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Environmental rheology for waste minimisation in the minerals industry

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Abstract

Dry disposal represents a paradigm shift in mining engineering. The tailings are engineered to suit the disposal requirements, as opposed to engineering a facility to accommodate the tailings. It is, therefore, important to understand how the material properties and operational parameters can be modified to produce the desired transport and deposition characteristics of the tailings. For thickened tailings disposal, dry stacking and paste fill, the rheology must be well understood to ensure maximum efficiency of the entire disposal operation. The paper presents the disposal of bauxite residue (red mud) as a case study and outlines alternative and simplified methods of rheological characterisation. The effect of both shear and compression history on pipeline transport is examined in order to identify favourable processing schemes. Prediction of the slope formed by the deposition of de-watered tailings is necessary to ensure maximum storage efficiency and stability. The slope is found to be dependent on rheological properties such as yield stress and viscosity, operational parameters such as depositional flowrate, and the topography or slope of the underlying base. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Rheology; Minerals; Topography; Tailing disposal; Mineral processing

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1. Introduction

Technological advancements in mineral processing have increased the feasibility of refining low grade ores. Because of this progression and continual depletion of high grade ore deposits, much larger volumes of waste material are produced. At the same time, increasing environmental legislation and cost competitiveness dictate that these wastes must be disposed of in a manner that is both environmentally acceptable and economically viable.

In the past, mine tailings have typically been deposited as dilute slurries in large dams. The disposal area required has been large and the associated costs high. In addition to land costs, the construction and lining of large dams is expensive. Reclamation and rehabilitation is a difficult and lengthy process as the dam may take many years to fully dry and consolidate.

Conventional ‘wet’ methods of tailings disposal are problematic because of the ever present risk of ground water contamination and difficult rehabilitation. Furthermore, tailings dams are at risk of failure due to leakage, instability and liquefaction. Since 1970, there have been 35 major tailings dam failures world-wide, resulting in at least 471 human deaths and untold environmental damage [1]. In addition to safety and environmental considerations, there is a distinct world-wide trend towards minimising water use and storage to reduce operational costs and increase the profitability of mine operations.

The means to dramatically reduce dam failures and the subsequent environmental impact is available in the form of dry disposal. Dry disposal techniques present significant safety advantages over conventional wet disposal. Dry disposal requires that tailings be thickened or de-watered prior to disposal. Schemes such as dry stacking, thickened tailings disposal and paste fill all involve the deposition of de-watered tailings to improve water and reagent recovery and decrease tailings volumes and footprint. This reduction in the tailings footprint will increase the ease with which the site can be rehabilitated.

Dry stacking involves the progressive deposition of de-watered tailings onto sloped, under-drained drying beds. Once a drying bed is covered to the desired depth, the discharge point is moved to an adjacent bed to allow the freshly covered area to dry via evaporation and under-drainage [2]. When all drying areas are covered, the process is repeated by returning to the original (now dry) bed and depositing a fresh layer of tailings. The dry stacking method allows the timing and depth of successive depositions to be varied to accommodate changes in climate and material characteristics [3].

Thickened tailings disposal involves deposition of the de-watered waste material from a central disposal point to form a tailings stack of conical geometry [4]. The formation

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of such a cone is advantageous as the need for high dam walls is eliminated and the stability of the deposit is enhanced through improved consolidation. In addition, problems associated with steep tailings slopes and the surface ponding of slimes are avoided. Land utilisation is improved as higher tailings densities are achieved compared with conventional disposal methods. The deposit is fully drained and consolidated at decommissioning so the reclamation procedure is simplified [5].

Paste fill is used for back-filling underground mines in order to ensure adequate support properties for the overlying land and to reduce the surface placement of tailings. The thickened tailings that form the paste are often mixed with small amounts (3–5%) of cement to increase the paste's strength characteristics [6]. The paste usually flows in a pipe by gravity down a mineshaft and then horizontally to the area being filled. Once deposited, the material must spread sufficiently to fill the void whilst quickly consolidating to provide the required strength to support overlying land and enable mining of adjacent areas.

Dry disposal represents a paradigm shift in engineering. The tailings are engineered to suit the disposal requirements, as opposed to engineering a facility to accommodate the tailings. It is, therefore, important to understand how the material properties and operational parameters can affect tailings' transport and deposition characteristics.

The ability to de-water tailings to the high concentrations required and to economically pump the material from the thickener to the disposal are essential for the design and implementation of dry disposal systems. Concentrated suspensions usually exhibit non-Newtonian behaviour, so determination of the disposal plant operating conditions requires a thorough understanding of the shear rate and/or shear history dependence of the tailings.

The prudent design of a dry disposal system, whether it be dry stacking, thickened tailings disposal or paste fill, requires prediction of the angle of repose, or slope formed by the deposited tailings. Prediction of the slope formed by the tailings allows the residue area to be sized to ensure maximum storage efficiency and stability. If the relationship between the tailings' rheology, operating conditions and the depositional behaviour is known, the desired slope of the deposit can be achieved by manipulating the operating or rheological parameters.

An inclined plane apparatus has been used to identify and understand the parameters affecting the deposition behaviour of de-watered mineral tailings. The scope of parameters examined include rheological properties such as yield stress and viscosity, operational parameters such as depositional flowrate, and the topography or slope of the underlying base. An industrial tailings slurry, a synthetic swelling clay suspension and a mineral slurry were used to develop a model relating the material properties and operating conditions to the depositional slope formed.

The implementation and optimisation of dry disposal methods involves three concurrent and interdependent rheological studies to determine:

1. the concentration required for optimum spreading and drying of the tailings once deposited;
2. the optimum conditions for pipeline transport; and
3. the feasibility of de-watering the tailings to the required concentration.

2. Shear rheology

2.1. Measurement

Characterisation of the shear rheology allows determination of the spreading characteristics, the requirements for pipeline start-up and the conditions for minimal energy expenditure during pipeline transport from the thickener to the prepared disposal area.

The rheological characterisation of concentrated mineral suspensions requires specialised equipment and techniques. Mineral suspensions are generally non-Newtonian fluids at high solids loadings, exhibiting a yield stress, which is the minimum stress required for material deformation and flow to occur. Furthermore, the rheology of many suspensions is time-dependent (thixotropic) and shear rate sensitive (shear thinning or pseudo-plastic).

The shear thinning often evident in mineral suspensions is attributed to the alignment of particles or flocs. An increase in the shear rate from rest results in the alignment of particles in the direction of shear, therefore, providing a lower resistance to flow.

