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In situ measurement of fluid fine tailings rheology

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Abstract

Understanding the viscosity and yield stress of fluid fine tailings is essential for effective computational fluid dynamics modelling in the oil sands industry. These rheological properties influence key processes such as paste interaction with sand deposition, dredging operations, and containment failure analysis. However, obtaining representative measurements of these properties is challenging. Due to their sensitivity to shear history, the rheological properties of fluid fine tailings can undergo irreversible changes during sampling and transport, leading to non-representative data generated at significant costs.

This study introduces a modified rheological testing method using a patent pending variable-rate vane shear testing apparatus (VR-eVST). In situ field tests were conducted at 9 distinct locations within a tailings containment facility near Fort McMurray, Alberta, Canada. When deployed directly in the tailings deposit, the initial VR-eVST results indicate that in situ rheological properties may be significantly higher than those obtained from laboratory measurements performed after sampling and transport.

At each location, fluid tailings were also sampled for parallel ex situ testing using both the VR-eVST and a laboratory concentric cylinder rheometer. Under the tested conditions, the tailings exhibited Bingham plastic behaviour, with strong agreement between the 2 geometries. The results confirmed that sampling-induced shearing can lead to significant underestimation of rheological properties.

Planned further study includes exploring alternative rheological models, refining the equipment design to constrain the shear boundary, and expanding testing to a broader range of tailings types. This early-stage research demonstrates the potential of the VR-eVST method to more-accurately measure the in situ rheological properties of fluid fine tailings, ultimately leading to improved facility management and safety.

Keywords: *rheology, fluid fine tailings, in situ measurements, Bingham fluid properties, oil sands, tailings management, dredging*

1 Introduction

1.1 Background and motivations

The mining and processing of bitumen from Canada's oil sands ore generates vast volumes of tailings waste. Fluid fine tailings (FFT) are a subset of the waste stream composed of clays, sand, silts, process water, residual bitumen, organics, and process additives. These slurries remain in stable suspension and are particularly resistant to dewatering due to the dominance of intermolecular and colloidal forces over fine clay particles. In the absence of human intervention, centuries are required to achieve the consolidation required for remediation efforts. As of 2023, FFT inventory in Alberta has exceeded 1.4 billion cubic metres (Alberta

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Energy Regulator 2024) and continues to increase. Tailings inventory directly impacts a mine’s ability to avoid production delays or shutdown by limiting the amount of material that can be processed before storage capacities are met. It also influences regulatory compliance, safety risks, and long-term mine planning, making effective tailings management essential for sustained operations. In accordance with the Alberta Energy Regulator’s *Directive 85* (Alberta Energy Regulator 2016), operators must forecast and report fluid tailings inventories and ensure deposited materials are ready to reclaim within 10 years of deposition ceasing. Thus, oil sands operators are motivated from social, environmental, and economic pressures to safely and responsibly manage the liabilities stemming from oil sands tailings.

The non-Newtonian flow properties of tailings slurries are a key input into daily material handling operations, engineering calculations and treatment processes, and safety models. Parameters such as yield stress and viscosity influence effective dredge planning and dictate sand entrainment, mixing behaviours, and material displacement. Understanding these properties is crucial to safety and environment, as they are used to inform runout behaviour predictions. A better understanding of the relationship between solids content and yield stress would allow better estimation of breach outflows in the event of a loss of containment (Fontaine & Martin 2015). In the realm of tailings planning, the effective infilling of a tailings deposit also requires comprehensive knowledge of tailings rheology, as it dictates the material’s flow into the deposit area. The resulting deposit layer thicknesses and the slope gradients will dictate the volume available for storing solid or liquid waste. An increase in tailings yield stress will also allow an increased beach slope, but the relationship is complex and requires case-by-case investigation (Li 2011). Rheological properties are often used as inputs for further engineering analysis, such as computational fluid dynamics modelling (CFD), and therefore accuracy is paramount. Industry’s current best practices for rheological measurement of industrial slurries involves collecting samples and then testing under laboratory settings. However, due to the complex thixotropic nature of FFT, the act of sampling and transport required for ex situ testing introduces unavoidable sample disturbance and leads to property changes, which are often unknown. As an example, a previous study on the dynamics of cone formations during dredging concluded that CFD modelling frequently overpredicted cone size and underpredicted the cone formation rate due to discrepancies between laboratory-determined rheology and true in situ behaviour (Bugg et al. 2022). Significant costs are incurred when unplanned dredge moves become necessary. Furthermore, the time required for sampling and ex situ testing prevents rapid decision-making for time-sensitive processes such as dredge placement.

Earlier work by the authors demonstrated a proof-of-concept that a modified shearing protocol applied using a VR-eVST could be deployed directly into a tailings deposit (McGowan et al. 2024). However, uncertainties remained regarding the determination of sheared fluid boundaries when using the VR-eVST vane geometry. In the current work, an expanded scope of experiments was conducted at a tailings storage facility in northern Alberta and incorporated parallel testing using a laboratory concentric cylinder rheometer and updated testing methodology to determine shear boundary conditions.

1.2 Theory

Industrial suspensions such as FFT commonly exhibit non-Newtonian fluid behaviours arising from the predominance of colloidal particles such as fine clays. Oil sands tailings are commonly represented in literature by the Bingham plastic rheological model (Litzenberger & Sumner 2004; Schaan et al. 2004). The Bingham model is the simplest model which captures the fundamental rheological properties of tailings, including the yield stress and viscosity.

The Bingham plastic fluid model rheological equation (Bingham 1922) is:

$$\tau = \mu_p \dot{\gamma} + \tau_B \tag{1}$$

where:

τ = shear stress (Pa)

μ_p = plastic viscosity (Pa.s)

$\dot{\gamma}$ = shear rate (s^{-1})

τ_B = Bingham yield stress (Pa).

