Available online at www.sciencedirect.com
SCIENCE DIRECT®
Int. J. Miner. Process. 70 (2003) 3–21
INTERNATIONAL JOURNAL OF MINERAL PROCESSING
www.elsevier.com/locate/ijminpro

Analysis of the slump test for on-site yield stress measurement of mineral suspensions

S. Clayton[a], T.G. Grice[b], D.V. Boger[a,*]

[a] *Particulate Fluids Processing Centre, Department of Chemical Engineering, University of Melbourne, Parkville, Melbourne, Victoria 3010, Australia*
[b] *Australian Mining Consultants, Melbourne, Victoria 3000, Australia*

Received 14 May 2002; received in revised form 16 July 2002; accepted 9 October 2002

Abstract

The slump test, originally used to determine the 'workability' of fresh concrete, has since been adapted for use in the minerals industry. The slump test finds extensive industrial application for monitoring material consistency in tailings disposal operations. The parameter used as the indicator of consistency is the slump height, an empirical value, which is only relevant for the specific material being tested. We propose that the yield stress, a unique material property, is a better measure of consistency. Models relating the slump height to yield stress have been developed for the cone [Matériaux et Constructions (Paris) 17 (1984) 117; Christensen, G., 1991. Modelling the flow of fresh concrete: the slump test. PhD thesis, Princeton University; Canadian Geotechnical Journal 28 (1991) 457; Journal of Rheology 42 (1998) 865] and cylinder [Journal of Rheology 40 (1996) 1179] slump tests. In this investigation, a direct comparison of the cone and cylinder models for yield stress measurement of mineral suspensions is undertaken. The analysis clearly shows that the cylinder model more accurately predicts the material yield stress. A strong case is made for the replacement of the widely used cone test with the simpler, cheaper and more accurate cylinder test.

Keywords: slump test; mineral suspensions; paste fill; yield stress; rheology

1. Introduction

The ASTM standard cone slump test (ASTM, 1998) originated for testing the 'workability' or consistency of concrete. A schematic of the test is presented in Fig. 1. The test

* Corresponding author. Tel.: +61-3-8344-7440.
E-mail address: d.boger@unimelb.edu.au (D.V. Boger).

0301-7516/03/$ - see front matter
doi:10.1016/S0301-7516(02)00148-5

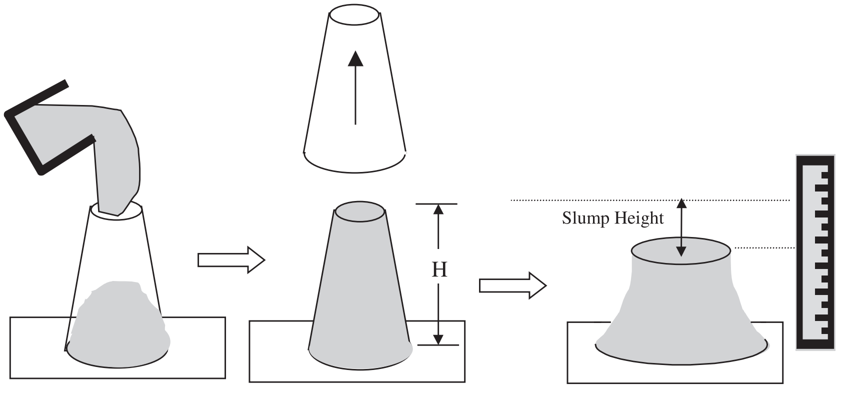

Fig. 1. Schematic of the cone slump test.

involves filling a frustum of a cone in a specified way, removing the cone vertically and measuring the distance that the concrete 'slumps'. The distance is defined as the slump height. The slump height must fall within a given range for the concrete to be acceptable. If the slump height is too great, then the flowability is increased but the final strength of the concrete is reduced. Conversely, if the slump height is below the desired value, the concrete will be too stiff and will not flow into the tight corners of moulding.

The slump test has since been developed to measure the workability of a variety of time-independent inelastic fluids, including mineral tailings suspensions. The slump test presently finds extensive industrial application in surface and underground tailings disposal operations in which the dilute tailings produced in processing are concentrated to a high solids concentration for disposal. A result of the highly concentrated nature of the tailings is the presence of an appreciable yield stress, which is the minimum shear stress for irreversible deformation and flow to occur. The yield stress increases exponentially with solids concentration (Boger, 1998) so a small change in concentration can result in a large change in the yield stress. Consequently, control of material consistency in waste disposal operations is critical.

The slump height measured via the slump test is generally used as the control parameter. The slump height, an empirical measure of consistency, is dependent on both the material yield stress and density, which in turn are dependent on chemical composition, particle specific gravity and particle size. In a mining context, these factors may vary with changes in ore origin or changes in ore processing. As a result, utilisation of the slump height as the sole parameter of consistency for waste disposal systems could potentially lead to problems. Therefore, the yield stress, a unique material property, is the preferred indicator of consistency. If the slump height could be related to the yield stress, then the slump test would be a simple and ideal technique for on-site yield stress measurement.

Several analytical models have been developed to relate the slump value to a corresponding yield stress, and to predict the slumping behaviour of the material. The slump models are derived from first principles with model variables expressed in dimensionless form. Thus, the slump models are not empirical and provide a material-independent, unique relationship between yield stress and slump height. The first analysis was made by Murata (1984), followed by Christensen (1991) who corrected a simple integration error made by Murata. Rajani and Morgenstern (1991) and Schowalter and Christensen (1998) have further investigated the conical test. There is some uncertainty in the yield stress measurement techniques used in these papers so it is difficult to make any firm conclusions as to the validity of the model.

The slump test was first adapted to a cylindrical geometry by Chandler (1986) for the alumina industry. Chandler realised there was a relationship between the slump height and flow behaviour of the bauxite residue he was testing, but did not analytically relate the two. Pashias et al. (1996) developed a model for the cylindrical geometry, comparing the results from the model with those from the static vane test. The results compared favourably. The authors also investigated the sensitivity of the slump height to sample structure, material, aspect ratio, lift rate and measurement time and found that slump measurement is essentially independent of these factors.

