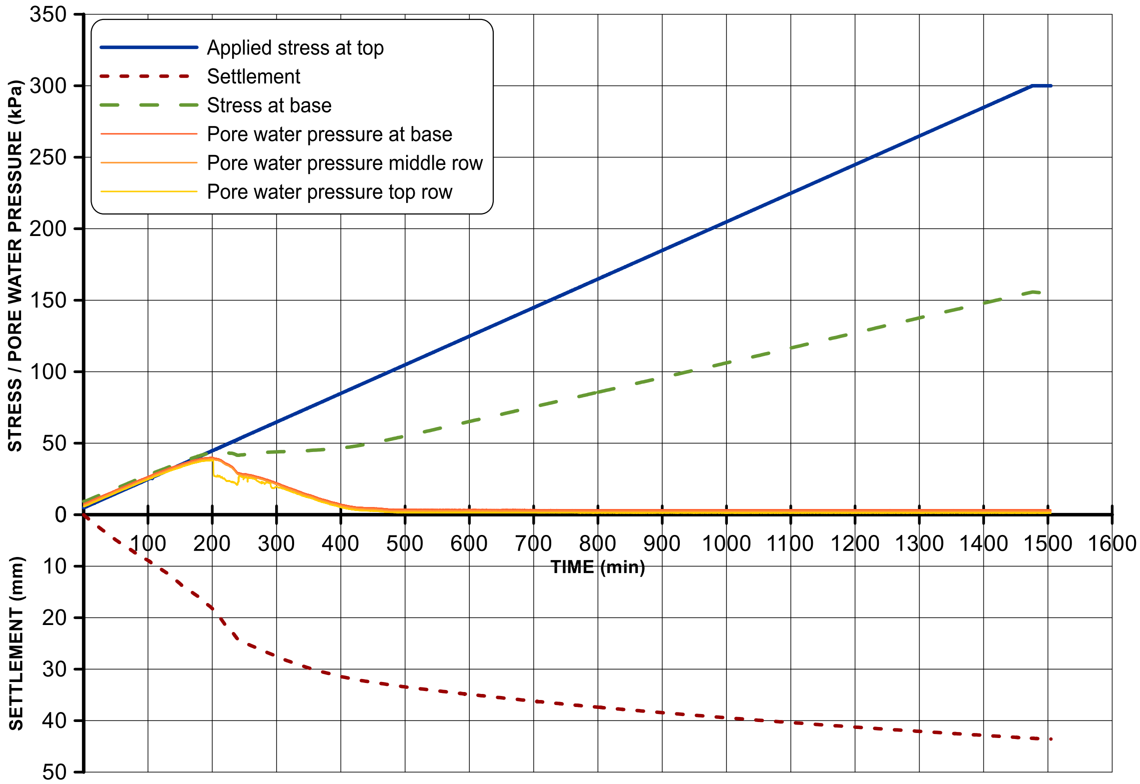


Figure 4: Results of slurry consolidation Test 3.

