Limitations to the Use of the Modified Slump Test for Yield Stress Determination

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ABSTRACT

The critical importance of rheology to the understanding of the behaviour of paste and thickened tailings is now well established and beyond dispute. It has been shown to be important at all stages of the tailings management process, from initial preparation, through transportation to final deposition and spreading. Whereas there has probably always been an innate recognition of the importance of viscosity, it is only recently that an appreciation of the critical importance of the yield stress has emerged. A potentially viable method of measuring yield stress is the modified slump test. Although the developers of the method indicated in their early papers some of the potential limitations of the method and its suitability primarily as an index test or a quality control test, there is always the danger that it may in fact become a de facto standard test procedure, replacing other more accurate testing procedures simply because it is cheaper.

Some limitations to the use of the slump test as a measure of yield stress are discussed in this paper, with a view to highlighting the potential problems that may be encountered and to caution against the indiscriminate use of the procedure. It does not suggest that the technique does not have a very valuable contribution to make in testing thickened and paste tailings, but rather that it should always be checked against techniques such as the shear vane if a new material is being tested or some change in the preparation process has occurred.

1 BACKGROUND

The yield stress is usually defined as the shear stress that has to be overcome to initiate significant flow. As discussed by Nguyen and Boger (1998) and Clayton et al. (2003) amongst others, it influences the pump start up pressure, pipeline pressure losses, thickener underflow density and final beach slope angle. Given this importance and the need to therefore measure yield stress accurately (and preferably at low cost), a number of advances occurred over the past two decades.

The most accurate and repeatable method of measuring the shear yield stress is the vane apparatus. The equipment is similar to that used in geotechnical engineering for measuring the in situ undrained shear strength of soils and this similitude in relevant material properties is discussed later in the paper. The vane used in testwork on thickened tailings is of course much smaller than the conventional shear vane and is confined to use on small specimens, usually carried out in the laboratory.

An alternative technique, one that can be used on site and does not require expensive and sophisticated equipment or highly trained operators, was provided by the development of the modified slump test. The procedure is a variation on the cone slump test used in the civil engineering industry as an indicator of the workability of concrete. For concrete, the measured slump height is used directly as the indicator of workability and no further processing of the information is required. This is probably why many people in the mining industry, when using the slump test, simply quote the slump height. However, as explained in some detail by Clayton et al. (2003), the slump height itself is not sufficient, but must be used in conjunction with the bulk density to provide a meaningful interpretation of the measurement. In civil engineering construction applications, concrete always has essentially the same bulk density and this issue does not arise.

2 EVALUATION OF YIELD STRESS USING SLUMP MEASUREMENTS

The slump test was initially developed to evaluate the workability and consistency of fresh concrete. It was adopted by Pashias et al. (1996) as a simple means of determining yield stress. They showed that the slump height could be related directly to the yield stress, using the theory originally suggested by Murata (1984) and corrected by Christensen (1991). The procedure typically uses a 100 mm diameter cylindrical container about 100 mm long, giving an aspect ratio of 1:1. The test is usually performed in three steps as follows:

- Filling the cylinder with the tailings material and ensuring that air voids are avoided.
- Carefully lifting the cylinder to allow the material to slump under its own weight.
- Measuring the change in height caused by slumping at the three lowest points to the nearest 0.5 mm and averaging these values.

This procedure is straightforward and well known in the industry. It is summarised here to provide a basis for some of the discussion that follows later in the paper. In a recent comparison by Clayton et al. (2003), the cylindrical slump test as adopted in the thickened tailings industry proves to be more amenable to an analysis that provides a fundamental measure of yield stress than the conical device used in the concrete industry. They indicate that potential inconsistencies between yield stress measurements using the slump test and a technique such as the vane method may be overcome by simply using longer cylinders (thus increasing the aspect ratio). However, as shown later, this may not always be the solution to discrepancies between various test techniques and there may be something more fundamental causing the discrepancies.

3 VERIFICATION OF THE SLUMP TEST AS A MEANS OF MEASURING YIELD STRESS

The modified slump test procedure was described by Pashias et al. (1996). They compared results from the cylindrical slump test with vane test results and reported good correlation for materials that included red mud from the bauxite industry, titania and zirconia. In a later study, Gawu and Fourie (2004) similarly reported good correlations between the two techniques for mineral sands slimes, zinc tailings and oxide gold tailings. The latter material produced a variance of up to 30% between the two techniques, which was significantly higher than the other materials tested, where the variance was typically no more than 10 to 15%. The correlation was still regarded as satisfactory and the potential for using slump as an independent measure of yield stress suggested.

