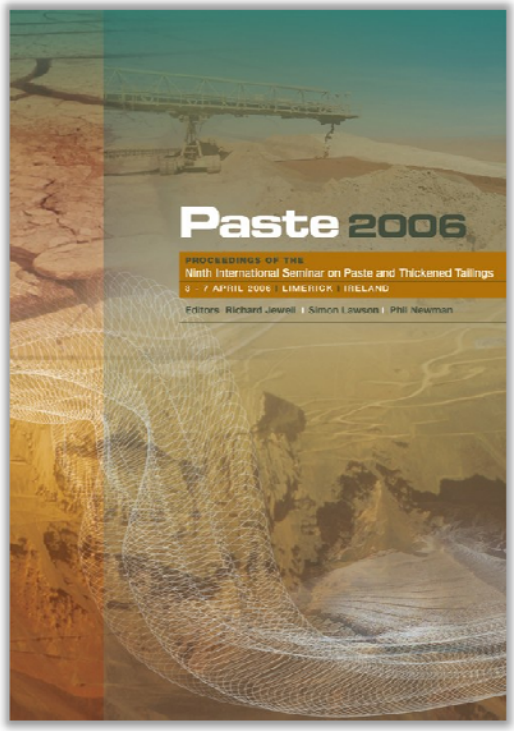
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# Understanding the Thickening Process

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## 1 INTRODUCTION

The thickening process is the primary method of producing high solids slurries for the minerals industry. Thickener outputs can accommodate a range of tailings disposal options from low yield stress, easily pumped suspensions for disposal in conventional 'wet' tailings dams to more concentrated slurries for delivery to 'dry disposal' and backfill applications. The thickening process, although operated successfully in a large range of sites around the world, is poorly understood and predictive design of thickening devices is still empirical. Although predictive models of thickening do exist, the correlation to reality is often poor and there is a desperate need to bring the two together to make rational improvements to thickener design and operation. Therefore, whilst some would dismiss the models as being unacceptable for predictive design, they are very useful in formulating expected operational trends and providing an understanding of the directions one should take in improving operational performance. The aim of this article is to bring together model, laboratory and in-field results to elucidate the state of the art in understanding thickener operation from first principles.

## 2 PRINCIPLES

In simple terms, dewatering in a thickener involves gravity acting on the density difference between the solid particles and the carrier liquid (usually water), enabling the solid particles to settle. As the solids concentration of the slurry increases, the settling rate progressively slows and above a critical solids concentration known as the gel point, $\phi_g$, the slurry exhibits a network structure and forms a bed at the base of the vessel.

Historically, improvements in the performance of industrial thickeners have been based on selecting conditions that produce desired properties in settling test behaviour, such as the free settling rate, final sediment solids concentration, viscosity or shear yield stress. These tests have proved useful in optimising thickener performance and are loosely based on suspension material properties, but they do not enable quantitative prediction of thickener performance. Such prediction requires a more thorough understanding of the physical suspension properties that determine the rate and extent of dewatering. This is not to suggest that the current tests should be abandoned, just that they should be enhanced where or whenever practical.

Compressive yield stress and permeability have been established as fundamental physical properties that determine suspension dewaterability (Buscall and White, 1987). To determine these properties across the solids concentration regime typical of thickener operation (very dilute feed to thickened underflow), experimental techniques have been developed to allow rapid and comprehensive dewaterability characterisation. These tests include batch settling, gravity permeation, centrifugation and pressure filtration (de Kretser et al., 2001; Green, 1997; Green et al., 1998; Lester et al., 2005; Usher et al., 2001). In the case of batch settling tests (Lester et al., 2005), the testing is straight forward and reliable and can be performed both on-site and in the laboratory. The subsequent extraction of the fundamental physical properties is not trivial but has been packaged into a software tool that is reasonably quick to use.

To complement the measurement of the material properties of the flocculated suspensions to be dewatered, numerous authors have presented fundamentally based equations and computational algorithms for predicting transient thickener performance (Bürger et al., 2000; Lester, 2003; Martin, 2004) and steady state thickener performance (Garrido et al., 2003; Green, 1997; Landman et al., 1988; Landman et al., 1994; Usher and Scales, 2005) from material properties algebraically related to the compressive yield stress and permeability. The outputs of these algorithms enable understanding of how process variations can affect dewatering performance. The key disadvantage of the transient algorithms is that they require large amounts of computation time to model a wide range of conditions. Use of the quicker, simpler steady state thickening algorithms enables a wider range of conditions to be modelled.

As an example of the outputs of these models, the case of a suspension of flocculated red mud from the washer train of an Australian refinery is shown in Figure 1. In this case, the algorithm derived by Usher (Usher and Scales, 2005) has been applied to predict the performance. To achieve this end, experimental permeability and compressibility data was obtained on-site using a combination of batch settling tests and filtration. The data from these tests was curve fitted with an appropriate algorithm such that the non-continuous experimental data could be input to the model and a broad range of scenarios investigated. Other inputs to the model included feed solids, solution viscosity, solids density (to allow conversion from weight to volume percent solids) and thickener geometry. A range of throughput and bed height scenarios are presented in Figure 1.

At high throughput, usually given as a solids flux (tonnes of solids/hr/m$^2$), the model predicts that the thickener will give underflow solids that are independent of the operational bed height. As solids flux decreases, the underflow will reach the gel point of the suspension and the dependence on the operational bed height will become more important. The underflow will also exhibit a shear yield stress above the gel point and operational points based on suspension yield stress or slump height could be incorporated into the same figure. This would obviously require a separate determination of the shear yield stress or slump height as a function of solids concentration. The solids concentration in Figure 1 is given as a volume fraction of solids although it is relatively easy to provide a conversion to weight fraction of solids if the solids density is known.

A closer look at the model data indicates that for underflow solids up to and just in excess of the gel point, the operation of the thickener is limited by permeability alone in that any enhancement in the permeability of the settling flocs will increase the underflow solids. The effect of bed height will be important for solids concentrations above the gel point but the operation will still be limited by permeability unless the solids flux is very low. A survey of thickener operations shows that since the ability to rake and pump the underflow solids is limiting, the majority of operational thickeners will be permeability limited and provided they are run at a bed height in excess of 2-3 meters, operational changes that enhance the settling rate of the flocculated solids or the permeability of the solids bed will be beneficial to improving either of underflow solids or solids throughput.

