Pahoehoe to paste: Rheological field methods for characterizing overland tailings flow behaviour

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ABSTRACT: A rheological description of mine tailings sheds light on the material's flow behaviour. In the realm of thickened tailings, where fluids adopt solid-like behaviours as transitional materials, rheology plays a crucial role in overland flow and deposit formation.
Beyond laboratory measurements, rheological behaviours may be ascertained using fast and simple methods that are readily applied in the field.
The modified slump test and the so-called bucket rheometer are highlighted as two such techniques applicable to mine tailings. Furthermore, techniques borrowed from earth sciences, including volcanology, may provide additional tools for describing the overland flow of complex, viscous fluids. Simple measurements like flow velocity and flow depth provide an indication of material viscosity, while the geometry of channel levees may provide an estimate of yield strength. The change of rheology can be measured as a function of distance travelled or time flowing by making measurements at intervals down the deposit for any given flow event. The change in rheology as a function of distance may result in variation in deposit geometry and deviations from expected performance in terms of dewatering and strength gain.
The use of field measurements allows for rapid quality control during operations, giving an indication of plant performance, and insight for future planning of tailings deposition. The field methods summarized in this paper are theoretically and empirically validated and have been applied to a variety of materials by previous authors. The techniques are simple and easily adopted by planners, technical staff, and field operators who may have minimal or no background in rheology.

1 INTRODUCTION

1.1 *Tailings Rheology*

A rheological description of mine tailings sheds light on the material's flow behaviour. This information is commonly applied to aspects of tailings transport systems including pump selection and pipeline or launder design; however, less emphasis has been placed on using rheological methods to characterize and predict the overland flow and depositional behaviour of tailings once it has left the pipe. The study of flow is an important concept with broad applicability to tailings management, and more generally to design challenges for extractive industries (Nyugen & Boger, 1998; Boger, 2009).
As designers trend away from slurries with water-like behaviour, rheology plays an ever important role. In the realm of thickened tailings, where fluids adopt solid-like behaviours as transitional materials, rheology plays a crucial role in overland flow and deposit formation. For operators with sub-aerial tailings facilities to manage, an understanding of the flow and depositional behaviour of the tailings is essential.
Beyond laboratory measurements, rheological behaviours may be ascertained using fast and simple methods that are readily applied in the field. Practitioners have developed and refined field methods for quantifying tailings rheology in the field (Pashias & Boger, 1996; Fisher *et*

al., 2007; Boger, 2009). Though the use of these simple "field" methods comes with limitations, we propose that the uncertainty associated with the measurements is commensurate with the range of variability of material behaviour due to process and operational conditions. The use of field measurements allows for rapid quality control during operations, giving an indication of plant performance, and insight for future planning of tailings deposition.

1.2 *Why Field Data Matters*

Laboratory testing is rather well established, standardized, semi-automated (in many cases) and produces reliable results. So why, you might ask, would one need rheological data from the field? We propose several advantages to field-scale testing in this section.

First, scale is of tremendous significance. Much as a hydrogeologist demands that her subsurface model comprises a representative elementary volume ("REV") such that the heterogeneity of the subsurface is accounted for in her model, the diligent rheologist must insist that measurements of flow behaviours respect the internal structure and external forces associated with the flow of concentrated suspensions. The complexity of scale-dependence is compounded when additional processing is encountered – flocculation and thickening – and macrostructures are created in what was once a relatively homogenous (though maybe segregating) slurry. Observations at the scale of field flows demonstrate the variability and spectrum of flow behaviours and material characteristics otherwise missed in matrix-driven laboratory testing, however methodical in design.

Second, the field scale amplifies factors such as moisture loss through evaporation, bleed water release and energy losses due to natural boundary conditions (e.g. lubrication along the channel wall or friction due to segregating particles) - factors which may be negligible or undetected at the scale of a laboratory test. Thus the observation of field flow is the only true measure of flow behaviour as influenced by natural physical processes.

Though the use of these simplistic field methods comes with limitations, we propose that the uncertainty associated with the measurements is commensurate with the range of variability of material behaviour due to process and operational conditions.

2 COMMON RHEOLOGICAL PARAMETERS OF INTEREST

2.1 *Measurement overview*

The measurement of flow behaviour is termed *rheometry* and employs a variety of equipment, from bench rheometers, to viscometers, to simple inclined planes. More recently has MRI-based technology and other non-invasive methods been developed to study the internal structure and flow behaviour of complex fluids (Coussot, 2005).

The goal of the most common and valuable rheometric studies is to define the relationship between the rate of shearing of a fluid and the measured shear stress – in effect, how much force or energy is required to move a fluid at a given rate.

Several important parameters are derived from such investigations – these are described in the following sections. Other parameters (storage moduli for instance) carry value but are not easily measured in the field and fall beyond the scope of this paper.