In a discussion to the paper by Gawu and Fourie (2004), results were reported that did not provide good correlations between slump and vane measurements (Crowder and Grabinsky, 2005). For a number of tailings obtained from hard rock mines, where the fine particles were clay sized but consisted of rock flour rather than clay minerals, they obtained poor correlations between the two techniques, with the discrepancy between the two techniques increasing as the yield stress increased above 200 Pa. They pointed to the differences in mineralogy between the two studies (where the work by Gawu and Fourie tested material having a measurable plasticity index and containing clay minerals, whereas Crowder and Grabinsky tested tailings containing no clay minerals and hence no measurable plasticity index), and this observation is elaborated on in this paper. Once the conditions within a slump test have been reconsidered, some recent work on Kimberlite tailings from a diamond mining operation is also discussed.

In short, given the importance of the yield stress in the performance of thickened tailings systems and the increasing prevalence of the use of the modified slump technique, it is worth reconsidering the applicability of the slump test and applications where its use should perhaps be discouraged.

4 INTERPRETATION OF THE SLUMP TEST

Pashias et al. (1996) provide an interpretation of the slump test that is worth reconsidering. Figure 1 shows the basis of their analysis, where the initial state is contrasted with the final state. On the right, the material has slumped a total amount of ‘s’, which is the value measured at the end of the test. There is an unyielded portion (i.e. where the shear stress is less than the yield stress), h_0, below which is a region of height, h_1, in which yielding has occurred.

The unyielded height can be shown to be given by:

$$h_0 = \frac{2\tau_y}{\gamma} \quad (1)$$

where τ_y is the yield stress and γ is the bulk unit weight.

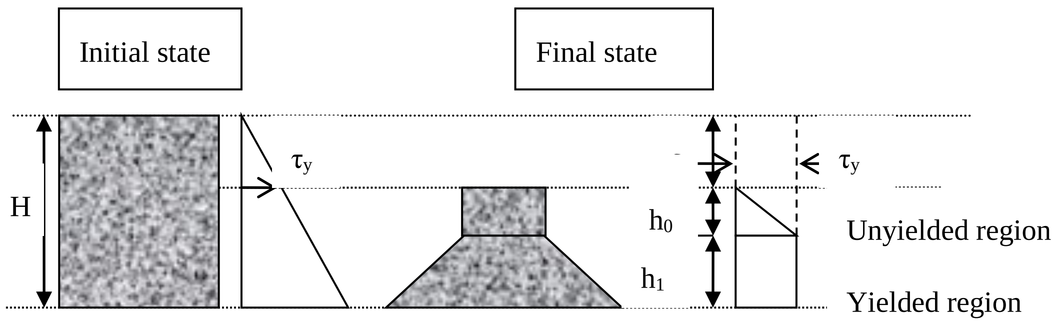


Figure 1 Schematic representation of the initial and final state stress distributions (after Pashias et al., 1996)

This is similar to the calculation in civil engineering of the stable height H of a vertical cut in a cohesive (clayey) material, where $H = 2C_u/\gamma$ and C_u is the undrained shear strength, measured using a conventional shear vane apparatus.

An interesting outcome of this calculation is the restriction on yield stress for which the slump test remains relevant. For example, if a tailings material had a bulk unit weight of 14 kN/m^3, (i.e. a density of about 1400 kg/m^3), no slump would be measured if the yield stress was equal to or greater than 700 Pa. Further, if the yield stress were of the order of 600 to 700 Pa, the slump would be so small that measurement errors would be of the same order of magnitude as the measured slump. Intrinsic to the interpretation of the slump test is the assumption that yielding and spreading of the material within the yielded zone occurs uniformly in a lateral direction, with the maximum shear stress remaining at the yield value.

