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Rheological testing for dam break modelling

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Abstract

The rheology of tailings that have been discharged onto a tailings storage facility (TSF) and allowed to sediment out, consolidate and then undergo liquefaction is significantly higher than the rheology of the slurry in the initial discharge stream. This can be ascribed to a combination of factors that include higher solids concentration, stress state and history, re-establishment of flocculant bonds, and natural coagulation and agglomeration measurement of the rheology of the liquefied tailings therefore requires that samples undergo similar sedimentation and consolidation processes without disturbing the samples. In addition, many TSFs are constructed of two different materials, where coarser tailings are separated from the tailings stream using hydrocyclones and used to contain and confine finer tailings or applied as drainage layers. On liquefaction of the fines, the liquefied rheology will be influenced by the coarser, better-drained tailings as this is entrained with the fine tailings. Moreover, some of the supernatant water that accompanies the liquefied tailings during flow liquefaction will be entrained with the tailings, effectively diluting the liquefied slurry and impacting the rheology. All of these factors need to be considered in the course of a dam break analysis due to the influence of rheology on the fluid dynamics during flow and therefore of the resulting inundation characteristics. This paper describes laboratory and semi-pilot scale testing methods developed and applied by the authors in dam break analyses. The tests are able to address the factors of sedimentation, consolidation, stress history, material combinations and mixing, as well as supernatant water. The influence of these factors as measured in the tests is described.

Keywords: *rheology, rheological testing, dam break, flow slide, liquefaction*

1 Introduction

The flow characteristics of liquefied tailings during a dam break are dependent on a range of factors such as flow rate, channel geometry, bed resistance and the rheology of the non-Newtonian fluid. The rheology results from van der Waals forces and flocculant bonds that draw particles of tailings together, increasing their shear resistance during flow. In general, the measurement of rheology can be carried out in a range of different ways as listed in Figure 1. All methods rely on the application of measurable shear stress and rate to a fluid over a known fluid depth or width within which the maximum velocity of the fluid can be estimated. The tests are run at a range of velocities and the shear resistance plotted against the shear rate, which is the ratio of the velocity to the depth or width of the fluid in the apparatus.

The resulting correlation between shear resistance and shear rate can then be applied in the full-scale by estimating the shear rate of the flow in the full-scale and, from this estimating, the shear resistance which acts to slow the fluid movement.

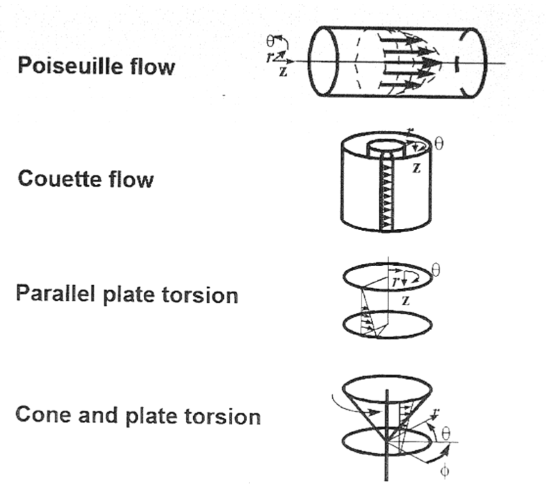


Figure 1 Common methods for measuring rheology

Several additional factors need to be considered when assessing the rheology of the liquefied flow from a tailings dam break. These are:

- The influence of sedimentation, drainage, consolidation and stress history. After discharge onto the TSF during operations, the tailings settle out on the beach and dewater through bleeding, seepage and evaporation. This results in densification over time, with the densification further enhanced by the suction pressures generated during dewatering and potential partial desaturation.
- The influence of embankment materials that may be entrained in the process of releasing the liquefied tailings. These materials may comprise soils or sandy tailings which have the tendency to affect rheology by virtue of their own properties as well as increasing friction during flow.
- The influence of water that may dilute the liquefied tailings (slurry) as residual water, and the slurry flow out of the break.