A number of investigations have been completed to relate slump height and yield stress for the cone and cylinder geometries, but comparison of the two geometries for yield stress measurement of the same material has not previously been undertaken. In this investigation, yield stress values as determined from the cylinder and cone slump tests and related models are compared to yield stress values determined utilising the well-established vane technique (Nguyen and Boger, 1983, 1985).

2. Materials, measurements, and experimental procedure

2.1. Materials

Titanium dioxide (TiO_2) pigments are used extensively in the paint industry, and have been well characterised by Liddell (1992, 1996). The TiO_2 pigment, supplied by Tioxide Chemicals, used in experiments had an inorganic alumina coating, an isoelectric point of 7.6 and a density of 4000 kg/m^3. The TiO_2 suspension was prepared by initially diluting the titanium pigment with pH-treated distilled milli-Q water (pH 10). The pH of the distilled milli-Q water was altered by the addition of concentrated KOH. The pH of the diluted titanium dioxide sample was raised to 10 to completely disperse the sample and then mixed well with a high shear mixer. The pH was then lowered to the isoelectric point by the addition of concentrated HNO_3.

A mineral tailings paste sample supplied by BHP Minerals-Cannington is representative of the paste from the disk filter–spiral flow mixer system on site. The paste sample has a specific gravity of 3.1 kg/m^3 and a pH of approximately 7.

2.2. Measurement

Yield stress measurements were made using the vane technique (Nguyen and Boger, 1983, 1985). A PHM82 standard pH meter was used to measure pH. The dimensions and material of construction of the slump cones and cylinders utilised in the investigation are listed in Tables 1 and 2. The cone slump mould was designed as specified in Australian

Table 1
Dimensions and material of construction of the ASTM slump cone and the AS2701.5 slump cone

Cone	Height H (mm)	Top radius R_0 (mm)	Base radius R_H (mm)	Construction material
ASTM	300	50	100	sheet metal
AS 2701.5	150	25	50	sheet metal

Standard AS 2701.5 (Standards Association of Australia, 1984). In industry, the ASTM standard cone slump test is used. The slump test procedure and the material of construction for the cone are the same for the ASTM test and the AS 2701.5 test. The difference between the tests is that the dimensions (top diameter, bottom diameter and height) of the ASTM cone are double the dimensions of the AS 2701.5 cone. Consequently, the volume of the ASTM cone (5.5 l) is eight times greater than the volume of the AS 2701.5 cone (0.69 l). For laboratory experiments, the AS 2701.5 cone slump test is therefore more practical.

2.3. Experimental procedure

The conical slump test was completed as per Australian Standard AS 2701.5. There is no standard for the cylinder test so the conical test methodology was adapted for the cylinder. The cylinder was filled with sample, the top of the cylinder was smoothed over and the cylinder lifted slowly and evenly. The change in height between the cylinder and deformed material was measured. The midpoint of the slumped material was taken as the representative height. Heights were measured with a ruler to the nearest 0.5 mm. Density and concentration were measured at the time of testing.

3. Theory

Analytical slump test models have previously been developed for the cone and cylinder slump tests. The cylinder model is generalised for any-sized cylinder, whereas the cone model is specific for a cone with a base diameter twice that of the top diameter. This requirement led to the development of a generalised cone model to allow direct comparison with the cylinder model. The cylinder theory developed by Pashias et al. (1996) is also presented to enable easy comparison with the generalised cone theory.

Schematic diagrams for the cylinder and cone tests are presented in Figs. 2 and 3, respectively. The schematics display the important variables and the stress distributions involved in slumping.

3.1. Assumptions and development of cylinder and cone slump models

It is assumed that removal of the slump cylinder or slump cone does not deform the material in any way. The initial undeformed material is therefore assumed to be either a perfect cylinder or a perfect truncated cone. Practically, this will only be achieved for perfect slip at the inner surface of the slump cylinder or slump cone.

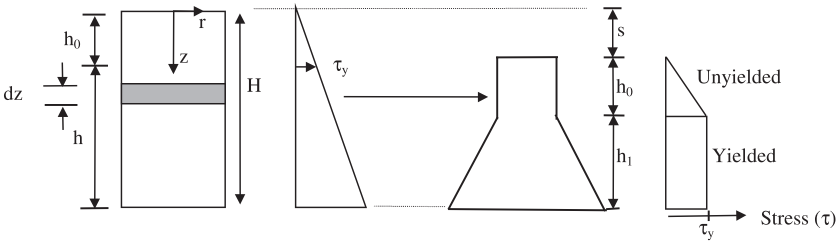

Fig. 2. Schematic diagram of the cylinder slump test, showing initial and final stress distributions (developed from Pashias et al., 1996).

The only stress acting on the material is assumed to be a vertical stress associated with the material's own weight. Therefore, the pressure (P) in the material at some height (z) below the top surface can be expressed as the weight of material above position z.

$$\text{Cylinder}: \ P|_z = \rho g z \tag{1}$$

$$\text{Cone}: \ P|_z = \frac{\rho g H}{3}\left(\frac{R_0}{R_H - R_0}\right) \times \left(1 + \frac{z}{H}\left(\frac{R_H - R_0}{R_0}\right) - \frac{1}{\left(1 + \frac{z}{H}\left(\frac{R_H - R_0}{R_0}\right)\right)^2}\right) \tag{2}$$

where H is the height of the undeformed material, ρ is the density of the material, g is the acceleration due to gravity and other variables are defined in Figs. 2 and 3.