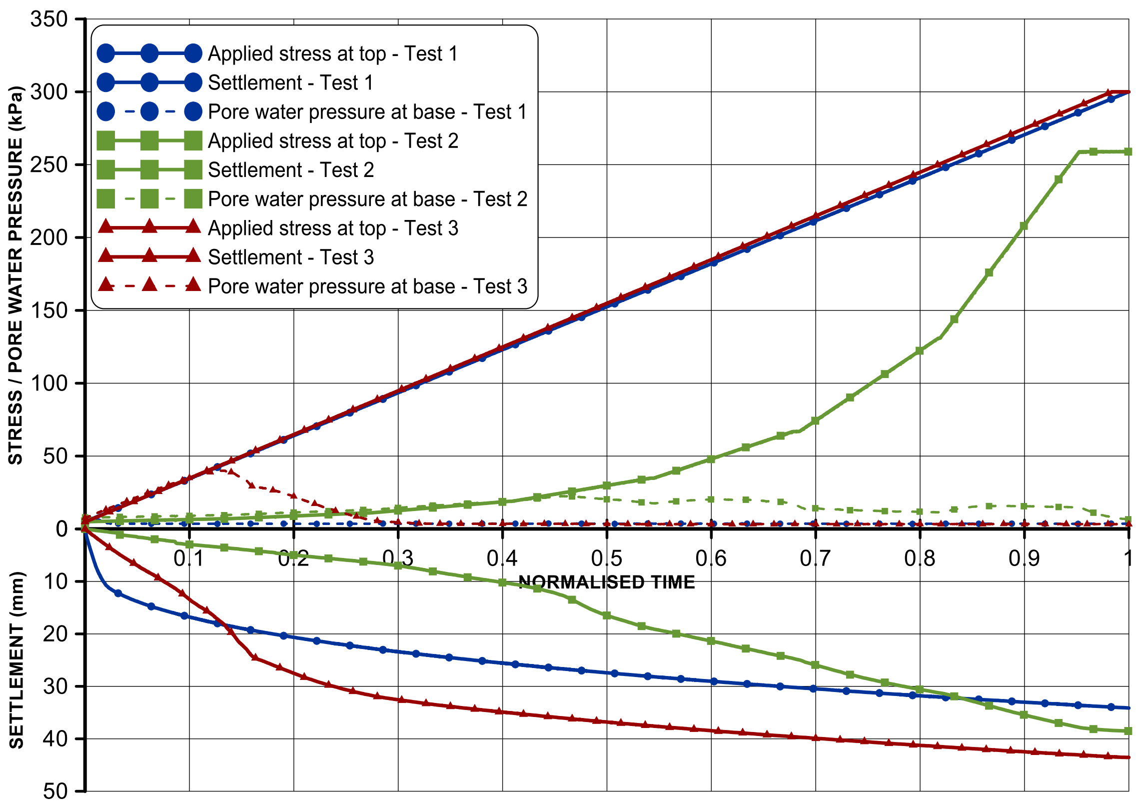
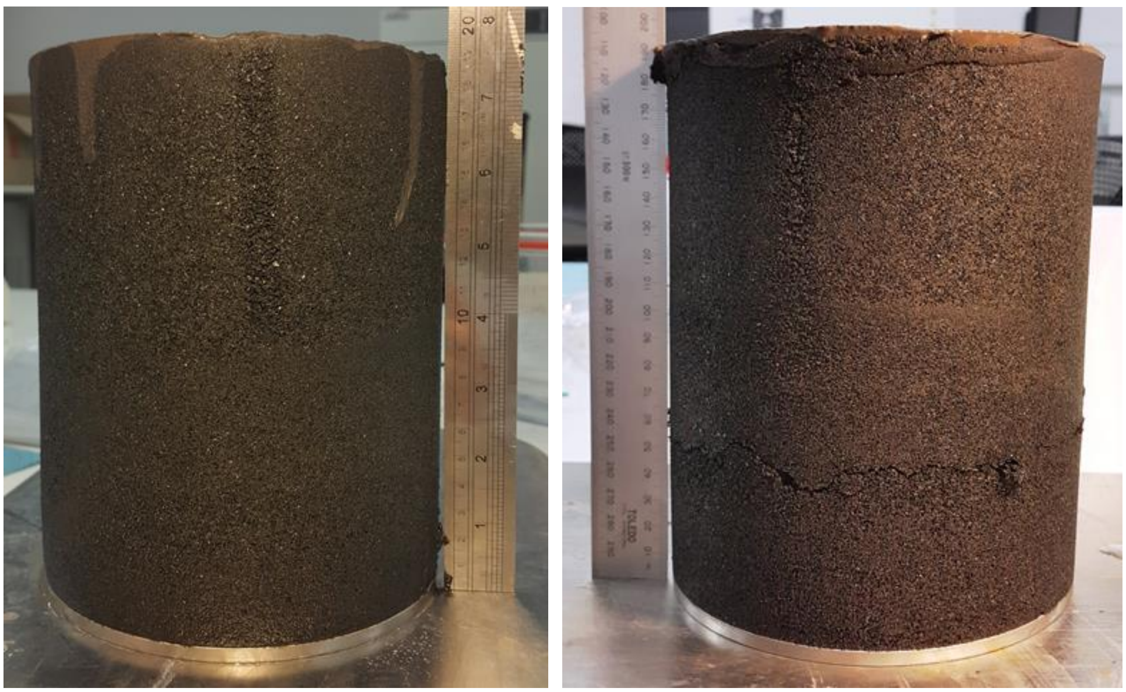


Figure 5: Comparison of results of all three slurry consolidation tests.

The high settlements that occurred at the beginning of all three tests, in the absence of pore water pressure dissipation, may be attributed to the leakage of water around the piston, the compression of inevitable air bubbles (air also becomes entrained in a tailings stream), and the rearrangement of particles. In Tests 1 and 3, the settlement curves started to flatten after the dissipation of pore water pressure. However, in Test 2 the incremental loading and retarded dissipation of pore water pressure, retarded the rate of settlement.