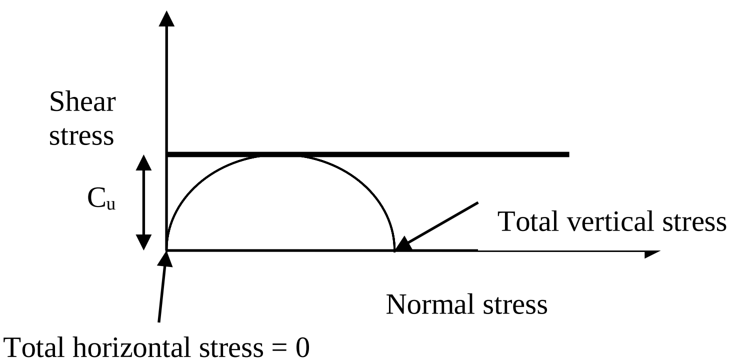


Figure 2 Schematic of principal stresses immediately after removal of cylinder in slump test

In terms of conventional geotechnical engineering, we could represent the stress condition at the transition to the yielded region as shown in Figure 2. The total horizontal stress is zero and the total vertical stress is γh_o. Prior to lifting the cylinder, the material is under essentially isotropic stress conditions, with the horizontal total stress equal to the vertical total stress. Once the cylinder is lifted, there is an almost instantaneous decrease in the horizontal total stress. In geotechnical terms this would be accompanied by an equally rapid change in the pore water pressure (also initially hydrostatic). This change in pore pressure is almost impossible to predict numerically and would have to be measured with high sensitivity and frequency transducers, which is beyond what can be countenanced for a test procedure that is meant to be both quick and inexpensive.

A consequence of a rapid change in pore water pressure is a rapid change in effective stress within the slumped material. In geotechnical engineering, it is the effective stress conditions that dictate behaviour (shear strength and volume change) and hence ideally a knowledge of the changing effective stresses in a slump test is necessary to carry out a conventional geotechnical analysis. However, there has long been a recognition that pore pressures cannot always be measured or accurately predicted (as is the case in the slump test) and recourse is made to what is termed a total stress analysis, in which the shear strength is expressed in terms of total stresses and the yield criterion is simplified, e.g. the Tresca yield criterion. This is what is used in the analysis of allowable vertical cut heights (in the short term) in clay soils and is, as explained before, similar to the analysis presented by Pashias et al. (1996) of the slump test.

So where does this leave us? With tailings that behave as an undrained material in the short term (e.g. water does not drain appreciably from the pores during the slump test itself), the analysis to determine the yield stress is reasonable. This would include materials that have some content of clay minerals that provide a degree of cohesiveness and a low permeability that hinders rapid drainage. On the other hand, tailings having little or no clay minerals and that are cohesionless in nature are unlikely to be amenable to testing using the slump technique. As an extreme example, consider a hydraulic fill typically used in some backfill applications, where the fines have been removed by cycloning and the coarse fraction comprises the backfill. A slump test on material of this type (if uncemented) would produce a cone of material on the laboratory bench top, with no measurable, free-standing 'unyielded' region.

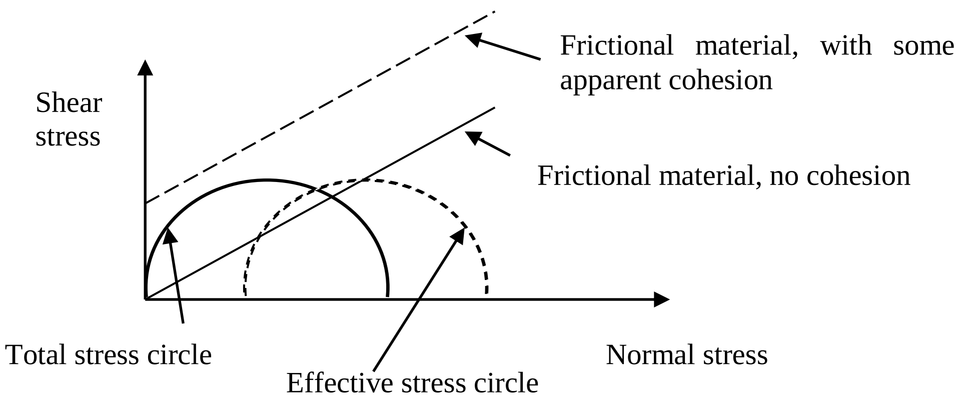


Figure 3 **Illustration of how effective stresses in yielding mass of slumped material may violate strength criterion, violating assumptions inherent in interpretation of slump tests**

In terms of effective stresses, the simple diagram in Figure 3 illustrates the problem. If there is no effective stress strength component provided by apparent cohesion and the strength is purely frictional in nature, a decrease of the total horizontal stress to zero will probably result in the effective stress conditions violating the effective stress yield criterion, thus producing a 'failed' mass that simply takes up a conical slumped profile. The dashed line in Figure 3 illustrates a material that has some (small) apparent cohesion in addition to a frictional strength component and may thus be able to sustain a vertical height of unyielded material. Calculating these allowable heights for a material such as that shown by the dashed line is beyond the scope of this paper. What is important, however, is the realisation that the slump test may be completely inappropriate for certain mineral slurries, particularly those consisting of non-cohesive particle assemblies.

