Online rheology monitoring of a thickener underflow

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Abstract

The perceived need for accurate and reliable methods of measuring suspension rheology in real time arises from the greater demands being placed on mineral processing operations. To extend mine life and reduce TSF footprint the adoption of finer grinds, higher solids concentration and high clay ores result in complex multi-phase suspensions that need close monitoring to optimise thickener performance, pipeline transport and tailings deposition. Often the control of the processing or transport of these suspensions can be related to its rheology. However, due to the involved nature of rheological measurement for suspensions and the nuanced interpretation of data necessary to produce useful decisions, rheometry has only seen limited application in process monitoring. A robust unit that can measure, analyse and interpret the rheology of a process stream continuously and unattended is needed. The CSIRO has developed an online rheometer to address this problem. This paper describes the process prior to the deployment of the online rheometer to an Australian goldfield site, comparing online rheological measurement to benchmark laboratory values.

**Keywords:** *slurry rheology, online rheometer*

1   Introduction

An accurate, reliable and robust means of measuring suspension rheology in real time has applications in thickener control, pipeline transport, pump operations and tailings deposition (Chryss et al. 2012). The need for this technique has arisen from the greater demands being placed on mineral processing operations (Calvo et al. 2016). The trend towards finer grinds, higher solids concentration and higher clay contents because of variable ore grades, water resource and tailings storage facility (TSF) footprint restrictions result in complex multi-phase suspensions. These suspensions can alter and restrict operating windows and close monitoring is needed to optimise unit performance. Due to the involved nature of rheological measurement for suspensions and the nuanced interpretation of data necessary to produce useful decisions, rheometry has only seen limited application in mineral process monitoring. The expected main influences on the rheology of mineral suspensions and thickened tailings are:

- Volume concentration of the solid phase.

- Particle size distribution and particle shape.

- The state of flocculation.

Measuring rheology online can provide data that, in association with other measurements or prior knowledge of conditions, can indicate change in any of those three factors. A unit that can measure, analyse and interpret the rheology of a process stream continuously and unattended has been developed by CSIRO Mineral Resources as an answer to this problem. The CSIRO online rheometer is an automated capillary rheometer that samples, tests and analyses data continuously and unattended. This paper will compare the results from the online rheometer to bench scale rheometry with examples of complex behaviour and discuss the process of deploying a unit to site, which is currently underway.

2 Principle of operation

The capillary viscometer is a well-known rheometry method used for Newtonian fluids (Barnes et al. 1989). The CSIRO online rheometer is a variation of this technique that takes a side stream of the process fluid of interest (Figure 1). This could be a thickener underflow, ore pipeline etc. The sampling point is chosen to ensure a representative sample is taken. Discussion of how this is achieved with typically varying process streams is beyond the scope of this paper. The instrument then measures the pressure drop generated over a pipe of known dimensions for a series of known volumetric flow rates. Changing the flow rate within the rheometer generates a range of shear rates and allows the non-Newtonian rheological properties to be measured. Control of the flow rate is achieved by including a variable frequency drive (VFD) controlled progressive cavity pump in the line. Figure 1(c) shows the arrangement of the unit. The fluid enters the unit from the right side of the drawing into the larger pipe, through a U into a smaller diameter pipe and then to the inlet of the progressive cavity pump. Measurement takes place on the suction side of the pump to avoid degrading the sample. From the pump, slurry travels through a Coriolis meter and then returns to the process downstream of the sample point or to a sump. The use of two pipes of differing internal diameter has several advantages. A wider range of shear rates can be measured and any coarse particle settling will be detected. Although capillary rheometry is a robust measuring method for homogeneous fluids, homogeneity is problematic for suspensions. A pseudo-homogeneous suspension (a material which is isotropic at the measurement scale) in laminar flow will produce results from both pipes that sit on a single curve in a rheogram. If coarse particle settling occurs or entrained gas is present, then the output from the different diameter pipes will not be coincident. This is checked by the inbuilt software on the rheometer via the method shown in Section 2.1. By this method non-viscometric data (due to sedimentation, turbulence etc.) can be rejected. The unit can be set to run on a fixed time cycle of high-to-low shear rates, generating a fresh rheogram every time, with the option to flush and refill the rheometer between cycles. The shear rates and time of shear are adjustable to suit the material being investigated and the frequency of measurement can be anywhere from every 10 minutes to once daily.

(a)

(b)

(c)