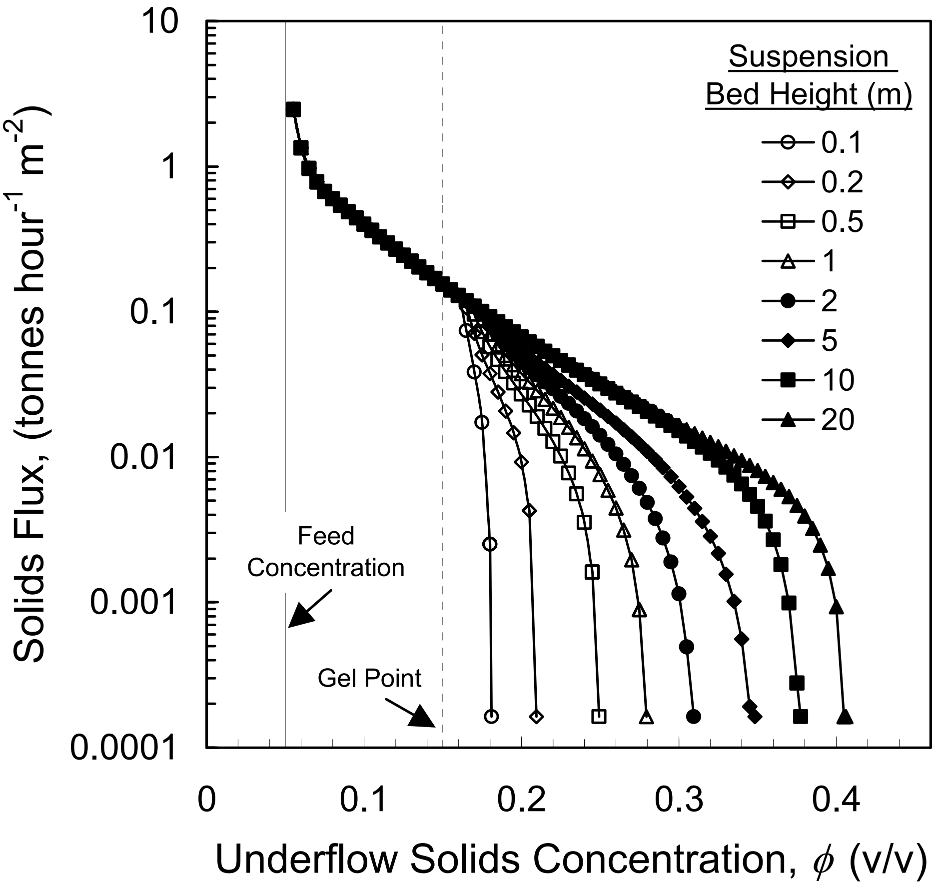


**Figure 1** **Typical steady state converging base thickener model prediction of the solids flux as a function of underflow solids volume fraction for a range of suspension bed heights for an Australian alumina plant (red mud) slurry (Usher, 2002)**

## 3 MODEL PREDICTIONS AND INDUSTRIAL REALITY

### 3.1 Modelling

The model predictions presented in Figure 1 allow comparisons of process performance with model predictions for thickening operations. Quite obviously, every operational scenario will produce a different model output. Perhaps more importantly, changes in floc formation conditions as either a change in the solids concentration of floc formation or a change in the dose or type of flocculant will produce a different model output. This is because the material properties, measured as either the compressibility of permeability of the flocculated suspension have been shown to be sensitive to the changes in floc dose and conditions.

The validation exercise also gives an indication of the level to which factors other than those observed in simple settling tests influence the rate and extent of dewatering. The functional inputs to the model only incorporate settling, hindered settling and network compressibility in the absence of shear. The role of raking and other shear processes on enhancing dewatering are not included. Qualitatively and anecdotally, these processes will be important. Observations for simple batch settling tests show that in the presence of raking or shear, enhancements in settling rate are common. Figure 2 is an example of laboratory data from a simple batch settling test in the presence of raking. A clear improvement in settling is observed that more detailed analysis shows is due to an enhancement of the settling in both the hindered settling regime and in the escape of liquid from the network bed of particles at the bottom of the cylinder, as also occurs in a thickener.

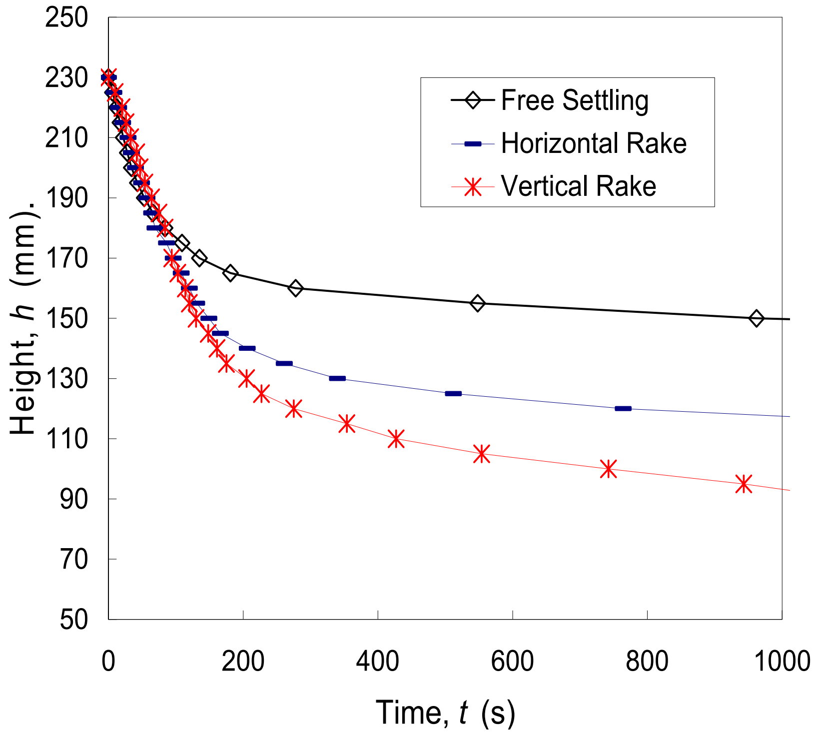


**Figure 2 Transient batch settling test data for a normal settling test (free settling), settling with a horizontal rake and settling with a vertical rake**

An example of the comparison of the prediction of the thickener model against an operational scenario for red mud thickening in the alumina industry is shown in Figure 3. The modelling data is for two bed heights, namely 2 and 5 meters. The input data for the model was measured on-site using samples taken from the underflow and re-flocculated using the same dose of polymer as in the actual device.