Ugaz & McPhail (2022) showed that there is a significant increase in the rheology of the liquefied tailings through consolidation. These authors demonstrated that the rheology of the slurry can be correlated with the state parameter of the tailings prior to liquefaction. On this basis the anticipated rheology of the liquefied tailings in the full-scale can be predicted based on state parameter data from cone penetration testing as well as laboratory testing on samples of recovered tailings.

Incorporation of embankment materials into the standard rheological tests is problematic in two ways. Firstly the embankment materials are generally larger in maximum particle size than the tailings, necessitating a larger gap between the moving surfaces in the typical rheology tests. With the larger gap comes a tendency to settle out in the apparatus and, for high yield stress materials, the gap between surfaces may not be fully sheared, thereby complicating analysis. Secondly, it is necessary to mix the materials representatively, which requires an estimate of the degree of entrainment.

To account for the above factors and limit the issues with typical rheological testing, a range of new tests has been developed and applied in practice. These methods, considering each of the above factors separately, are set out below.

2 Measurement of the rheology of consolidated-liquefied slurry

The authors have developed a box rheometer as indicated in Figure 2. Features of the set up are as follows:

- A steel box into which the slurry is poured. One side of the box can be lowered pneumatically, which induces liquefaction of the tailings and allows the liquefied slurry to flow out of the box. The base of the box is equipped with filter-compatible drainage sand to allow drainage of the slurry, with drainage controlled using a valve.

- A table onto which the liquefied slurry flows during the test.
- 3D cameras located above the box and the table to capture the flow geometry at a rate of 60 frames per second.
- Moisture and suction sensors fitted to the walls of the box to allow measurement of the changes in moisture content and suction as consolidation takes place.

A test typically entails the following:

- Preparation of three to four boxes which can be wheeled into place against the table at the start of each test.
- Charging of the boxes with slurry in layers, allowing the drainage and consolidation of each layer before introducing the next layer. Typically three layers are placed.