(d)
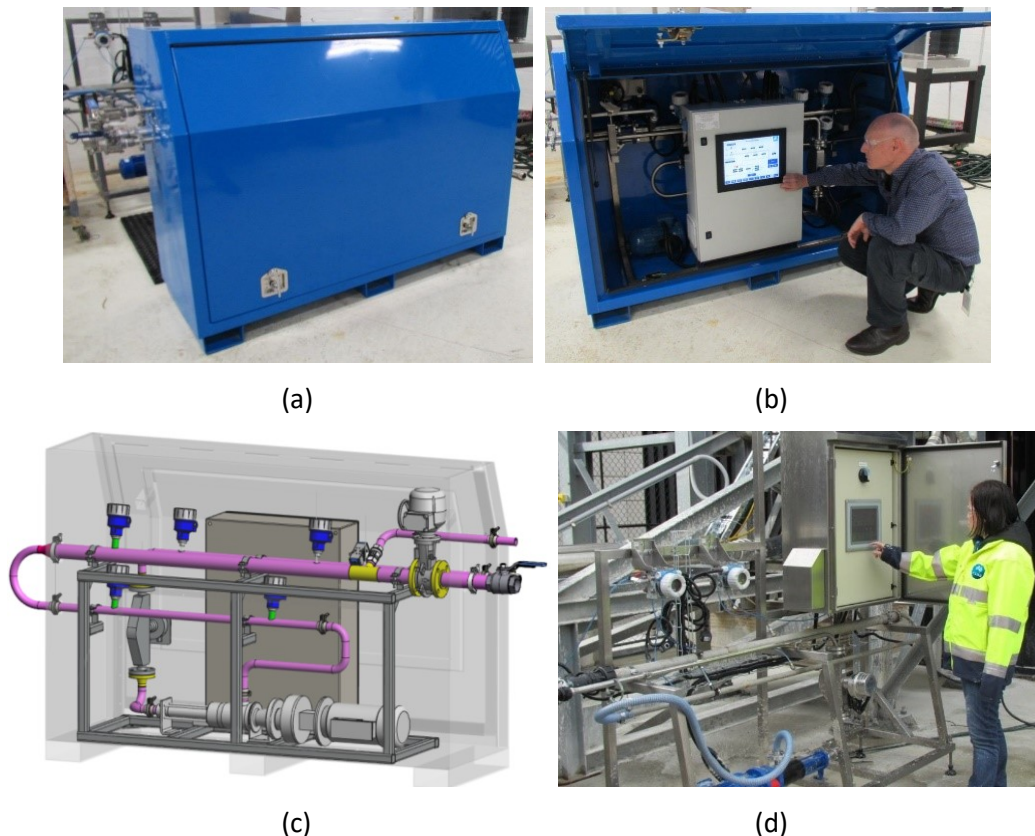
Figure 1 (a) The online rheometer field deployable configuration; (b) Internal view; (c) Diagram of unit from rear; (d) Monitoring rheology in a 100 mm slurry pipeline with a prototype online rheometer

2.1 Rheometry of non-Newtonian suspensions

The processing of the data is handled automatically by the on-board computer. The wall shear stress is generated from the measured pressure drop and the apparent wall shear rate (8V/D) is generated from the volumetric flow rate. The 8V/D value is identical to the wall shear rate for Newtonian fluids only and for non-Newtonian suspensions the extended Buckingham Equation 1, is fitted to the data (Govier & Aziz 1977). Use of this equation assumes yield-pseudoplastic behaviour, which can be represented by the Herschel–Bulkley rheology model Equation 2. The Herschel–Bulkley is a good representation of a wide range of slurry behaviour (Forbes & Chryss 2017).

$$\frac{32Q}{\pi D^3} = \frac{8V}{D} = \frac{4(\frac{1}{k}(\tau_w-\tau_y)^{(1+n)})^{1/n}}{\tau_w{}^3}\left[\frac{(\tau_w-\tau_y)^2}{\frac{1+3n}{n}} + \frac{2\tau_y(\tau_w-\tau_y)}{\frac{1+2n}{n}} + \frac{\tau_y{}^2}{\frac{1+n}{n}}\right] \tag{1}$$

$$\tau = \tau_y + k\dot{\gamma}^n \tag{2}$$

where:

τ	=	shear stress.
τ_w	=	wall shear stress ($\tau_w = \frac{D\Delta P}{4L}$).
τ_y	=	yield stress.
$\dot{\gamma}$	=	shear rate.
Q	=	volumetric flow rate.
D	=	pipe internal diameter.
V	=	mean fluid velocity.
ΔP	=	pressure drop.
L	=	pipe length.
k and n	=	parameters in the Herschel–Bulkley equation.

2.2 Rheological method for data comparison

During the preparation for site deployment of the online rheometer, or for validation of the data generated onsite, benchmark rheology values are needed for comparison with online rheometer results. Bench scale (laboratory) rheometry is the most common method for characterising suspension rheology. Bench scale also allows for measurement of thixotropy and slip effects. Accurate rheological characterisation of non-Newtonian multi-phase mixtures such as tailings slurries is best achieved in profiled Couette geometries. It is also frequently necessary to repeat measurements in differing geometries to detect experimental artefacts. The range of shear rates required to match the online rheometer test conditions could be covered by using a concentric cylinder (Couette) geometry with a 38 mm inner cylinder and a 41 mm outer (stationary) cylinder, and a 31 mm inner with 41 mm outer. The inner and outer surfaces of the Couette geometry were profiled to minimise (but not eliminate) slip artefacts. A Haake Rheostress RS1 rheometer was used throughout the comparisons described here and temperature control was maintained via a recirculating water bath, with test temperatures matched to those in the online rheometer measurements within ±0.1°C.