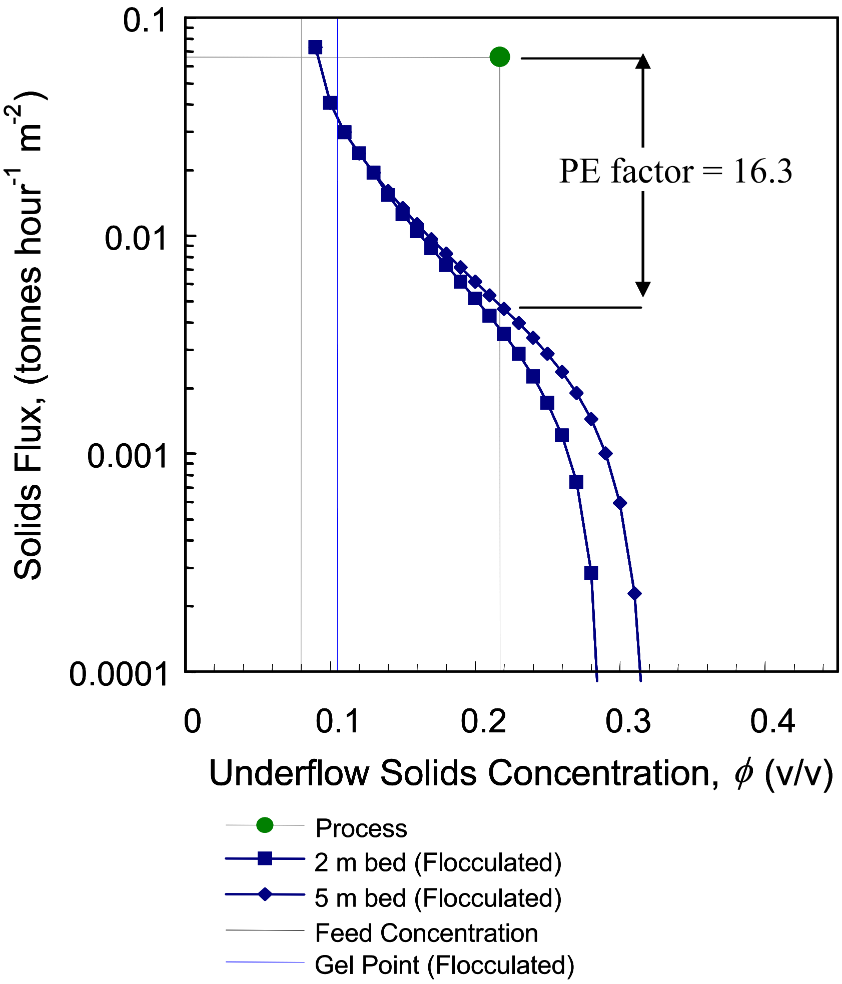


**Figure 3 Red mud thickener performance and model prediction of the solids flux versus observed underflow solids volume fraction. The difference between predicted and actual performance is indicated as a performance enhancement (PE) factor (Usher, 2002)**

Whilst there is a possibility that the material was not flocculated in an identical manner, the difference in predicted versus actual performance is substantial. In terms of the solids flux through the thickener, the difference was a factor of 16.5. This has been labelled as a performance enhancement (PE) factor in Figure 3. The model predicts that at the operational flux, the red mud would achieve an underflow solids concentration less than the gel point. The reality is an underflow solids concentration in excess of the gel point and indeed, in this case, the material had a yield stress approaching 100 Pa.

## 3.2 Operational outcomes

Analysis of a range of industrial thickeners from the processing of gold ores, red mud, coal tailings, potable water sludge and clay suspensions shows that current mathematical models generally underestimate thickener throughput at a given underflow solids concentration. Performance enhancement factors of up to 100 have been observed for selected materials in high rate thickeners. Whilst these performance enhancements are quite variable, more typical figures of between a factor of 5 and 20 have been observed for conventional thickening operations. Some other results for a range of thickeners are shown in Figure 4.

The operational outcomes compared to the model predictions should and do give the modelling community cause to question the physical description of the sedimentation process that is incorporated into the models. As stated earlier, this is simplistic in that it assumes that a floc settles, becomes hindered in its settling and then forms a bed. Compression in the bed due to particle self weight causes further consolidation. This is more sophisticated than a Kynch style flux approach (Kynch, 1952) and one could reasonably argue that in terms of just sedimentation and consolidation, the approach cannot be flawed since it is able to describe batch settling accurately and consistently. Indeed, the experimental parameter estimation procedures typically use batch settling as a basic input.

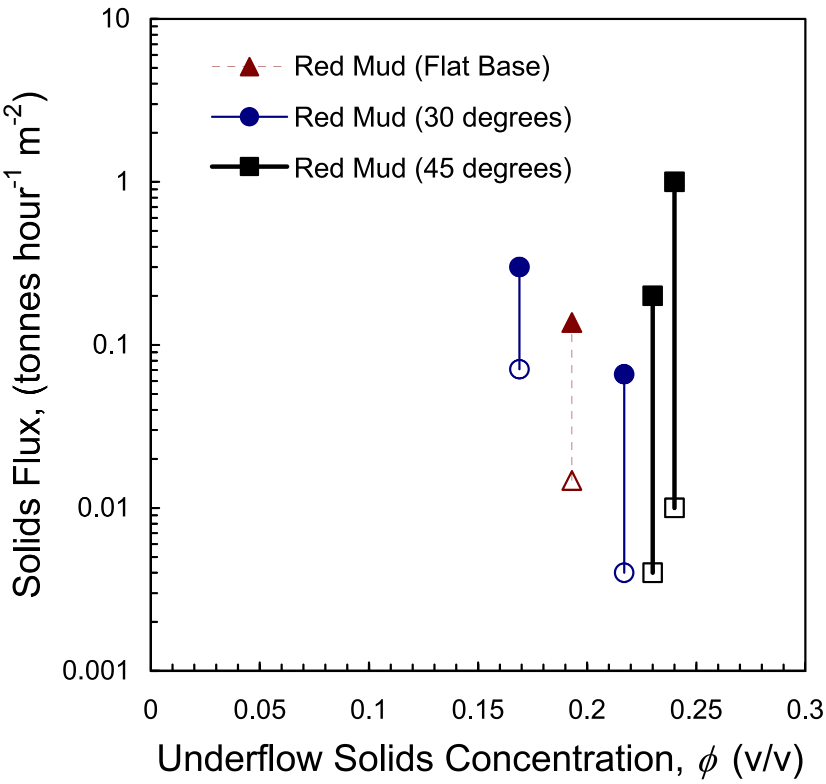


**Figure 4 Industrial thickener performance and model prediction of the solids flux versus observed underflow solids volume fraction. The data is for thickeners with shapes ranging from a flat base to a deep cone thickener with a cone angle of 45° (data obtained from Usher, 2002)**

It has long been believed that the difference between the model predictions and operational reality is the role of raking of the bed to aid consolidation and channelling in the thickener to aid the release of water. Whilst this is obviously important, an interesting observation from Figure 3 is that the model predicts an underflow solids of less than the gel point. This observation and subsequent modelling of the data in Figure 2 for the case of raked solids in a batch settling test, shows that whilst raking of the bed enhances settling and improves both the rate and extent of dewatering, this alone is not enough to account for the observed performance enhancement factors.