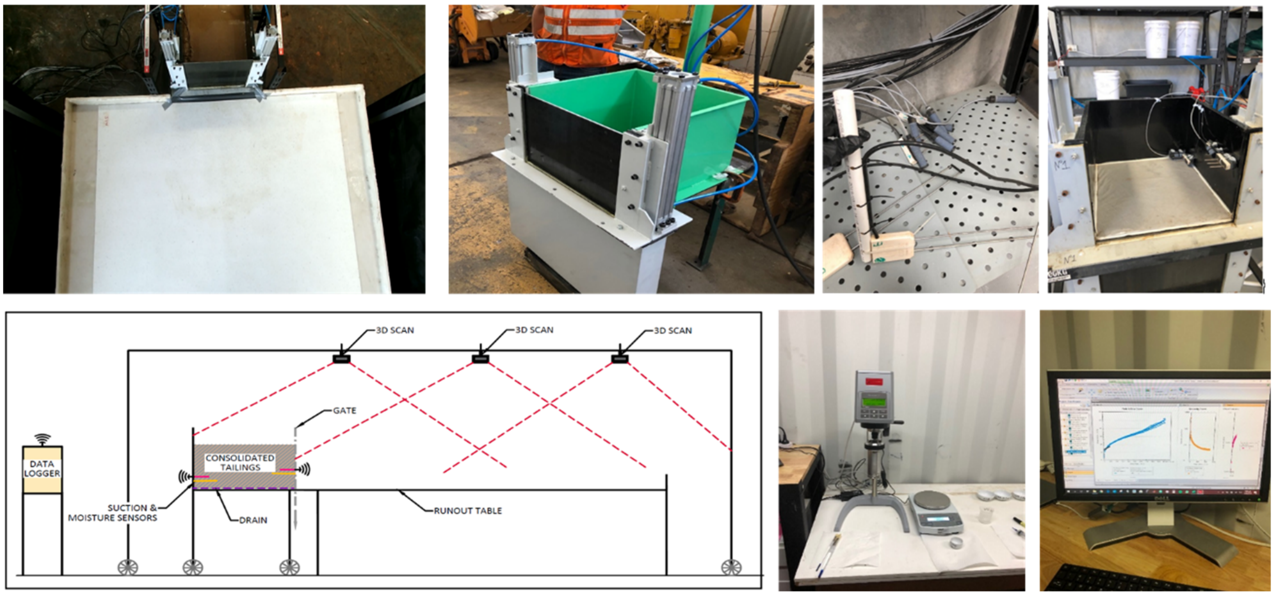


Figure 2 Box rheometer setup

- Recovery of samples from the boxes immediately before opening for the performance of rotary viscometer tests. These tests are performed over several cycles to fully shear the slurry and obtain an estimate not only of the peak shear resistance of the unsheared slurry but also the fully sheared resistance.
- Recording of the outflow and, from the videos, determining the flow rate, flow depth, velocity, flow profile, hydraulic radius and centroid with distance and time.
- Back-analysis of the flow using computational fluid dynamics (CFD) software by varying the rheological parameters until the modelled flow characteristics from the box over the duration of the test are close to the observed characteristics – a calibration process. These calibrated rheological parameters are then applied using the same CFD software in the modelling of the full-scale dam break.
- Correlation of the rotary viscometer data with the calibrated rheology from the CFD modelling of the box test. Generally the rotary viscometer rheology is lower than the CFD calibrated rheology due to sample disturbance generated in the sampling process and loading of the sample into the rotary viscometer.

Figure 3 shows typical post-processing results from analysis of the 3D video data from the box rheometer test using Viscometrix software developed by the authors. On the left are views of the box; the view from the overhead camera in black and white, and an isometric with a heat map of depth. On the right are plots of flow area, width, hydraulic radius and centroid at selected distances from the box along the line of flow, as well as plots of volume and depth along the line of flow. All of these plots are available at any frame of the video or time from opening of the box.

Figure 4 shows a comparison between a video of a box rheometer test and results from CFD modelling during the calibration process. The authors have found that the CFD modelling is able to replicate the video data to a remarkable level of accuracy.

Figure 5 shows typical shear stress and shear rate data from the box rheometer plotted against rotary viscometer data. The high initial peak shear resistance representative of unsheared slurry is replicated in both the box rheometer and the rotary viscometer tests. The repeated cycles of increasing and decreasing shear rate in the rotary viscometer increase the total shear experienced by the slurry causing a progression from the unsheared state to the fully sheared state. The high reading from the rotary viscometer in the left graph may be due to turbulence in the viscometer due to the high shear rate.