The upper range of the measurements in the concentric cylinder geometry can be limited due to the inaccuracies caused by the onset of Taylor-Couette eddies, a secondary flow effect at high shear rates. Due to the higher viscosities encountered in the current tests the data was largely unaffected and the correct shear rate (allowing for the non-Newtonian fluid effect) was obtained by using an integration approach for the Couette inverse problem (MacSporran 1989). This method is generally more successful than a differential approach due to the inevitable noise present in real data. Repeat results were combined and averaged. The

comparison between Couette and online rheometer results are shown in Figure 2 for homogeneous fluids. The match for both Newtonian and non-Newtonian fluids is as expected for pure fluids, confirming that the online rheometer is producing accurate rheological data. Complications in measurement and comparison were encountered during the rheological measurement of multi-phase suspensions. This is discussed in Section 3.
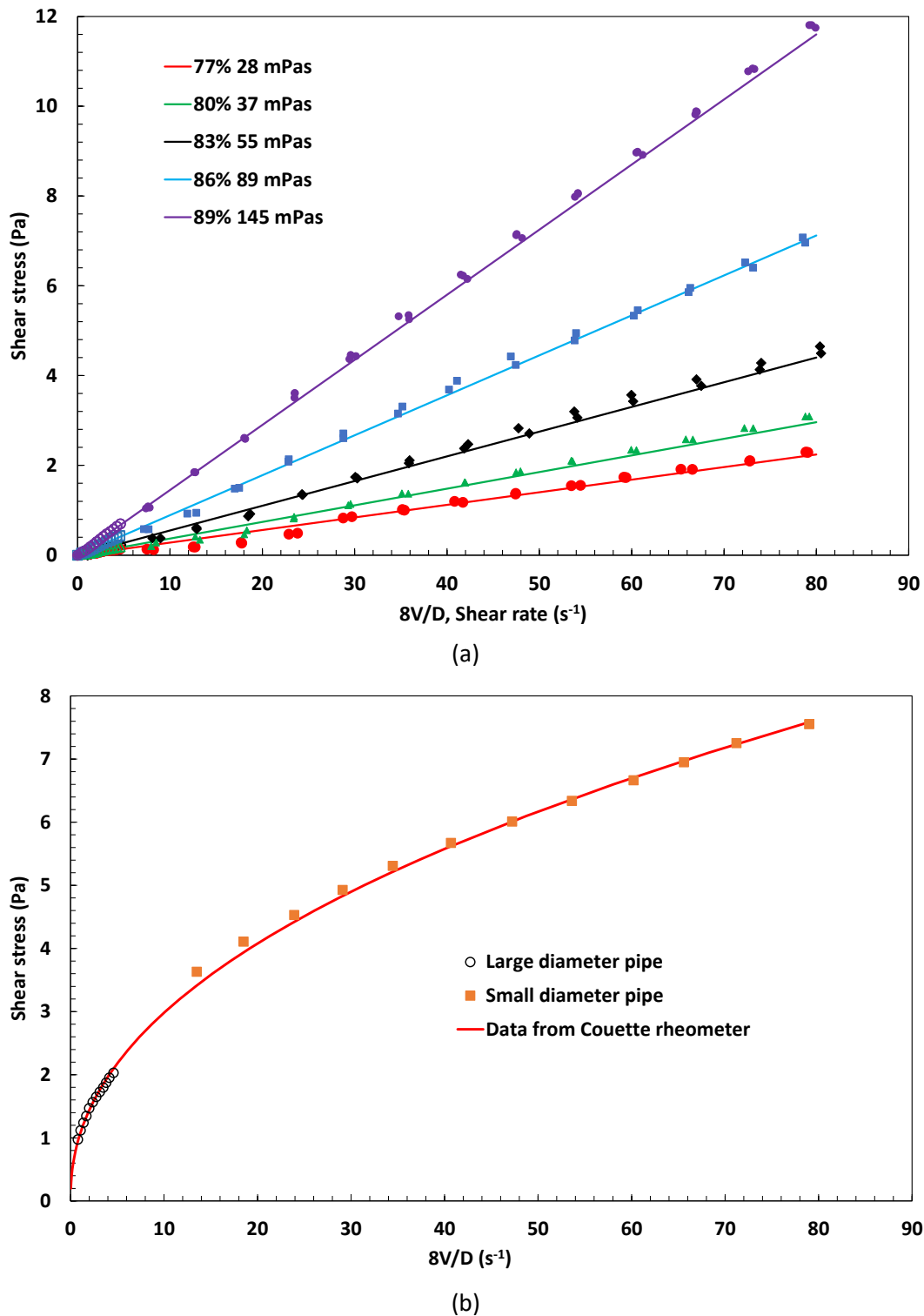

(a)

(b)

Figure 2   (a) Online rheometer output with glycerol solutions, Newtonian fluids; (b) Comparison of Carbopol solution data from Couette rheometry (solid line); and online rheometer (filled shapes, 19 mm diameter pipe, open shapes 48 mm)

Rheology of mineral suspensions is often reduced to just the yield stress for simplicity. Yield stress is often used as a proxy for wider rheological characteristics or physico-chemical properties. The measured yield stress of a suspension varies depending on measurement and modelling methods (Nguyen & Boger 1992). The two most self-consistent methods are vane measurement or rotational rheometry with a yield-pseudoplastic model fit. The two techniques often do not agree and produce different values for strongly networked materials, as the vane is a static test and rotational rheometry a dynamic one. The alternative of using a Bingham model fit to a rheogram or the lowest measured shear stress to determine yield stress depends on the range of shear stresses measured and will tend to be inconsistent and larger in magnitude than the other methods (Barnes 1999). The method used by the online rheometer is to extract the yield stress value in the Herschel–Bulkley model (Equation 2 in Section 2.1). The estimation of yield stress is improved in this method by the inclusion of low shear rate measurements.

