3

Chapter 3

Rheological Concepts

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3.1 PREAMBLE

Current practice in the minerals and oil sands industries often involves pumping the bottom stream from a clarifier at low concentration to a waste disposal site or tailings storage facility (TSF). For conventional low-density tailings this is invariably contained by earthen embankments, although, in some parts of the world, this waste is still being pumped into rivers or into the sea. There is no doubt that the industry is changing and moving towards thickening the clarified waste to a varying extent, which can lead to thicker tailings, paste tailings, or a direct mine stope fill. There are many reasons to move in this direction related to water recovery, the environment and, perhaps, even economic reasons (see Chapter 2). The industry is moving towards a situation that will ensure a disposal site involves less risk, is stable and environmentally acceptable. In the future we will even see rehabilitation taking place while deposition is still taking place and not only at the end of the mine's life, which is the current practice if the company is still in operation.

Once the clarified waste stream in these industries is thickened above a certain consistency it will exhibit non-Newtonian behaviour. Therefore, the determination of the disposal system design and operating conditions requires a thorough understanding of the rheological characteristics of the material, both in shear and compression. The implementation and optimisation of a thickened disposal strategy involves three concurrent and independent rheological studies to determine:

- The concentration required to achieve the optimum characteristics for management and/or storage of the particulate waste fluid.
- The optimum conditions for pipeline transport to the storage area.
- The feasibility of dewatering the slurry to the required concentration prior to transportation.

Thickened disposal is defined here as any system designed to take advantage of a high-density thickened and/or paste tailings. This chapter provides an informed background to ensure the appropriate rheological issues are addressed as part of the overall tailings design and management strategy.

The main criterion for the success of a tailings management system is to implement and operate a safe and environmentally responsible system at minimum cost. Exploitation and manipulation of the transport and deposition characteristics of the tailings are vital to ensure that the appropriate disposal system is operated successfully.

A thickened disposal system is selected and designed to minimise the pumping energy required whilst delivering a material at the velocity, yield stress and viscosity needed for the desired slope and spreading characteristics for surface deposition, and/or the desired characteristics for mine stope fill. This chapter elucidates the significance of rheological characterisation for the planning, design, operation and optimisation of thickened disposal systems that are considered here to include dry stacking, central thickened tailings disposal, and paste backfill.

3.2 SUMMARY FLOWSHEET FOR THE SELECTION, DESIGN AND TESTING FOR THICKENED DISPOSAL IMPLEMENTATION

Figure 3.1 summarises the rheology-based decisions, considerations and test work required for a proposed implementation strategy in flow chart form. Any greenfield site should examine the entire process, ranging from thickening through to the ultimate disposal. Often the issue is dealt with by particular consultants and/or contractors for each part of the process; one for thickening, one for pumping, and another for the construction and management of the disposal site. An integrated approach is required. Note that in addition to the rheology and rheological properties, the chemistry can also be quite important; clay is a major issue in many mineral waste tailings. When clays are present in the orebody the waste product can be very difficult to handle and will often not consolidate to any significant concentration. Some mineral, sand mine, and oil sand processors do not know the specific types of clay they are or will be encountering. Understanding the basic chemistry of the clays in the waste material is important as sometimes it can be changed to have a considerable impact on the ultimate disposal strategy (see Chapter 5 for more information on slurry chemistry). As an example of the importance of clay chemistry, Figure 3.2 illustrates a clay at 25% w/w solids, where the flow characteristics vary dramatically with method of dispersion. Dispersion with water only (left) yields a potter's clay, while controlled dispersion with 1 M $CaCl_2$ (right) yields a settling, well-behaved suspension. Uncontrolled dispersion (centre) yields a non-settling viscous suspension. Clays in the uncontrolled dispersed state often end up in tailings ponds and never consolidate.