Based on the above, it could be that all that is necessary is to determine whether clay minerals are present in the tailings and if so, the slump method provides a viable technique for measuring yield stress. Unfortunately there is emerging evidence that there may be other circumstances in which the technique may be inappropriate, even for materials with a high content of clay minerals.

4.1 Effect of pH on Viability of Slump as a Measure of Yield Stress

The dependence of yield stress on a parameter such as pH has been demonstrated by Liddell and Boger (1994) and Scales et al. (1999), among many others. They characteristically show a parabolic profile with a maximum in the yield stress being coincident with the iso-electric point, which is the pH value corresponding to zero zeta potential. Another example of the effect of pH is provided by Dunn (2005), who tested specimens of flocculated Kimberlite tailings at three different pH values. The material properties of the tailings are given in Table 1 and the measured vane yield stress values at a solids content of 62% shown in Table 2.

A pH of 8.6 provides a much lower yield stress than the other pH values. Vietti and Dunn (2005) discuss this observation in the context of the importance of the salinity and pH of the mineral slurry. They propose a 'behavioural map' that includes pH and exchangeable sodium percentage (ESP). The suggestion is made that at certain combinations of pH and ESP, the flocculated tailings slurry behaves in a 'non-interactive' (dispersed) way, where the particle-to-particle attraction is minimal and a very low solids content slurry (2 to 3% solids) would remain in suspension interminably. As the pH and/or ESP values change, the slurry moves into the 'interactive' (coagulated) zone in which interparticle attraction dominates and a dilute slurry of this material produces a rapid-settling mixture. In terms of yield stress it produces a higher value for the same solids content, compared with material that falls within the 'non-interactive' zone. The material in Table 2 at pH values of 6.2 and 11.5 were shown to fall squarely within the 'interactive' zone. The relevance of these observations can be seen by referring to Figure 4. Figure 4 shows a comparison of yield stress values obtained from both the vane and the slump testing procedures, for the flocculated Kimberlite material prepared at the same three pH values as given in Table 2. For material within the 'interactive' zone, there is excellent agreement between the vane and slump test results. However, at a pH of around 8.6, the agreement is very poor, with differences between vane and slump tests increasing to more than 100% once the solids content exceeds about 65%.

Table 1 Characteristics of Kimberlite tailings

Specific gravity	Percentage <75µm	Exchangeable sodium percentage	pH
2.4	75%	32%	8.6

Table 2 Yield stress as a function of pH for Kimberlite tailings

pH	6.2	8.6	11.5
Yield stress (Pa)	169	56	352

The slump provides a distinctly lower yield stress than the vane, which manifests as a higher amount of slump and is consistent with the argument that the slump test cannot be used for material where interaction between particles is a minimum, such as non-clayey tailings or even some clay-based tailings in a particular state of flocculation or with particular conditions of surface chemistry.

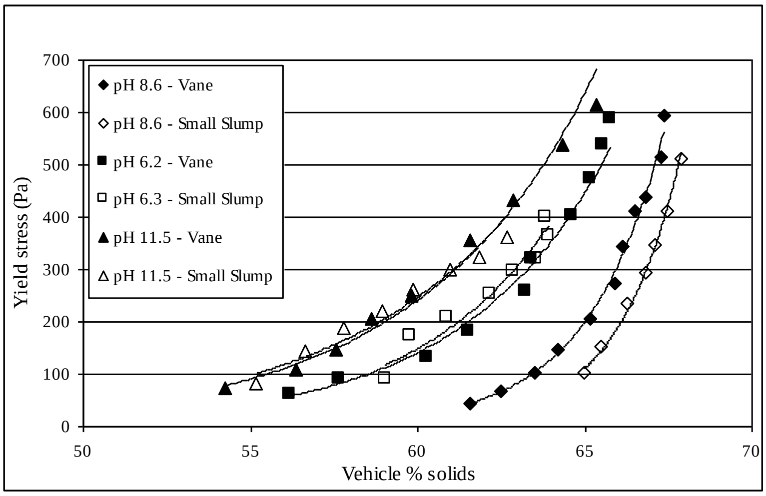


Figure 4 **Comparison of yield stress from slump and from vane tests on Kimberlite tailings**