2.3 Factors affecting rheology and rheometry of suspensions

In dilute slurries, such as used in conventional tailings disposal, particles are conveyed with water, a Newtonian fluid, and the solids and water behave as two separate phases. The move towards higher concentration tailings suspensions, enabled by advances in thickener technology and driven by the complex economics of tailings disposal, has muddied this division. As the solid concentration increases, inter-particle forces become increasingly dominant and the fine particles combine with the conveying fluid, usually water, to form a non-Newtonian slurry, which behaves as a new and very different carrier fluid. Whether all of the particles can be considered to form part of this carrier fluid depends upon both the surface chemistry of the materials involved and the particle size distributions (Sengun & Probstein 1989). Invariably some of the larger particles will not contribute to the slurry carrier and will be conveyed as a coarse particle burden by the carrier. These larger particles, which usually occur at low volume concentrations, can be removed from the slurry before measurement with no detectable effect on the measured rheology, and minimal change to slurry density. This is of advantage to the online rheometer as it reduces settling in the lines and pump wear.

Measurement artefacts degrade the usefulness of rheological measurements and are a complication encountered during the rheological measurement of multi-phase suspensions. While these are often ignored in simple viscosity measurements they do not produce universally correct values and the resulting data will not allow comparisons to be made between different instruments or to predict pipeline behaviour (Chryss et al. 2005). Due to the presence of a solid phase and/or flocculation slip artefacts were detected during the current set of measurements. This occurs when the relative velocity at the interface between instrument and sample is non-zero. The effect is minimised in larger scale flows and with larger gaps in Couette rheometers. Slip artefacts produce apparent viscosity values that underestimate true values. The effect is worse for small measurement geometries as shown in Figure 3(a). Here the smaller Couette gap (blue line) creates a greater discrepancy. Large measuring geometries, such as used in the online rheometer, reduce the effect of slip to the point that it can be disregarded, which is a significant advantage for the instrument. Thixotropy (the reduction of viscosity with time of shearing) makes it difficult to obtain steady state rheology data. The green curve in Figure 3(b) shows the approach to steady state at a fixed shear rate. Interestingly the corresponding small gap data (blue curve) shows the complex output resulting from slip and thixotropy occurring simultaneously.
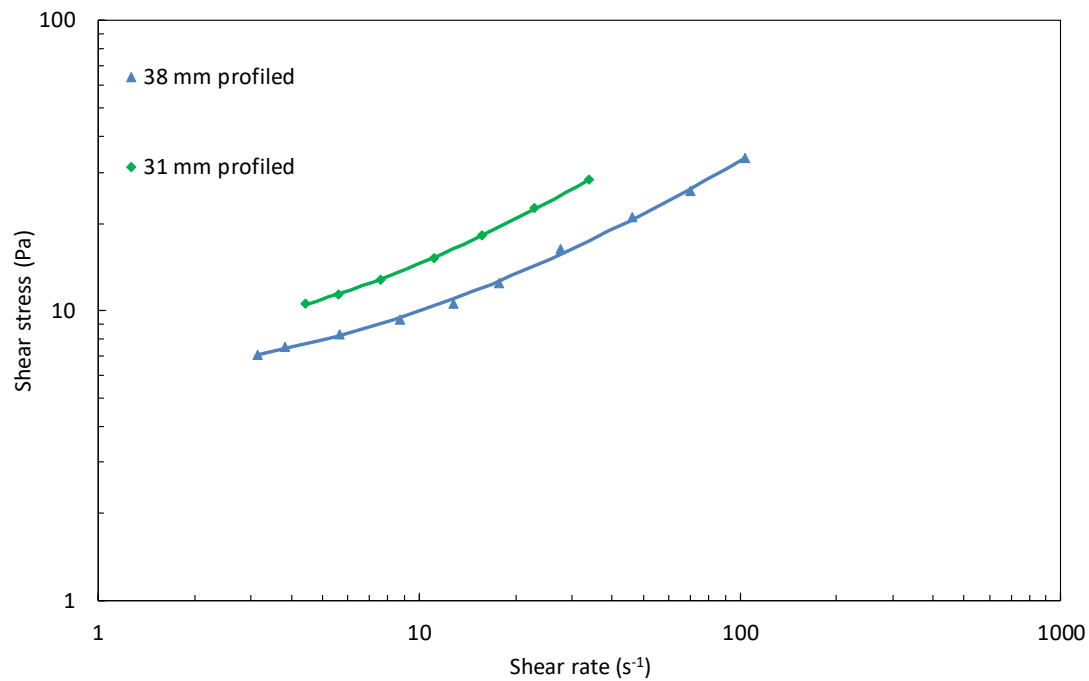
(a)
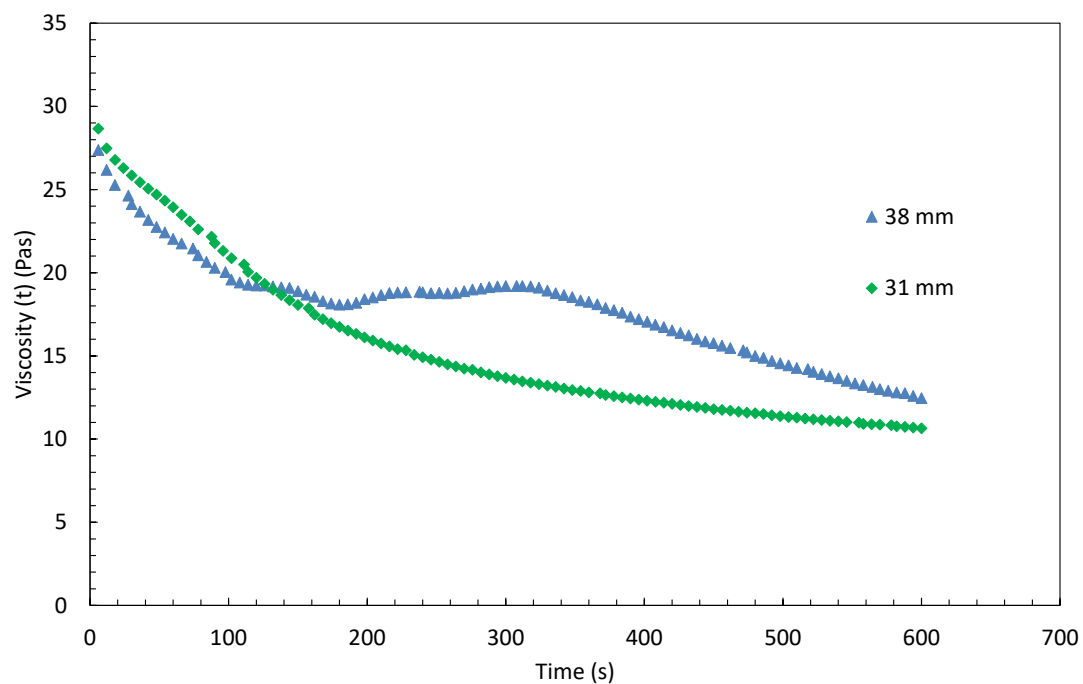
(b)