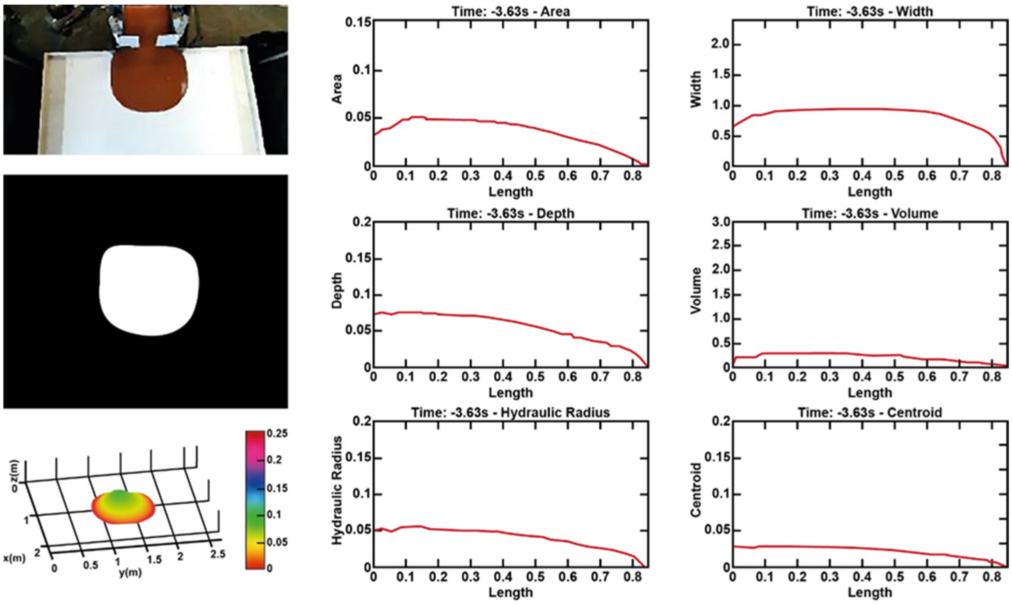


Figure 3 Typical post-processing box rheometer results from Viscometrix

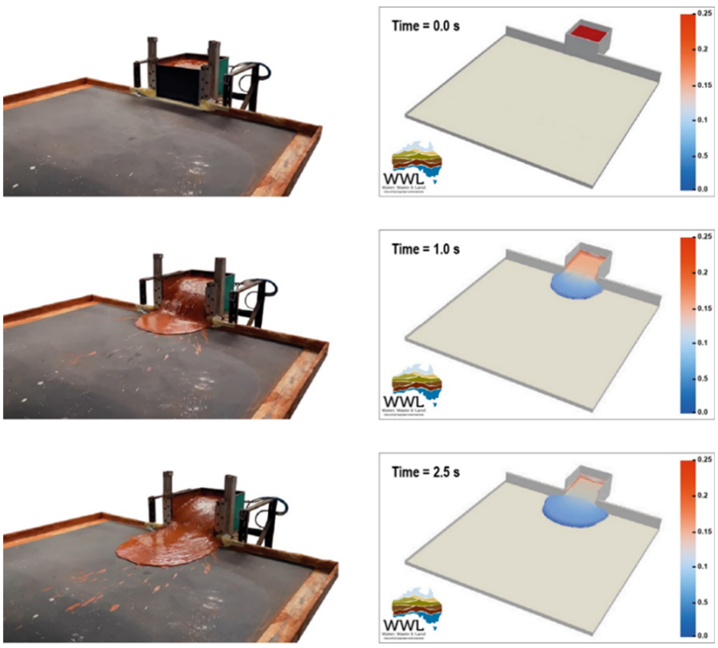


Figure 4 Comparison of box and CFD images

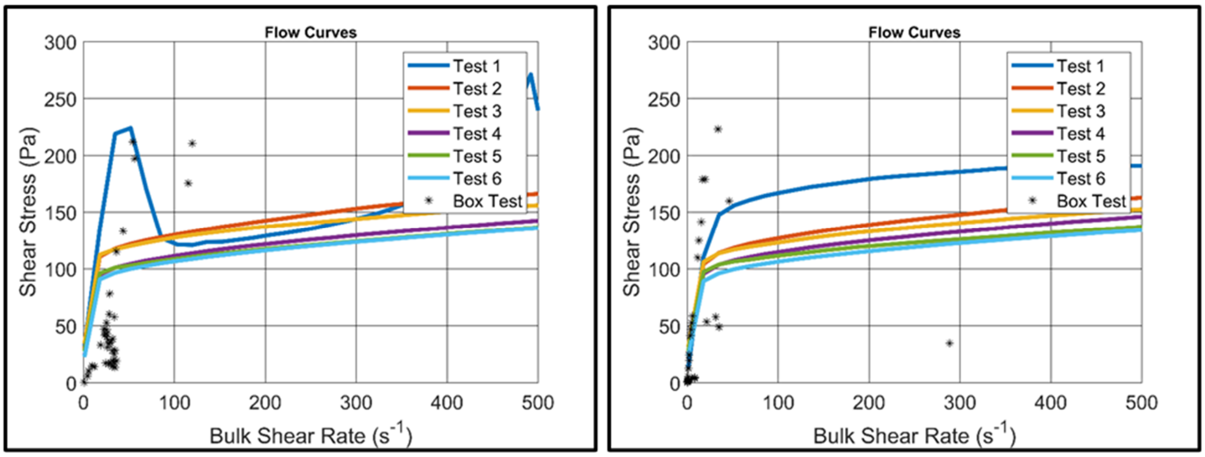


Figure 5 Typical flow curves from the box rheometer and rotary viscometer tests

The authors have further developed a small-scale test for estimating the rheology of consolidated slurry using a rotary viscometer with minimal sample disturbance. Figure 6 shows a bob and cup for the rotary viscometer that has been designed to allow basal drainage for consolidation as well as provide a support system for suspending the bob in the slurry so that the test can be conducted with minimal sample disturbance. Also indicated is a shear vane. The tests are conducted in pairs, with one of the pair being a bob and cup and the second being a vane within a cup. The vane allows estimation of the brittleness of the sample at the time of testing as well as providing an estimate of the static yield stress. Several pairs are set up and tested at increasing periods. Measurement of changes in moisture content and therefore void ratio are taken and compared with critical state line data to estimate the state parameter at the start of the test. The test will be most representative for higher concentration slurries where segregation after pouring the slurry into the cup should be low.

Figure 6 Consolidated slurry testing using a rotary viscometer

Figure 7 shows typical results from the consolidated rotary viscometer testing over a range of consolidation times. It is noteworthy that the peak shear stress increases rapidly after only a few days of consolidation.