Rheological properties are commonly measured using a rheometer with concentric cylinder geometry. This configuration is comprised of a stationary outer cup and rotating inner cylinder. The fluid being measured is first loaded into the cup, and the spindle is then inserted. As the inner cylinder rotates, the torque response to imposed rotation rate allows the interpretation of rheological properties. The Reiner-Riwlin equation which describes Bingham plastic behaviour in concentric cylinder geometry (Reiner 1949) is:

$$\omega = \frac{T}{4\pi L\mu_p}\left(\frac{1}{R_1^2} - \frac{1}{R_2^2}\right) - \frac{\tau_B}{\mu_p}\ln\left(\frac{R_2}{R_1}\right) \tag{2}$$

which can be re-arranged to produce:

$$T = 4\pi L\frac{R_1^2R_2^2}{R_2^2-R_1^2}\mu_p\omega + 4\pi L\ln\left(\frac{R_2}{R_1}\right)\frac{R_1^2R_2^2}{R_2^2-R_1^2}\tau_B \tag{3}$$

where:

ω = angular velocity (rad/s)

T = torque (N.m)

L = inner cylinder length (m)

μ_p = plastic viscosity (Pa.s)

R_1 = radius of rotating inner cylinder (m)

R_2 = radius of stationary cup or radius of shear (m)

τ_B = Bingham yield stress (Pa).

L, R_1 and R_2 in Equations 2 and 3 are known quantities, which allows for relatively straightforward model fitting. However, while the concentric cylinder setup is widely used in laboratory applications, several shortcomings make this geometry less desirable for industrial slurries. First, as the inner cylinder is inserted in a cup partially filled with the fluid being measured, the fluid is forced into the gap between the cylinder and cup walls. As this gap is narrow by design, significant shear forces are imparted into the fluid sample. This can lead to irreversible changes to the fluid properties for samples that have strong shear-history dependency. Second, wall slip may be a critical concern for suspensions laden with fine solid particles. Wall slip arises from a localised near-wall solids-depletion effect (Barnes 1995), and torque readings can be artificially low as a result. Both the narrow-gap shear and wall slip issues are exacerbated by the presence of polymer flocculants which are commonly used in FFT treatment. Finally, the presence of settling sand in FFT may introduce non-homogeneity in the sample during testing, which is a common rheometry error source.

Vane geometry can be used to mitigate or eliminate these concerns. The fluid sample is minimally disturbed during geometry insertion due to the relatively slim profile of the 4-bladed vane (Nguyen & Boger 1983). Further, the wall slip is significantly reduced because the plane of yielding occurs within the fluid as opposed to a boundary between 2 surfaces (Fisher et al. 2007). It is also less susceptible to errors arising from the presence of sand and other large particles (Talmon et al. 2023). A vane is commonly used to measure the undrained shear strength, or yield stress, in soft soils using a standardised slow rotation rate (ASTM International 2001; Chandler 1988). The geometric parameters for concentric cylinder and vane are shown in Figure 1.

The objective of this study is to investigate the application of an accelerating rate of rotation, and the potential to measure Bingham plastic rheological parameters for industrial slurries in situ within a tailings deposit. For in situ applications, complications arise for fluids exhibiting a yield stress. Yield stress is a rheological property in some non-Newtonian fluids that describes the minimum shear stress which must be overcome to initiate shearing. The shear stress at the edge of the rotating vane blade is always at a maximum and decays outwards due to frictional losses. When the local shear stress decays below the yield stress of the substance, any material beyond this boundary essentially behaves as a soft solid and does not deform (Fisher et al. 2007). In this case, the sheared region does not extend to reach the container edges, making the determination of the thickness of the sheared fluid problematic and the calculation of the Bingham plastic fluid parameters impossible.

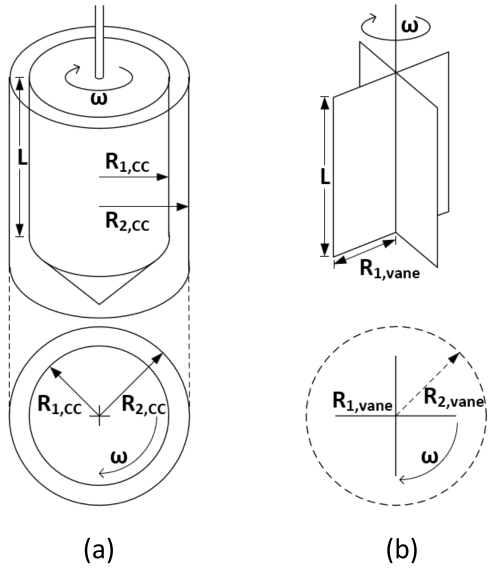

Figure 1 Geometric parameters for (a) concentric cylinder and (b) vane rheometry attachments

This study examined rheological behaviours at 3 scales: small laboratory samples with a concentric cylinder rheometer (20 mL), intermediate container tests using the VR-eVST vane (20 L), and deployment of the same VR-eVST under true in situ conditions within a tailings containment. To estimate the shear radius for in situ vane measurements, parallel tests using both concentric cylinder and vane configurations were conducted. In situ testing using VR-eVST and sampling were performed at 2 individual locations each with several depths within one tailings storage facility. Untreated FFT stored at this containment area are dredged, then treated prior to placement in a designated disposal area. Effective FFT treatment is contingent on predictable and consistent tailings feed properties and therefore accurate in situ rheological properties of FFT are required to enable optimal dredging operations.