Figures 6 (a) and (b) show the consolidated specimens removed from the slurry consolidometer cell at the completion of Tests 2 and 3. The removed specimens are seen to be self-supporting, and amenable to sub-sampling for moisture content, suction and particle size distribution determination, although these results are not reported herein. It was also observed that the consolidated specimens were still not fully-saturated, as they were seen to contain some air bubbles. This would also be the case on deposition of the tailings from the end of an elevated pipe in the field.



(a) (b)

Figure 6: Specimens removed from cell at completion of: (a) Test 2, and (b) Test 3.

The settling of the slurry resulted in the segregation of particles in each of the three layers placed, with the coarser-grained particles settling rapidly towards the base of each layer, and the finest-grained particles settling last on the top of each layer. The presence of fines on the top of the specimen is likely the cause of the build-up of pore water pressures on initial loading, until pathways through them develop via essentially hydraulic fracturing and bypassing along the wall of the cell (Dobak *et al.* 2015). Figures 7 (a) and (b) show the top of the specimen removed from the slurry consolidometer cell at the end of Test 3. A layer of fines on top of the specimen is clearly seen, and the variation in particle size between the top fines layer and the underlying coarser-grained tailings is clear in Figure 7.

(a) (b)

Figure 7: Top of specimen after Test 3, showing: (a) layer of fines, and (b) underlying coarser particles.

5 DISCUSSION

The following sections present a preliminary analysis of the results of the slurry consolidation tests based on a presumed effective stress distribution with depth through the specimen to allow the estimation of average hydraulic conductivities.

5.1 Effective stress

Assuming a parabolic distribution of pore water pressure and wall friction with specimen height, the distribution of stress with specimen height will also be parabolic, as shown in Figure 8. Parabolic stress distributions are a reasonable assumption given that the top of the specimen is the only drainage boundary, and wall friction will be highest towards this boundary.

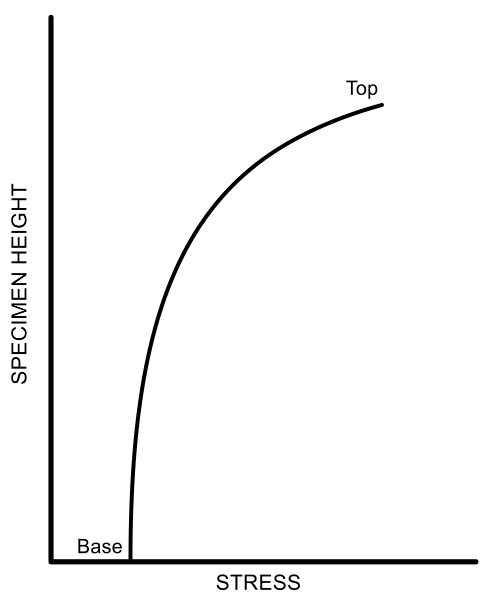


Figure 8: Assumed parabolic distribution of stress with specimen height.

Based upon an assumed parabolic stress distribution, the average applied stress over the height of the specimen σ_{av} is given by:

$$\sigma_{av} = \sigma_{top} - (2/3)\,(\sigma_{top} - \sigma_{base}) \tag{1}$$

where σ_{top} is the applied stress at the top of the specimen, and σ_{base} is the stress measured at the base of the specimen.

From Equation (1), the average effective stress σ'_{av} over the height of the specimen is given by:

$$\sigma'_{av} = \sigma_{av} - (2/3)\,u_{base} \tag{2}$$

where u_{base} is the excess pore water pressure at the base of the specimen.

Figure 9 shows the estimated average effective stress with time normalised by the total test duration for the three slurry consolidometer tests. It can be seen in Figure 9 that the initial average effective stress is zero until the pore water pressures begin to dissipate, and that this is retarded for about one third of the test duration due to the incremental increase in the rate of loading.