The material is assumed to behave as an elastic solid, for which the maximum shear stress that can act on a body when a pressure (P) is applied to it in a normal direction is

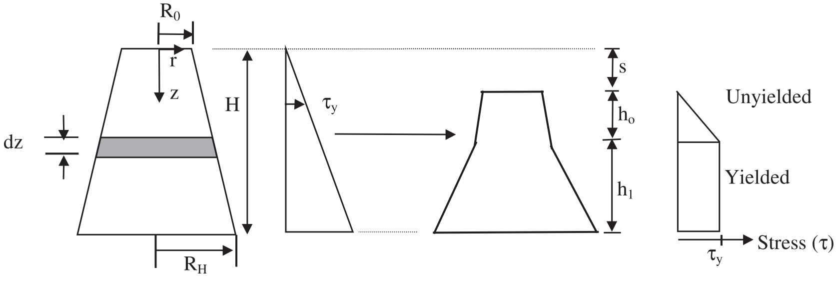

Fig. 3. Schematic diagram of the conical slump test, showing initial and final stress distributions (developed from Schowalter and Christensen, 1998).

equal to half the pressure (Hibbeler, 1997). For the dimensionless form (denoted by (′)), the stress is scaled with ρgH and the height with H.

$$\text{Cylinder}: \quad \tau\,|_z' = \frac{1}{2}z' \tag{3}$$

$$\text{Cone}: \quad \tau\,|_z' = \frac{\alpha}{6}\left(\left(1+\frac{z'}{\alpha}\right) - \frac{1}{\left(1+\frac{z'}{\alpha}\right)^2}\right) \tag{4}$$

Where

$$\alpha = \frac{R_0}{R_H - R_0}$$

α is a dimensionless quantity relating the top and base radii of the cone.

The results are expressed in terms of dimensionless variables to enable generalisation of the slump model for different-sized slump moulds and different yield stress materials. The dimensionless variables are defined as follows:

$\tau_y' = \tau_y/\rho gH$ = dimensionless yield stress,
$s' = s/H$ = dimensionless slump height,
$h_0' = h_0/H$ = dimensionless height of undeformed region,
$h_1' = h_1/H$ = dimensionless height of deformed region.

Eq. (3) illustrates a linearly increasing stress distribution along the height of the cylinder, from 0 at the top to a maximum at the base. Eq. (4) illustrates a nonlinear distribution for the cone.

At some point (h_0') along the height of the undeformed cylinder or cone, the material experiences a stress that is larger than the yield stress (τ_y') and the material flows (slumps) until the stress is reduced to the yield stress. In the material above the yielded region, the vertical stress does not exceed the yield stress and the region remains unyielded.

In the slumping process, it is assumed that the interface layer between the yielded and unyielded material is a horizontal surface that moves down as the material beneath it flows. Therefore, the final height consists of an unyielded region (h_0) and a yielded region (h_1). The height of the dimensionless unyielded region (h_0') can be determined by substituting τ_y' for $\tau|_z'$ in Eqs. (3) and (4) for the cylinder and cone tests, respectively.

$$\text{Cylinder}: \quad \tau_y' = \frac{1}{2}h_0' \tag{5}$$

$$\text{Cone}: \quad \tau_y' = \frac{\alpha}{6}\left(\left(1+\frac{h_0'}{\alpha}\right) - \frac{1}{\left(1+\frac{h_0'}{\alpha}\right)^2}\right) \tag{6}$$

In the portion of material that yields, the height can be divided into elements of thickness dz and radius r_z, which reduce to thickness dz_1 and radius r_{z1} after slumping. Fig.

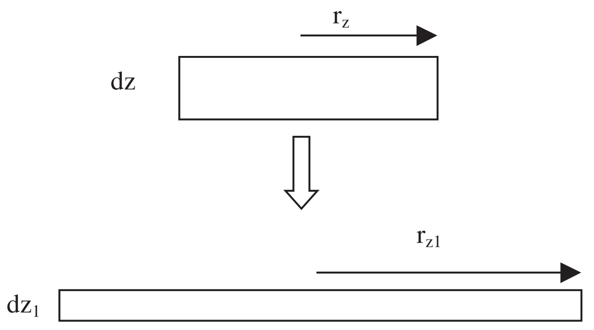

Fig. 4. Deformation of an element of thickness dz to thickness dz_1.

4 presents a schematic of the deformation of an element. During deformation, it is assumed that all horizontal sections remain horizontal, and slumping is due only to radial flow. For this assumption to be valid there must be perfect slip at the base. For an incompressible fluid, the volume of each element remains constant. Therefore, thickness dz_1 can be related to thickness dz by:

$$\text{Cylinder and cone}: \ (r\,|_{z_1})^2 \mathrm{d}z_1 = (r\,|_z)^2 \mathrm{d}z \tag{7}$$

Flow occurs until the cross-sectional area increases such that the stress required to support the weight of material above any given plane is reduced to the yield stress. Thus, the product of stress and the cross-sectional area is proportional to the weight of material above the plane:

$$\text{Cylinder and cone}: \ (r\,|_{z_1})^2 \tau_y = (r\,|_z)^2 \tau\,|_z \tag{8}$$

The height h_1 can then be evaluated by integrating for dz_1 over the yielded region, i.e. from H to h_0.

$$\text{Cylinder and cone}: \ h_1 = \int_{h_0}^{H} \mathrm{d}z_1 \tag{9}$$

The next step is the substitution of Eqs. (3), (7) and (8) into Eq. (9) for the cylinder and substitution of Eqs. (4), (7) and (8) into Eq. (9) for the cone. Integration of the resultant equations yields the following expressions for h_1':

$$\text{Cylinder } h_1' = -2\tau_y' \ln(h_0') \tag{10}$$

$$\text{Cone } h_1' = 2\tau_y' \ln\left(\frac{\left(1+\frac{1}{\alpha}\right)^3 - 1}{\left(1+\frac{h_0'}{\alpha}\right)^3 - 1}\right) \tag{11}$$

The expression for the dimensionless slump height is as follows:

$$\text{Cylinder and cone}: \ s' = 1 - h_0' - h_1' \tag{12}$$

Substituting Eqs. (5) and (10) into Eq. (12) for the cylinder and Eq. (11) into Eq. (12) for the cone yields the final expressions relating dimensionless slump height and dimensionless yield stress.

$$\text{Cylinder}: \ s' = 1 - 2\tau_y' \left[1 - \ln(2\tau_y')\right] \tag{13}$$

$$\text{Cone}: \ s' = 1 - h_0' - 2\tau_y' \ln\left(\frac{\left(1 + \frac{1}{\alpha}\right)^3 - 1}{\left(1 + \frac{h_0'}{\alpha}\right)^3 - 1}\right) \tag{14}$$

The Australian Standard and ASTM slump cones have a base diameter (R_H) twice that of the top diameter (R_0). Therefore, $\alpha = 1$ and Eqs. (4), (6), (11) and (14) simplify, as expected, to the equations produced in the investigation by Schowalter and Christensen (1998).