2 Methodology

2.1 Pre-study material characterisation

Prior to conducting the rheological study, companion gamma piezocone penetration tests (GCPTu) were performed at each location to characterise the test material. Figure 2 presents the GCPTu results for location 1, including rheological parameters determined in situ by the VR-eVST. Field vane shear testing is widely used in geotechnical practice to measure the undrained shear strength and sensitivity of fine-grained soils following standards such as ISO 22476-9 (International Standard Organization 2020) and ASTM D2573 (ASTM International 2001). The VR-eVST used in this study is an electronically instrumented field vane test that enables the operator to apply a programmed shear rate profile, which may be constant per the referenced geotechnical testing standards, or accelerating which is typical for rheological measurements. The system incorporates an internal inclinometer that monitors vane inclination during insertion. The vane blade and torque load cell are advanced to the target depth using metallic rods and is held at a fixed elevation during testing by the vane motor which is mounted at surface. Torque is measured continuously in the downhole torque load cell as the vane is rotated under an accelerating angular velocity profile, allowing in situ measurement of shear stress and shear rate curves. Undrained shear strength (Su) from GCPTu was compared to a pseudo undrained shear strength obtained from the VR-eVST. Undrained shear strength (Su) from GCPTu was compared to a peak shear stress obtained from the VR-eVST, which is considered as a pseudo undrained shear strength. This value was determined under accelerating angular velocity conditions, rather than the constant rate used in a standard vane shear test. The influence of this acceleration on undrained strength has not been considered in this study.

Passive gamma measurements were used to estimate solids content, fines content, and the material behaviour index (MBI) following the tailings behaviour type methodology (Entezari et al. 2022). Earlier sampling supported this characterisation, and there is good agreement between laboratory and in situ determinations of solids content, fines content, and MBI. The GCPTu responses exhibit typical FFT characteristics, with tip resistance (qt) broadly comparable to dynamic pore pressure (u2) and minimal friction sleeve (fs) engagement, as expected in fluid-rich material. This response confirms that the material at location 1, and similarly at location 2, meets the conditions required for the rheological testing. Figure 2 illustrates these characteristics and the associated rheological parameters obtained in situ.

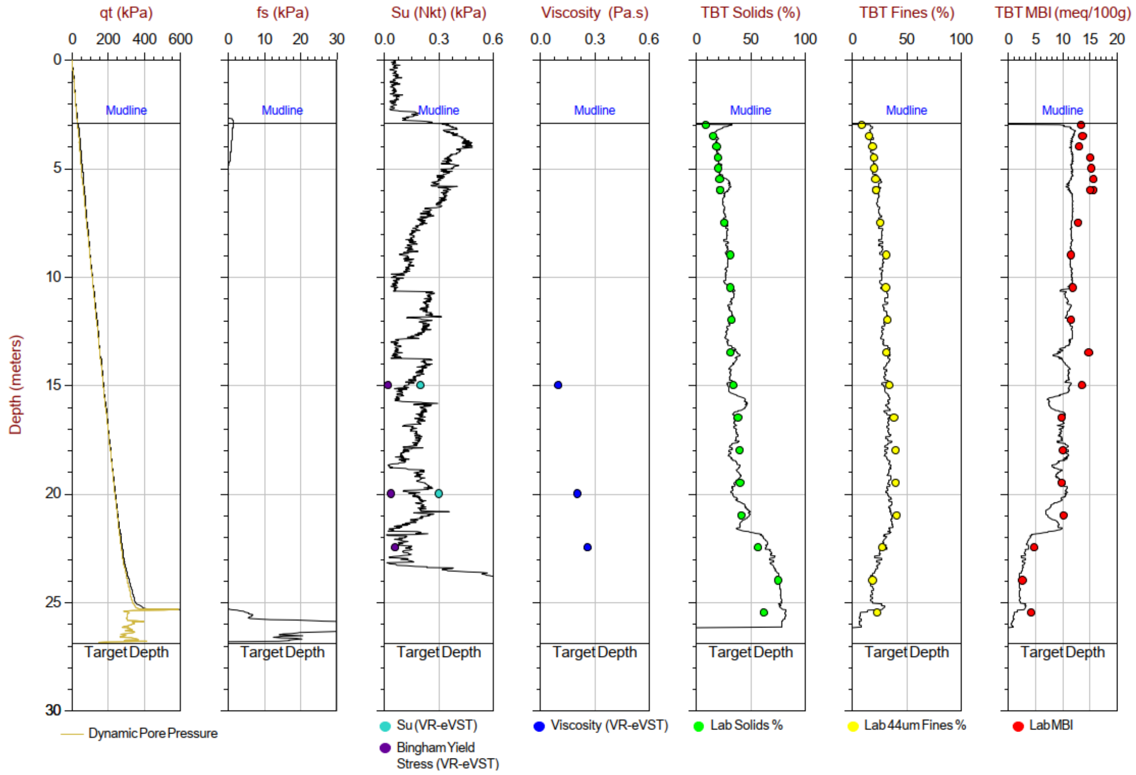

Figure 2 GCPTu test conducted at location 1, presenting in situ results, including Bingham yield stress, viscosity and undrained shear strength (Su) obtained from the VR-eVST. The solids, fines and MBI have been obtained through laboratory testing and the application of Entezari et al. (2022). TBT = tailings behaviour type

2.2 Field testing and sample collection

The in situ field experiments were conducted using the VR-eVST apparatus with a 4-bladed vane . The vane had a rectangular profile ($L = 0.3$ m, $R_{1,vane} = 0.075$ m). The controlled shear rate rotation protocol was a linear increase from 0 to 15 rpm over 10 minutes, immediately followed by a linear decrease back down to 0 rpm over another 10 minutes. Torque response to the imposed rotation speed was measured. Testing locations, depths, and in situ temperature at torque load cell during testing are summarised in Table 1.