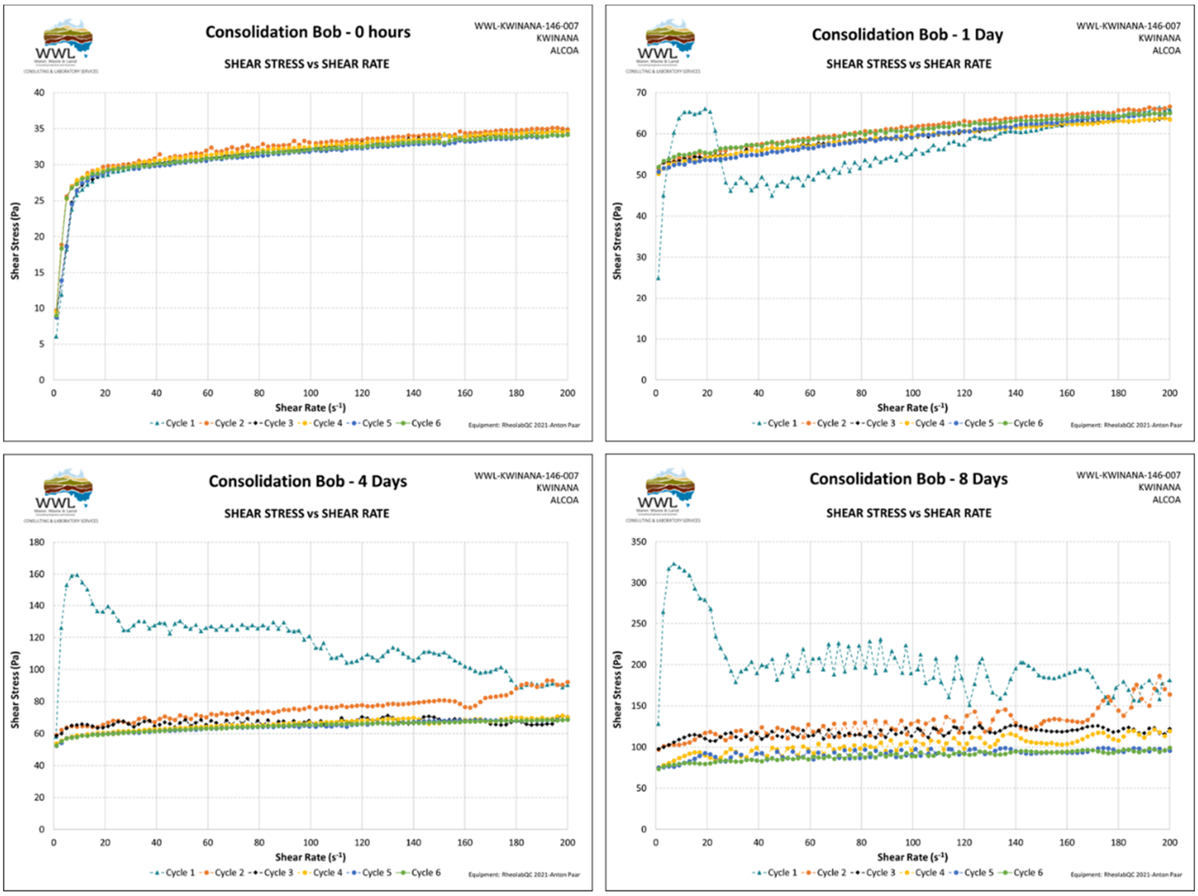


Figure 7 Typical results of consolidated slurry testing using a rotary viscometer

3 Measurement of the rheology of mixed slurry

As previously noted it is not practical to conduct tests for the measurement of the rheology of the liquefied tailings slurry mixed with embankment materials or dried coarser tailings that may have deposited in layers within a rotary viscometer. However, the box rheometer is ideal for this. Layers of sand or soil can be placed in contact with the gate on the box and slurry poured behind this within the box, thereby generating a two-zoned sample. Similarly, layers of sand can be placed between the layers of consolidated tailings to represent drainage zones. Typical combinations are indicated in Table 1.

Table 1 Typical material combinations in mixed slurry box rheometer tests

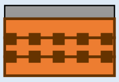
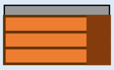
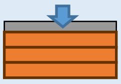
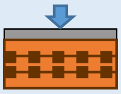
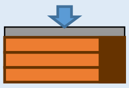
Box number	Description	Consolidation period	Water	Weight	% soil
1 	3 layers of tailings in stages	9 days, 3 days per layer	No water	No weight	0