4.2 A Further Difficulty — Neglecting Strain Softening Materials

In geotechnical engineering it is relatively common to deal with material that exhibits strain softening characteristics, i.e. beyond a peak value of shear strength, the strength drops off to some residual value that is less than the peak value. A good example of this is provided by Dunn (2005) for a specimen of the Kimberlite tailings at a pH of 6.2, shown in Figure 5. Despite the fact that the material was thoroughly mixed prior to testing, (with the mixing time being determined by the time it took to reach a yield stress value that did not change with further increases in mixing time) and was within the 'interactive zone' described by Vietti and Dunn (2005), it still exhibits some degree of strain softening. The ratio of the peak yield stress to the residual value (as indicated in Figure 5) is often referred to as the brittleness or sensitivity of a soil or similar material. In a vane test, the value usually reported is the value of the peak yield stress, as this is the value that would have to be overcome to initiate flow in a pipeline for example. Intrinsically, it appears that the strain softening phenomena is ignored, presumably because it is assumed to either be conservative (lower yield stress means less pumping resistance) or because it is assumed that pumping to the tailings storage facility will completely mask any strain softening by completely destroying any residual 'structure'.

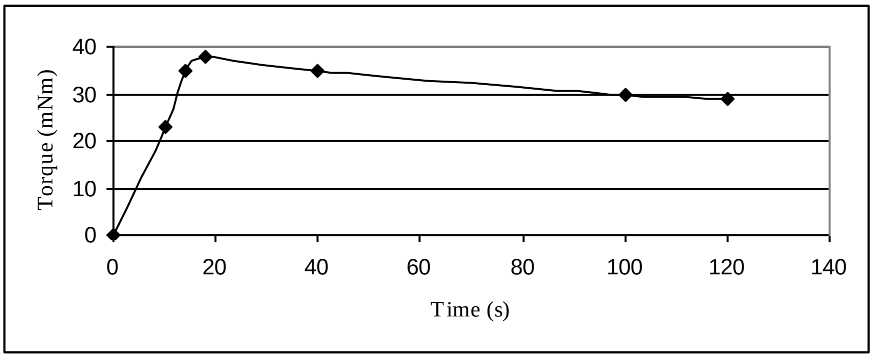


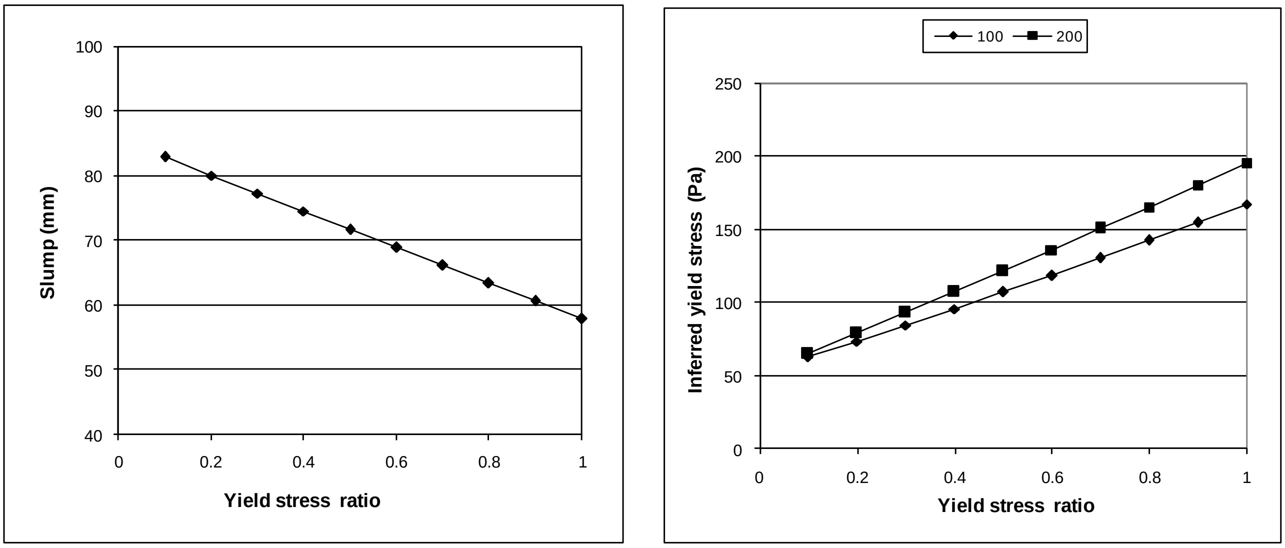
Figure 5 **Illustration of strain softening in vane test on Kimberlite tailings (pH value = 6.2)**