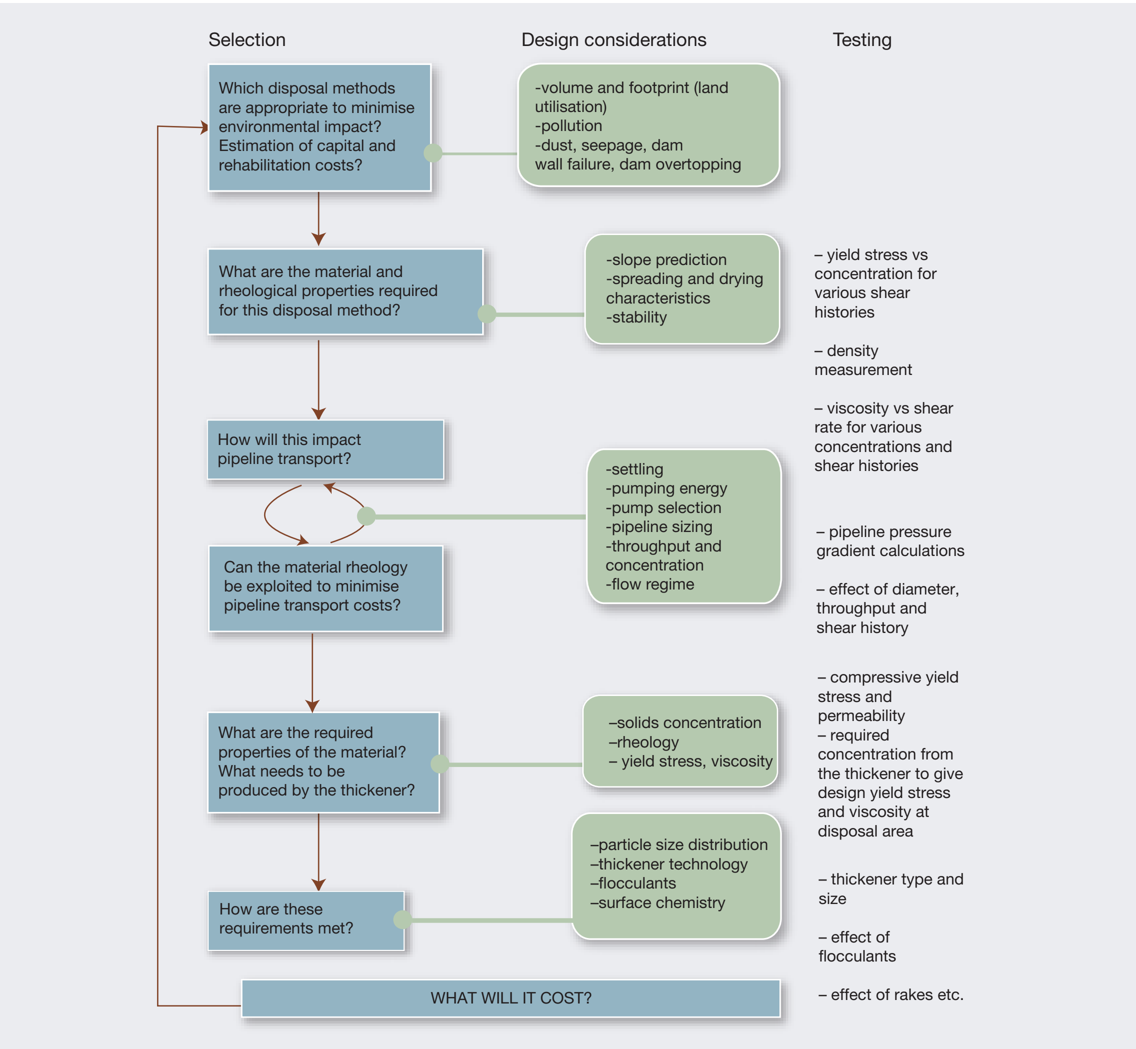

FIGURE 3.1 Planning, design and testing flow sheet

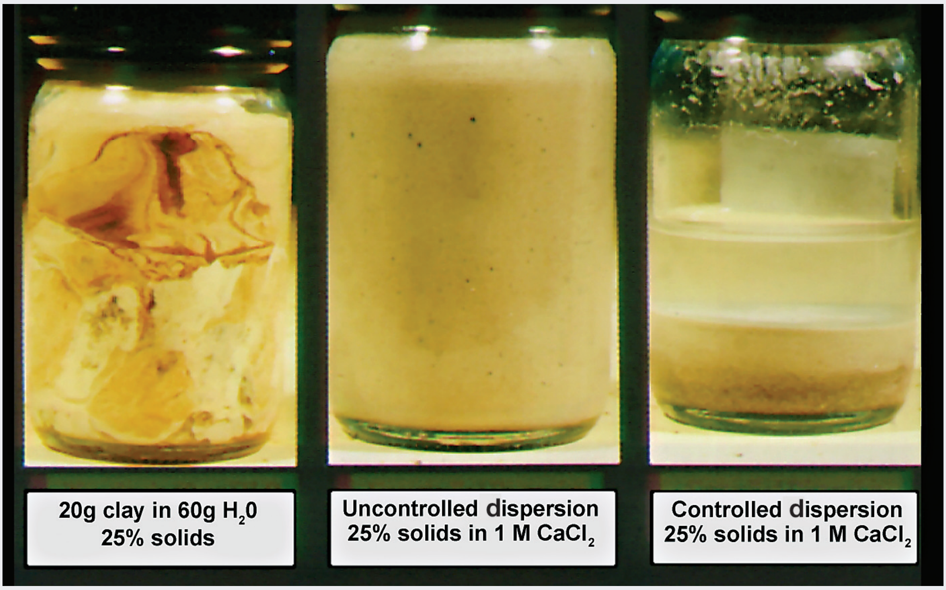

FIGURE 3.2 Controlled dispersion of a montmorillinite clay

3.3 THE IMPORTANCE OF RHEOLOGY IN A THICKENED DISPOSAL IMPLEMENTATION STRATEGY

By considering tailings rheology at all points during the design phase, implementation strategies can be developed for new operations or existing systems optimised to reduce operating costs and/or the impact on the surrounding environment, and for the recovery of the water.

The strategy proposed in this chapter looks at designing the tailings to suit the surrounding environment, with consideration being given to the choice and operation of the disposal method. Figure 3.3 briefly summarises the steps involved in determining a disposal strategy. It is important to note that the design sequence begins at the disposal point and works upstream (back) to the thickening stage.

Point 1 in the design sequence represents the choice of the disposal method and the rheological properties required to achieve the desired footprint and shape of the final deposit (depositional requirements). Point 2 refers to the pumping and pipeline conditions needed for optimal transport whilst ensuring the tailings reach the disposal site

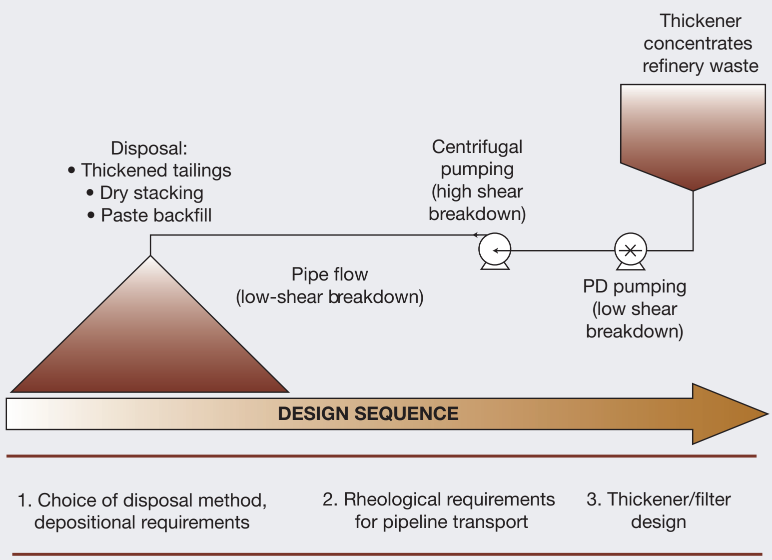

FIGURE 3.3 Suggested approach for the determination of tailings disposal system and requirements

with the rheological properties necessary for the chosen disposal method (pipeline requirements). Rheological properties sometimes change in the pipeline itself.

Once the depositional and pipeline issues have been quantified and optimised on paper, it is possible to determine the thickening requirements represented by point 3 in Figure 3.3. The thickener should be designed and operated to produce the required tailings' properties via determination of thickener size and geometry, and control of flocculation and pre-treatment requirements. If the thickener requirements cannot be achieved then the process is repeated.

For clarity, the design sequence is depicted in Figure 3.3 as a linear sequence. However, in reality the disposal system and thickener should be designed using an iterative approach in order to optimise the entire disposal operation.