2 	3 layers of tailings with soil between	9 days, 3 days per tailings layer	With water	No weight	26
3 	3 layers of tailings in stages with soil in front	9 days, 3 days per layer	With water	No weight	16
4 	3 layers of tailings in stages	12 days, 4 days per layer	No water	Weight (151 kg)	0
5 	3 layers of tailings with soil between	12 days, 4 days per layer	With water	Weight (151 kg)	23
6 	3 layers of tailings in stages with soil in front	12 days, 4 days per layer	With water	Weight (151 kg)	24

Figure 8 shows typical results for the tests from Table 1. A low shear rate range is shown for clarity. It is evident that the embankment materials can have a very significant effect on the rheology to the extent that it may back up into the dam break and reduce the volume of liquefied slurry released.

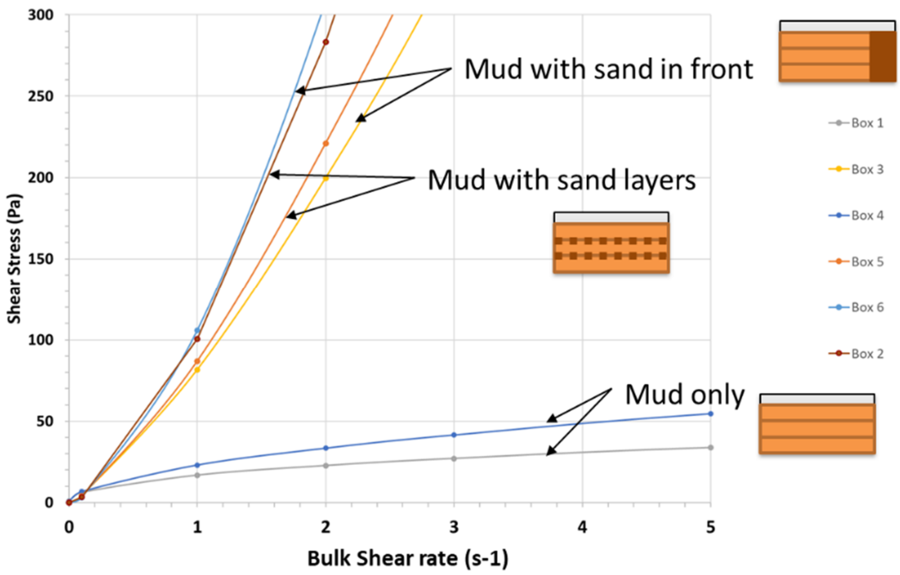


Figure 8 Rheology of mixed materials testing per Table 1

By conducting the tests with a range of thicknesses of soil or sand, either in front of or between the layers of tailings, the correlation between rheology and the proportion of the volume of soil or sand relative to the volume of tailings can be established. In the full-scale these ratios may vary depending on the method of formation of the TSF and the dam break location.