Thixotropy is the result of structural breakdown under shear and manifests itself as a decrease in the viscosity and yield stress with time for a given, constant shear rate. As time of shear elapses, the rate of breakdown will decrease, as fewer structural bonds are available for breakdown. Structural reformation may take place and the rate of this process will increase with time of shear due to the increasing number of bonding sites available.

Measurement of fundamental flow behaviour may be undertaken using a capillary rheometer [7–9]. The capillary rheometer generates shear stress–shear rate data for the determination of pumping energy requirements in addition to describing the influence of thixotropy and pseudo-plasticity.

Particular care must be taken to eliminate diameter and end effects in the use of capillary rheometers. In order to minimise the possibility of wall and end effects, both L/D (tube length/tube diameter) and D/d_{50} should be greater than about 60, where the d_{50} is the median particle size of the suspended particles [10].

To test for wall effects, it is necessary to undertake runs using two tubes of the same length, but differing diameter and compare the results. The results should be the same in the absence of wall effects. To test for end effects, two tubes of the same diameter, but differing lengths are used and the flow results are compared. The results again should be the same in the absence of end effects.

A significant amount of work on the measurement of the yield stress of mineral suspensions has been completed at the University of Melbourne. From this work, novel and simplified measurement techniques have resulted. The Vane-shear instrument and technique allows direct and accurate determination of the yield stress from a single point measurement of incipient yielding [8,10,11] and avoids the need to extrapolate flow data. Furthermore, the particle shape effects that can contribute to slip are eliminated by the use of the Vane, where the material yields on itself rather than a solid surface. All yield stress data presented in this paper were obtained using the Vane-shear method. Many workers world-wide have adopted the Vane-shear method and confirmed its applicability for all types of yield stress materials [12–16].

In an attempt to further simplify yield stress measurement, the ‘slump test’ has been modified to accurately evaluate the yield stress of mineral suspensions [17,18]. This technique has been typically used to determine the flow characteristics of fresh concrete. The slump test is conducted using only a cylinder and a ruler, eliminating the need for sophisticated equipment and allowing easy, on-site yield stress measurement by plant operators. A small cylinder is filled with sample and removed to allow the material to ‘slump’ under its own weight. A simple theory is then used to determine the yield stress from the slump height [18].

2.2. Shear rheology results

The flow properties of concentrated mineral suspensions vary significantly with solids concentration and type, however, a number of common characteristics have been observed for concentrated suspensions in general. The strong dependence of the rheology on solids concentration is exemplified in Fig. 1. This figure shows the yield stress as a function of solid concentration for a number of industrial slurries. In all cases, the yield stress was measured using the Vane technique [8]. The concentration is given as a mass percentage as this is common practice in industry and the solids densities were not available.

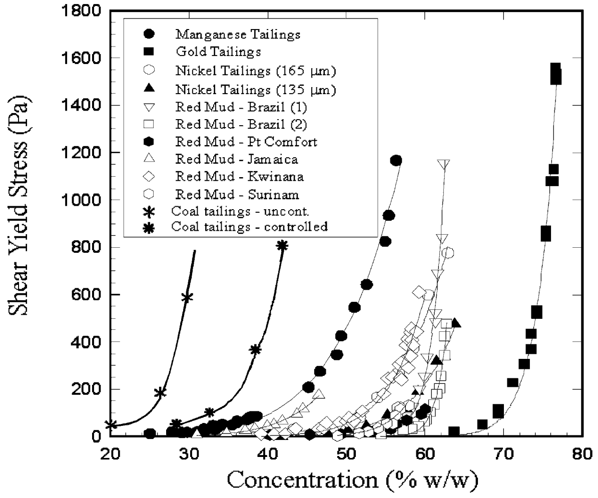

Fig. 1. Yield stress as a function of concentration for a number of mineral tailings.

Although the relationships vary for the different materials, all materials exhibit an exponential rise in the yield stress with concentration. Furthermore, for all materials the yield stress begins to rise rapidly beyond 80–100 Pa, regardless of the concentration. It is expected that comparison of the data on a volumetric basis would result in the curves being closer together provided there are no significant differences is surface chemistry effects.

The concentration at which the yield stress begins to rise rapidly is significant when optimising pumping energy requirements; further explained in Section 3. The yield stress must be sufficient to allow laminar pipeline transport and prevent solids deposition, but not so high that start-up problems will be encountered.

The presence of a yield stress is essential for dry stacking and thickened tailings disposal to ensure that the material comes to rest at the required angle of repose for stability and maximum storage capacity. An adequate yield stress also ensures that particle size segregation does not occur and that the final tailings stack will be homogeneous.

To ensure that a wide range of material properties were available for slope prediction experiments, three suspensions with varying degrees of pseudo-plasticity and thixotropy were used.

Rheological characterisation of both red mud and a titanium dioxide suspension was undertaken using a capillary rheometer. Laponite, a synthetic clay suspension, was characterised using a controlled stress cone and plate viscometer due to the short time scale of thixotropy. The yield stress of all three materials was determined using the Vane technique [8].

2.2.1. Red mud

Fig. 2 shows the decrease in viscosity with increasing shear rate (shear thinning) for a number of concentrations of red mud. It is evident that the reduction in the viscosity is greater for higher solid concentrations.

To determine the effect of shear history on the flow properties, the suspension is sheared (by mixing) between measurement of the shear stress–shear rate behaviour by capillary rheometry. Typical flow data for 47 wt.% bauxite tailings samples (red mud) from alumina production are shown in Fig. 3. The effect of shear history on the yield stress is determined concurrently using the Vane technique or the slump test (Fig. 4).

Capillary rheometry data in Fig. 3 illustrate a yield stress material that is strongly thixotropic and shear thinning. Although knowledge of the shear thinning behaviour is imperative, for many materials the time-dependent nature, which results in thixotropic behaviour, has a more significant influence on the flow properties.

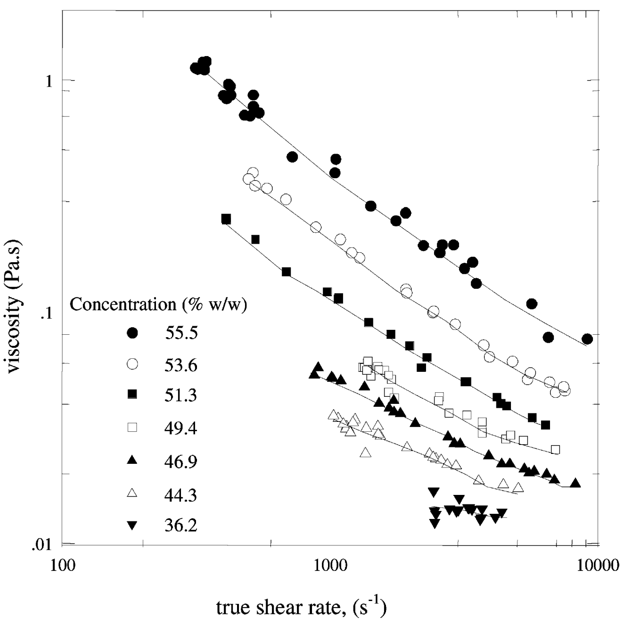

Fig. 2. Red mud: equilibrium viscosity vs. shear rate for various solids concentrations.