3.4 IMPORTANT RHEOLOGICAL CONCEPTS

Rheology is the study of the deformation and flow of matter. In terms of fluid flow, materials may be classified as either Newtonian or non-Newtonian fluids. The viscosity (η) of a fluid is defined as the ratio of the shear stress (τ) to the shear rate ($\dot{\gamma}$), as shown in Equation 3.1. In many flows, the shear rate is equivalent to the gradient in velocity.

$$\eta = \frac{\tau}{\dot{\gamma}} \tag{3.1}$$

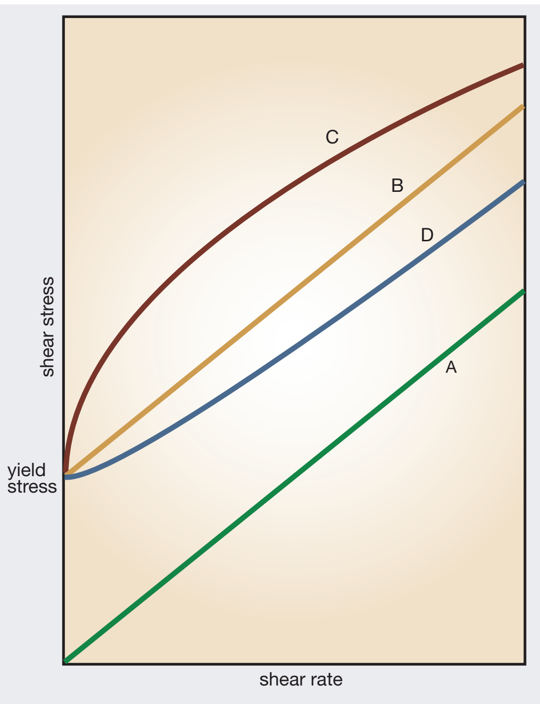

FIGURE 3.4 Typical flow curves. A) Newtonian; B) Bingham (yield-constant viscosity); C) Yield-pseudoplastic; D) Yield-dilatant

Inelastic Newtonian fluids exhibit a linear relationship between the applied shear stress and the shear rate, as shown in Curve A in Figure 3.4. Flow is initiated as soon as a shear stress is applied. The linear relationship between the shear stress and the shear rate indicates a constant viscosity.

Concentrated mineral tailings often display non-Newtonian flow behaviour in that they possess a yield stress. The yield stress (τ_y) is the critical shear stress that must be exceeded before irreversible deformation and flow can occur. For applied stresses below the yield stress, the particle network of the suspension deforms elastically, with complete strain recovery upon removal of the stress. Once the yield stress is exceeded, the suspension exhibits viscous liquid behaviour where the viscosity is usually a decreasing function of the shear rate. Yield stress behaviour is shown by the constitutive relationships of Equations 3.2 and 3.3.

$$\dot{\gamma} = 0 \qquad \tau < \tau_y \tag{3.2}$$

$$\tau = \tau_y + \eta_{(\dot{\gamma})}\dot{\gamma} \qquad \tau > \tau_y \tag{3.3}$$

Curve B on Figure 3.4 shows a yield stress followed by a linear shear stress – shear rate relationship, commonly known as Bingham behaviour. Although not a true viscosity according to Equation 3.1, the gradient of this line is referred to as the Bingham plastic viscosity.

Table 3.1 lists typical yield stress values. The values listed for thickened tailings disposal ranging from 30 to 100 Pa are indicative of those used in the alumina industry today. There are other thickened tailings strategies where the material is discharged and flows like a river delta, where the yield stress would be greater than 0 but below 30 Pa. Mine stope fill is a true paste material where the yield stress, in our experience, can become as high as 800 Pa.

TABLE 3.1 Typical yield stress values

Substance	Yield stress (Pa)
Tomato sauce	15
Yoghurt	80
Toothpaste	110
Peanut butter	1900
Thickened tailings disposal	30–100
Mine stope fill	250–800

In addition to yield stress behaviour, the viscosity of the material will vary with shear rate. As the shear rate is increased, pseudoplastic or shear thinning materials exhibit a decrease in the viscosity (Curve C, Figure 3.4). Dilatant or shear thickening materials exhibit an increase in viscosity with increasing shear rate (Curve D, Figure 3.4). Dilatant behaviour, although relatively rare, is sometimes observed in mineral suspensions. For the different fluid categories, various empirical flow models are used to describe the flow behaviour. The most commonly used equations are the Ostwald–De Waele model for shear thickening or shear thinning materials, the Bingham model for yield stress materials and the Herschel Bulkley model for yield stress, shear thinning or yield stress, shear thickening materials.

Ostwald–De Waele power law model:

$$\tau = K\dot{\gamma}^{n} \tag{3.4}$$

Bingham model:

$$\tau = \tau_B = \eta_B\dot{\gamma} \tag{3.5}$$

Herschel Bulkley model:

$$\tau = \tau_{HB} + K\dot{\gamma}^{n} \tag{3.6}$$

In these equations, K and n are experimentally determined constants.

The shear thinning nature of industrial tailings is attributed to the alignment of particles and/or flocs in the flow field. An increase in the shear rate from rest, results in instantaneous alignment of particles in the direction of shear, thus providing a lower resistance to flow. As such, the suspension will show a decreasing viscosity with increasing shear rate.

Data on mineral suspensions are often not available at low shear rates. A common practice is to extrapolate the linear portion, say, of Curve C in Figure 3.4 to the y-axis and refer to this as the yield stress. This is a Bingham yield stress which bears no relationship whatsoever to the true yield stress of the material. The linear portion of the curve being fitted in this way sometimes is appropriate for pipeline design but a yield stress determined in this way is far from adequate for the design of a thickener; more accurate yield stress measurements can be and should be made.

The most complicated non-Newtonian behaviour, which can be observed in mineral and tar sand, and associated industries, is time-dependent behaviour. Here, the shear stress is a function of both shear rate and time of shear. Basically, this is the case where the alignment of the particles and/or flocs occurs on a timescale which can be observed in the rheometer. The classical example of this behaviour is for red mud in the alumina industry (Boger et al., 2002). For such materials, the viscosity depends both on shear rate and time, whilst the yield stress also varies with time. When such a material is encountered it is necessary to see how the yield stress varies with time and to measure the shear stress in the material in a rheometer as a function of time at particular shear rates. Alternatively, with a constant stress rheometer, fix the stress and watch how the shear rate varies with time. Thixotropic behaviour is the most common, where the viscosity decreases with shear rate and time. Rheopectic behaviour, the time-dependent dilatant behaviour analogue, is observed far less often, but when it does occur, it can present disastrous consequences. Here, the viscosity increases with shear rate and time. Such behaviour is quite perplexing for the engineering community, where the tendency is, when in doubt put in more energy, or hit it harder with a hammer. For example, in a mixing vessel, if the viscosity increases with shear rate and time then any effort to get better mixing by increasing the rotational rate of the impeller will, and can, result in catastrophic consequences. We have seen this happen on a few occasions in the past with mineral suspensions. It is very important to have a basic classification of the particulate fluid to be encountered in your industry.