Recent work (Gladman et al., 2005) shows that it is the role of very low shear processes in both the settling and hindered settling regions of the thickener as well as in the bed of the thickener that is critical to performance enhancement. These low shear processes result in a slow change in floc structure that is not able to be quantified in a classical batch settling experiment because the time domain in free and hindered settling in most batch settling experiments is short (of order seconds). This is in contrast to steady state thickening where this time domain may extend for hours. This leads to the postulate that the role of the bed height in enhancing compression in a thickener is probably outweighed by the role of increasing residence time for floc restructuring in shear. The role of rakes and pickets in allowing the restructuring to happen on a far shorter time scale is also noted although excess shear has been shown to be highly detrimental to the enhancement (Gladman et al., 2005). Modelling of thickener performance with shear of the free settling, hindered settling and bed regions, although the result of rudimentary experiments, shows that this factor is able to account for performance enhancements of up to 20. It is likely that this will be extended for flocs with a different structure. The encouraging sign is that the model is now able to predict a wide range of operational scenarios.

# 4 CONCLUSIONS

The discussion in this article has focussed on the measurement of the parameters important to thickening and the modelling of operational thickeners using these parameter inputs. This has produced an enhanced level of understanding of the factors that are important to thickener operation and provided a quantitative prediction of thickener performance for the first time. The lessons learnt through this exercise are that an increase in thickener solids flux or underflow solids are manifest in improvements in settling and bed permeability behaviour. It is common to approach such an improvement through increased floc dosage which in turn manifests as a faster free settling rate in the thickener. The modelling information shows that this is not sufficient and it is the ability of the floc to restructure in shear that is a more critical operational parameter. It is expected that this conclusion will provide a better understanding of the choice of flocculants in thickening and equally, the choice of raking elements and shear rates employed.

# ACKNOWLEDGEMENT

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# Rheological Assessment – A Road Map for Plant Designers and Operators

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## 1 INTRODUCTION

One of the fundamental prerequisites for the design and implementation of a successful thickened tailings or paste systems is a comprehensive understanding of the rheological characteristics of the material. Although rheological characterisation is often out-sourced, it is essential that design engineers and plant operators have a grasp of the variables which must be considered, the questions that need to be addressed and familiarity with rheological assessment principles in order to determine the validity of data provided for the purpose intended. Good rheological data for one particular sample under one specific set of testing conditions is generally insufficient for design and/or optimisation of entire processing systems and the related equipment. An 'up-front' understanding of how rheological parameters affect and influence operations will result in more efficient and sustainable plant performance and can mitigate many potential problematic issues. This paper is designed to be a rheology road map, guiding the reader through a checklist of rheological questions to ask and issues to address - from sampling to testing protocols, data analysis and informed data application.

## 2 OUTLINE

This paper aims to highlight, and demonstrate by example some of the critical issues for effective rheological assessment. These issues include the practice of understanding the influence of ore type and processing conditions in the concentrating plant, quantification of the physical characteristics of the feed stream to the tailings plant, measurement of rheological parameters, applicability of the results and techniques to assess these parameters, including testing and modelling.

Not all pertinent issues will be discussed in detail in this limited paper. The intention is to publish a more comprehensive road map within the next year.

## 3 ORE VARIABILITY

The mineralogical composition and physical constitution of ores varies between mineral types and deposits, as well as within a given deposit which will be manifest during the period of extraction. Understanding how these variations impact on the 'processability' of ores and the tailings' flow behaviour is an essential step in quantifying the variability in rheological parameters and thereby mitigating project risk, and/or ensuring sustainable operation of the processing plant.

### 3.1 Mineralogy and particle size distribution

Where it is known that the ore body contains significant variations in mineralogy, for example clay seams in a coal deposit or limonites and saprolites in a nickel laterite deposit, reconciling mineralogy with the resultant rheological characteristics provides important information for determination of ore blending plans and the expected range of operating conditions for the concentrating plant.

Due to changes in mineralogy and effects such as weathering, there can be large variations in the friability and therefore particle size distribution (PSD) throughout the ore body and during the life of mine. The deviation in PSD must be determined from the outset as particle size dramatically affects the rheology of slurries and pastes and thus the ease of processing and disposal.

Changes in mineralogy and/or PSD within a deposit can mean an order of magnitude variation in the tailings yield stress (the stress required to initiate flow) at a given solids concentration and can be the difference between a successful and unsuccessful tailings disposal operation. Figure 1 illustrates the variations in the yield stress profiles of samples from one lateritic nickel deposit as a result of changes in mineralogy. Note that for a yield stress of 200 Pa, the solids concentration varies from approximately 42 wt% to 56 wt%, or alternatively, at a solids concentration of 50 wt%, the material properties range from those of a solid i.e. not pumpable with an unmeasurably high yield stress, to a yield stress of about 30 Pa i.e. easily pumpable with the consistency of cream.

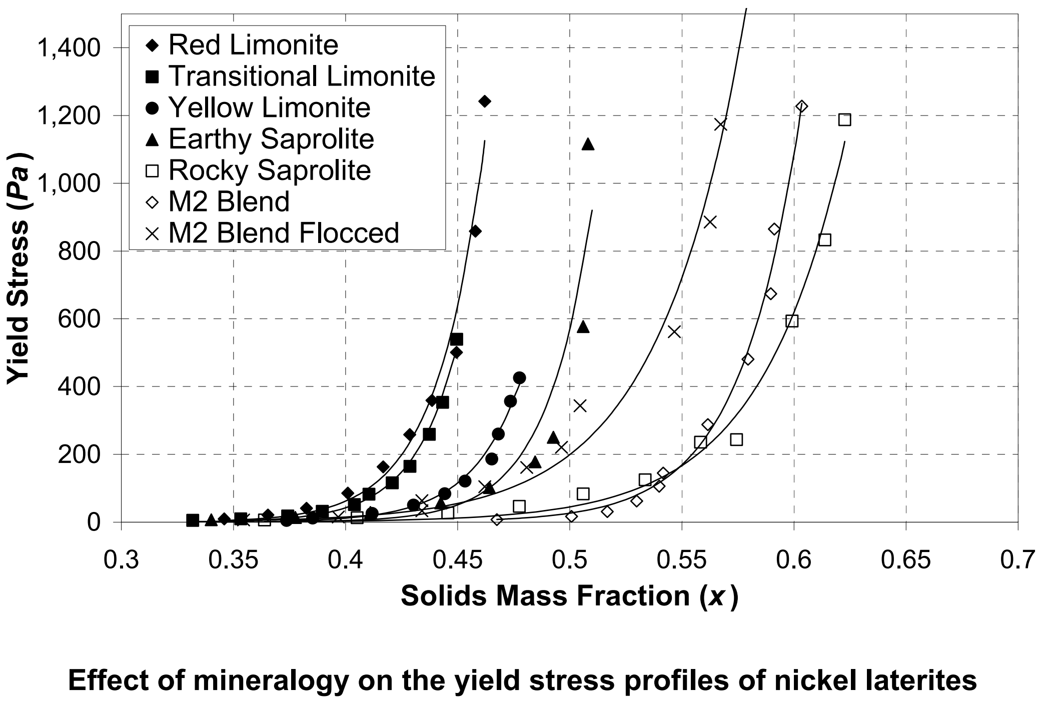


**Figure 1 Effect of mineralogy on the yield stress profiles of nickel laterites**

An example of the effect of particle size on the yield stress profile of a bauxite sample is shown in Figure 2. As observed for varying mineralogy, changes in the PSD can translate to dramatic changes in the yield stress for a given solids concentration. In the case shown, for a solids concentration of 67 wt%, the yield stress could be anywhere from 10 Pa to 110 Pa.