Table 1 Sampling locations, depths, and in situ temperature

Sample ID	Sample location	Depth (m)	In situ temperature (°C)
A	Location 1	5	20.6
B	Location 1	10	19.4
C	Location 1	15	15.3
D	Location 1	20	12.3
E	Location 1	22.5	10.8
F	Location 2	10	11.3
G	Location 2	12	11.1
H	Location 2	14	11.0
I	Location 2	16.5	10.9

At the conclusion of each test, a 20 L tailings sample was retrieved from the in situ test location and collected into a plastic pail for further parallel testing with the VR-eVST. To enable a direct comparison between field and laboratory results, a Brookfield RST laboratory rheometer with CCT-25 concentric cylinder geometry was transported to the field to perform tandem measurements with the VR-eVST. The goal of simultaneous testing was to minimise the effect of shear and rest history. The dimensions of the CCT-25 concentric cylinder attachments were L = 0.037 m, $R_{1,CC}$ = 0.0125 m, and $R_{2,CC}$ = 0.0135 m. Rotation rate for the CCT-25 cylinder was scaled up such that the maximum speed at the edge of the rotating cylinder matched that of the field equipment. Therefore, the laboratory rheometer protocol was a controlled shear rate test, linearly increasing from 0–90 rpm over 10 minutes, then linearly decreasing to 0 rpm over another 10 minutes. With limited time to conduct parallel testing, samples C, D, E, H and I were prioritised, as they originated from a greater depth within the tailings containment. These samples had the highest solids content and were most likely to exhibit non-trivial rheological behaviour. Temperature was not controlled during rheological testing and was assumed to be equal to ambient conditions (in situ temperature for in situ measurements, 5–10°C for field testing, and 21°C for laboratory measurements). Following the parallel testing, each 20 L pail was sealed and transported back to Edmonton, Alberta for sample characterisation and further testing. Characterisation included measurement of solids content, pH, electrical conductivity (EC), and clay content by methylene blue index (Kaminsky 2014).

2.3 Calculations

Rheological flow sweep data was plotted as cylinder angular velocity (ω, [rad/s]) versus torque (T, [N.m]). Due to the floc structure of the colloidal clays, some thixotropic behaviours were expected in FFT samples. Typically, the return ramp phase of the shearing protocol is preferred for the calculations, as the initial transient strength of the tailings are de-structured, enabling more-stable post-peak readings. A linear trendline was fitted to the dataset to fit the Bingham plastic rheological model. From Equation 3, the slope and intercept of the trendline are:

$$slope = 4\pi L \frac{R_1^2 R_2^2}{R_2^2 - R_1^2} \mu_p \quad (4)$$

$$intercept = 4\pi L \ln\left(\frac{R_2}{R_1}\right) \frac{R_1^2 R_2^2}{R_2^2 - R_1^2} \tau_B \quad (5)$$

For both concentric cylinder and vane operation, L and $R_{1,CC}$ depend on the inner cylinder geometry and are known values. Similarly, $R_{2,CC}$ for concentric cylinder is the radius of the stationary cup, provided sufficient torque is applied to ensure complete shearing across the rheometer gap. However, during vane operation in an unbounded fluid, $R_{2,vane}$ represents the radius at which yielded, flowing fluid ceases (i.e. shear strains are essentially zero) and is not readily or accurately determined. Equation 4 is first used with concentric cylinder data to determine viscosity ($\mu_{p,CC}$). Then, Equation 4 is re-arranged to allow estimation of $R_{2,vane}$ with vane data (Equation 6).

$$R_{2,vane} = \sqrt{\frac{R_{1,vane}^2 Slope}{Slope - 4\pi L R_{1,vane}^2 \, \mu_{p,CC}}} \tag{6}$$

This re-arrangement relies on parallel testing between concentric cylinder and vane geometries and assumes that the sample viscosity remains the same between the 2 testing geometries. The μ_p term in Equation 6 is calculated using the concentric cylinder data. Finally, the calculated value of R_2 is used in Equation 5 for vane measurements and compared against the value obtained by concentric cylinder measurement to evaluate the error.

3 Results and discussion

3.1 Characterisation results

Characterisation results for all tailings tested are summarised in Table 2.

Table 2 Basic characteristics of tested tailings samples

Sample ID	Depth (m)	pH	Electrical conductivity (mS/cm)	Solid wt%	Methylene blue index (mEq/100 g)
A	5	7.32	3.48	23.0	13.4
B	10	7.30	3.26	32.2	11.1
C	15	7.48	2.90	34.4	11.5
D	20	7.38	2.60	40.6	10.2
E	22.5	7.84	2.31	50.3	5.9
F	10	7.47	2.37	30.5	13.3
G	12	7.52	2.25	33.4	11.1
H	14	7.79	2.83	35.7	12.6
I	16.5	8.13	2.54	36.7	11.3

As expected, solids content of tailings increased with depth. The volume fraction of solids has a strong influence on fluid rheology, and tailings viscosity is expected to increase with depth. Clays are a higher fraction of the solids in FFT at the shallower regions, as evidenced by higher Methylene blue index values at smaller depths. Rheological properties are also expected to be influenced by pH and EC. Kaolinite clay particle edge and face surfaces both carry a negative charge, and dispersive forces dominate under alkaline conditions. As kaolinite is one of the primary constituents of FFT clay, both viscosity and yield stress would be expected to decrease at higher values of pH (Michaels & Bolger 1964). Similarly, higher EC values and ionic strength collapse the electric double layer surrounding clay particles and encourage greater interparticle interaction (Mietta et al. 2009). In the present study, neither pH nor EC varied significantly (pH 7.30–8.13; EC 2.25–3.48 mS/cm) with sampling location nor depth.

3.2 Concentric cylinder rheometer measurements

Bingham plastic rheological parameters were calculated by applying a linear trendline fit to a flow curve of torque versus angular velocity, such as that shown in Figure 3. Due to the thixotropic nature of tailings, the 'ramp down' data was more stable and representative and therefore used in calculations. However, significant thixotropy was not as evident in the laboratory test results, as these samples had undergone the most cycles of transportation, homogenisation, and other sources of shearing. For the concentric cylinder measurements, the geometric input parameters used in Equation 3 were known (L = 0.037 m, $R_{1,CC}$ = 0.0125 m, $R_{2,CC}$ = 0.0135 m). Using the slope and intercept obtained from flow curves such as Figure 3, the plastic viscosity (μ_p) and Bingham yield stress (τ_B) can be directly calculated. Results from concentric cylinder testing on each sample are summarised in Table 3.