As slump height is the measured variable, it would be desirable to express the results for the two models as implicit equations, with dimensionless yield stress in terms of dimensionless slump height. However, without simplification, this is not possible and the results are interpreted graphically, via interpolation from tabulated results or via iteration. In a typical experiment, the slump height is measured, converted to dimensionless slump height, and then, via one of the three methods, the dimensionless yield stress is determined. The actual yield stress is then calculated by multiplying the dimensionless yield stress with $\rho g H$.

4. Results and discussion

4.1. Comparison of the cone and cylinder slump tests

4.1.1. Slump test results

A series of slump experiments were completed to enable a direct comparison of the cylinder and cone slump tests and related models. Slump tests were completed at a variety of solids concentrations for a titanium dioxide pigment suspension and a Cannington paste sample. The accuracy of the cone and cylinder slump models was assessed by comparing the yield stress determined via the vane technique with the yield stress determined via the slump test and related theoretical model. The cone and cylinder slump models are derived from first principles with model variables expressed in dimensionless form. Therefore, the slump models are not empirical and provide a material-independent, unique relationship between yield stress and slump height.

The results for the slump experiments are presented in Fig. 5 in terms of dimensionless slump height as a function of dimensionless yield stress. A dimensionless slump height of 1 corresponds to no slumping (solid-like behaviour) while a dimensionless slump height of 0 corresponds to complete slumping (liquid-like behaviour). The dimensionless slump height values were determined directly from the slump height while the dimensionless yield stress values were determined directly from the independent vane method. The cylinder slump measurements were completed with a range of slump cylinders, as described in Table 2, while the cone tests were completed with a AS 2701.5 (laboratory)

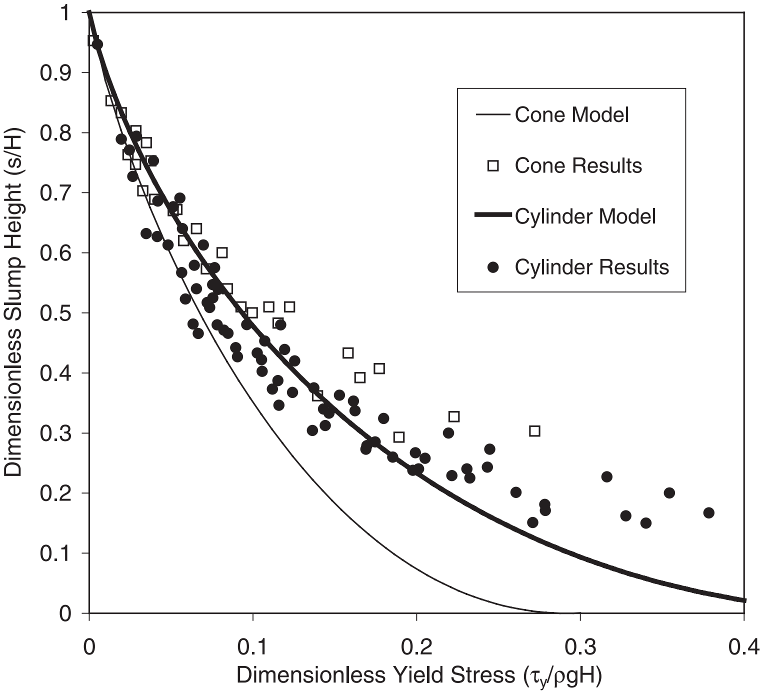

Fig. 5. Cylinder and cone ($\alpha = 1$) slump test results and theoretical models displayed in the form of dimensionless slump height versus dimensionless yield stress.

slump cone. To enable comparison of the experimental results and theoretical predictions, graphical representations of the cylinder model (Eq. (13)) and the cone model (Eqs. (6) and (14)) are included in Fig. 5.

It is evident that for dimensionless yield stresses ranging from 0 to 0.2 (or dimensionless slump heights greater than 0.25), the cylinder slump model accurately predicts the relationship between the cylinder slump height and the vane yield stress. The results indicate that the cylinder slump model is most accurate when the dimensionless yield stress is relatively low and the slump height is large. Consequently, increasing the cylinder height should maintain a dimensionless yield stress value and dimensionless slump height within the accurate region. An analysis of cylinder height is discussed in detail later in Section 4.2.

Table 2
Dimensions and material of construction of the three slump cylinders used in experiments

Cylinder	Height *H* (mm)	Diameter *D* (mm)	Construction material
1	75	75	PVC
2	102	102	PVC
3	120	120	Perspex
4	200	200	sheet metal

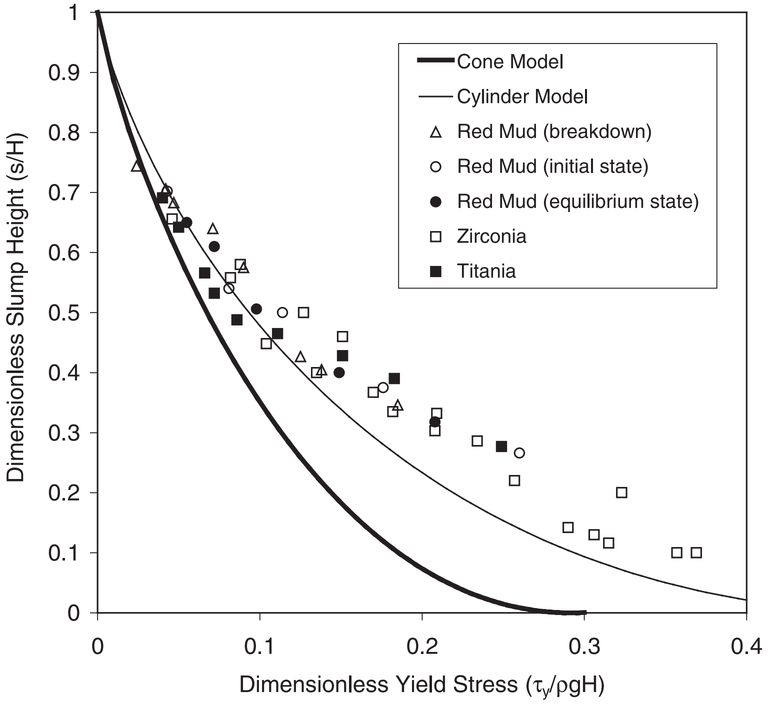

Fig. 6. Slump results from Pashias et al. (1996).