2.2.2. Titanium dioxide suspension

Titanium dioxide (TiO_2) is a pigment used in the paint industry and was used in this study to model a flocculated mineral suspension. The pigment used has a solids density of 4100 kg/m^3. The flow behaviour of a 60 wt.% solids titanium dioxide suspension was determined and is illustrated in Fig. 5. The suspension was found to be a yield stress material and was shear thinning and non-thixotropic. Fig. 6 shows the yield stress–concentration profile for titanium dioxide.

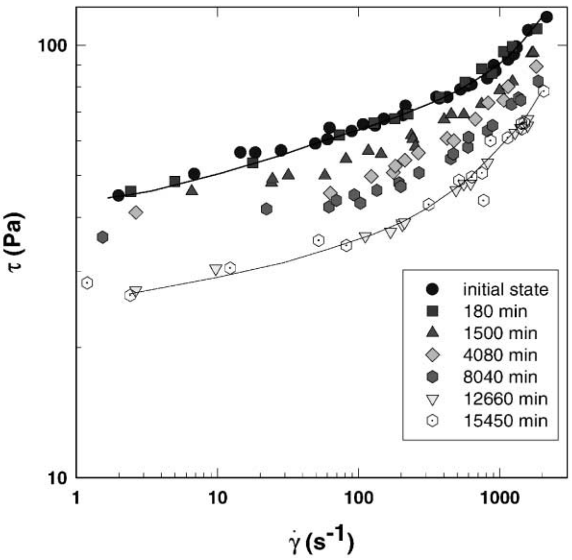

Fig. 3. Shear stress vs. shear rate variation with shear history.

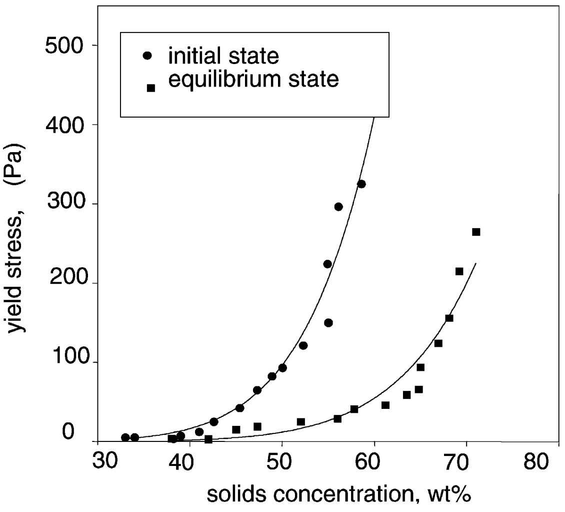

Fig. 4. Decrease in the Vane yield stress due to thixotropic breakdown.

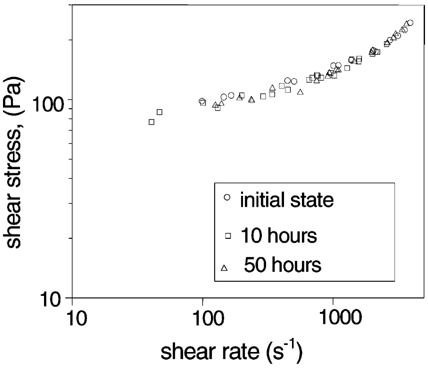

Fig. 5. Flow behaviour of 60 wt.% TiO_2.

2.2.3. Laponite

Laponite RD (hydrous sodium lithium magnesium silicate) is a synthetic layered silicate that swells in water to give a transparent colloidal dispersion. It is used industrially

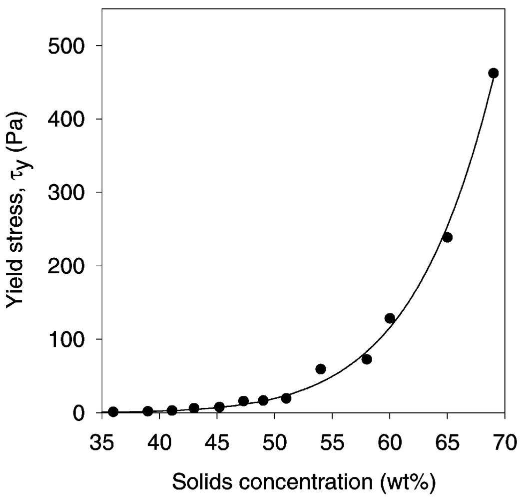

Fig. 6. TiO_2 yield stress vs. concentration.

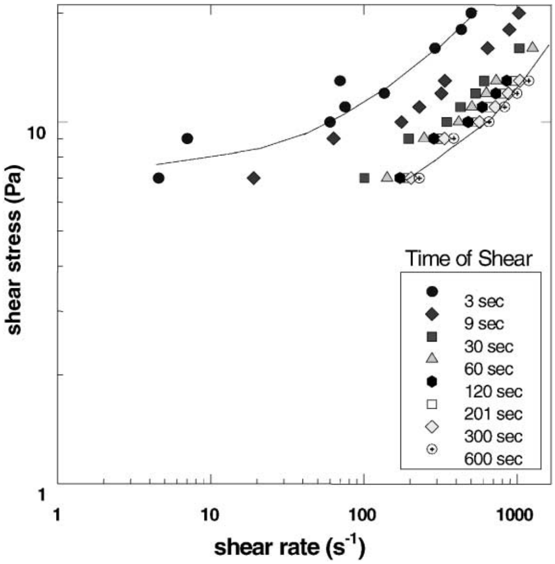

Fig. 7. Flow behaviour of 2.5 wt.% Laponite.