This paper is focussed on the interpretation of the slump test and it is in this context that it is worth considering the potential importance of strain softening. Consider again the conditions represented in Figure 1. Within the yielded region, the shear strength is assumed to remain equal to the peak value. However, if the available strength drops rapidly to a lower residual value (τ_r), it must result in additional settlements occurring and the magnitude of h_1 will decrease while h_0 should remain unchanged (since the peak yield stress has not been reached in this zone). Assuming the yield strength τ_r dropped to a fixed proportion of the peak value, the effect on the measured slump height can be calculated. The resulting slump height is shown in Figure 6a for a material having a bulk unit weight of 14 kN/m^3 and a peak yield stress of 100 Pa. The yield stress ratio, shown on the abscissa, is the ratio of the residual to the peak yield stress. Thus for a material that shows no strain softening but has a yield stress of 100 Pa, the measured slump would be about 58 mm. If the residual value decreased to half the peak value, the measured slump would be approximately 71 mm. There is clearly quite a significant difference and this difference translates into a difference in the inferred yield stress value.

Figure 6b shows the yield stress value that would be inferred if an operator used the slump height given in Figure 6a to back-calculate the yield stress using the approximate equation suggested by Pashias et al. (1996), shown in Equation 2.

$$\tau_y' = \frac{1}{2} - \frac{1}{2}\sqrt{s'} \qquad (2)$$

where τ_y' is the dimensionless yield stress (τ_y/γ) and s' is the dimensionless slump height (s/H), where H is the cylinder height.



(a) (b)

Figure 6 **Illustration of the effect of strain softening on (a) the resulting slump and (b) the inferred yield stress, where results are included for cylinder heights of both 100 mm and 200 mm**

Remembering that the assumed yield stress was in fact 100 Pa, the first thing to ask is why the inferred yield stress does not equal 100 Pa when the sensitivity is unity (i.e. no strain softening). After all, if no strain softening occurs, the method suggested by Pashias et al. (1996) should produce the correct estimate of the yield stress, i.e. 100 Pa. This inconsistency can be attributed to the approximation made by Pashias et al. (1996) in their original paper. Equation 2 is an approximation to the correct dimensionless slump height, achieved by neglecting terms containing τ_y' that have an exponent greater than unity. Whilst this may be a reasonable approximation in many cases, as is evident from the study by Pashias et al. (1996), the approximate result (Equation 2) can vary significantly from the exact theoretical solution (and indeed from measured values of yield stress). The authors did highlight that Equation 2 is indeed only an approximation, but in presenting the comparison between the exact and theoretical solutions on a plot of dimensionless variables (τ_y' versus s'), the significance of the approximation is somewhat lost.

To illustrate the problem further, Figure 7 shows a plot of the true yield stress (assume this has been obtained using a vane apparatus) against the value inferred using Equation 2. To derive this plot, the 'true' yield stress was used to calculate the slump height using Equation 3 and then using Equation 2 to calculate the inferred yield stress. Intuitively one would expect the inferred value to equal the true value, but the approximation suggested by Pashias et al. (1996) has the effect of producing a match that is sometimes poor. This is illustrated in Figure 7 where the 'true' yield stress is plotted against the inferred yield stress for two different values of slurry bulk unit weight. A number of features arise from this comparison. Firstly, the discrepancy is worst at values of true yield stress of less than about 100 Pa, with the error being approximately 100% for a true yield stress of 100 Pa. At higher values of yield stress (say 400 Pa), the discrepancy is similar to that measured at 100 Pa, but the percentage error is significantly lower. It is also interesting to note that the error is worse as the bulk density increases, so for tailings containing minerals with a high specific gravity the problem is exacerbated.