3.5 RHEOLOGICAL PROPERTY MEASUREMENT

There are entire books written on rheological property measurement (rheometry). For particulate fluid suspensions and, in particular, more concentrated suspensions like those that will be encountered for thickened tailings disposal, many of the rheological instruments available will not be applicable. All of those relying on a small gap between the shearing surfaces, like a cone and plate geometry or a parallel plate geometry, generally are not used and are not applicable in the industry. The most common instrument used is that which relies on Couette flow, involving confinement of the sample between a rotating cup and a stationary bob, or (vice versa) a rotating bob and a stationary cup. Here, the torque is measured as a function of rotational speed

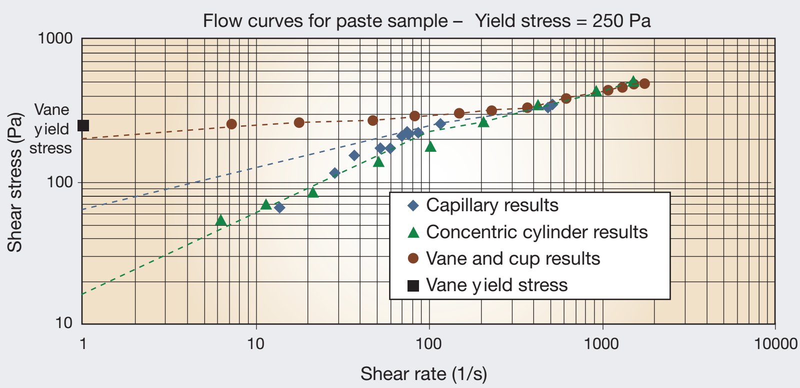

FIGURE 3.5 Flow curves for a mine stope fill sample, yield stress = 250 Pa

and can be interpreted to determine the shear stress as a function of shear rate. Extrapolation of data to zero shear rate from such an instrument is generally not a good way to determine the yield stress. Sedimentation of the sample in a Couette rheometer and slip at the wall are common problems. Another way to obtain shear stress – shear rate measurements generally is with a capillary rheometer or from actual pipe loop-test data obtained in laminar flow. Here, the wall shear stress:

$$\tau_w = \frac{D\Delta p}{4l} \tag{3.7}$$

where Δp, the fully developed flow pressure drop in a pipe of length l is measured as a function of the apparent wall shear rate $8V/D$, where D is the pipe or tube diameter and V is the average velocity in the pipe. The wall shear rate:

$$\dot{\gamma}_w = \frac{3n' + 1}{4n'}\left(\frac{8V}{D}\right) \tag{3.8}$$

can be determined from the slope of a log–log plot of τ_w versus $8V/D$ The shear rate dependent viscosity is then $\eta = \tau_w / \dot{\gamma}_w$. Data of this type are very useful for design purposes (see Chapter 8).

Figure 3.5 shows flow curves for a mine stope fill material with a yield stress of 250 Pa. Note the discrepancy in the data at lower shear rates. The capillary results and the concentric cylinder results agree for shear rates in excess of 300 s^{-1} but deviate and drop away significantly at the lower shear rates from those obtained with the vane and cup. If the inner rotating cylinder in a Couette apparatus is replaced by a vane, problems associated with slip are generally eliminated. The true yield stress of the material shown in Figure 3.5 was about 250 Pa, whereas the data obtained both from the capillary and from the concentric cylinder present values of 64 Pa or 17 Pa, depending on the extrapolation used. The huge difference would have a very significant effect on design, particularly of a thickener. The first lesson to learn is that data obtained with a concentric cylinder rheometer and sometimes with a capillary rheometer will often be in significant error at low shear rates. Great care must be taken, particularly if used to determine a yield stress.

In summary, the rheological measurements of most interest for thickened tailings are generally obtained with a concentric cylinder apparatus and/or from a capillary rheometer. The vane and cup, which is a relatively new technique, represents what we believe is the best way to go in terms of determining both the yield stress and basic shear rate – shear stress data for viscous shear thinning suspensions.

3.6 RHEOLOGICAL REQUIREMENTS FOR THE CHOSEN DISPOSAL METHOD

We will now move step-by-step through the procedure recommended in Figure 3.3.

3.6.1 Depositional requirements — Point 1, Figure 3.3

Often an essential depositional requirement is to deliver tailings to the disposal point with a yield stress sufficient to support the largest particles and ensure a homogeneous suspension where segregation does not occur. Differential segregation upon deposition will result in a non-uniform deposit slope and inefficient use of the disposal area. The relationship between the solids concentration and the yield stress should be determined in the first instance to indicate the minimum concentration necessary to obtain this yield stress.

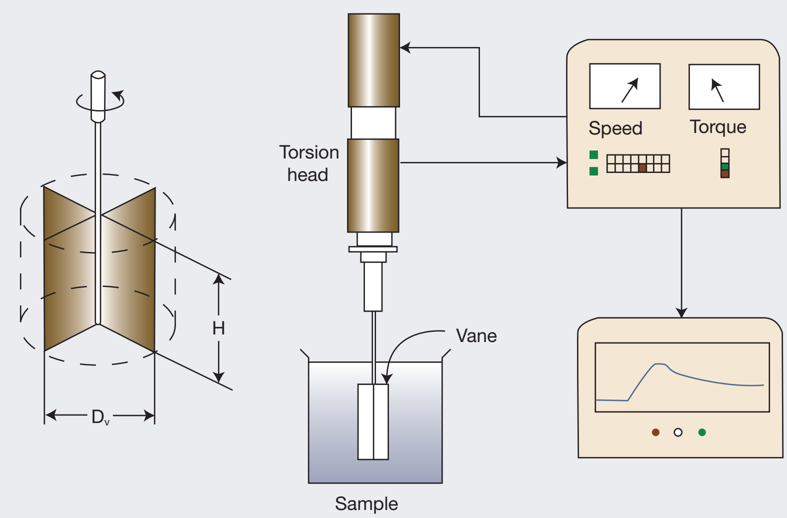

FIGURE 3.6 The vane technique

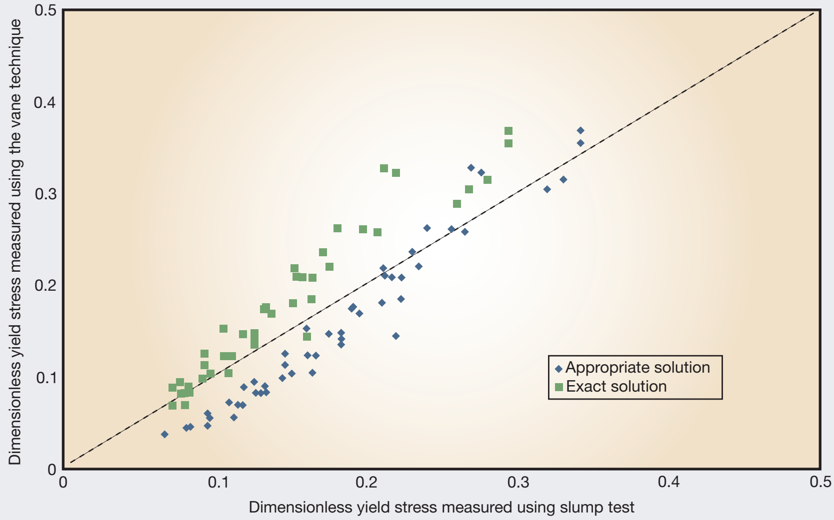

FIGURE 3.7 **Comparison of yield stress measuring techniques**

A significant amount of work on the measurement of the yield stress for mineral suspensions has been completed. From these works, 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 (Nguyen, 1983; Nguyen and Boger, 1983, 1985). Many workers worldwide have adopted the vane-shear method and confirmed its applicability for all types of yield stress materials (Yoshimura et al., 1987; James et al., 1987; Avramidis and Turian, 1991; Liddell and Boger, 1996; Pashias, 1997).