Figure 3   Slip and thixotropy of copper tailings in Couette measurements (a) Slip artefact shown by the higher viscosity of the geometry with the larger measuring gap; (b) Convoluted effect of slip and thixotropy. Copper tailings sheared at 1.0 s^{-1}

3   Online rheometer trials

As a prelude to deploying the online rheometer to mine sites several tailings slurries were characterised. The bench scale rheometry and online rheometry were compared to determine the suitability of the suspension for rheological testing and to optimise pipe diameters for the viscosity range and thixotropic response. Three examples of tailings slurry that were tested in this way are shown here.

3.1 Copper tailings

A copper tailings thickener underflow (slurry density 1,565 kg.m^{-3}) was tested and is shown in Figure 4. The pseudo rheogram (Figure 4(a)) shows a difference in measurement between the large pipe (48 mm internal diameter) and the small pipe (19 mm internal diameter). This is due to thixotropic effects (Figure 3(b)) causing the suspension to not be fully sheared by the time it has left the large diameter pipe. This is not the case for the small diameter pipe, the higher shear rates experienced allow steady state to be reached more rapidly. The true rheogram (Figure 3(b)) compares Couette data to values taken from the small diameter pipe. Here the effect of slip is apparent, with results less affected as the measurement geometry dimensions increase. It can be inferred that the online rheometer provides the more representative rheological data, if the small diameter pipe only is used. In this instance the pipe diameters would be adjusted to smaller sizes (and higher shear rates) before site deployment.
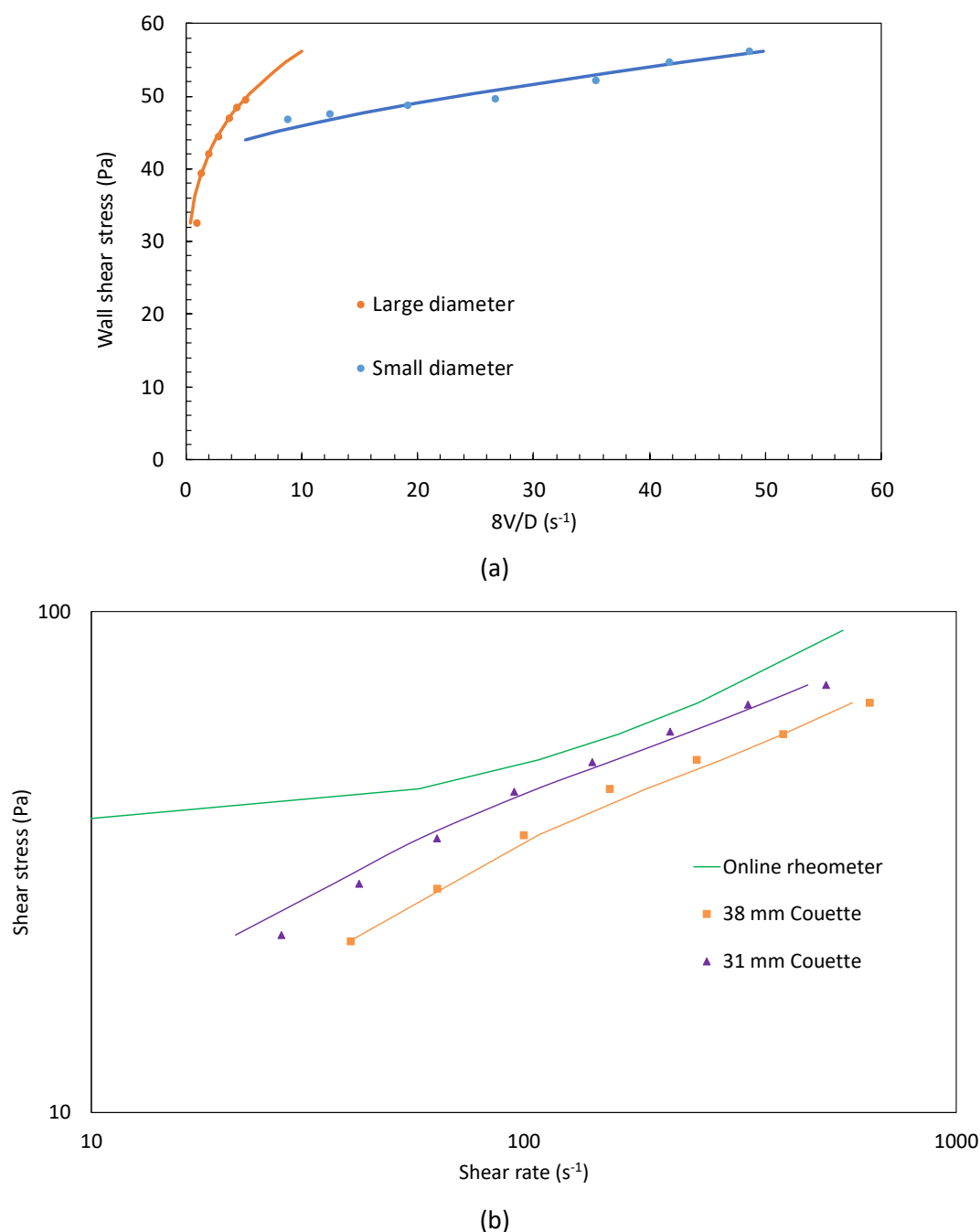

(a)

(b)

Figure 4 (a) Pseudo rheogram of copper tailings tested in the online rheometer; (b) Rheogram comparing online rheometer data to Couette measurements highlighting slip behaviour

3.2   Gold/antimony tailings

Tailings thickener underflow (slurry density 1,410 kg.m^{-3}) from a gold/antimony mine was characterised in the same way as Section 3.1, but in this case utilising smaller pipe diameters, a large pipe (21.4 mm internal diameter) and the small pipe (19 mm internal diameter). The comparison between the two types of rheometer can be seen in Figure 5. The data from both pipe diameters match in the region of shear rate overlap due to the minimisation of thixotropic effects. The online rheometer is again producing higher viscosity values than the Couette due the ubiquitous slip artefact in the Couette geometry.
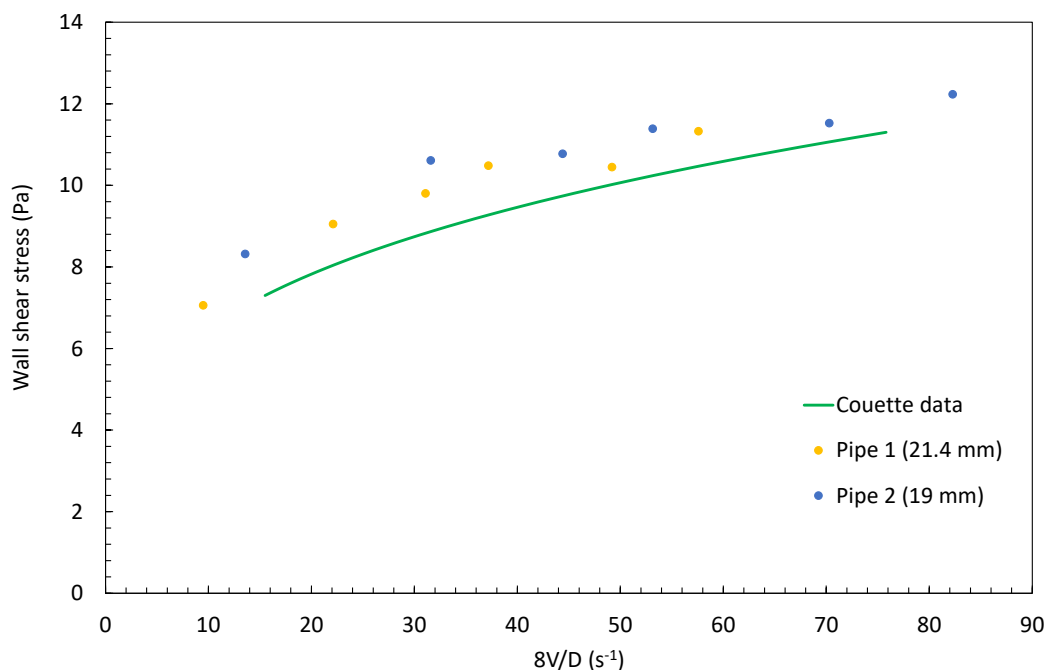