The cylinder slump test results shown in Fig. 6 are reproduced from Pashias et al. (1996) and are presented to complement the results from this investigation. Comparing Figs. 5 and 6, it is evident that the trends are similar and that there is a similar degree of scatter. Furthermore, a wide range of materials were utilised in the two investigations, highlighting the independence of the dimensionless slump model on the test material.

Further observation of Fig. 5 indicates that in contrast to the good agreement between the cylinder model and results, the cone model does not accurately predict the relationship between cone slump height and the vane yield stress. It is evident that the cone model underpredicts the yield stress over the range of yield stress values tested. Closer analysis of the results reveals that the cone results are actually more closely predicted by the cylinder model than the cone model. A more detailed analysis of this observation is completed in Section 4.3.

4.1.2. Slump theory

In this section, the derivations and resultant equations for the cylinder and cone geometries are compared and evaluated. The simplest way to compare the derivations is to visually analyse the equations presented in Section 3. A visual inspection indicates that throughout the derivation, the equations for the cone model contain more variables and terms than the cylinder model, leading to a more complex relationship between the yield stress and slump height. For the cylinder model, a single equation relating dimensionless slump height (s') and dimensionless yield stress (τ'_y) is derived (Eq. (13)). In contrast, the expression for the dimensionless slump height for the cone model is a function of both the dimensionless height of the unyielded region (h'_0) and the dimensionless yield stress. The dimensionless unyielded region h'_0 cannot be eliminated from the expression for slump height as Eq. (6), relating τ'_y and h'_0 cannot be rearranged to express h'_0 as a function of τ'. As a result, two equations (Eqs. (6) and (14)) are required to determine the yield stress with the cone model.

Additionally, the cone equations must be modified for a change in the ratio of the cone top and base diameters, i.e. a change in the α value, while the cylinder model remains constant for a cylinder of any aspect ratio. To illustrate the effect of a change in the value of α, graphical representations of the cone model for different values of α are presented in Fig. 7. It is apparent that for α values ranging from 0.001 to 100 there is a significant shift in the cone model. It is interesting to note that as α approaches infinity (see $\alpha = 100$), the top diameter approaches the base diameter and the cone geometry is equivalent to the cylinder geometry. The cone model for $\alpha = \infty$ therefore coincides with the curve for the cylinder model.

The variability of the cone model for different α values highlights a significant disadvantage of the cone geometry compared to the cylinder geometry. The cone test must be completed with a cone engineered to specific dimensions while the cylinder test can be completed with any cylindrical mould such as a section of pipe or even a beer can.

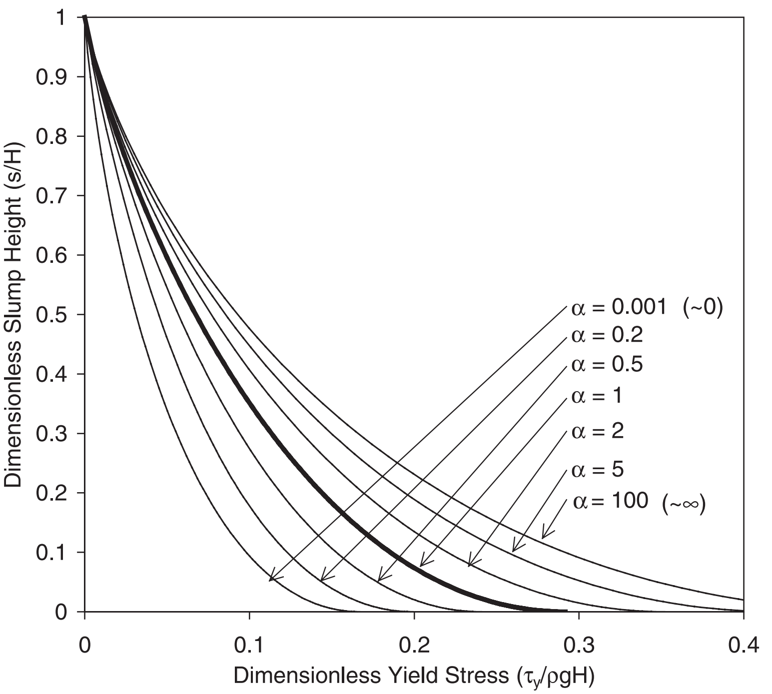

Fig. 7. Effect of a change in the value of α in the slump cone model.

4.1.3. The slump test and industry

The ultimate use of the slump test will be in industry where a simple, accurate, robust and cheap measurement technique is desired. For industrial application, the cylinder slump test has many advantages over the cone slump test:

- Most importantly, the cylinder test and model provide a more accurate determination of yield stress than the cone test and model.
- The cylinder model is mathematically simpler which is important for operators who may not have a strong background in mathematics.
- Due to the more complex cone geometry, the cone is more difficult to fill, leading to the likely presence of air bubbles which can adversely affect the results.
- The shape of the slumped material is less consistent for the cone test, especially at high yield stress values.
- Cylinder slump measurements can be completed with a section of pipe or even a beer can, whereas cone measurement must be completed with a cone manufactured to certain specifications.

4.2. Slump results for varying cylinder height

The results presented in Fig. 5 indicate that the yield stress values determined with the cylinder test and related model deviate from the vane results at dimensionless yield stress values above 0.2 (s' values less than 0.25). As yield stress and slump height are converted to dimensionless quantities by division with ρgH and H, respectively, a change in cylinder height will affect both quantities. Therefore, it is proposed that an increase in cylinder height will maintain the dimensionless yield stress value and dimensionless slump height within the accurate region. To verify this prediction, cylinder slump tests were completed with cylinders of varying height (maintaining an aspect ratio of 1). Fig. 8 presents a plot of the yield stress determined via the slump test against the yield stress determined with the independent vane test for the different slump cylinders. It is evident that with increasing cylinder height, the yield stress predicted with the slump model deviates from the vane results at increasing yield stress values. For cylinder heights of 75, 102 and 120 mm, the deviation is observed at yield stress values of 250, 350 and 500 Pa, respectively. No deviation between the results is observed for the 200-mm cylinder.