Figure 3.6 shows an illustration of the four-bladed vane and the technique for yield stress measurement. Basically, the vane, attached to a torsion measuring head, is carefully inserted into the test material and rotated at a low speed where the torque as a function of time is measured. The maximum in the torque curve is related to the yield stress via Equation 3.9, where T_m is the maximum torque; D_v is the diameter of the vane; and H/D_v is the aspect ratio of the vane cylinder.

$$T_m = \frac{\pi}{2} D_v \left(\frac{H}{D_v} + \frac{1}{3}\right) \tau_y \qquad (3.9)$$

In an attempt to further simplify yield stress measurement, the "slump test" has been modified to accurately evaluate the yield stress of mineral suspensions (Showalter and Christensen, 1998; Pashias et al., 1996; Boger et al., 2002). The technique has typically been used to determine the empirical flow characteristics of fresh concrete and is important in mine stope fill. The slump test is conducted using an ASTM standard slump cone, or with a cylinder and ruler, eliminating the need for sophisticated equipment and allowing easy, on-site yield stress measurement by

TABLE 3.2 **Slump height versus yield stress: density dependence**

Variable	Coal tailings	Gold tailings	Lead–zinc tailings
Specific gravity (kg/m^3)	1450	2800	4100
Solids concentration (%w/w)	36	75	75
Slurry density (kg/m^3)	1120	1930	2310
Slump height (mm)	203	203	203
Calculated yield stress (Pa)	**160**	**275**	**330**
Predicted pressure drop (kPa/m)*	**5.07**	**8.13**	**9.60**

*Pressure drop prediction assumes:

- Bingham material
- Bingham viscosity – 1 Pa.s
- Horizontal pipeline
- Pipeline internal diameter = 200 mm
- Pipeline velocity – 1 m/s

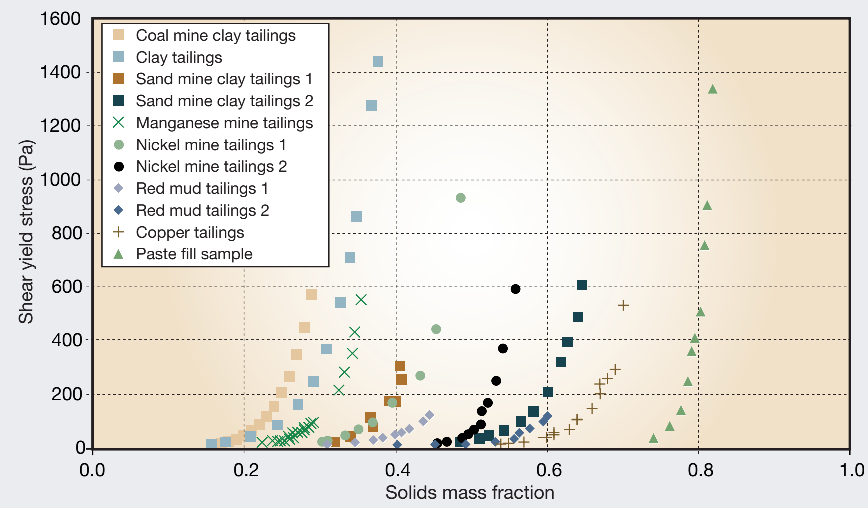

FIGURE 3.8 **Yield stress concentration data for different industry waste streams**

plant operators. We recommend the use of a cylinder. The equation for evaluating the yield stress from a slump height measurement is given in Equation 3.10:

$$\tau'_y = \frac{1}{2} + \frac{1}{2}\sqrt{S'} \quad \text{(approximate solution)} \qquad (3.10)$$

where τ'_y is the yield stress dimensionalised with respect to ρgh; and S' is the dimensional slump measurement, which is dimensionalised with h, the height of the slump cylinder; ρ is the density of the suspension; and g is the acceleration due to gravity.

A comparison of the yield stress derived from the slump measurement and the yield stress measurement with the vane is shown in Figure 3.7. Users of the slump method persist in measuring the slump in a linear dimension, centimetres of slump. This is an empirical measure and will vary from material to material depending upon its density. Table 3.2 eloquently illustrates the point that the slump is not a unique physical property measurement. Here, a coal tailings, a gold tailings, and a lead–zinc tailings, are all

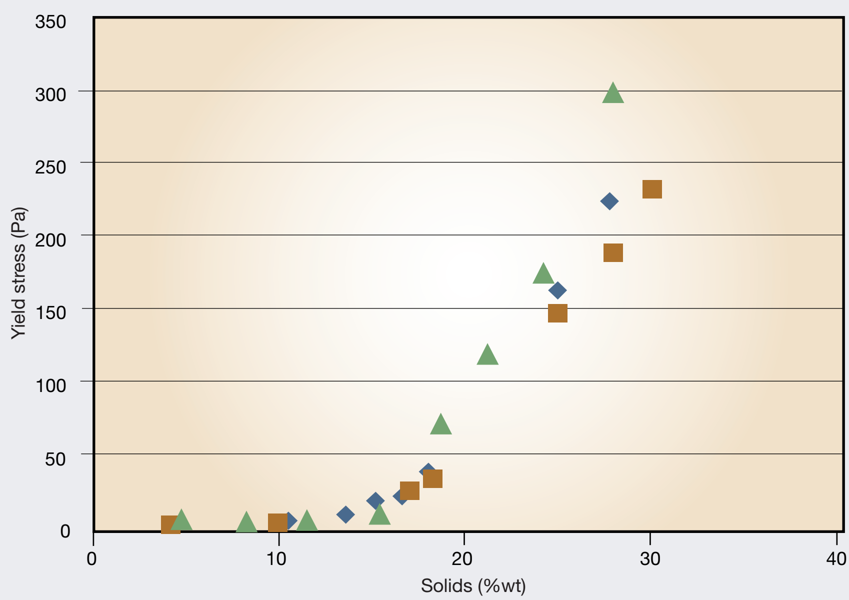

FIGURE 3.9 **Yield stress concentration data for clay waste from the phosphate industry**