$$s' = 1 - 2\tau_y{}' [1 - \ln(2\tau_y{}')] \tag{3}$$

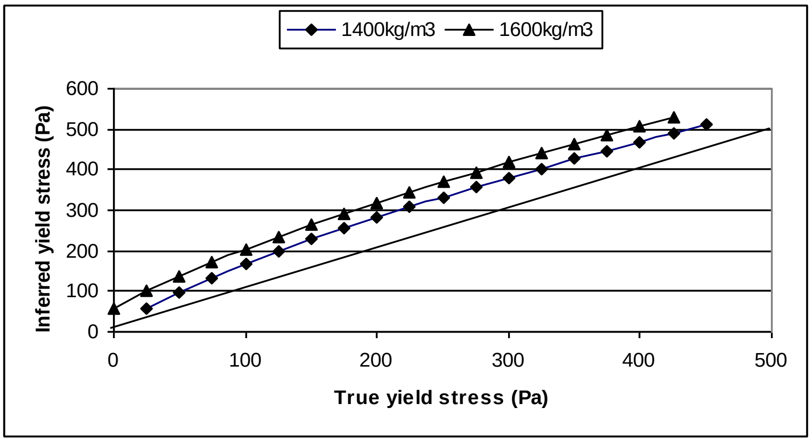


Figure 7 **Comparison of inferred yield stress versus true yield stress for two different density tailings, showing effect of simplified method of interpreting slump test results**

Returning to our discussion about strain softening and its effect on the inferred yield stress, the results in Figure 7 show that for a bulk unit weight of 14 kN/m^3, a true yield stress of 100 Pa produces an inferred yield stress of 167 Pa, which is the result shown in Figure 6b for a material that shows no strain softening (yield stress ratio = 1). Considering Figure 6b again, it can be seen that the correct yield stress value (100 Pa) is derived when the sensitivity (or yield stress ratio) is around 0.45. It could be argued that the two effects thus tend to cancel one another out, but this kind of unintended compensation of errors does not constitute a sound approach to such an important problem as that of correctly measuring the yield stress.

5 DISCUSSION

The yield stress is now correctly considered to be a fundamentally important parameter in predicting all aspects of the engineering behaviour of thickened tailings, whether it be preparation, thickening, transportation or deposition. Although the modified slump test has found wide use in the industry for measuring yield stress, this paper suggests that care should be taken in applying the procedure to new, previously untested materials without at least carrying out some calibration tests using other, more accurate tests such as the vane test.

The somewhat surprising finding emerged that the simplified method of interpreting the information from a slump test can lead to sometimes significant overestimates of the true yield stress, with this effect being pronounced at low (about 100 Pa) values of yield stress. Another factor that has been shown to potentially impact on the interpretation of the slump test is strain softening of paste or thickened tailings upon shearing.

If the tailings within the yielded zone of the slump cylinder experiences strain softening to some value of residual yield strength that is lower than the peak value, it will result in more slump occurring than if no strain softening took place at all. This causes an underestimate of the true yield stress. It appears that these two effects may in fact be compensating to some extent, but it is suggested that this degree of uncertainty in interpretation of experimental data is unacceptable. Consequences of underestimating the yield stress will be larger than expected pumping pressures, whereas overestimating the yield stress will result in beach slopes on the tailings storage facility being lower than predicted.

Although it is true that many thickened tailings are fully sheared before testing and that this should destroy any residual structure in the material, it cannot be assumed that this is always the case. In addition, some materials regain a degree of structure with standing time after shearing and if the yield stress tests are not carried out very soon (within minutes sometimes) after mixing, a degree of structure, and thus susceptibility to strain softening, may develop (Dunn, 2005). It should be noted that there are instances where shearing prior to testing may be inappropriate, e.g. for thickener rake drive torque requirements or pump start-up, as in these cases pre-shearing will give inappropriate and misleading results.

6 CONCLUSIONS

It is shown in this paper that the following aspects can all distort the validity of yield stresses obtained from slump tests:

- Non-plastic tailings should not be tested using the slump cylinder. The lack of cohesive forces renders the method of interpretation incorrect. The same is true for materials that are altered to produce non-interactive or dispersed particles by changing factors such as pH or salinity.
- The simplified method of interpreting yield stress from slump height can significantly overestimate yield stresses, particularly for values less than about 100 to 200 Pa.
- Materials that undergo strain softening will produce underestimates of the yield stress, with the degree of underestimation increasing as the brittleness (degree of strain softening) increases.

The slump test provides an extremely valuable index test and should be used in a quality assurance capacity. It is suggested that it is inadvisable to use it for determining design parameters (yield stress) unless it is backed up with other, more detailed testwork, or unless the material is already well understood and the confirmatory work has thus effectively already been done.

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