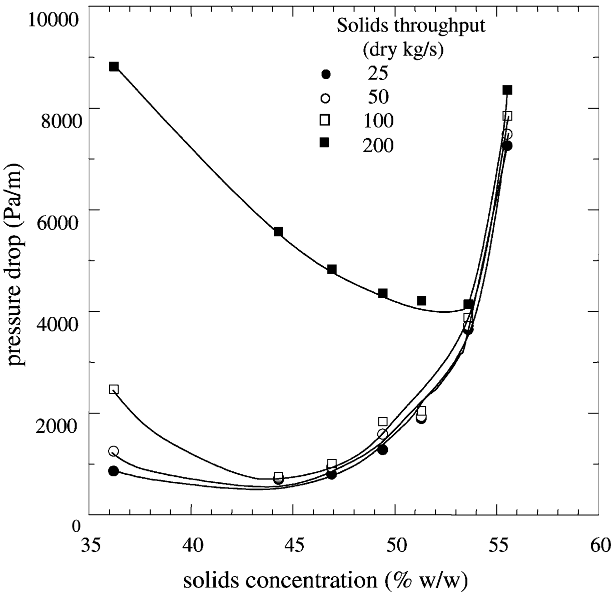

Fig. 8. Red mud: pumping energy requirements as a function of solids throughput and concentration.

as a thickener for toothpaste, paints and cosmetic formulations. Laponite was included in this study as it is very highly thixotropic and shear thinning and represents an extreme case of these rheological attributes. As shown in Fig. 7, thixotropic breakdown occurs on a very short time scale. Also observed, but not shown here, is the fast thixotropic recovery of Laponite to its original rheological state.

2.3. *Modification of shear rheology*

As shown above, a knowledge of the effects of concentration, shear rate and shear history allows the rheology of a given mineral suspension to be modified and exploited. Although knowledge of these 'macro' effects is imperative, it is also possible to manipulate the rheology by altering the physico-chemical properties of the suspension.

The rheology of most mineral tailings is governed primarily by the surface chemistry of the fine particles in the suspension [19,20]. Modification of the rheology may be accomplished by varying the surface chemistry of the fine particles using pH, the concentration of dissolved salts or by the type and concentration of flocculant or dispersant. Alternatively, since the rheology is governed by fine particles, altering the particle size distribution will also change the flow properties [10,16].

For tailings containing swelling clays, e.g. coal tailings containing sodium–montmorillonite, the de-watering process and the rheology of the de-watered material is dominated by the surface chemistry of swelling clay platelets rather than fine particles. An increase in the ionic strength (salt concentration) suppresses swelling and leads to favourable rheological properties for pipeline transport and deposition [21].

3. Pumping energy determination

For red mud in laminar flow, the data in Fig. 2 can be used directly to determine the pipeline pressure drop and energy requirements for given pipe sizes and flow velocities. In the turbulent regime, the rheological data are used in conjunction with an empirical correlation. An exhaustive list of correlations were reported in Munn [22]. Munn concluded that the method proposed by Dodge and Metzner [23] was suitable for plastic materials irrespective of particle size. Other authors favour different methods [24,25].

For a given solids throughput and pipe diameter, Fig. 8 highlights the presence of an optimum concentration, where the pumping energy is minimised. The optimum concentration for all throughputs is found to correspond to the laminar–turbulent transition region [10], where the solids loading is higher than the optimum, flow will be laminar, but the large increase in the viscosity and yield stress results in an increase in the pressure drop. For solids loadings much less than the optimum, the total volume of material to be transported increases resulting in high flow velocities, turbulent flow, higher friction factors, and therefore, higher pressure drops.

For thixotropic materials, such as red mud and some nickel tailings, an additional complication to pressure drop prediction exists due to the changing nature of the rheology with shear history. A state of dynamic equilibrium, where the rate of breakdown of the structure and the structural reformation rate are equal is possible. However, due to the extended times required for equilibrium to be reached, this state is not always achieved in industrial applications. Generally, the material in the pipe will be in a partially sheared state, where the shear stress–shear rate behaviour is still changing with the time of shear.

Pipeline design and pumping energy determination requires knowledge of the structural state of the material. For highly thixotropic materials, problems may arise when using flow curves generated in a laboratory environment due to the difficulties in ensuring that the material is in the same structural state as in the pipeline.

The only region in which one can be sure of the structural state of the material is the equilibrium state. In equilibrium state, flow both the viscosity and yield stress are reproducible. For fully sheared equilibrium state, flow curves to be used as master curves and applied to partially sheared slurries, it is necessary to quantify the effect of shear history on the generated flow curves.

From Fig. 3, it can be seen that although the yield stress and viscosity of red mud tailings decrease significantly from the initial state to the equilibrium state, the actual shape of the flow curves appears relatively constant. This observation is further investigated to determine the ramifications for pipeline energy transport prediction [26].

In order to determine the variation in flow curve shape with shear history, the curves shown in Fig. 3 were superimposed by vertically shifting so that the intercept was the yield stress for the equilibrium case (Fig. 9).

It can be seen from Figs. 3 and 9 that thixotropy manifests itself primarily as a variation of the yield stress and the actual shape of the curve is relatively constant [26]. Because of the constant shape, the yield stress can be used to quantify the structural state of the material. Therefore, if both the yield stress at the pipeline conditions and any flow curve for the material are available, the shape of the curve can simply be shifted along the *y*-axis to coincide with that yield stress.

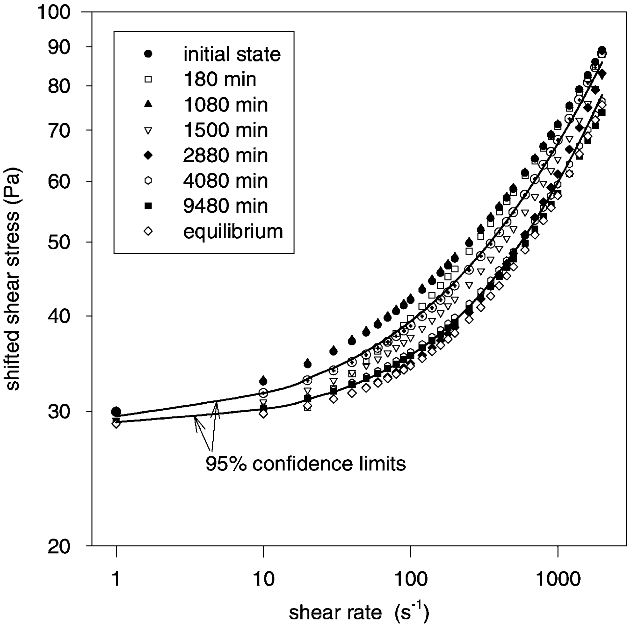

Fig. 9. Red mud flow curves vertically shifted to a common yield stress. The 95% confidence limits are shown.

The resulting shifted curve can then be used directly to calculate the shear stress, hence, the pumping energy required at the desired shear rate for laminar flow, or in conjunction with the Dodge and Metzner correlation for turbulent conditions.