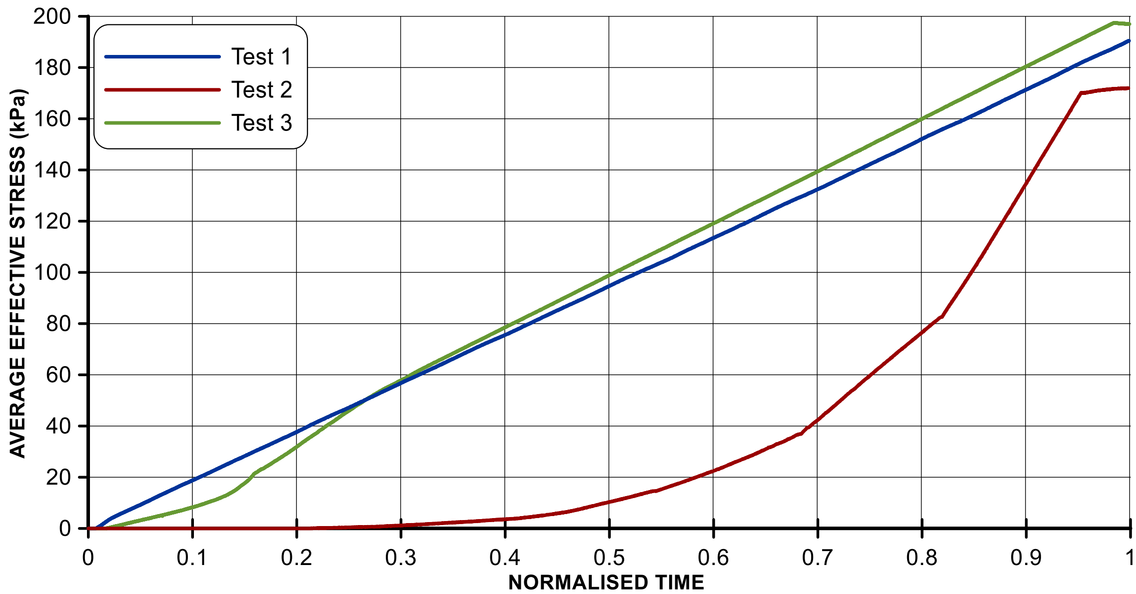


Figure 9: Estimated average effective stress with normalised time for the slurry consolidometer tests.

5.2 Hydraulic conductivity

The average hydraulic conductivity of the slurry consolidometer specimens may be estimated using Darcy's Law:

$$k = q\,/\,(A.i) \tag{3}$$

where k is the hydraulic conductivity, q is the volumetric rate of seepage, A is the cross-sectional area of the specimen, and i is the hydraulic gradient.

Assuming *i* = 1, a reasonable assumption since only limited water collected of the top of the piston, and that the change in volume of the specimen is equal to the water released, the average hydraulic conductivities over the period during which the initial excess pore water pressure dissipates in each of the slurry consolidometer tests may be calculated. Table 5, presents the estimated average of hydraulic conductivities for the initial parts of the three slurry consolidometer tests.

Table 2: Estimated hydraulic conductivity.

Test	Dissipation time (min)	Change in the volume (m^3)	Hydraulic conductivity (m/s)
1	225	0.0001413	6E-07
2	168	0.0004594	3E-06
3	300	0.0002650	8E-07
Average	231	0.0002886	1.5E-06

There is acceptable agreement between the estimated hydraulic conductivities for the three slurry consolidometer tests. Furthermore, the values obtained are in agreement with typical hydraulic conductivities for coal tailings of up to 1E-06 m/s (Williams 2005).

6 CONCLUSION

In the laboratory, settling and consolidation testing of tailings to assess their storage volume requirements are conventionally carried out in quite separate apparatus, with no over-lap between them. A laboratory settling column test is typically used to estimate the settling behaviour of a given tailings slurry from a relatively low solids concentration, and laboratory consolidation testing of tailings is typically carried out in an oedometer or a Rowe cell, which generally require the specimen to be self-supporting; that is, soil-like rather than slurry-like.

This paper describes three combined settling and consolidation tests performed on a particular coal tailings at an initial solids concentration of 22 to 23% by mass, representative of thickened coal tailings discharged to a surface TSF, in a purpose-built slurry consolidometer. The thickened coal tailings were collected from Jeebropilly Coal Mine in the Ipswich Coalfields of south-eastern Queensland, Australia. In each of the slurry consolidometer tests, different continuous loading sequences were applied to determine what would adequately represent the rate of rise of tailings in the field, while minimising the total test duration. For the particular coal tailings tested, a constant rate of loading appears optimal, and can be as high as 0.2 kPa/min, as applied in Test 3, since this reduces the duration of laboratory consolidation to only 1 day, without compromising the data obtained (induced excess pore water pressures largely dissipated during the course of the test). In the field, the equivalent 25 m height of tailings would result in correspondingly slower rates of consolidation due to the 100-fold greater flow path length.

It is considered that the slurry consolidometer offers a powerful new apparatus for the combined settling and consolidation testing of tailings to estimate their volume storage requirements in the field. Further testing with the apparatus is required to further optimise the test methodology and to further develop the interpretation and analysis of the data obtained. The use of the apparatus then needs to be extended to a range of tailings types.

7 ACKNOWLEDGEMENT

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