Field μ_p and τ_B were measured using the concentric cylinder rheometer near Fort McMurray, and performed as single runs on samples C, D, E, H and I. Lab μ_p and τ_B were measured using the same rheometer and attachments in a laboratory setting on samples after transportation back to Edmonton. They are presented as average values ± one standard deviation following triplicate testing.

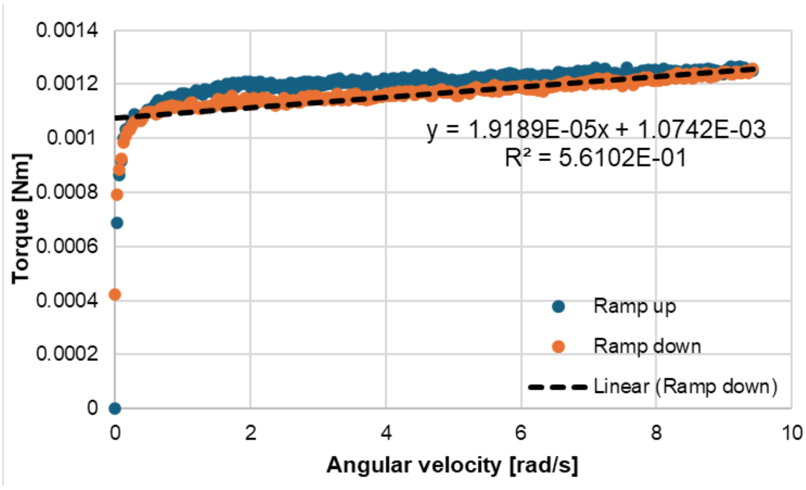

Figure 3 Linear trendline fit to rheological flow curve from measurement on sample E, made in a laboratory setting

Table 3 Calculated values of μ_p and τ_B from concentric cylinder rheometer measurements performed in field and laboratory settings

Sample ID	Depth (m)	$\mu_{p,field}$ (Pa.s)	$\tau_{B,field}$ (Pa)	$\mu_{p,lab}$ (Pa.s)	$\tau_{B,lab}$ (Pa)
A	5	N/A	N/A	0.011 ± 0.001	9.20 ± 0.03
B	10	N/A	N/A	0.012 ± 0.001	18.01 ± 0.09
C	15	0.03	17.24	0.013 ± 0.001	21.64 ± 0.22
D	20	0.04	30.20	0.010 ± 0.001	34.63 ± 1.03
E	22.5	0.09	24.07	0.038 ± 0.001	27.45 ± 0.06
F	10	N/A	N/A	0.017 ± 0.004	16.61 ± 0.36
G	12	N/A	N/A	0.013 ± 0.001	16.12 ± 0.08
H	14	0.05	27.46	0.018 ± 0.003	28.83 ± 0.55
I	16.5	0.04	29.83	0.018 ± 0.008	26.96 ± 0.84

Significant changes in plastic viscosity are observed in the samples following vehicular transportation of sample containers and re-homogenisation before laboratory testing, as evident in comparing samples tested in both field and laboratory settings. A comparison of the plastic viscosity and Bingham yield stress values measured in the field compared to a laboratory setting using a concentric cylinder rheometer is shown in Figure 4. Laboratory-measured viscosities were often less than half the value measured in the field. Clays and other fine particles with FFT settle into a packed structure over time, increasing the strength and viscosity. A breakdown in the existing structure is induced by repeated disturbance via transport and homogenisation, and lead to decreased viscosity measured in the laboratory setting. This issue can be exacerbated if the tailings have previously been treated by a polymer-based flocculant. However, the FFT tested in the present scope were untreated, and therefore changes in viscosity cannot be attributed to mechanical degradation of flocculant. Conversely, Bingham yield stress of the samples measured in the laboratory setting generally increased by 1–5 Pa for most samples tested. This increase may be partially attributed to sample evaporation over time but is not fully explained and warrants further investigation.

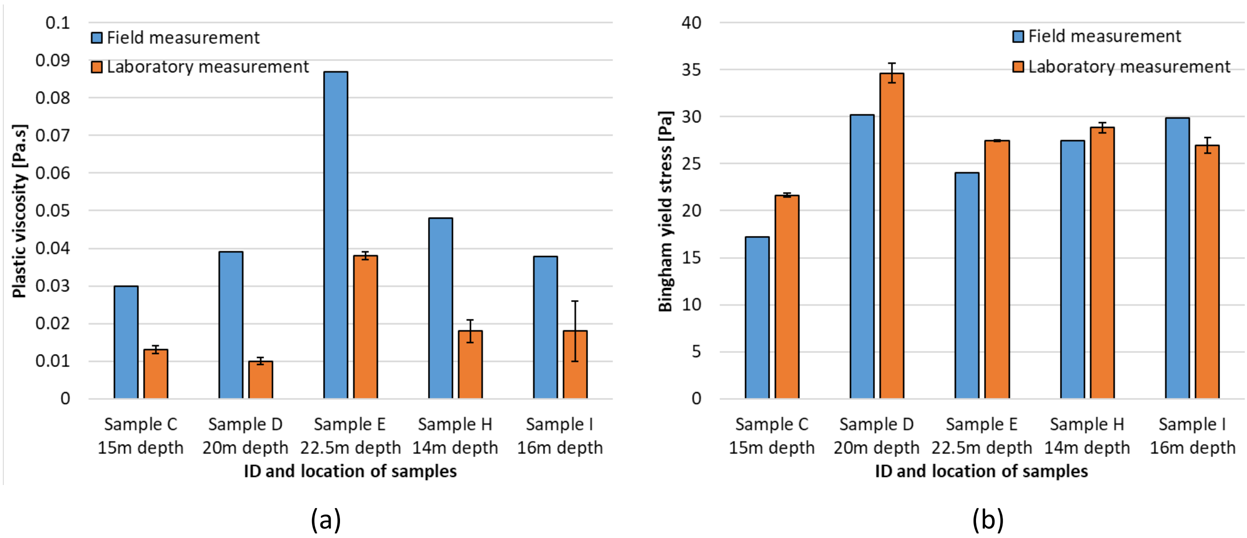

Figure 4 Comparison of (a) plastic viscosity and (b) Bingham yield stress measured using concentric cylinder rheometer at field setting and laboratory setting