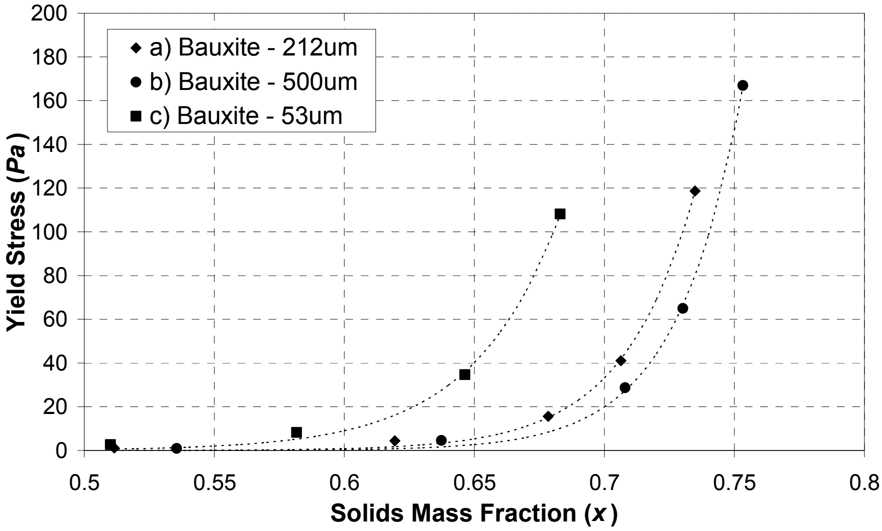


**Figure 2 Effect of PSD ($d_{90}$) on the yield stress profiles of bauxite ores**

## 3.2 Sample preparation

The importance of testing a representative sample can not be understated. Those who frequently conduct rheological testwork understand the critical nature of sample preparation and management in order to ensure that the results of their investigations will accurately reflect the applied process conditions.

Whether the samples are a result of pilot plant trials or full scale plant operation, at times there may be a delay between sample generation and testing. In the event of this delay, it is important to consider the effects of sample aging and transport.

Sample aging is particularly important for flocculated samples where the flocculant may degrade over time, samples generated at elevated temperature where cooling may affect the rheology and samples containing clays, where clays may delaminate and swell over time. In these cases, on-site testing is recommended at the time of sample generation and the process temperature.

During transportation to a testing facility both aging and shear history effects may be significant. As the sample is transported it is inevitable that the shear history experienced will differ from plant conditions. Obviously, in the case of shear history dependent materials (where the rheology varies with *time* of shear, for example flocculated materials, clays, red mud and many nickel tailings) this will result in variations in the measured rheology compared with plant conditions. Settling and particle size segregation is also likely, requiring the sample to be homogenised and resuspended prior to testing.

Often the very act of preparing a sample for testing will alter the rheological properties, especially in the case of flocculated samples where the floc structure may be delicate and easily destroyed. Among the most difficult information to obtain is that required for determination of thickener rake drive torque requirements and thickener underflow pump requirements. The material that the rake and underflow pump must deal with will be freshly flocculated and relatively unsheared. However, sample generation, collection and testing will impart shear on the flocculated and thickened sample.

Although extensive efforts are made to minimise the effects mentioned, they are sometimes unavoidable and often the only prudent approach is to ensure the data is utilised with awareness of the limitations imposed by sample preparation.

# 4 BASELINE RHEOLOGY TESTWORK

Although specific information is required for the design of individual unit operations, in general a baseline rheological characterisation consists of the following suite of tests.

## 4.1 Particle size distribution (PSD) and mineralogy

Although not strictly speaking part of rheological testwork, as stated in section 2, reconciliation of the PSD and mineralogy (using x-ray diffraction for example) with the rheological characteristics can be particularly useful for mine planning and blending requirements where there is significant ore variability. Design of operations relies on an understanding from the outset of the variability expected in rheological properties attributable to the ore type, blended or unblended, being processed and transported.

## 4.2 Shear history effects

The simplest method of assessing the effect of shear history is to measure the yield stress (or torque) as a function of shearing time at a fixed shear rate. Many concentrated suspensions, particularly flocculated or coagulated suspensions, posses a networked structure which may be broken down as they are subjected to shear. Figure 3 for example, shows the yield stress reduction for a nickel sample to an equilibrium value with time of shear.

It is important to understand the rate and extent of this breakdown process to ensure rheological testing is conducted at the appropriate shear history condition for which the data is to be applied. In the case of thickener rake drive torque requirements and underflow pump sizing for example, testing should be conducted in the unsheared state as this represents the state of the material that the rake must deal with. For pipeline calculations and prediction of the depositional flow characteristics for slurry/paste that has been sheared by centrifugal pumps, testing may need to be conducted in a fully sheared state to avoid over design of the pumping system. Centrifugal pumps impart a particularly high shear intensity which may reduce the pumping energy requirements through breakdown of the paste structure, thereby reducing the yield stress and viscosity.

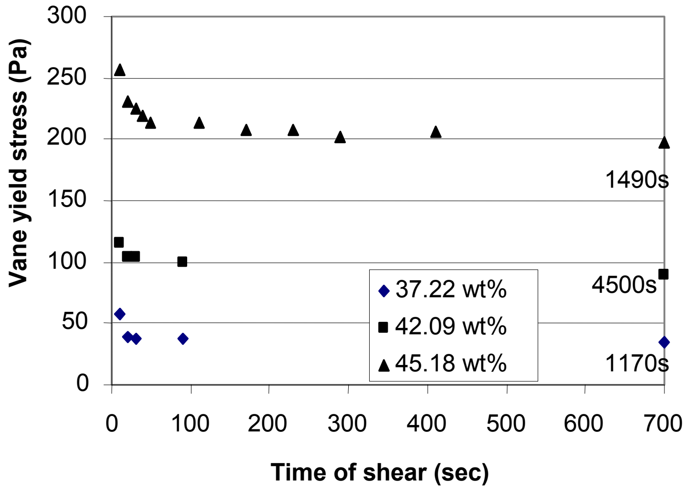


**Figure 3** **Vane shear yield stress vs time of shear for a nickel sample showing the eventual equilibrium state**

There are times when it is not possible to replicate the shear history conditions anticipated in reality (they are generally not known a priori) so understanding the rate and extent of variation in the rheology is important for informed use of data for design or optimisation.