Figure 5   Gold/antimony tailings, Couette and online rheometer results showing slip effects

3.3   Oil sands tailings

Although not a thickener underflow, mature fine tailings (MFT) from oil sands processing has some similar properties to mineral tailings and does require constant rheology monitoring. MFT has a complex rheology due to the combination of clay and bituminous particles. The sample used is MFT ex-tote from a site in the Fort McMurray region in Canada. The solids content was 32.4 wt.%. Due to the bitumen component of the MFT, several modifications were made to the online rheometer before operation. A heater was fitted to the progressive cavity pump to maintain a stream temperature of approximately 40°C. Trials at ambient temperature had resulted in a bitumen accumulation in the pump stator. The elevated temperature did not affect the rheological measurement, as the pump is after the measurement section. The stator used was made of a high nitrile rubber. This material is a compromise between hydrocarbon resistance and wear resistance. To remove coarse solids from the MFT, a Y Strainer was fitted at the feed end of the rheometer. The coarse solids present in the sample tend to settle in the large pipe section, accumulating over time and affecting the pressure drop measurement. Removing the low volume fraction of coarse solids from the MFT does not affect the rheometric output, as they do not contribute to the actual rheology of the MFT and makes little impact on measured slurry density.

Several aspects of MFT rheology make it a challenging material to reproduce results across different measuring methods and therefore generate an accurate characterisation. It can be seen from the Couette measurements in Figure 6(a) that MFT is quite thixotropic, which is most pronounced at low shear rates. At a shear rate of 0.01 s^{-1}, over two minutes of shearing is required to approach a stable viscosity value, and less than one minute for a shear rate of 0.05 s^{-1}. This presents difficulties when operating a capillary device, as seen in Section 3.1. In Figure 6(b) the data is comparable between methods with small deviations due to thixotropy in the large pipe (48 mm internal diameter) and at low shear rates.
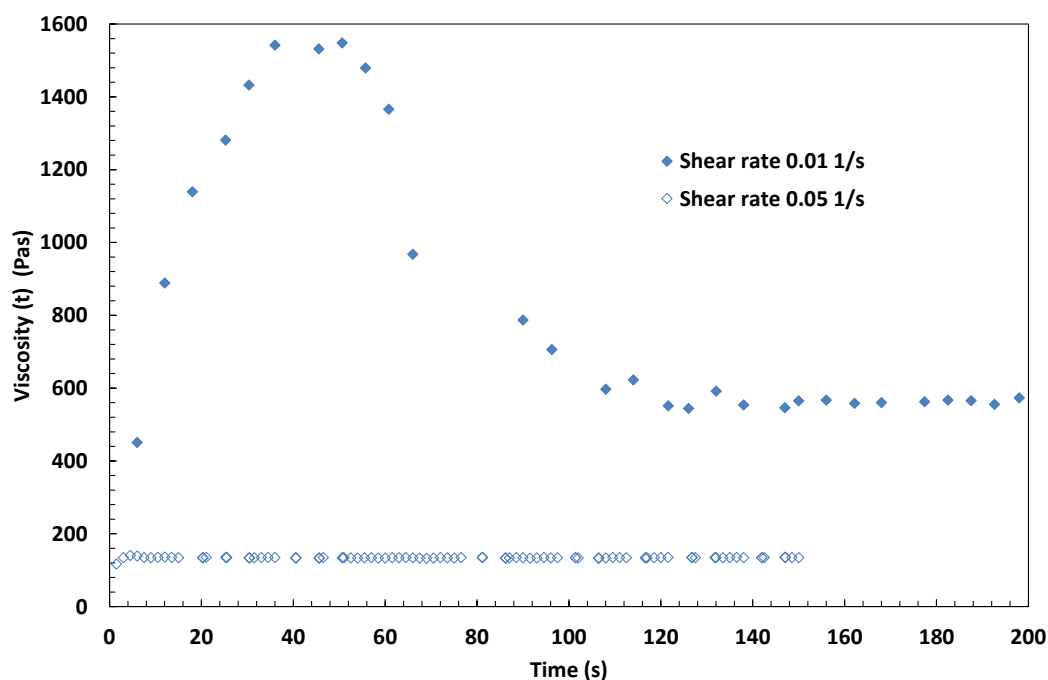
(a)
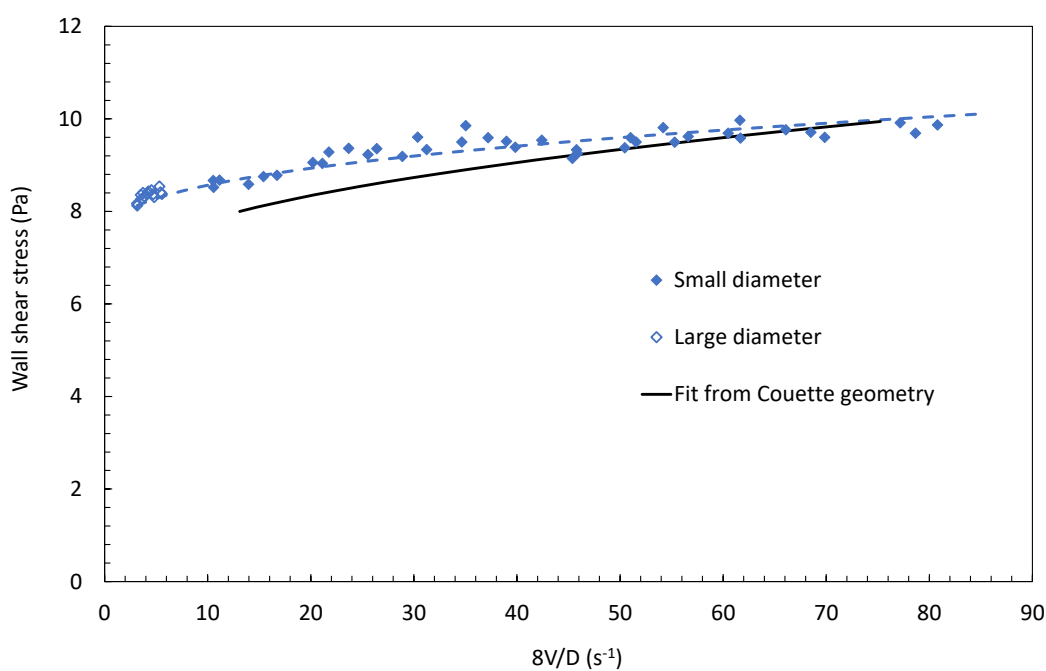
(b)