To ensure that the yield stress used is representative of the structural state of the material in the pipe, it is recommended that the slump test [18] be used on-site at the time of sample collection. This method eliminates further thixotropic breakdown during transport and re-suspension or thixotropic recovery due to time delay. The slump test has the added advantage of being inexpensive and simple to perform and analyse.

Pressure drops predicted using the shifted and unshifted flow curves were compared with measured pressure drops from a pipeline at the Alcoa Kwinana residue plant. The pipeline had an internal diameter of 0.15 m and was 133 m long to the point of sampling. Tailings solids loadings between 35 and 45% were sampled. For each concentration, the yield stress was measured on-site immediately after sample collection. The yield stresses were in the range of 17–103 Pa, depending on the solids concentration and the shear history. The measured pressure drops over the pipeline ranged from 80 to 265 kPa.

The capillary rheometer was used to construct flow curves some time later. Due to the delay, some settling of the slurry had taken place so agitation was required to re-suspend the solids. Because of the delay and added shear, it was difficult to determine the structural state of the material at the time of collection.

In order to predict the pressure drop, the Vane yield stress was used to transpose the flow curve to the appropriate shear stress corresponding to a zero shear rate. For data in laminar flow, the shear stress was then determined for the shear rate of interest directly from the shifted flow curve. The pipeline operated in laminar flow for generalised Reynolds numbers less than 2100. Determination of the expected pressure drop was relatively simple given the dimensions of the pipeline used. The calculated pressure drops were then compared with those measured during the pipeline runs.

For pressure drop prediction in turbulent flow the Dodge–Metzner method was used. Flow was considered to be turbulent for generalised Reynolds numbers greater than 2100. The onset of turbulence is usually deemed to occur at generalised Reynolds numbers greater than 4000, however, in this case, turbulent flow was observed at lower values by a dramatic change in the sound of the flow in the pipeline. Results are summarised in Fig. 10.

Using the shift method, the deviation from the measured pressure drop ranges from −10 to +42% (average: +14.3%). These deviations are significantly lower than pressure drop predictions based on the unshifted flow curves, with deviations ranging from −79 to +88% (average: −42.06%). The proposed semi-empirical shift method provides a much improved prediction of the pressure drop for red mud, where the flow behaviour is dependent on shear history.

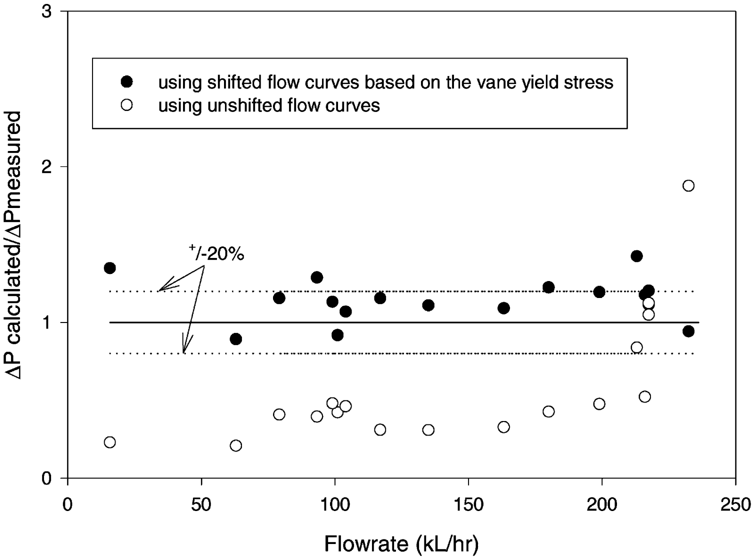

Fig. 10. Comparison of the measured and calculated pressure drops for Kwinana red mud based on shifted and unshifted flow curves. Solids concentrations range from 35 to 45 wt.%.

In both cases, a large contributor to the discrepancy between predicted and measured pressure drops is the frictional loss due to valves and fittings. The pipeline used contained six tee pieces and associated valves, resulting in significant, non-accounted for frictional losses. The small diameter of the sampling port and valve could also have subjected the slurry to high shear stresses, resulting in a lower calculated pressure drop than the true value. In the case of non-Newtonian slurries, the pressure loss due to these fittings is difficult to estimate. Even so, for the cases studied, it is evident that the shifted flow curves provide a significant improvement for pressure drop prediction for thixotropic red mud tailings.

4. Slope prediction

Prediction of the angle of repose, or slope formed by the deposition of de-watered tailings is a difficult issue that has not been successfully dealt with in the past [27]. The work undertaken here aims to identify and understand the parameters affecting the deposition behaviour of concentrated mineral tailings. The scope of parameters examined includes rheological properties such as the yield stress and viscosity, operational parameters such as depositional flowrate and the topography or slope of the underlying base.

4.1. Inclined plane apparatus and testing procedure

Fig. 11 shows a schematic diagram of the inclined plane apparatus used for slope prediction experiments and the shape of the stationary fluid on the inclined plane. Prior to a run, the density of the material was determined. For inclined plane testing, a sample was placed in the fluid reservoir and the height of the material in the reservoir recorded. The angle of the base, θ was determined to the nearest 0.1° using a digital level. Once the gate was lifted, the material flowed down the plane and came to rest at a natural angle of repose, θ_r. Once flow had ceased, the angle of repose of the material (relative to the plane surface) was measured. The length of flow and the fluid height at the origin and the distal end (toe) were measured for determination of this angle as indicated in Fig. 11. A sample of the material was taken for immediate determination of the yield stress using the Vane technique.

The flow behaviour of red mud tailings is best described using a Herschel–Bulkley model, which contains a yield stress term followed by a power law term to describe the changing viscosity with shear rate. However, for the purposes of the slope prediction work, the Bingham model provided an acceptable approximation to the flow behaviour. During an inclined plane test, the tailings initially flow with a high velocity and slow before coming to rest. Because of this large variation in the velocity, it was necessary to use a constant, representative Bingham viscosity in analyses rather than a shear rate dependent viscosity.

The Bingham model contains a yield stress term (τ_y) followed by a constant viscosity term (η_B) as shown in Eq. (1):

$$\tau = \tau_y + \eta_B \gamma \quad (\tau > \tau_y) \tag{1}$$

where τ is the shear stress and γ the shear rate.

Tests were conducted for base angles ranging from 0 to 4°. Materials with yield stresses in the range of 17–210 Pa were used. The Bingham viscosities ranged from 0.006 to 0.035 Pa s.