Although the behaviour shown in Figure 3 is common, there are instances where the effect of shear history varies as a function of the rate of applied shear. The presence of high aspect ratio particles in some tailings results in the observed yield stress either increasing or decreasing depending on the shear history imparted, as shown in Figure 4. The apparent reversibility and range of potential structural states suggests that definition of an equilibrium condition is purely subjective and shear history dependent. In cases where this type of behaviour is evident, it is important to ensure that the shear conditions that will be experienced in the plant are well understood and reproduced as closely as possible during sampling and testing.

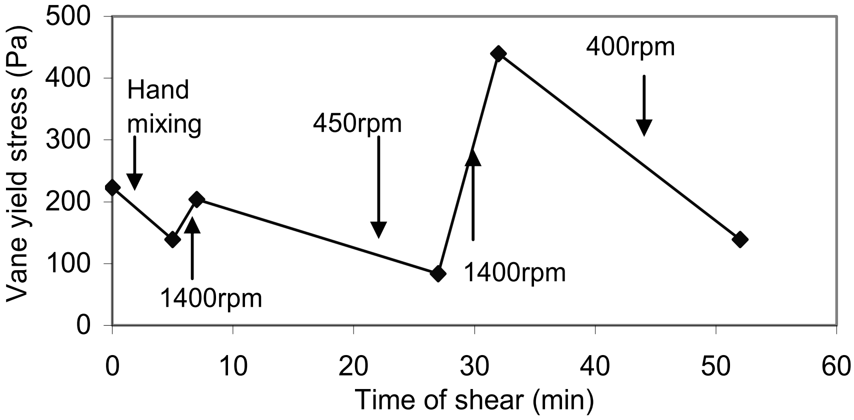


**Figure 4** **Yield stress progression with varying intensity of applied shear**

## 4.3 Yield stress profile

Following determination of the effect of shear history, the yield stress as a function of solids concentration should be determined for the appropriate shear history condition to define the operating window. Figure 5 illustrates the variation in yield stress behaviour due to shearing for a flocculated thickener underflow tailings sample.

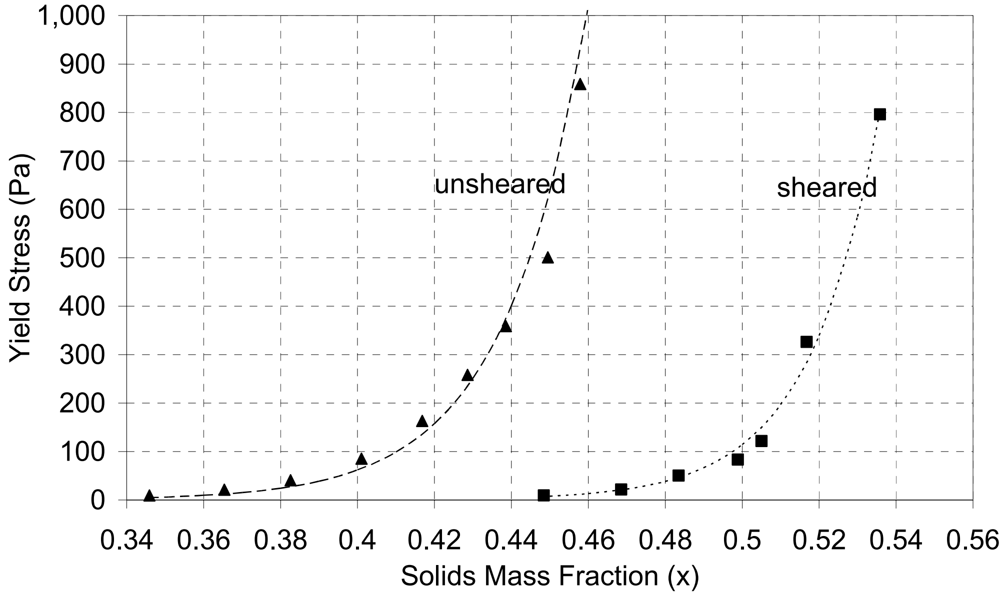


**Figure 5 Yield stress profiles - unsheared and sheared flocculated thickener underflow**

As shown above, yield stress profiles generally display exponential or power law trends. The yield stress profile should be determined over a wide range of solids concentrations extending beyond the anticipated operating concentration to indicate where on the curve the operational point lies. A design operating point near the ‘elbow’ of the curve, where the yield stress increases dramatically with minor variations in solids concentration, could be problematic because of the narrow operating window and difficulty controlling the paste concentration to such a specific value.

In addition to the effect of shear, and to further highlight the effect of PSD, a decrease in the PSD will shift the curve to the left i.e. a higher yield stress for a given solids concentration. Conversely, a coarse PSD will shift the curve to the right, but with a more abrupt transition from liquid to solid-like behaviour i.e. a sharper ‘elbow’ in the curve.

## 4.4 Shear stress vs shear rate

A flow curve, or rheogram measures the shear stress as a function of shear rate and therefore the viscosity as a function of shear rate. Flow curves need to be measured over the anticipated operating range indicated by yield stress profiles and may also need to encompass a range of shear histories (from unsheared to fully sheared). Figure 6 demonstrates the importance of testing under the appropriate conditions by showing the effect of shear through the thickener underflow pump and pipeline for a red mud paste. Using the thickener underflow rheology to design the pipeline system or deposition characteristics could lead to serious problems in the process design.