3.3 Parallel vane and concentric cylinder rheometer measurements in a container

The evaluation of vane measurements in this study was enabled by conducting paired testing on FFT using concentric cylinder and vane geometry simultaneously. The analysis approach required the following steps: First, the radius of the fluid being sheared by the vane ($R_{2,vane}$) was determined by measuring the viscosity of an FFT sample using the concentric cylinder laboratory rheometer ($\mu_{p,CC}$). Next, $\mu_{p,CC}$ is input into Equation 6, and allows the $R_{2,vane}$ to be calculated. Finally, the calculated value of $R_{2,vane}$ is then input into Equation 5 to calculate $\tau_{B,vane}$, or the Bingham yield stress determined by vane data. Under ideal circumstances, if the vane measurements can perfectly replicate concentric cylinder measurements, the Bingham yield stress values from the vane test should exactly match what was calculated by the concentric cylinder test. Discrepancy in the predicted Bingham yield stress value is the error in the measurement method. Use of this method assumes that the sample exhibits the same viscosity and Bingham yield stress whether measured by concentric cylinder or vane geometry. In the present study, the assumption is justified because the parallel samples have undergone nearly identical shear history and are tested in tandem.

The VR-eVST vane was tested directly in the 20 L container of FFT, while a 20 mL subsample was obtained for the paired concentric cylinder test. Table 4 shows the Bingham yield stresses calculated for both methods. The percentage difference in Bingham yield stress estimated from the vane data relative to the concentric cylinder measurement is also shown. $R_{2,vane}$ indicates the estimated radius of shear for the vane. Finally, $(R_2\text{-}R_1)_{vane}$ represents the thickness of the sheared fluid region beyond the vane edge.

Table 4 Estimated $\tau_{B,vane}$ and $R_{2,vane}$ from VR-eVST measurements in comparison to parallel concentric cylinder measurements

Sample ID	$\mu_{p,CC}$ (Pa.s)	$\tau_{B,CC}$ (Pa)	$\tau_{B,vane}$ (Pa)	% diff, τ_B	$R_{2,vane}$ (mm)	$(R_2-R_1)_{vane}$ (mm)
C	0.030	17.23	18.83	9.29	77.77	2.77
D	0.039	30.20	29.04	−3.84	79.55	4.55
E	0.087	24.07	25.31	5.15	80.14	5.14
H	0.048	27.46	28.14	2.48	77.45	2.45
I	0.038	29.83	24.82	−16.79	78.50	3.50

80% of the test pairs exhibited less than a 10% difference between VR-eVST vane and concentric cylinder results, demonstrating strong agreement and showing potential of the VR-eVST to estimate rheological properties. The calculated shear radius indicated that the shear zone region ranged from 2.45–5.14 mm beyond the vane edge. Feasibility of eventually eliminating the reliance on paired concentric cylinder measurements is supported by this narrow range of values. Determination of how the region thickness changes across testing conditions and sample types will validate the VR-eVST as an independent tool for rheological analysis. To further develop this approach and enhance method robustness, additional testing across FFT samples from varied locations, depths, and material properties is recommended.

3.4 In situ vane rheometer measurements

The goal of this study was to establish a connection between laboratory rheology measurements and in situ testing without the need for sampling. True in situ values of viscosity and yield stress for FFT are expected to be higher than tailings that have been dredged or sampled, transported, homogenised, or otherwise disturbed prior to testing. An example of in situ flow curve data collected by the VR-eVST is presented in Figure 5.

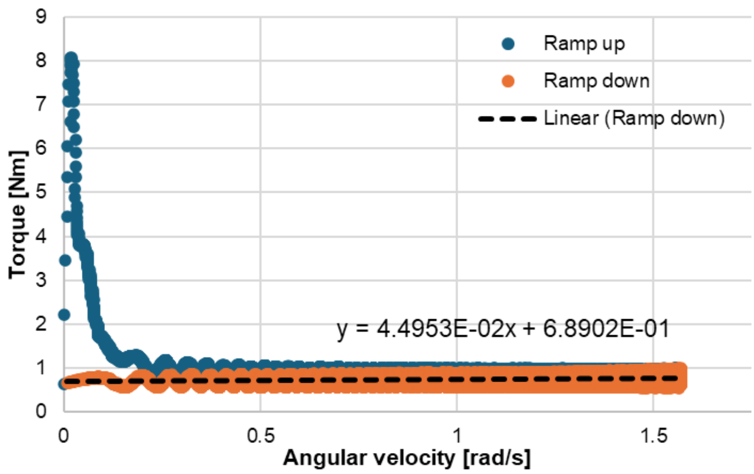

Figure 5 Linear trendline fit to rheological flow curve from sample E, measured in situ using VR-eVST

The in situ measurements reveal a pronounced initial static yield stress (or undrained shear strength) during the ramp-up phase of shearing – a characteristic behaviour of tailings that have undergone a rest period and require additional stress to initiate shear. At the onset of shearing, the peak yield stress rapidly decays. Further investigation into the relationship between peak and residual strength, as well as the energy input and time needed to transition between these states, would provide valuable insights. The sinusoidal pattern observed in Figure 5 is explained by a minor axial eccentricity in the vane, which could be exacerbated by a slight rocking motion in the rig when a water cap is present over the FFT. Although more efforts will be made to reduce the interference of vane positioning and improve rig stability, the structured variation in the data is expected to have minor impact in the average trendline of the data used for calculation.