The significant conclusion of the cylinder height analysis is that the slump cylinder height can be increased to enable accurate yield stress determination of high yield stress materials. Therefore, the deviation of the slump prediction for dimensionless yield stress values above 0.25 does not reduce the applicability of the slump test for the minerals industry.

4.3. Detailed analysis of the cone results

The results presented in Fig. 5 indicate that the cone model does not accurately predict the relationship between cone slump height and the vane yield stress. Furthermore, the results actually correspond more closely to the cylinder model. A proposed explanation for this result is that the material yields within the cone, causing

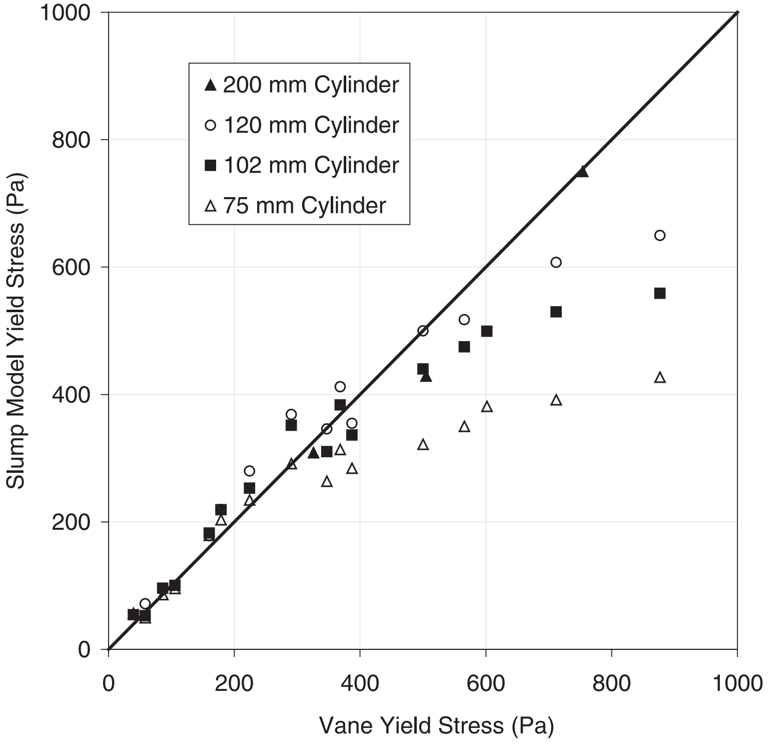

Fig. 8. Comparison of slump model yield stress and vane yield stress for different cylinder heights, maintaining an aspect ratio of 1.

the material to be extruded through the base diameter. Therefore, the slumping behaviour observed for the cone is predicted to be equivalent to the slumping behaviour for a cylinder with a diameter equal to the cone base diameter. This proposition was examined by measuring the top or extrusion diameter of the material after slumping occurred. Both cylinder and cone slump tests were completed for a range of yield stress values. The results are listed in Table 3. For the cylinder tests, the extrusion diameter is almost identical to that of the slump cylinder. However, for the cone tests, the extrusion diameter of the slumped material is far greater than the top diameter of the slump cone. In fact, the extrusion diameter of the slumped material is closer to the base diameter of the cone.

Photographs of a cylinder slump test and a cone slump test, presented in Fig. 9a and b, respectively, provide a visual illustration of the cylinder-like behaviour. It is apparent that in both tests the paste is extruded through the base diameter. The results indicate that the underlying assumptions for the cone model are not satisfied in the cone slump test. Clearly, the material at the top of the cone must flow to result in the increased diameter, implying that the initial undeformed material is not shaped as a truncated cone. Therefore, the cone theory is not applicable for prediction of the cone slump results. It must be emphasised that

Table 3
Analysis of the extrusion diameter for cylinder and cone slump tests

Sample details		Extrusion diameter (mm)		
Material	Yield stress (Pa)	Cone (top $D=50$ mm, base $D=97$ mm)	102-mm-diameter cylinder	75-mm-diameter cylinder
Paste	450	92	104	77
Paste	272	95	103	76
Paste	170	95	104	75
Paste	119	97	105	77.5
Paste	62	98	110	78
Paste	35	100	112	82
Titania	158	96	100	74

the results do not indicate that the cone theory is inaccurate but rather that the cone slump test does not satisfy the assumptions made in the development of the cone model.

An extension to the investigation is to analyse the experimental cone data as if the experiments were completed using an equivalent cylinder with a diameter equal to the extrusion diameter. Such an analysis enables detailed quantitative evaluation of the proposition that the cone test exhibits cylinder-like behaviour. In the analysis, the volume of the equivalent cylinder is equal to the laboratory cone volume of 687 ml. From the extrusion diameter, the initial height (H) of the undeformed material is determined. The slump height measured for the cone is subsequently converted to the slump height for the equivalent cylinder. Fig. 10 presents the cone results and the equivalent cylinder results. When analysed as a cylinder, the results from the cone test clearly fall on the cylinder curve, therefore further verifying the cylinder-like behaviour.

4.4. Yield stress versus slump height

In the minerals industry, the slump test finds the most extensive application in paste fill operations which utilise the waste tailings to fill the underground cavities created in mining. Prior to transport to the underground cavity, the paste is combined with a small amount of cement to provide adequate support for mining of adjacent stopes. To maximise the disposal of tailings and to minimise the cement usage, paste fill systems operate at concentrations typically ranging from 70% to 90% solids by weight. At these high concentrations, the paste yield stress is extremely sensitive to changes in solids concentration and effective control of paste consistency is essential. Fig. 11 presents a plot of yield stress versus solids concentration for a Cannington paste fill sample. The plot illustrates the exponential relationship between the yield stress and solids concentration and highlights the region of operation for paste fill operations relative to the majority of mining applications.