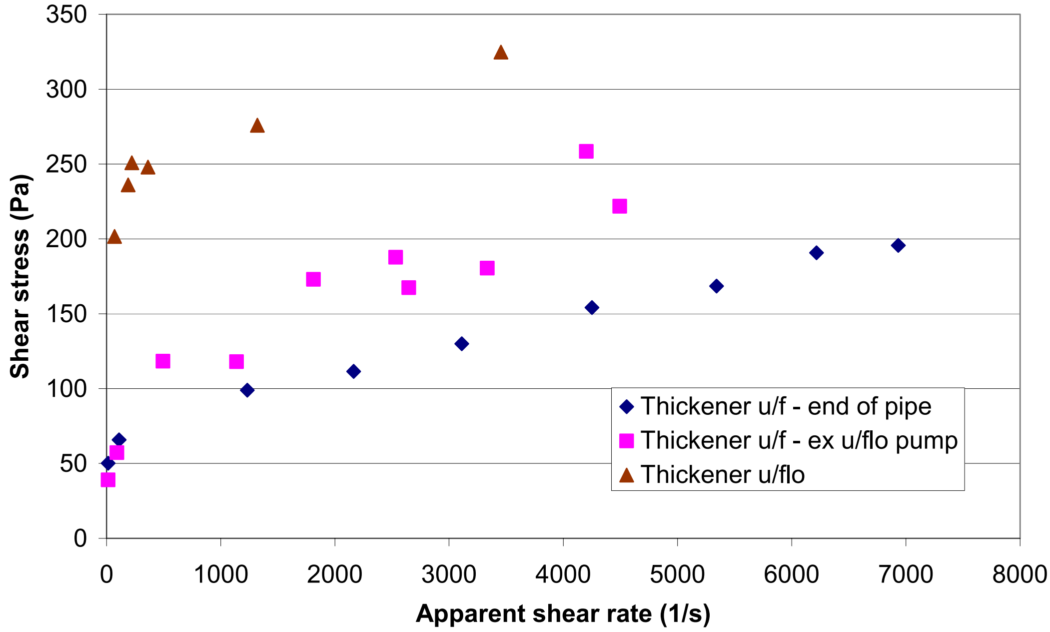


**Figure 6 Flow curves for a red mud paste showing progressive structural breakdown**

# 5 TESTING METHODS AND ISSUES

Some testing methods are more appropriate for a particular application than others. However, what is more important is that those conducting measurements and those applying the data generated have an understanding of the issues associated with various testing methods. Rather than describe particular test methods in detail, this section aims to comparatively discuss critical issues for each method.

## 5.1 Slump testing

Quoting a slump height is useful as a relative measurement for a particular material only. Slump height is not a material property, but rather relates to the yield stress (a material property) through the density. Unless it is used to calculate a yield stress, the slump height is only good for relative measurements for a particular material. Table 1 shows how three samples displaying the same slump height can have very different yield stresses in reality resulting in a wide variation in the pumping energy requirements. Slump testing is most useful as a quick and simple method of comparing sample yield stress or a as an on-site quality control method.

**Table 1 Yield stress and pipeline pressure drop for a fixed slump height**

| | Coal Tails | Au Tails | Pb/Zn Tails | |
|---|---|---|---|---|
| Solids SG (kg/m$^3$) | 1450 | 2800 | 4100 | *dP Prediction assumes |
| Solids conc.(%w/w) | 36 | 75 | 75 | Bingham viscosity=1 Pa.s |
| Slump height (mm) | 203 (8") | 203 (8") | 203 (8") | Pipe ID = 200 mm |
| Yield stress (Pa) | 160 | 275 | 330 | Pipeline Velocity = 1 m/s |
| Predicted pressure drop (kPa/m)* | 5.07 | 8.13 | 9.6 | Horizontal pipeline |

## 5.2 Rotational methods

Rotational rheology testing, including vane and couette (cup and bob) methods are convenient, being highly portable, requiring small sample volumes and provide a low cost alternative to pipeloop tests (section 5.3). If used prudently rotational methods are accurate, however there are a number of factors to be considered when applying data obtained using rotational devices.

Many testing facilities employ ramped measurements, where the shear stress is measured as the shear rate is progressively increased (or decreased) from one value to the successive value. There are a number of issues associated with this testing approach which need to be considered:

- Each measurement is dependent on the shear rate and duration of shear of preceding measurements in the sweep.
- Particle migration away from the shearing surface may take place over the duration of the test resulting in measurement of a low concentration region not representative of the bulk sample. For smooth bobs rotating in a cup, slip may occur at the bob surface, again resulting in measurement of a low concentration region not representative of the bulk sample.
- For shear thinning or thixotropic slurries, the reduction in the yield stress and viscosity over the duration of the test may result in particle settling and the formation of a concentration gradient along the length of the shearing surface.
- Evaporation at high temperature may be significant, thereby increasing the concentration of the sample being tested over the duration of a test.

For the majority of slurries and pastes, ramped measurements are inappropriate and a superior approach is to conduct individual measurements at successive shear rates with minimal, gentle homogenisation of the sample between measurements.

A good way to check the validity of flow data from rotational testing (or any testing for that matter) is to compare the low shear rate data with an independently measured vane yield stress. If the low shear rate data does not coincide with the yield stress this indicates that one or more of the above factors may be prevalent.

### 5.3 'Pipe' methods

A tubular geometry is often preferred given the similarity with pipeline flow. Examples include capillary (small tube) rheometry and pipeloop tests. For capillary testing care must be taken to eliminate wall and end effects by ensuring that the tube length and diameter are appropriate for the PSD of the sample. In order to minimise the possibility of wall and end effects, both $L/D$ (tube length / diameter) and $D/d_{50}$ should be greater than about 60 where the $d_{50}$ is the median particle size of the suspended particles.

Pipeloop testing is often performed to verify simpler rheological testing eg. rotational methods, and to indicate the parameters such as settling velocities in the presence of shear. One of the disadvantages with pipeloop tests is that the sample is continually recirculated, making determination of shear history effects difficult. Pipeloop tests are rarely conducted as part of an initial rheological characterisation programme as they are more time consuming, expensive and large sample sizes are required.

## 6 DATA ANALYSIS AND APPLICATION

No matter how 'good' rheological data is, it is imperative that the end-user ensure that rheological information is applied appropriately. One of the first things to consider is whether the data is relative or absolute. Relative data, for example slump heights for a particular material or flow data obtained for a different shear history condition to that of the process, can be useful in it's own right, but the user must be aware that the information may be best for ranking, comparative or 'indication of change' purposes rather than direct design input.

### 6.1 Automated instrument analyses

Many commercial rheometer software packages use models which are unsuitable for yield stress fluids and employ a Newtonian analysis for materials which are clearly non-Newtonian. A competent testing facility will be aware of this and analyse the raw instrument readings appropriately rather than relying on inappropriate automated analyses.

### 6.2 Rheological models

Flow data, or shear stress ($\tau$) as a function of shear rate ($\dot{\gamma}$) is often presented in the form of a rheological model. The most commonly used models are the Bingham and Herschel-Bulkley models, shown in Equations 1 and 2 respectively.

Bingham Model: $$\tau = \tau_{yB} + \eta_B \dot{\gamma} \tag{1}$$

Herschel-Bulkley Model: $$\tau = \tau_{yHB} + K\dot{\gamma}^n \tag{2}$$

The Bingham Model has historically been used for prediction of pipeline transport requirements, where the shear rates of interest are of the order of 10 to 100 $s^{-1}$. For pipeline start-up conditions, rake drive requirements and vessel agitation, the shear rates of interest are much lower (zero for pipeline start-up conditions and rake drive requirements and 5 to 15 $s^{-1}$ for agitation), so the Bingham parameters are largely unsuitable.