$\mu_{p,in\ situ}$ and $\tau_{B,in\ situ}$ have been calculated by applying the $R_{2,vane}$ values obtained through the parallel 20 L container tests, as shown in Table 5. The $\mu_{p,lab}$ and $\tau_{B,lab}$ values represent the rheological parameters that represent conventional laboratory testing. The percentage difference quantified the discrepancy calculated between the laboratory results and estimated in situ properties at the tested location. Viscosity estimates based on in situ measurements showed significant differences from the laboratory measurements, indicating laboratory results may be under-representing the viscosity of tailings by a factor of nearly 20 times.

Table 5 Comparison of calculated μ_p and τ_B from laboratory versus in situ measurement

Sample ID	$R_{2,vane}$ (mm)	$\mu_{p,lab}$ (Pa.s)	$\mu_{p,in\ situ}$ (Pa.s)	% diff, μ_p	$\tau_{B,lab}$ (Pa)	$\tau_{B,in\ situ}$ (Pa)	% diff, τ_B
C	77.77	0.013	0.102	685	21.637	22.66	5
D	79.55	0.010	0.205	1,950	34.631	37.69	9
E	80.14	0.038	0.263	592	27.450	60.86	122
H	77.45	0.018	0.311	1,628	28.825	98.49	242
I	78.50	0.018	0.278	1,444	26.958	40.86	52

3.5 Repeated cyclic shearing at a single location

The VR-eVST vane shear protocol was performed 6 consecutive times in situ at the sample D location to better understand the role of shear in the thixotropic breakdown of rheological properties. Flow curves generated from the vane are presented in Figure 6. For each shearing cycle, in situ plastic viscosity and Bingham yield stress were calculated using the $R_{2,vane}$ value determined from the parallel vane/concentric cylinder tests (Tables 4 and 5), and assuming $R_{2,vane}$ remains constant. The relationship between the estimated rheological properties for each shearing cycle is shown in Figure 7. Results from the first shearing test (cycle 1) could not be adequately interpreted, likely because the FFT was still experiencing a rapid thixotropic breakdown from the initial peak yield stress that could not be adequately described by the Bingham plastic fluid model. Over cycles 2–6, viscosity was observed to decay quickly, reaching half the value observed in test 2 after 5 cycles of shearing. Conversely, the Bingham yield stress remained relatively unchanged. This could be because yield stress in FFT decays significantly faster than viscosity and had already reached a minimum value over the course of the first test.

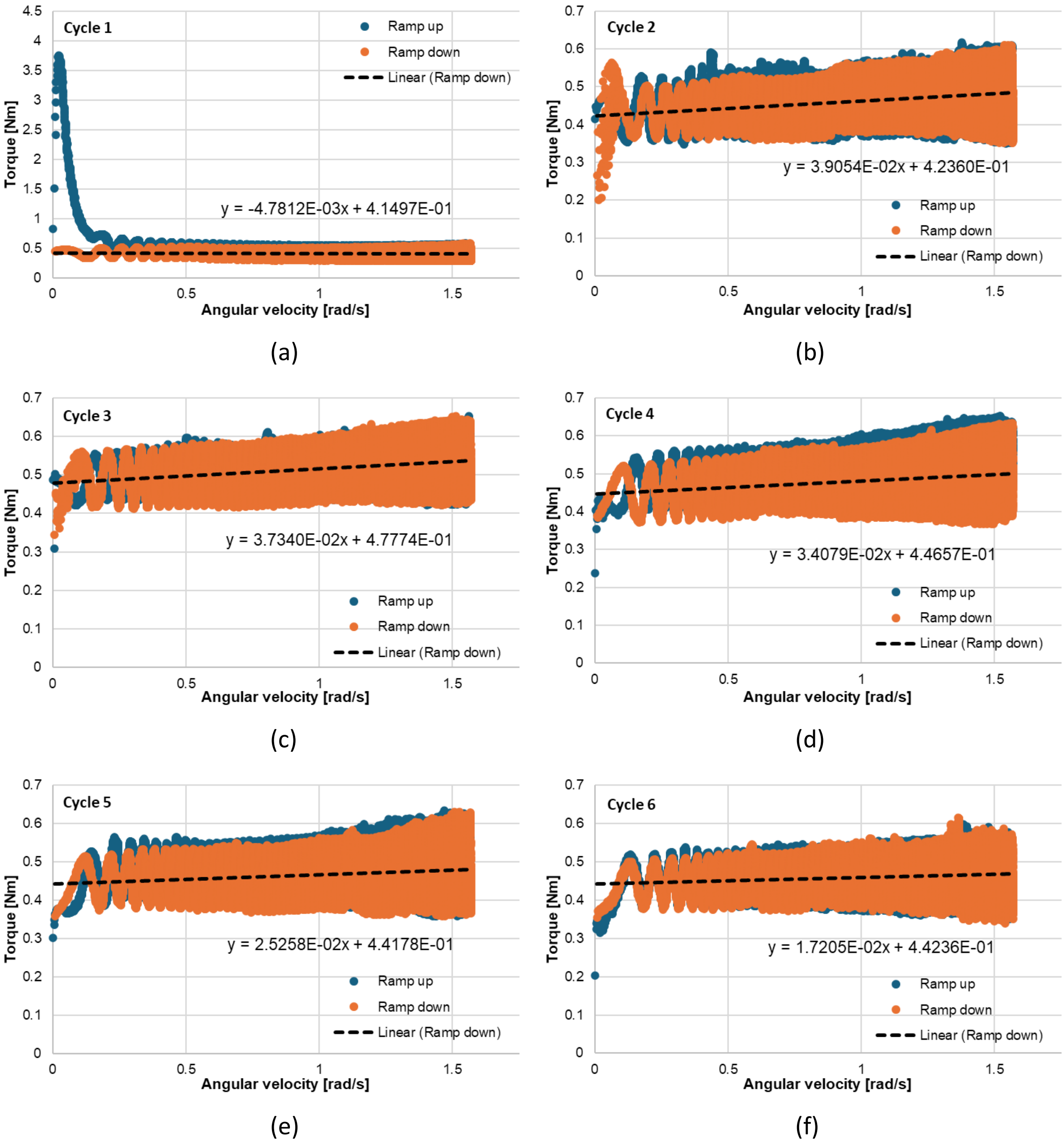

Figure 6 Flow curves collected over 6 consecutive shearing cycles with unchanged position. (a–f) Cycles 1–6. Testing conducted at location of sample D