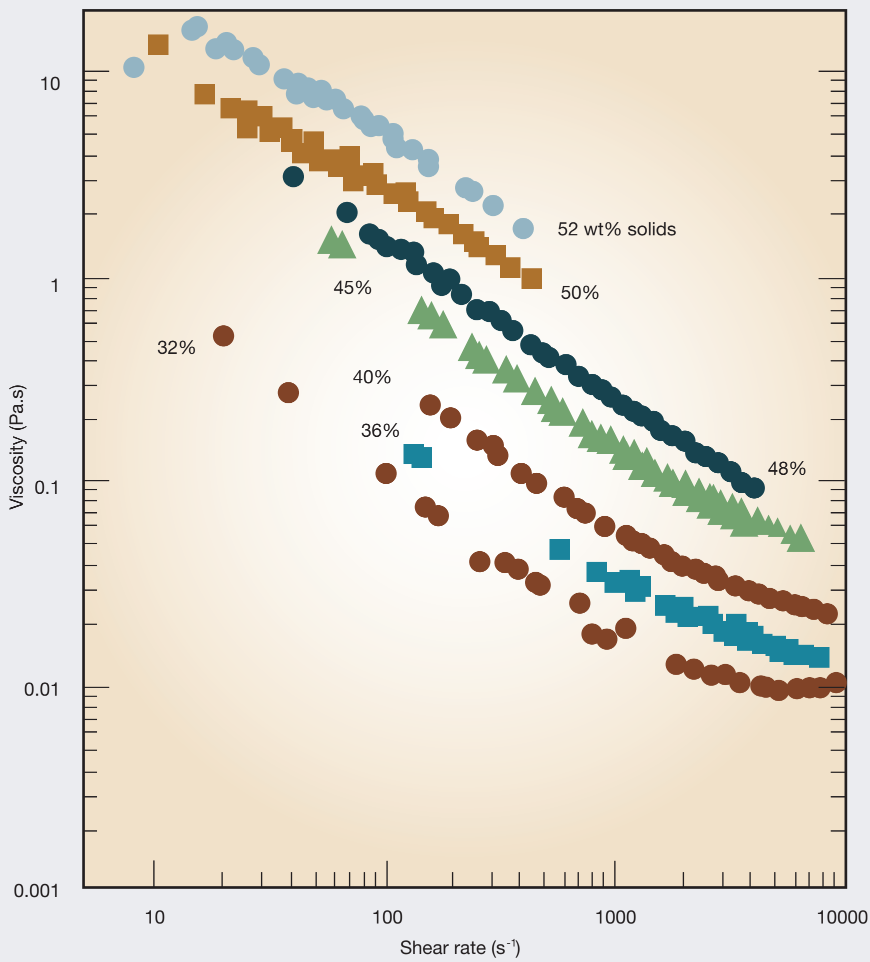

FIGURE 3.10 **Viscosity shear rate data for a coal washery thickener underflow**

concentrated to a stage where they produce the same slump, 203 mm. Hence, at first glance they all appear to be the same in terms of their flow characteristics. This, however, is not so. The three materials are vastly different in that their yield stress varies from 160 Pa, to 275 Pa, to 330 Pa respectively, for coal, gold and lead–zinc tailings. If, indeed, we use these slump measurements as a Bingham yield stress, and if all the materials have the same Bingham viscosity of 1 Pa, the pipeline pressure drops will be vastly different. However, if the slump is converted to a yield stress, as per Equation 3.10, then we certainly see the difference in the materials.

The flow properties of concentrated mineral suspensions vary significantly with solids concentration, particle size and size distribution, pH and ionic strength. However, a number of common characteristics have been observed for concentrated suspensions in general. The strong dependence of rheology on concentration is illustrated in Figure 3.8, which shows the yield stress as a function of concentration for eleven different mineral tailings. The first thing that is obvious from the figure is that every material is different, even within the same industry, as was illustrated for the waste from bauxite residue (red mud) in the first edition of this Guide (Boger et al., 2002). All materials exhibit an exponential rise in the yield stress with concentration, with the yield stress generally beginning to rise rapidly for yield stresses beyond about 200 Pa. Remember now the range of yield stresses used for the various thickened exercises. For thickened tailings the yield stress might range from a very low value to about 30 Pa. High-density thickened tailings for distribution on the surface generally are handled at yield stresses of about 30-100 Pa and it is now believed that suspensions can be pumped up to a yield stress of about 200 Pa with a centrifugal pump. Paste backfill materials are often handled at yield stresses significantly higher than 200 Pa. The type of curve shown in Figure 3.8 is the first step in evaluating the potential for a particular waste-disposal strategy, based on the material properties of the tailings. The concentration at which the yield stress begins to rise rapidly is very significant, particularly when optimising pumping energy requirements.

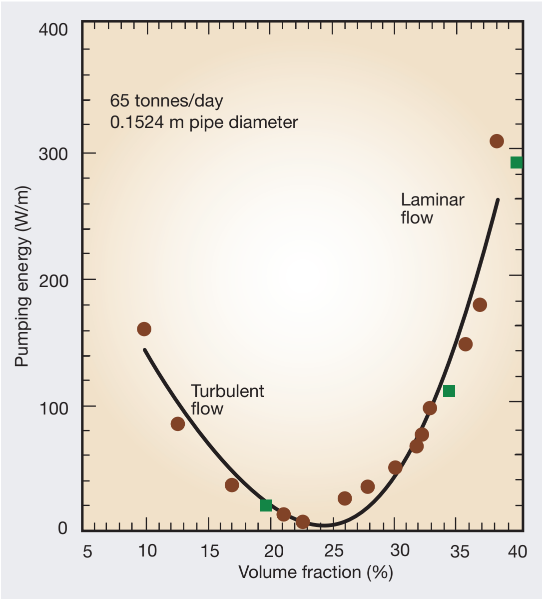

FIGURE 3.11 **Optimum concentration for pumping the coal washery underflow**

As already stated, for thixotropic materials shear history must be taken into account when determining the yield stress – concentration relationship. During a design phase it is unlikely that the extent of structural breakdown during pipeline transfer will be known. As such, the yield stress – concentration relationship should be determined for structural states ranging from the initial (rest) to the equilibrium state (fully sheared).

From data like that shown in Figure 3.8, the concentration range required to produce the desired yield stress can be determined. The slope obtained for a given material enables the disposal area to be sized. Increase in the yield stress will generally produce a steeper slope and reduce the footprint; however, even today it is not possible to precisely predict the slope of the angle of deposition from yield stress measurements only.

Figure 3.9 shows the yield stress as a function of solids concentration for the fine particle clay waste stream in the phosphate industry. The fine particle waste produced in this industry causes the most difficulty in terms of consolidation. Generally, these materials are pumped to disposal areas at concentrations less than 10% by weight and consolidation in a dam to concentrations greater than 30% is rare. In some cses it may be possible to shift the curve in Figure 3.9 significantly to the right by controlling clay chemistry, resulting in a higher solids content and thus higher in situ dry density in the TSF.