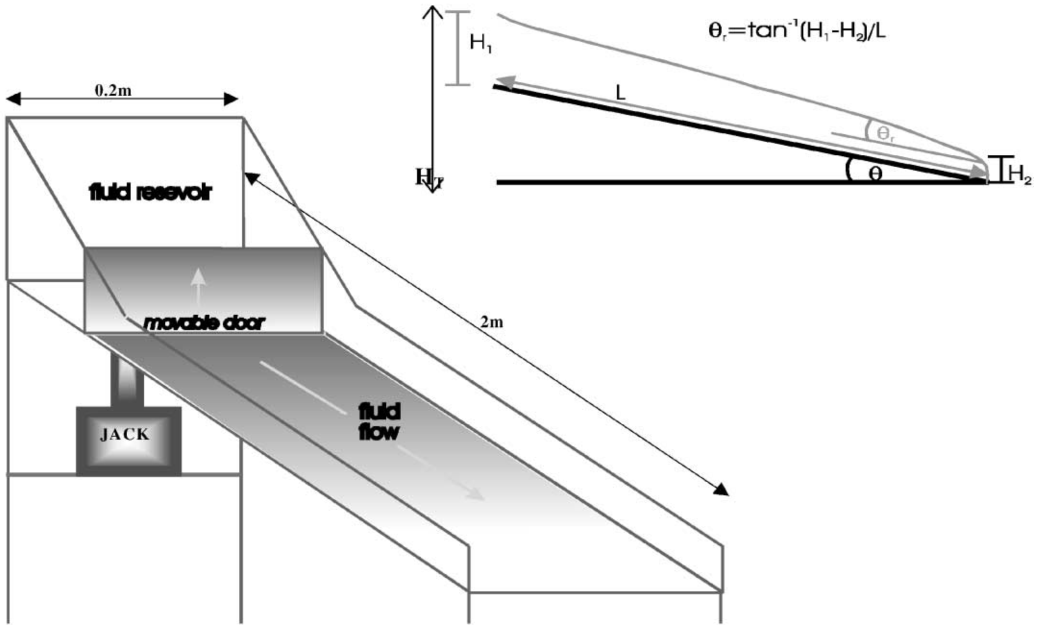

Fig. 11. Inclined plane apparatus and schematic diagram of stationary fluid on the inclined plane.

4.2. Inclined plane results

Fig. 12 shows the relationship between the angle of repose and the yield stress for a constant volume (constant initial height in the reservoir) of red mud deposited onto a flat plane. Both titanium dioxide and Laponite exhibited a similar linear relationship between the angle of repose and the yield stress, however, the gradients of the relationships for the three materials differed.

Inclined plane results presented in Fig. 13 show the angle of repose to be a consistent function of the base angle and the material yield stress for Laponite. Similar results were obtained for the red mud and titanium dioxide suspensions. As the base angle is increased for a given yield stress, the angle of repose decreases due to the greater apparent force of gravity. The initial volume of fluid in the reservoir was similar for all measurements shown.

An interesting observation arises when the reservoir volume is varied by filling it to a greater height. If the angle of repose depended on only the base angle and the yield stress, an increase in the volume deposited would result in a greater flow distance (Fig. 14), but the fluid would come to rest at the same angle of repose. Fig. 15 clearly shows

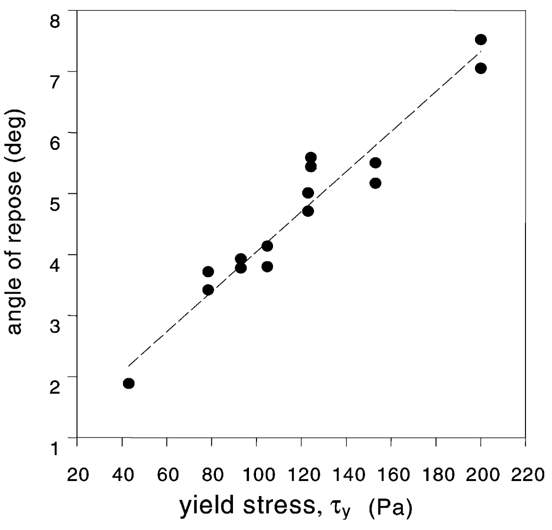

Fig. 12. Angle of repose vs. yield stress for red mud deposited onto a flat plane, constant initial height.

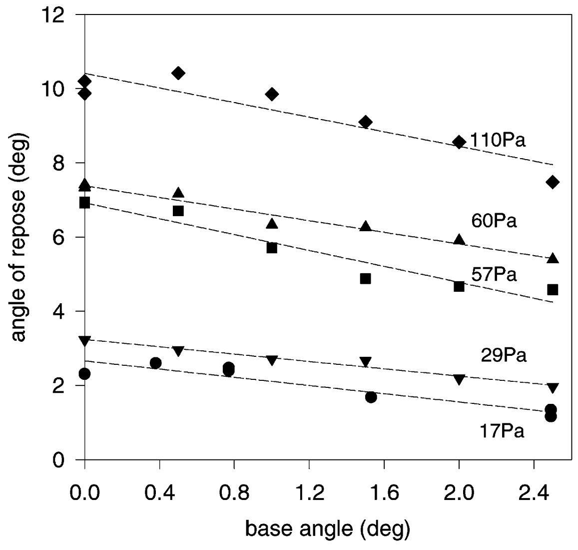

Fig. 13. Angle of repose vs. base angle for red mud at various yield stresses, constant initial height.

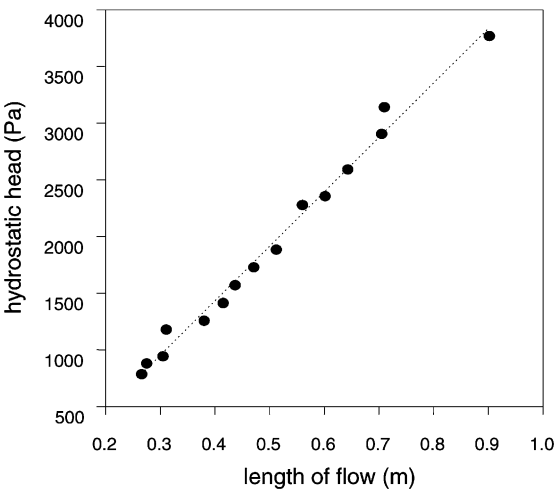

Fig. 14. Effect of hydrostatic head on flow length.

that this is not the case. As the volume of fluid deposited increases, the final angle of repose decreases, indicating that the material at the distal end of the flow is subjected to a greater 'pushing' force from the increased hydrostatic head.