Although fluid models are convenient the constants $\tau_{yB}$, $\tau_{yHB}$, $\eta_{B,}$, K and n are fitting parameters only, and may not be representative of the true flow characteristics of the material. This is particularly relevant in the case where a highly shear thinning material is described using a Bingham model. At high solids loadings, few slurries/pastes display true Bingham behaviour, yet Bingham parameters are often quoted. The Bingham model extrapolates high shear rate data to zero shear rate and may result in a significant overestimation of the true yield stress (the stress required for flow to occur) while the constant Bingham viscosity ($\eta_B$) does not indicate the variation in the true viscosity, defined as the ratio of the shear stress to the shear rate at a particular shear rate, especially at low shear rates. Figure 7 shows the discrepancy between the true, vane yield stress (shown in brackets) and the Bingham yield stress ($\tau_{yB}$) for a cemented lead/zinc tailings paste. Clearly, designing based on the Bingham yield stress would result in excessive conservatism, especially at high solids concentrations, where the Bingham yield stress may indicate unfeasible or uneconomic operation. The Herschel-Bulkley model generally provides a far better representation of the actual material behaviour.

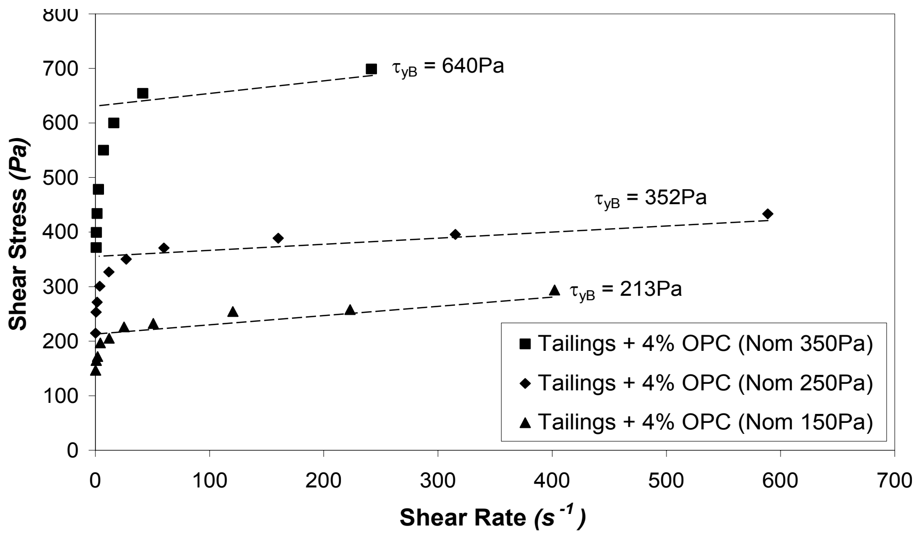


**Figure 7 Flow curves for a cemented lead/zinc tailings paste**

# 7 CONCLUSIONS

A simplistic roadmap has been developed to assist designers and operators to navigate through the following; rheological questions to ask, issues to address - from sampling to testing protocols, data analysis and informed data application. Figure 8 attempts to simplify this complex process by considering the effect of ore mineralogy, sample preparation and management, baseline tests required and test methods and data analysis and application.

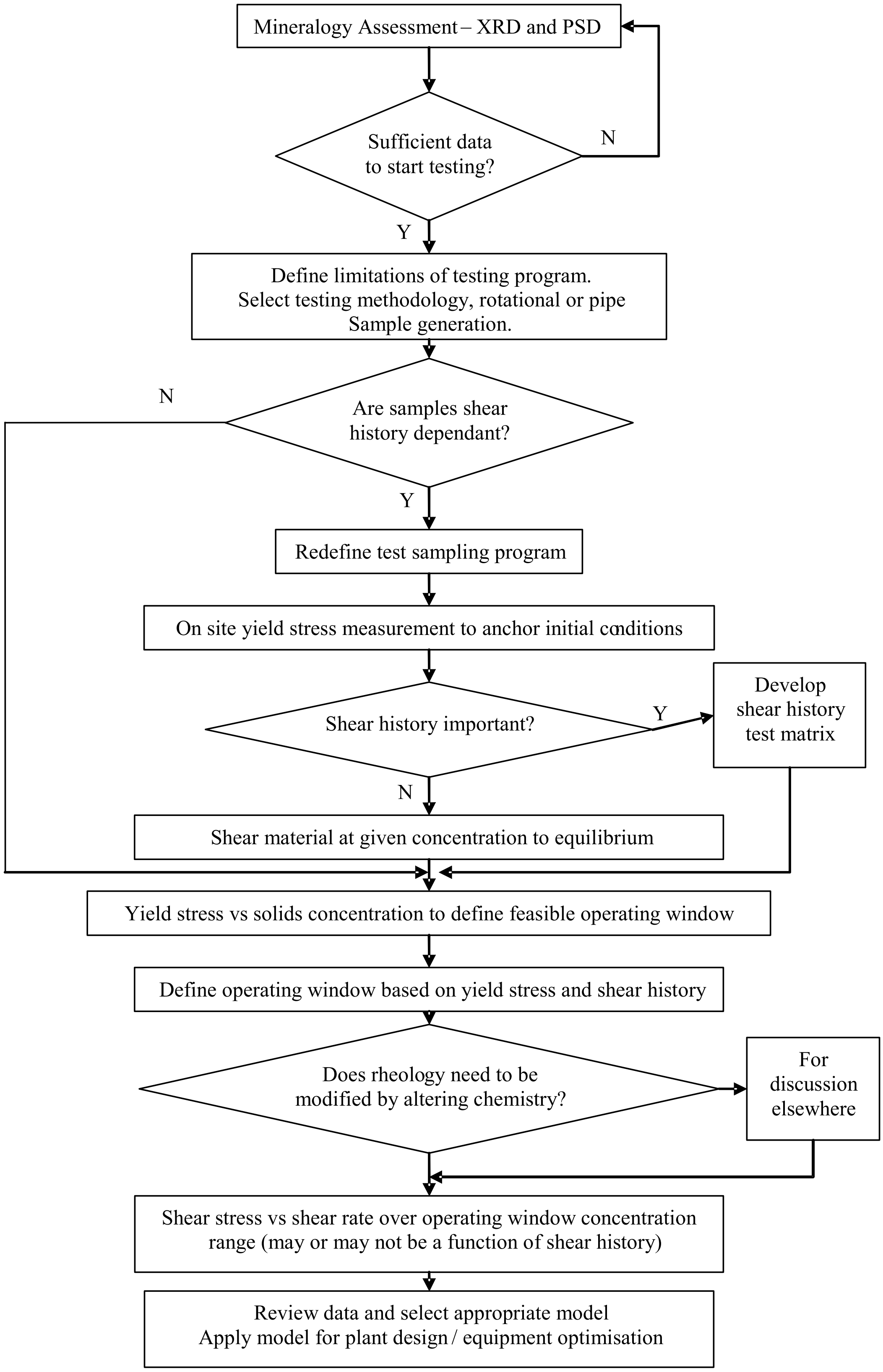


**Figure 8 Preliminary 'rheology roadmap'**