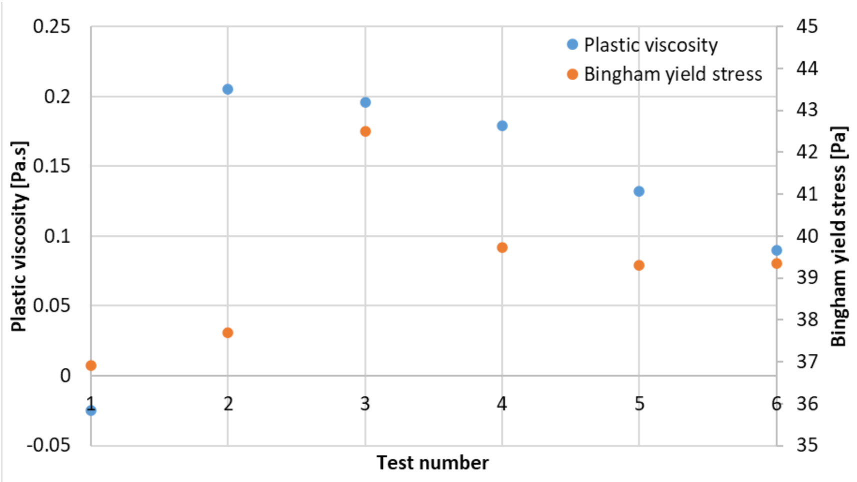

Figure 7 In situ plastic viscosity and Bingham yield stress changes over 6 consecutive shearing cycles. Testing conducted at location of sample D

3.6 Sources of uncertainty, mitigating strategies, and future work

Accurate rheology measurements must be performed on a homogenous suspension. Sources of non-homogeneity in FFT can be from the inclusion of sand particles, which can settle through the sample medium during measurement, or gas bubbles produced by microbial activity present within the tailings. Further investigations should be made into how much sample volume may be occupied by coarse solids or gas voids before rheological results are adversely impacted.

It is desired to eventually remove the requirement for parallel testing and allow the VR-eVST to operate as a standalone device for in situ rheology characterisation. Improvements in the rheological measurements were made by introducing parallel concentric cylinder testing to the vane testing in the present scope. Further improvements may be realised by conducting sufficient testing across a wide breadth of tailings samples with varying properties to better understand how the radius of shearing can be reliably estimated based on test conditions.

The present study measured but did not actively control the temperature of samples during measurement. Sample temperature is expected to influence rheological properties. Ambient temperatures in the laboratory setting typically lies between 18 and 22°C, warmer than the in situ temperatures of the majority of the FFTs sampled. Tests conducted on the tailings sampled into 20 L pails during the parallel investigation were conducted between 5 and 10°C, and in situ temperatures ranged between 10 and 20°C. Future laboratory testing may incorporate temperature control to better represent the temperature of in situ tailings.

Undisturbed tailings at depth were observed to have a yield stress which quickly decayed upon shearing. A better understanding of how quickly yield stress decays versus viscosity, and the factors that affect both, would enable more-accurate modelling of tailings behaviours.

Finally, tailings at depth within a storage facility are subject to increased pressure due to static head. At the current phase of investigation, laboratory rheology measurements have only been performed at atmospheric pressure conditions. Sample depressurisation following extraction from depth may exacerbate non-homogeneity due to gas pocket expansion and could contribute to misaligned ex situ measurements. However, the effect has not been quantified and warrants further investigation.

4 Conclusion

The present study contributes towards developing methods for in situ rheological characterisation of oil sands tailings. It has been demonstrated that laboratory rheological measurements of FFTs are prone to underestimating viscosity, primarily due to breakdown within the tailings microstructure during sampling, transport, and homogenisation. The observed discrepancies highlight the importance of developing reliable in situ testing methods that accurately capture the rheological behaviour of tailings.

Thixotropic breakdown was observed with both laboratory and field equipment, suggesting that, in practice laboratory, measurements may represent a lower bound of oil sand tailings viscosity:

- Field rheometer measurements and subsequent lab measurements using the same equipment after transportation and homogenisation produce a repeatable reduction of plastic viscosity.
- VR-eVST measurements in situ conducted repeatedly on the same specimen showed a reduction of plastic viscosity.

Parallel ex situ testing conducted with a concentric cylinder laboratory rheometer and VR-eVST field vane on the same sample rendered comparable results, which indicates promise for the method, reduces the reliance on sample extraction, and may enable more-accurate characterisation of tailings at its undisturbed state.

Future work should focus on expanding vane-based testing across diverse FFT sources and further refining the calculation methodology for shear boundary conditions. Incorporating yield-pseudoplastic rheological behaviours may allow for better model fitting. A better understanding of how gas voids, entrained coarse particles, pressure and temperature affect in situ rheology measurements may help improve accuracy and applicability. Advancing understanding into how yield stress and viscosity in tailings decay as they are sheared are critical for modelling tailings behaviours. This could further support the improvement of tailings remediation performance across the oil sands industry and inform strategies for safer, more-effective tailings management and reclamation.

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