In order to take the effect of the hydrostatic head into account, a dimensionless yield stress (τ_y') shown in Eq. (2) was used:

$$\tau_y' = \frac{\tau_y}{\rho g H_T} \tag{2}$$

where H_T is the initial height of fluid in the reservoir plus the height of the reservoir above the horizontal as shown in Fig. 10, ρ the material density, and g the gravitational acceleration.

Fig. 16 shows the variation in the angle of repose with dimensionless yield stress (τ_y') for two samples of red mud, titanium dioxide suspensions and Laponite suspensions. The dimensionless yield stress was varied by changing the sample yield stress, the volume of fluid used or the angle of the base.

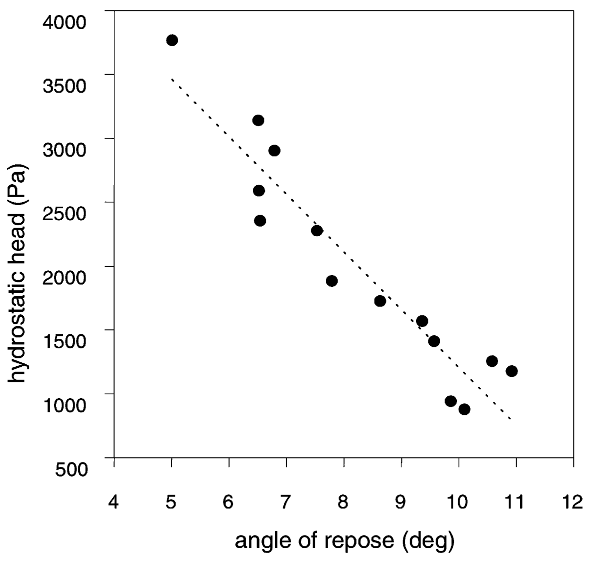

Fig. 15. Effect of hydrostatic head on angle.

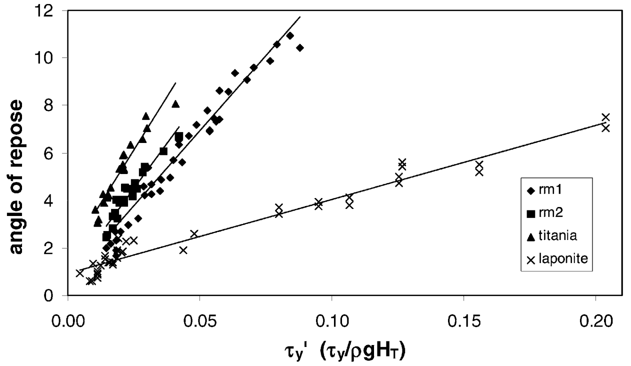

Fig. 16. Angle of repose vs. dimensionless yield stress for red mud, titanium dioxide and Laponite slurries.

It is evident from Fig. 16 that for each of the materials the angle of repose is a unique function of the dimensionless yield stress. The relationship indicates that the forces experienced by the free surface of the flow determine the angle of repose for a given material. The free surface of the flow will come to rest at an angle which is governed by the balance between the force required for flow to occur (the yield stress) and the 'pushing force' determined by the hydrostatic head. However, this relationship differs for the three materials, indicating that there is a material property not accounted for by the dimensionless yield stress alone.

4.3. Dimensional analysis

A dimensional analysis was carried out in order to investigate the material and geometrical parameters important in the inclined plane tests. Dimensional analysis allows the results and trends from the small scale situation to be compared to industrial observations. The parameters used are listed in Table 1.

The dimensional analysis indicated that the important dimensionless groups were the dimensionless yield stress (τ_y'), the Reynolds number (Re) and the Froude number (Fr), shown in Eqs. (3)–(5):

$$\tau_y' = \frac{\tau_y}{v^2 \rho} \tag{3}$$

Table 1
Parameters for dimensional analysis

Parameter	Symbol	Units	Dimensions
Angle of repose	θ	(°)	1
Plane width	W	m	L
Flow velocity	v	m/s	LT^{-1}
Slurry density	ρ	kg/m^3	ML^{-3}
Yield stress	τ_y	Pa (N/m^2, kg/(m s^2))	$ML^{-1}T^{-2}$
Viscosity	η	Pa s (kg/(m s))	$ML^{-1}T^{-1}$
Gravitational acceleration	g	m/s^2	LT^{-2}

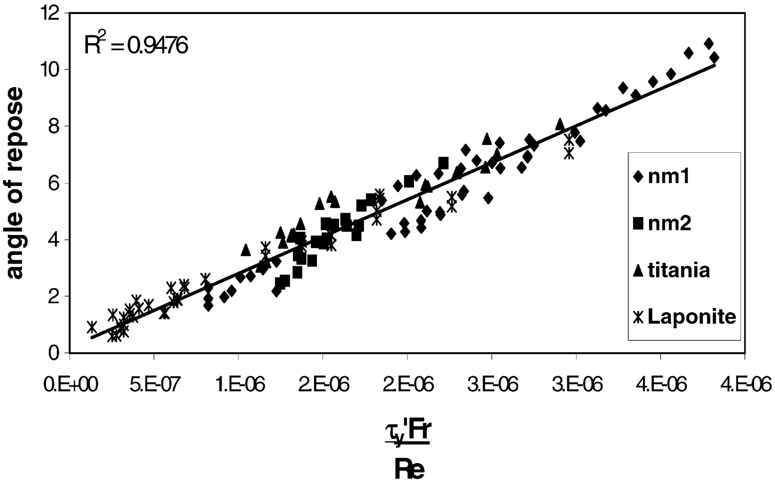

Fig. 17. Results of dimensional analysis: Angle of repose vs. $\tau_y' Fr/Re$.

Note: This definition of the dimensionless yield stress given in Eq. (3) is exactly half that given by the definition in Eq. (2).

$$Re = \frac{Wv\rho}{\mu} \tag{4}$$

$$Fr = \frac{v^2}{Wg} \tag{5}$$

therefore,

$$\theta = f(\tau_y', Re, Fr) \tag{6}$$

The instantaneous initial velocity was used in all of the dimensionless groups. In reality, as the fluid flows down the plane and comes to rest the velocity varies between this initial value and zero. The initial velocity was calculated by assuming that all of the potential energy (E_p) of the fluid in the reservoir was converted to kinetic energy (E_k) (i.e. negligible frictional losses).

$$E_p = E_k \tag{7}$$

$$\rho g H_T = \tfrac{1}{2}\rho v^2 \tag{8}$$

therefore,

$$v = \sqrt{2gH_T} \tag{9}$$

where H_T is the initial height of fluid in the reservoir relative to the horizontal, i.e. the height of fluid in the reservoir added to the height of inclination of the plane.