2.2 *Viscosity*

Viscosity is simply the ratio of shear stress divided by shear rate, or more generally the slope of the flow curve. For a simple ("Newtonian") fluid this slope will be constant, hence the viscosity is constant over any range of shear rate. For mine tailings, however, this is likely not the case. Most often, the tailings will exhibit a non-linear, non-Newtonian behaviour such that the slope of the flow curve decreases with increased shear rate (thus the flow curve flattens at higher shear rates). Consequently, the viscosity of most tailings will decrease with increased shear rate (shear thinning) – put another way, increase the rate at which the tailings are flowing and generally you will decrease its viscosity.

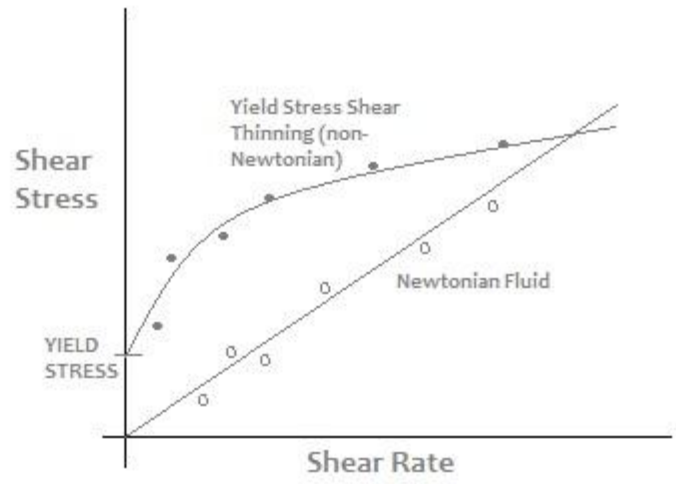

Figure 1. Flow curves for a Newtonian and non-Newtonian fluid as derived from discrete data points.

When the fluid viscosity is a function of shear rate, rheologists prefer the term *apparent* viscosity. Distinction is also drawn between *dynamic* and *kinematic* viscosity, the latter simply being the former divided by the fluid density. Dynamic viscosity is more commonly used in design and casual conversation.

The inverse of viscosity is fluidity. Thus a fluid with high viscosity has low fluidity and will tend to resist flow.

2.3 *Yield stress*

In a Newtonian fluid, such as water, the viscosity is fixed (or nearly so over a wide range of shear rates) and the shear stress approaches zero as the shear rate approaches zero. Thus the flow curve for such a fluid resembles a straight line with positive slope and an intercept equal to zero.

For mine tailings, and more generally for concentrated mineral suspensions, the flow curve intercept is typically not zero. The implication is that some minimum shear stress must be overcome for the fluid to flow and attain shear rates greater than zero. This minimum shear stress is referred to as the yield stress.

The true definition of the yield stress is actually not so straightforward, especially when viscosity is not constant. The problem results from extrapolating a tangent to the non-linear curve back to the shear stress axis. Some argue that this is not the “true” yield stress. For relative comparison of materials (i.e. 50% solids versus 60% solids), yield stress is a suitable metric; however, the flow curves should be interpreted in the same way to ensure comparable yield stress values. Figure 2 shows two different interpretations of yield stress.

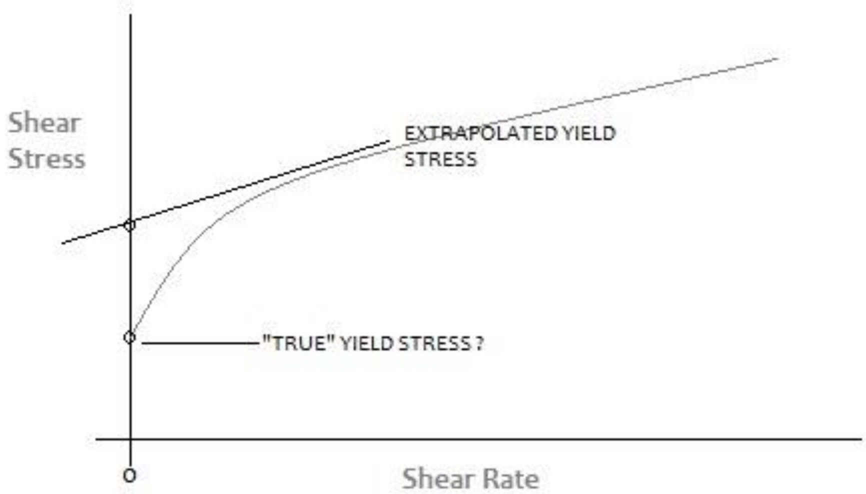

Figure 2. Two different interpretations of yield stress based on one flow curve.