3.6.2 Pipeline transportation requirements — Point 2, Figure 3.3

The data required as a first step in the design of a transmission pipeline for a tailings are viscosity – shear rate data as a function of concentration, such as the results shown in Figure 3.10 for an Australian coal waste stream. The material exhibited no significant thixotropy, was highly shear thinning, and demonstrated normal viscosity concentration behaviour. Also, the yield stress for this material was obtained as a function of concentration. Using the yield stress data and the viscosity – shear rate data for different concentrations, the results shown in Figure 3.11 were obtained. Here, the pumping energy requirements in

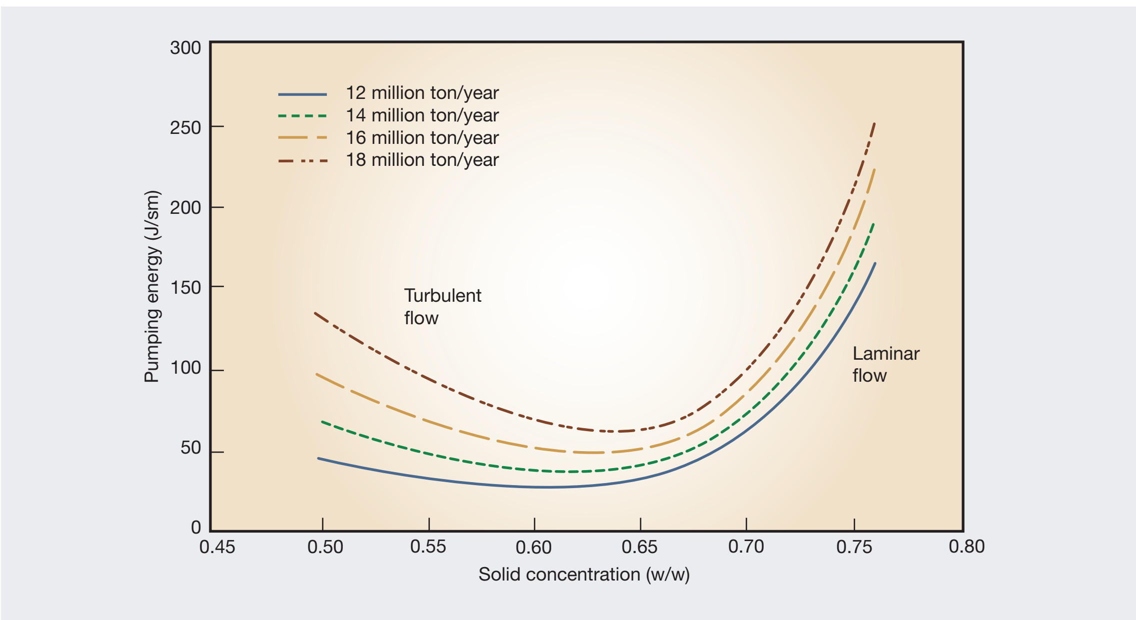

FIGURE 3.12 **The predicted pumping energy as a fraction of solids concentration for a 50.8 cm (20 inch) diameter pipeline at various capacities**

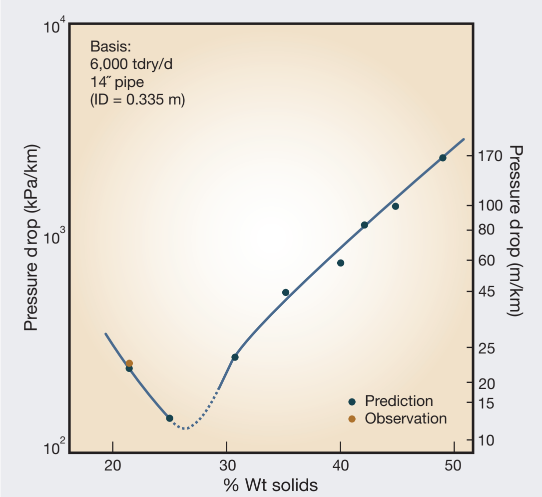

FIGURE 3.13 **Prediction versus observation in an existing bauxite-washing operation of the waste tailings**

watts per metre length of pipe are expressed as a function of volume fraction for the delivery rate expected in a 0.1524 m diameter pipeline. Notice that there is a minimum in the curve that coincides with the minimum energy requirement for pumping this material at this concentration. The basis of this calculation is the delivery of dry solids, hence the minimum in the curve. At the lower concentrations turbulent flow is present and, as the concentration is increased, effectively by removing water to maintain the dry solids constant, there is a transition between laminar and turbulent flow which occurs basically at the minimum. Almost all pipelines in the world today are transporting material in the turbulent flow regime using a critical velocity to keep the particles in suspension.

There is a great reluctance to move into the laminar flow region, even though the results in Figure 3.11 show that one could deliver the material at a much higher concentration for the same energy expenditure. There is a movement towards handling materials at higher concentrations for good environmental reasons and water recovery reasons, and thus we will have to deal with laminar flow pumping. The fear in dealing with a material in laminar flow is the sedimentation and blockage of the pipeline. In some instances, particularly for relatively uniform fine-particle suspensions, the type of prediction shown in Figure 3.11 is quite accurate. In others, where the particle size distribution is very broad with large particles, sedimentation and/or slip flows may occur in the pipeline, and hence the prediction may not be valid (see Chapter 8).

Figure 3.12 shows similar predictions, based on the basic rheological measurements for a 50.8 cm diameter iron ore pipeline at various throughputs. It is interesting to note that the minimum in the curves at about 65% solids is approximately where the pipeline is operated. This optimum has been determined by trial and error.

Finally, Figure 3.13 shows similar results for the washed waste from a bauxite mine in comparison to one data point of the measured pressure drop in the pipeline. Notice the excellent agreement. From the results shown in Figures 3.11 to 3.13, one might be tempted to conclude that on the basis of basic rheological measurements one can in fact predict and design a tailings pipeline from first principles. Unfortunately this is not true. As already stated, sometimes the prediction and actual performance agree, normally with fine particles of a relatively uniform size, but invariably with waste streams there is little agreement. Therefore, in addition to basic rheological measurements, most designers will resort to actual flow loop studies (see Chapter 8). We will not deal with design considerations for thixotropic materials as these were dealt with in the first edition of this Guide.

3.6.3 Thickening requirements: compressional rheology — Point 3, Figure 3.3

The aim of thickening is both to recover water into the process stream and produce an output slurry of a suitable rheology for pumping and, more particularly, for deposition purposes. To achieve this goal, knowledge of the compressional rheology of the slurry is desirable.