Having determined the relevant dimensionless groups, inspection of the parameters included indicates the appropriate form of the relationship between these groups and the angle of repose as shown in Eq. (10):

$$\theta = f\left(\frac{\tau_y Fr}{Re}\right) = f\left(\frac{\tau_y \eta}{\rho^2 W^2 g v}\right) \tag{10}$$

Eq. (10) shows that the angle of repose is governed by the balance between the parameters opposing flow (τ_y and η) and those contributing to flow. Application of the dimensional analysis to the inclined plane data in Fig. 17 shows that all of the data lie on a straight line with a correlation coefficient of approximately 0.95. The data points encompass a range of slurry densities (1000–2000 kg/m^3), viscosities (0.0058–0.0382 Pa s), yield stresses (17–126 Pa), flow velocities (1–2.4 m/s) and base angles (0–4°). The good fit indicates that the pertinent material and geometrical parameters have been included for the inclined plane case.

The results presented here indicate that a knowledge of the material rheology, the slope of the underlying base and the depositional velocity allows the angle of repose to be predicted. However, for this analysis to be applied to a tailings disposal situation, the effect of lateral spreading needs investigation.

5. Compression rheology

Although a thorough discussion on compression rheology is outside the scope of this paper, characterisation of compression rheology is necessary to determine thickening requirements and is an integral part of dry disposal design and implementation.

Prior to deposition, the slurry must be thickened to the concentration found in shear rheology tests to provide the desired deposition characteristics whilst ensuring that the material is still easily pumpable. Thickening is usually achieved using gravity thickeners with an appropriate polymeric flocculant. Choice of the flocculant and operating conditions within the thickener is determined by examining the shear, compression and permeability characteristics of the suspension.

The shear yield stress (the shear stress required for irreversible flow to occur) is important in the determination of piping and deposition behaviour. Likewise, the compressive yield stress, coupled with the permeability of the material, provide information regarding the feasibility of de-watering the residue to the concentration required for dry disposal. The compressive stress is the stress required for irreversible compression of the network structure and the permeability dictates the rate of de-watering and accounts for the hydrodynamic interactions between falling particles in a suspension [28].

In a conventional gravity thickener, a continuous network structure is formed through the aggregation of particles or flocs containing interparticle water. The compressive yield stress, beyond which the transmitted network pressure of the overlying structure will cause the collapse of the structure and syneresis of liquor, is concentration-dependant [28]. Increasing the compression zone depth by increasing the bed height subjects, the material at the bottom of the thickener to a greater applied pressure and the material will consolidate to a higher concentration.

An understanding of the compression zone depth required to overcome the compressive yield stress at a given concentration, and the variation in this relationship with factors such as flocculant dosage and shear history will facilitate optimisation of thickener performance [29].

While the compressive yield stress gives and indication of the underflow concentration possible, the permeability determines the rate of the de-watering process. Permeability is influenced by the liquor viscosity, the flocculation conditions and the solids concentration. The liquor viscosity can vary with temperature and dissolved solids concentration and affects the rate at which the liquid can move upward through the particulate matter [30]. Flocculation conditions (type, dose and addition method) affect the suspension structure formed, the relative amounts of entrapped inter and intrafloc liquid and the ease of liquid permeating through the structure.

A portable apparatus that is capable of determining the compressive yield stress and the permeability for use in thickener modelling to allow optimisation of the thickening process has been developed and built at the University of Melbourne [31].

6. Applications

Characterisation of the shear and compression rheology of mineral tailings using the aforementioned techniques has been instrumental in the development and implementation of dry disposal schemes in Australia and abroad.

Alcoa of Australia first implemented the dry stacking scheme in 1985, and has since adopted the method for all of its Australian and Suriname plants. Flow data were initially used for the pipeline design, prediction of optimum pumping conditions, determination of bed slope and thickener operation. Presently, rheological information combined with knowledge of how to manipulate the rheology is used for the optimisation of the entire disposal process.

The dry stacking disposal method has proved to be very successful in minimising many environmental, technical and economic problems inherent in the previous wet disposal schemes [16,32,33].

Paste fill at the BHP Cannington mine is presently being implemented [34] with a concurrent rheological study being undertaken in the Particulate Fluids Processing Centre [35]. Yield stress measurement via the slump test is used extensively to ensure that the material to be deposited underground will have the required spreading and strength properties.

The thickened tailings disposal at WMC's Mt Kieth nickel operation uses the thickener as a type of rheometer [36]. The yield stress of the thickener underflow is kept relatively constant (leading to a relatively constant depositional slope) using the torque reading of the rake in the thickener. The concentration of the underflow will vary with ore type as the relationship between concentration and yield stress will differ. If the underflow was kept at a constant concentration, the yield stress of the material being deposited would fluctuate and the constant depositional slope required for the formation of a uniform cone would not be obtained.

In the coal industry, the impact of general operating practices coupled with the modification of the rheology via surface chemistry will increase the tailings processing rate and decrease the water content of the residue [21]. Although full-scale commercial operation has not been implemented, significant improvements are anticipated in terms of plant economics, environmental and practical considerations.

7. Conclusion

Due to the complex rheology of mineral tailings under shear and compressive forces, knowledge of the rheological properties allows the design of a disposal scheme that takes best advantage of the material behaviour without affecting upstream plant performance. Furthermore, an insight into how to change or manipulate the rheology may facilitate waste disposal in a manner that is more environmentally and economically favourable than conventional methods.

The implementation and optimisation of dry disposal methods involves three concurrent and interdependent rheological studies to determine: (i) the concentration required to achieve the optimum spreading and drying characteristics of the tailings once deposited; (ii) the optimum conditions for pipeline transport; and (iii) the feasibility of de-watering the slurry to the required concentration. The technical methods outlined in this paper provide the rheological background required to complete these studies.

As environmental factors translate into economic issues, the push for minimising waste production using dry disposal methods is gaining popularity. The use of rheological information is of high importance in evaluating the pipeline transportation requirements, the angle of repose or slope formed and the de-watering requirements for thickened mineral tailings. The principles outlined in the examples given in this paper may be applied to many industries encompassing a wide range of waste materials.

The angle of repose formed by thickened slurries deposited onto an inclined plane can be predicted based on a dimensional analysis. The angle of repose for materials of varying rheology and density has been found to be a function of the dimensionless yield stress, the Reynolds and the Froude numbers. It is anticipated that the model will be a useful tool in the prediction of the angle of repose formed during the disposal of thickened tailings and pastes. Further work is required to determine the effect of lateral spreading in large scale industrial applications.

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