2.4 *Time-dependent behaviours*

When a sample of mine tailings is continuously sheared over a period of time it will tend to see a reduction in both apparent viscosity and yield stress. Such behaviour is termed *thixotropy*. This phenomenon results from restructuring of the entrained particles and internal structures of the fluid. Generally, after a period of rest the fluid will return to, or approach its original condition.

3 FIELD METHODS

3.1 *Slump test*

The slump test is a familiar tool for concrete workers, construction supervisors, and civil engineers – it has also crept into tailings vocabulary as well, particularly with the advent of thicknened and paste tailings which are capable of holding solid-like forms. The value of this jobsite test lies in its simplicity, transparency, and the reproducibility of results.

The slump test exploits the well-understood behaviour of an unconfined soil-like material yielding under self-weight. In the traditional test, the geometry of the initial test volume is standardized by use of a standard cone (ASTM C143M-10a). The deformation of the test volume is measured after the mass is released from the confining cone. The change in geometry of the soil volume – namely the decrease in height – relates to the shear strength of the specimen.

While the standard cone has been used for many decades in the construction industry, modified cones – rather cylinders – have been used for the study of tailings behaviour (Clayton et al., 2003). The dimensions and proportions of these modified slump cones vary in the literature. This author has had good success in correlating slump test results to direct yield stress measurements using a vane rheometer as described in Section 3.2. Figure 3 shows a simple field slump test set-up where the density is also ascertained using a laboratory grade balance.

Figure 4. Simple, modified slump test set-up for field rheology. Balance used for bulk density determination.

Furthermore, a recent variant called the *slump flow test* (ASTM C1611M) has been developed for self-consolidating concrete. This test provides an indication of the unconfined flow potential and a measure of viscosity (Section 2.2) by incorporating the time dimension into the analysis. To the author's best knowledge, this test procedure has yet to be applied to mine tailings.

3.2 *Vane rheometry*

Vanes are simple instruments, typically with four orthogonally arranged blades (rectangular in cross-section) with an assembled length-to-diameter ratio in the neighbourhood of 2:1. Coupled with a torque read-out and a method of controlling the rate of rotation (either mechanically, or manually by a skilled operator) the shear vane, as it is commonly called, provides a reliable and reproducible measurement principle. The advantage of the vane geometry is well documented for use in concentrated granular suspensions such as mine tailings (Coussot, 1997; Coussot, 2005, Fisher et al., 2007; Boger, 2009). Furthermore, better than any other rheometric principal, the vane geometry lends itself to applications where mine tailings dewater, desiccate, and consolidate to form true geotechnical materials – soils. By using the vane to measure rheology, and subsequently to characterize those geotechnical parameters that drive design and decision making – namely shear strength and sensitivity – the same measurement principle is carried over the continuum of material behaviour from water-like slurry to soil-like deposits of matured tailings. Hence the interpretation of such results is simplified and universally salient to process engineers and geotechnical engineers alike. Figure 4 shows a simple, manual vane rheometry for field rheology monitoring.

Figure 4. Manual vane for rheological field monitoring. Vane diameter is 150 mm.

3.3 *Field-scale flow monitoring*

Based on field experience and previous success, we propose several key flow monitoring strategies for compiling a rheological understanding of flowing tailings in a field-scale environment. Of course, the collection of such data requires that at least field-scale testing is undertaken and the author indeed recommends this as a prudent course of action. The methods described herein refer to a sub-aerial deposition scheme into semi-confined paddocks where the tailings flow in self forming channels and occasionally as sheets.

3.3.1 *Flow velocity & geometry*

Bulk flow velocity is easily estimated using the free surface velocity – for relatively shallow flows of yield stress fluids the free surface velocity will not differ significantly from the bulk flow velocity. Physical tracers (floating "pucks" or other highly visible objects) can be placed in the centerline of the flow for timing the movement of a channel or sheet flow across a deposition area. It is advantageous to install vertical measuring rods along the anticipated flow path so that linear travel distance can easily be estimated by the observer.

The geometry of flows (namely depth, width, and cross-sectional shape) is crucial for estimating shear rates and stresses along the flow boundaries. The geometry can be estimated visually or more exactly using submersible flow velocimeters to define the static boundaries if desired (but likely not necessary). Alternatively, in the case of channel flows, the rough geometry may be estimated by examining abandoned channels (i.e. where tailings are no longer flowing).

Through the study of fluids from water to lava flows, researchers have developed empirical relationships between flow velocity, depth, and viscosity for simple and complex fluids (Jeffreys, 1925; Nichols, 1939; Griffiths, 2000).