Figure 6 **(a) Mature fine tailings (MFT) thixotropic effect; shearing at a constant rate displays the viscosity variation, the effect is of shorter duration at higher shear rates; (b) MFT pseudo-rheogram comparing the online rheometer to Couette rheometry (large pipe 48 mm internal diameter, small pipe 19 mm internal diameter)**

4 Conclusion

The CSIRO's online rheometer is suitable for continuous monitoring of complex mineral suspensions rheology, including thickener underflows. The data produced by the online rheometer compares well with standard methods such as bench top rotational rheometers, and in the case of slip prone materials is sometimes more accurate. Although the installation of the online rheometer is relatively straight forward it

needs a detailed understanding of the slurry to be tested to determine the optimum tube geometry and measurement times for the range of expected rheology conditions prior to deployment. Once onsite it enables operational insights and near real-time monitoring of tailings steams that have not been possible through periodic offline laboratory test work.

The potential impact this sensor will have on operations across the mineral processing value chain is significant. Downstream, being able to measure and ultimately control tailings deposition properties will lead to more efficient placement of tailings, whether that be through steeper beach angles, improved dewatering properties, or improved water management. Upstream, the effect of grind size, flotation chemistry and deleterious gangue materials, like clays, on the operation of the tailings thickener and quality of the water returned to plant, will become quantifiable. For the first time, it will be possible to optimise all these parameters and react to changes, without needlessly increasing the slurry transportation risks.

References

Barnes, HA 1999, 'The yield stress-a review or '$\pi\alpha\nu\tau\alpha\ \rho\epsilon\iota$'-everything flows?', *Journal of non-Newtonian Fluid Mechanics,* vol. 81, pp. 133–178.

Barnes, HA, Hutton, JF & Walters, K 1989, *An Introduction to Rheology*, Elsevier Science Publishers, Amsterdam.

Calvo, G, Mudd, G, Valero, A & Valero, A 2016, 'Decreasing ore grades in global metallic mining: a theoretical issue or a global reality?', *Resources*, vol. 5, no. 4.

Chryss, A, Fourie, AB, Mönch, A, Nairn, D & Seddon, KD 2012, 'Towards an integrated approach to tailings management', *Journal of the Southern African Institute of Mining and Metallurgy*, vol. 112, no. 11, pp. 965–969.

Chryss, AG, Bhattacharya, SN & Pullum, L 2005, 'Rheology of shear thickening suspensions and the effects of wall slip in torsional flow', *Rheologica Acta*, vol. 45, no. 2, pp. 124–131.

Forbes, E & Chryss, A 2017, 'Fundamentals of clays; surface and colloid science, and rheology', in M Gräfe, C Klauber, A McFarlane & D Robinson (eds), *Clays in the Minerals Processing Value Chain*, Cambridge University Press, Cambridge, pp. 95–103.

Govier, GW & Aziz, K 1977, *The Flow of Complex Mixtures in Pipes*, Krieger Publishing Company, Huntington.

MacSporran, WC 1989, 'Direct numerical evaluation of shear rate in concentric cylinder viscometry using least-squares cubic splines', *Journal of Rheology,* vol. 33, no. 5, pp. 745–755.

Nguyen, QD & Boger, DV 1992, 'Measuring the flow properties of yield stress fluids', *Annual Review of Fluid Mechanics*, vol. 24, no. 47, pp. 47–88.

Sengun, MZ & Probstein, RF 1989, 'Bimodal model of slurry viscosity with application to coal-slurries. Part 1, Theory and experiment', *Rheologica Acta,* vol. 28, no. 382.