4 Measurement of the impact of dilution by overtopping water

Any residual water on the TSF at the time of the dam break and liquefied flow is likely to have an impact on the rheology of the slurry, depending on the extent to which mixing can occur. In addition, the water flowing over the slurry is likely to entrain tailings which will change its rheology. To assess this, box rheometer tests can be conducted with a layer of water on the topmost slurry layer as indicated in Figure 9.

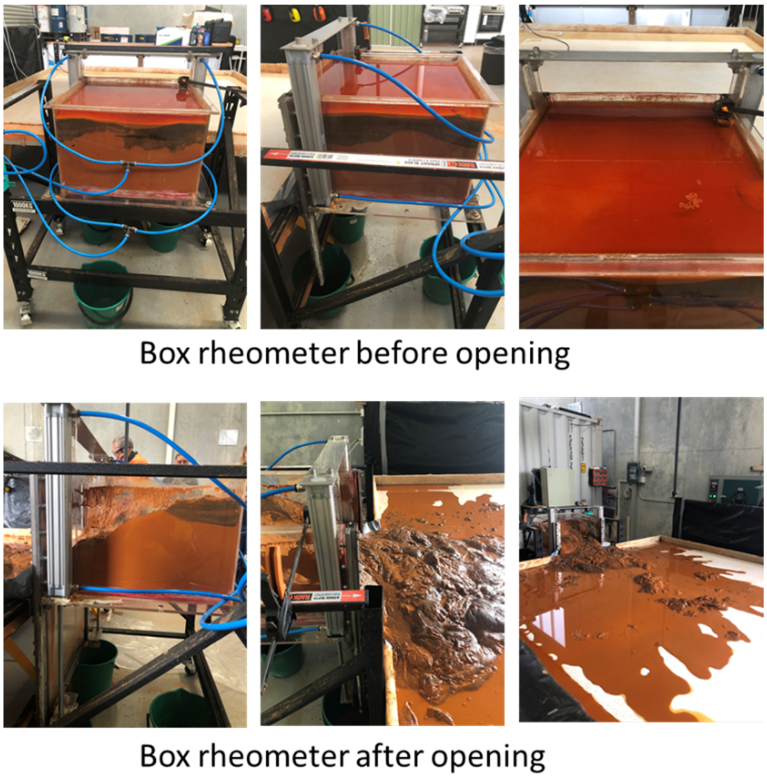


Figure 9 Box rheometer test with water

It is observed that generally the water flows significantly faster than the slurry but entrains some of the tailings through erosion. In the box rheometer test this is generally limited to the upper one to two centimetres of tailings. The sediment-laden water tends to smooth out and wet the flow path, reducing the basal flow resistance for the liquefied slurry following.

Calibration using CFD which is able to model the two materials together allows estimation of the rheology of both the sediment-laden water from calibration in the early stages of the flow as well as the liquefied slurry in the later stages of the flow.

5 Conclusion

This paper has described rheological testing on liquefied slurry which considers factors that serve to increase the rheology of the slurry. These factors include settling out of the slurry, which allows van der Waals forces to re-set, consolidation of the tailings after settling out, and mixing of the liquefied tailings with embankment or sand materials. The testing shows that these factors significantly increase the rheology of the slurry, which will have a significant impact on estimates of the outflow hydrograph, volume of slurry released, and flow distance and velocity. The testing methods described also enable assessment of the impact of free water on the surface of the tailings at the time of the failure, and provide insight into the extent to which water may dilute the liquefied slurry as well as the potential degree of entrainment of solids within the water.

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References

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