In paste fill operations, the ASTM cone slump height is generally used as the parameter to monitor paste consistency. The slump height is an empirical measure of consistency, which is dependent on both the material yield stress and density, which in turn are dependent on chemical composition, particle specific gravity and particle size. In a mining

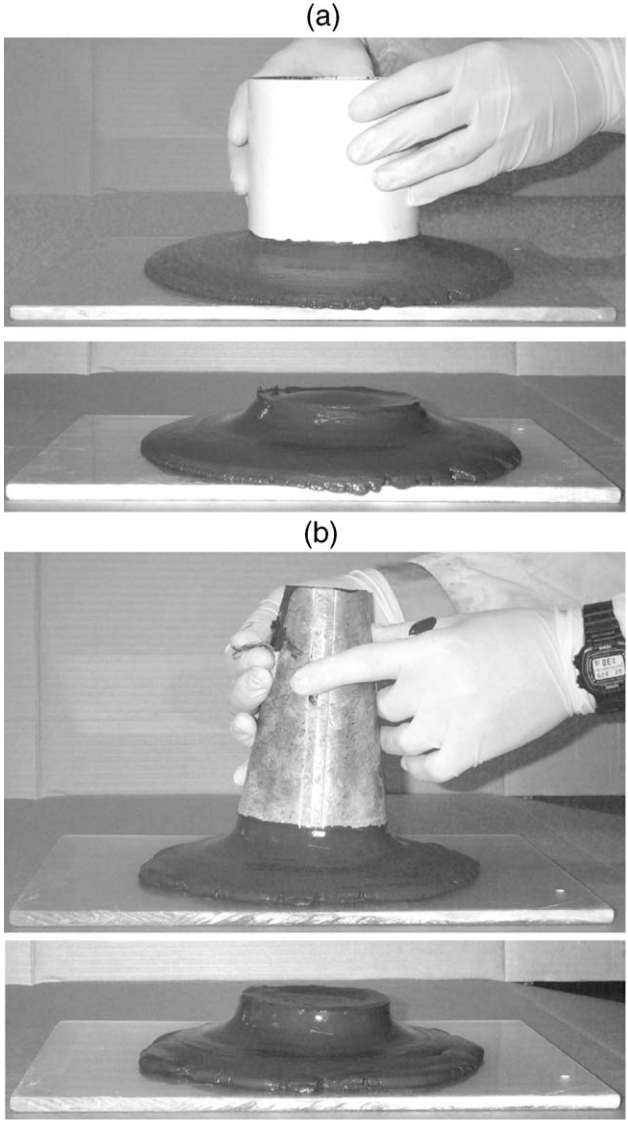

Fig. 9. Photographs of slumped material after the (a) cylinder test and (b) cone test. The photographs highlight that the extrusion diameter is equal to the base diameter for both the cylinder and cone slump tests.

context, these factors can vary with changes in ore origin or with changes in ore processing. Therein lies the potential for problems, as a variance in density will lead to a different paste yield stress for the same slump height. If the yield stress is too great, then the distribution system will not be able transport the material and the pipeline will block. Alternatively, if the yield stress is too low then the strength for a given cement dosage will

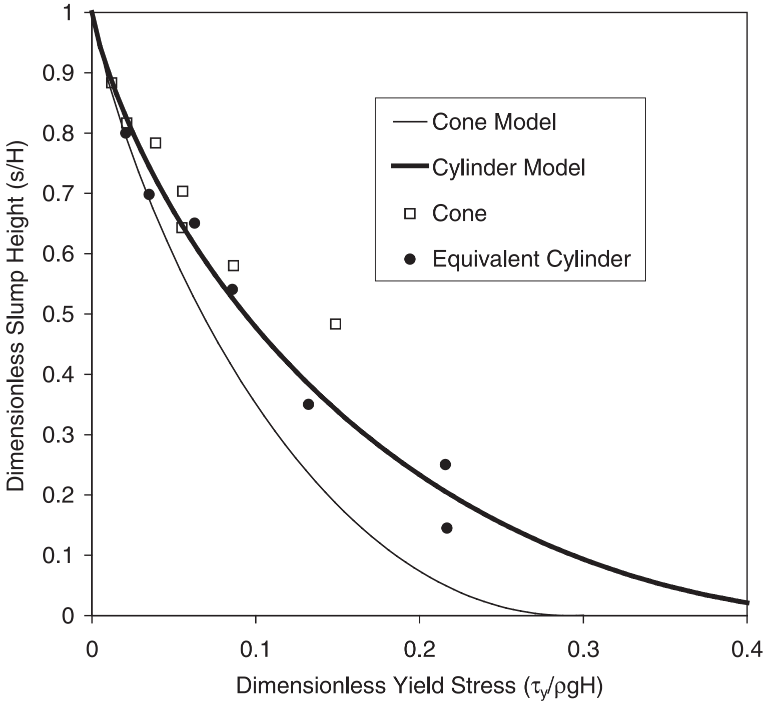

Fig. 10. Slump test results for laboratory cone experiments analysed with the cone model and with the cylinder model.

be reduced. In addition, the density of the material placed underground will be lower, leading to a reduction in the volume of tailings placed underground and a related increase in the volume of waste disposed of in aboveground tailings dams.

It is common industry practice to use the slump height to compare paste samples from different mines and also to design paste fill systems based on slump heights from other mines. Landriault (1992) states "The slump test is an ideal way to relate one paste to another. For paste fill transport, we aim for an 8-inch slump". Such use of the slump height has been widely published in the literature. For a given mine, factors such as particle size and specific gravity may be relatively constant and it is reasonable to directly compare slump heights. However, for different mines these factors can vary significantly, leading to vastly different yield stress values for a given slump height. Therefore, the industry practice of directly comparing slump heights involves a degree of risk.