3.3.2 *Channel flow levees*

As tailings flow in a channel, the flow rate within the channel may vary due to changes in process conditions, natural constrictions or other changes in flow geometry upstream of the observer. If the flow rate exceeds the capacity of the current channel geometry at a given location, then tailings will tend to overflow, or *overbank*, and create mini-deposits along the channel length. In this way, the channel may grow, or aggrade, a deposit perpendicular to the direction of flow. The flanks of these mini-deposits are analogous to natural levees along a river's reach. Indeed these geomorphological features are also evident in lava flows as documented by Hulme (1974). Volcanologists have applied empirical correlations between levee geometry and the rheology of the flows with success, allowing estimation of yield stress from levee width (Griffiths, 2000). Such correlations for tailings could also be developed for the purposes of quality control during deposition or for consideration during the design of deposition areas or paddocks. Figure 5 shows a cross section (looking parallel to flow direction) of a channel experiencing overbanking.

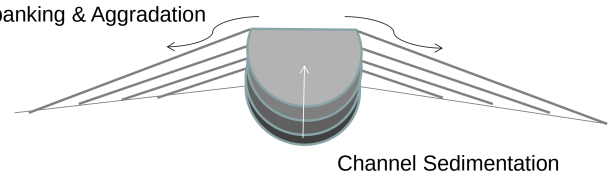

Figure 5. Cross-section of a channel experiencing overbanking and aggradation (looking parallel to flow direction).

3.3.3 *Changes in rheology in distance and time*

As introduced in Section 2.4, tailings flowing across a beach for a period of time (say two to five minutes for some typical long beaches) will experience prolonged shearing; hence, one might expect some time-dependent rheological changes to occur. Indeed, significant reductions in yield stress have been measured in the field by the author for high-clay thickened tailings under high-energy flow conditions. Practitioners reasonably argue that rheological change on the beach relative to changes that occur during the transportation of tailings in-pipe is negligible; however, the validity of this argument will depend on the sensitivity of the tailings and the energy of flow on the beach.

The change in tailings behaviour across the length of the beach should be acknowledged by designers and operators. For very sensitive materials or tailings prone to significant strength loss due to shearing, these fundamental changes in distance and time should be considered. Not only may the flow behaviour be altered across the beach, but the settling, dewatering, and ultimate consolidation characteristics of the tailings may also be impacted.

4 APPLICATION OF FIELD DATA IN DEPOSITION MANAGEMENT

Rheological data may be used in a number of ways to improve the operation of a tailings management facility. For the purpose of focusing this paper, the author will discuss the direct benefits of rheological field monitoring during the sub-aerial discharge of thickened tailings.

4.1 *Beach management & modelling*

While models of tailings beach development vary in theory and presentation, yield stress is widely accepted as an important parameter for beach formation, influencing both the run-out distance (beach length) and average beach slope (suppress for simplicity the fact that tailings beaches are curved in profile).

Back analysis of field-measured rheology may help to explain physical changes in the beach development over time (e.g. flattening or steepening of the beach) and help in devising corrective management strategies.

4.2 *Quality control*

The regular collection of rheological field data may help to gauge plant performance, operator diligence, or identify possible physical or chemical changes in the tailings feed or pore water. For example, pore water pH is known to have a significant influence on the rheology of some mineral suspensions (Coussot, 2005). Many such physical, chemical, or operational deviations could be identified by simple field tests, such as the slump test.

4.3 *Deposition area design*

While plant-side rheology may be well defined from bench testing prior to start-up, the field rheology may differ significantly and is likely less well understood. For this reason, pilot testing should be undertaken at a reasonable scale to characterize the tailings flow behaviour under field conditions.

An understanding of field-scale flow behaviour and how that behaviour changes in distance and time during deposition should be documented and considered when designing the management facility. For instance, a hypothetical deposition area may be reduced in slope and length if it is observed that the tailings are sensitive to shear, but a target shear strength is desired to maintain sheet-like flow across the beach. Conversely, an underlying slope may be increased, or beach lengthened, if the yield stress of the tailings does not significantly decrease with additional shear along the beach.

5 CONCLUSION

It was the goal of this paper to impress upon the reader the value of rheological field monitoring as opposed to relying solely on laboratory data. In closing, we summarize the following key points:

(i) Field data differs from laboratory data in that there is potential to capture the aspects of scale and true boundary conditions in the former. Monitoring a flow on whole may provide better insight into the material's true flow behaviour and conditioning when compared to laboratory testing.

(ii) Field rheology may be readily determined using rapid, easily administered tests such as the modified slump test or a set-up akin to the *bucket-rheometer* (Fisher *at al*., 2007). While the scale and boundary conditions many not necessarily reflect field flow behaviour in all instances, these tests benefit from the field conditioning of the tailings prior to testing.

(iii) Beyond standard rheological methods, more empirical relationships may be derived between macroscopic, geomorphological features like overbanked channel levees and key rheological parameters (such as yield stress or dynamic viscosity). Such techniques have been successfully applied in the earth sciences, particularly in volcanology.

(iv) Rheological field data may be used as a metric for monitoring operational performance. Furthermore, field data may provide the basis for implementing corrective management strategies during tailings deposition.

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