The compressional rheology of a slurry has three parameters of relevance to the prediction of the propensity of this same slurry to increase in solids in a thickener: the compressive yield stress, hindered settling function, and the gel point. The derivation of these parameters is well captured by the continuum theory of dewatering developed by Buscall and White (1987). In simple terms, the parameters describe an inter-phase drag or rate of fluid expression from a suspension under compression (hindered settling function) and the strength of the particulate network in compression (compressive yield stress). This approach implicitly assumes that the suspension of particles is both flocculated and, in the case of compression measurement, is at a concentration such that interparticle interactions within the suspension cause a continuous network to exist that must deform under load. The concentration equivalent to the onset of this networked behaviour is known as the gel point.

The measurement of the hindered settling and compressibility behaviour of a slurry is now well established for mineral suspensions, although complete characterisation is still confined to research laboratories. The compressive yield stress is measured through a combination of filtration, centrifugation and settled bed height experiments (de Kretser et al., 2001; Green et al., 1996) and the hindered settling function can be established from a combination of transient settling tests and filtration (de Kretser et al., 2001; Lester et al., 2005).

In a conventional gravity thickener, it is usual to add flocculants to the incoming slurry (see Chapter 6). The effect is both to produce aggregates with a faster settling rate and to improve the clarity of the overflow liquor through enmeshment of small particles into the aggregates. The faster settling rate of the flocculated aggregates is an important element in the prediction of thickener performance, since it has been established that the operation of most thickeners is permeability limited. In simple terms, although the compressive yield stress of a slurry dictates the maximum

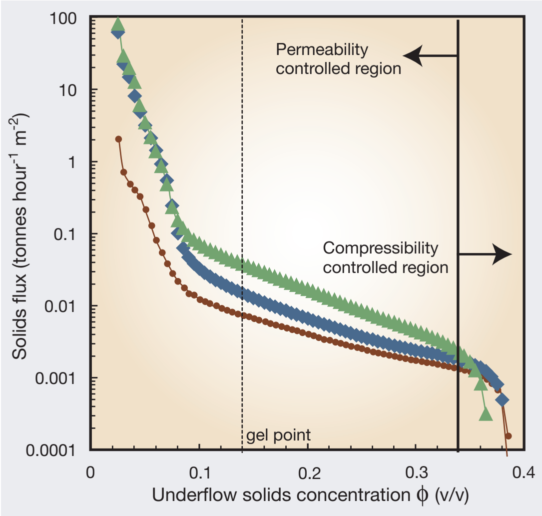

FIGURE 3.14 **Prediction of the solids flux through a thickener as a function of underflow solids for samples flocculated at three different flocculant doses. An increase in flocculant dose shifts the prediction to higher flux**

possible solids that could be achieved through thickening at a given bed height of solids in a thickener, this solids concentration is rarely, if ever, challenged in a steady state thickener because the rate of escape of liquor from the bed of particles limits the process.

One approach to achieving higher solids content in a thickener is to increase the residence time in the device. Therefore, the practice of running a large compressional bed in a thickener is opportune in that it both allows a longer residence time for the escape of fluid and increases the potential upper solids limit in terms of the compressive yield stress. Another option is to increase the aggregate settling rate. This is usually achieved through an increase in the flocculant addition rate. The overall effect is to improve the permeability of operation whilst limiting the maximum solids slightly. Given that thickener operation is permeability limited, the result is a higher output of solids. Figure 3.14 presents a typical flux operating curve for a thickener showing the regions of permeability and compressibility limited operation for three flocculation conditions. The vertical dotted line indicates the gel point for the slurry. The data are for an operating bed height of 5 m. Increasing the flocculant dose shifts the flux curve upwards and is beneficial for all but compressibility limited operations. The transition from permeability to compressibility limited behaviour is usually limited to settlement in TSFs.

The above analysis for a thickener can be achieved through either taking a sample on site that has already been flocculated, or flocculating in the laboratory and then, through settling, sedimentation and filtration tests, constructing a compressive yield stress and hindered settling function profile for the slurry at that particular flocculation condition. Changing the dose or manner of flocculation will change the profile and necessitate further testing. This information is then fed into a phenomenological pseudo two-dimensional model of steady-state thickening (Usher and Scales, 2005).

Intuition associated with the above discussion would suggest that the way to get to very high solids in a thickener is in fact to overdose with flocculant. Practitioners know this is not useful since the component of compressional rheology that has not been discussed is the effect of shear/raking processes in enhancing the rate of dewatering and improving the gel point of slurries. Recent work has begun to quantify these effects and has shown that the effect of raking processes in thickening is to dramatically lower the inter-phase drag in the system at a given solids content and increase the gel point of a suspension (Gladman et al., 2005). This effect is diminished as flocculant dose increases. Therefore, quantification of the compressional rheology of slurries shows that the appropriate interpretation of the role of flocculants in thickening is that at low flocculant dose, and a fixed bed height in the thickener, the underflow solids increase due to enhancement of the settling rate and reduction of the drag, and an increase in the gel point due to raking. There is a transition at higher flocculant doses to the enhancement being solely due to improvements in settling. This produces an optimum flocculant dose where the permeability is a maximum. This maximum will be flocculant specific and shear rate dependent.

3.7 CONCLUSION

Industries in the future producing particulate suspension wastes and delivering these wastes to storage areas at low concentration will move towards more responsible behaviour by thickening their waste, thereby recovering water, reducing the space required for waste management and, more importantly, reducing the risk associated with conventional TSFs. In order to remove water effectively from the waste stream, it is essential to have a basic knowledge of both shear and compression rheology, as the materials are non-Newtonian. Basic knowledge of both shear and compression rheology will allow a more optimal design of the disposal system. The disposal strategy must include examination of the whole process, which includes thickening, pumping and deposition, concurrent with optimum flocculation practice of the waste stream leaving the plant. For a waste disposal strategy to be effectively managed, it is essential that the specification of the waste stream be regarded as just as important as the specification of the product produced by the plant. Maybe one day we will even start to think about cleaner production instead of dealing with these wastes as an end of pipe problem.

The implementation and optimisation of dry disposal methods involves three concurrent and interdependent rheological studies to determine i) the optimum concentration required for the management of the tailings storage area, ii) the optimum conditions for pipeline transport, and iii) the feasibility of dewatering the slurry to the required concentration. The technical methods outlined in this chapter provide the rheological characterisation 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 this new technology. The principles outlined in the examples given in this chapter may be applied to many industries encompassing a wide range of waste materials.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the Particulate Fluids Processing Centre, a Special Research Centre of the Australian Research Council at The University of Melbourne, for the encouragement received for this work. In addition, the lead author would like to express his extreme thanks to the Alcoa Company of Western Australia for involving him in their work on red mud disposal, starting in the 1970s. Particular thanks to Peter Colombera (deceased), Don Glenister (Alcoa, retired), and to David Cooling, currently the International Disposal Manager for Alcoa.

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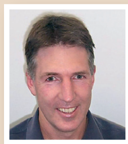

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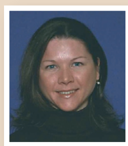

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