To emphasise the effect of density on the yield stress measured with the slump test, a comparison between tailings samples for a coal mine, a gold mine and a lead–zinc mine is presented. The samples give the same slump height but have varying solids concentrations and specific gravities. Table 4 displays the results. A comparison between the coal sample and the lead–zinc sample shows that a change in specific gravity or solids concentration can greatly affect the slurry density and consequently the yield stress. The yield stress

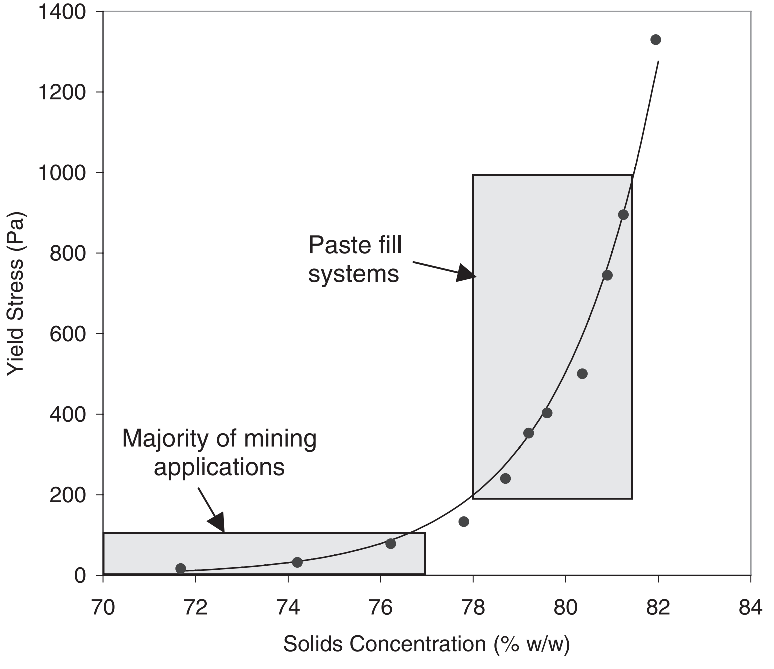

Fig. 11. Plot of yield stress versus solids concentration for a Cannington paste fill sample.

calculated for the lead–zinc sample is over twice that calculated for the coal sample of the same slump height.

Also included in Table 4 is the start-up pressure drop per meter requirement assuming a pipeline diameter of 150 mm. It is evident that the pressure drop requirement is directly proportional to the yield stress. Thus, doubling the yield stress doubles the pressure drop requirement. The results therefore emphasise that the utilisation of the slump height rather than the yield stress could have serious implications for equipment operation and pipeline transport.

Table 4
Comparison of the yield stress values and start-up pressure drops for three tailings samples with the same slump heights but different specific gravities

	Coal tailings	Gold tailings	Lead–zinc tailings
Specific gravity (kg/m^3)	1450 (Woskoboenko et al., 1987)	2800 (Grice, 2000)	4100 (Grice, 2000)
Solids concentration (% w/w)	36	75	75
Slurry density (kg/m^3)	1120	1930	2310
Slump height (mm)	203 (8 in.)	203 (8 in.)	203 (8 in.)
Calculated yield stress (Pa)	160	275	330
Start-up pressure drop per metre ($4\tau_0/D$) (kPa/m)[a]	4.3	7.3	8.8

[a] Assumes an internal pipe diameter of 150 mm.

5. Conclusions

A detailed comparison of the cylinder and cone slump tests has indicated that the cylinder is the superior geometry. Mathematically, the cylinder model is less challenging, and experimentally, the cylinder model more accurately predicts the material yield stress.

A significant recommendation of the investigation is that the yield stress is a better measure of consistency than the slump height. The slump height is an empirical value, which is dependent on both the material yield stress and density. In contrast, the yield stress is a unique material property, which can be directly compared for different materials.

The simplicity and accuracy of the cylinder slump test and related model makes it an ideal method for on-site yield stress measurement. The test is particularly useful in paste fill systems where precise control of material consistency is essential.

Acknowledgements

The slump investigation is supported by the Particulate Fluids Processing Centre and a grant from BHP Minerals-Cannington.

References

ASTM, 1998. Annual Book of ASTM Standards. Designation: C 143/C 143M-97 Standard Test Method for Slump of Hydraulic-Cement Concrete, vol. 04.02, Concrete and Aggregates, ASTM, 89–91.

Boger, D.V., 1998. Environmental rheology and the mining industry. Proceedings of the Sixth International Symposium on Mining with Backfill. The Australasian Institute of Mining and Metallurgy Publication Series, Brisbane, Australia, pp. 15–17.

Chandler, J.L., 1986. The stacking and solar drying process for disposal of bauxite tailings in Jamaica. Proceedings of the International Conference on Bauxite Tailings, Kingston, Jamaica. Jamaica Bauxite Institute, University of the West Indies, pp. 101–105.

Christensen, G., 1991. Modelling the flow of fresh concrete: the slump test. PhD thesis, Princeton University.

Grice, T.G., 2000. Personal communication.

Hibbeler, R.C., 1997. Mechanics of Materials, 3rd ed. Prentice-Hall, Upper Saddle River, NJ, pp. 530–536.

Landriault, D., 1992. Inco's backfill experience. Canadian Mining Journal, 39–47 (October).

Liddell, P.V., 1992. The rheology of titanium dioxide pigment suspensions. Proceedings of the 6th National Conference on Rheology. Australian Society of Rheology, Melbourne, Australia, pp. 55–58.

Liddell, P.V., 1996. The rheology of titanium dioxide pigment suspensions. PhD thesis, Department of Chemical Engineering, University of Melbourne.

Murata, J., 1984. Flow and deformation of fresh concrete. Matériaux et Constructions (Paris) 17, 117–129.

Nguyen, Q.D., Boger, D.V., 1983. Yield stress measurement for concentrated suspensions. Journal of Rheology 27, 321–349.

Nguyen, Q.D., Boger, D.V., 1985. Direct yield stress measurement with the vane method. Journal of Rheology 29, 335–347.

Pashias, N., Boger, D.V., Summers, J., Glenister, D.J., 1996. A fifty cent rheometer for yield stress measurement. Journal of Rheology 40 (6), 1179–1189.

Rajani, B., Morgenstern, N., 1991. On the yield stress of geotechnical materials from the slump test. Canadian Geotechnical Journal 28, 457–462.

Schowalter, W.R., Christensen, G., 1998. Toward a rationalization of the slump test for fresh concrete: comparisons of calculations and experiments. Journal of Rheology 42 (4), 865–870.

Standards Association of Australia, 1984. AS 2701.5—Method for Determination of Consistency-Slump Test, Australian Standard—Methods of Sampling and Testing Mortar for Masonry Construction.

Woskoboenko, F., Siemon, S.R., Creasy, D.E., 1987. Rheology of Victorian brown coal. Fuel 66, 1299–1304.