Quantifying the Effect of Pump Shear on Slurry Rheology — A Case Study at the Combined Treatment Plant

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ABSTRACT

The paste tailings systems at De Beer's Combined Treatment Plant has been operating since 2003, and as mining has progressed, the feed properties of the reclaimed ore have gradually changed. This has led to variations in the rheology of the tailings, and an extensive test campaign was conducted to quantify the new process parameters. Data was recorded at various points along the pipeline, and showed that the individual components in the system all affect the rheology to some extent. Significant changes in rheology occur at the thickener underflow pumps, which essentially shear the flocculated slurry and decrease the viscosity. As the slurry progresses through the system, there is a stepped decrease in viscosity to the discharge point. This paper will discuss the contribution of each component of the system; centrifugal, positive displacement pumps, and pipelines, to the shearing process.

If not properly understood, the consequences can be far reaching, especially when systems are designed on the basis of pilot plant test work and small scale deposition data using slurry that is not properly sheared, such as when peristaltic pumps are used. Immediate consequences are that the pumping system will be over designed to pump a more viscous than needed slurry, and long term consequences are that the beach slopes will be lower than anticipated, resulting in a tailings disposal site that has an insufficient footprint and capacity.

1 INTRODUCTION

Since 2003, the De Beers Combined Treatment Plant (CTP) has been depositing high density thickened slurry on the tailings impoundment using the central discharge placement philosophy. The system has been described in detail by Houman and Johnson (2003) and Johnson and Vietti (2003). The current deposition site was intended to provide several years of deposition, and was to be replaced by an in-pit deposition system into nearby depleted mine workings. The sites originally intended for in-pit deposition are no longer available, and a number of alternatives have been explored including the extension of the current facility for the remaining life of mine.

The extension of the current facility means that the current deposition and placement strategy need to be re-considered, as steeper deposition angles are needed to provide additional storage capacity within the available footprint. The current average beaching angles on the site are less than the original design specification of 1.5 degrees, although in the early years of operation values of 2 degrees were being obtained.

Several tests were conducted by the mine to assess the reasons for the lower than expected beach angles, and one set of data indicated that there was a substantial change in the measured slump of the material along the pipeline. Further work was needed to properly quantify the reasons for this change in measured slump, and this paper presents the outcome of a detailed investigation into the rheology and flow properties of the thickened slurry as it is pumped from the thickeners to the deposition site.

As a result of this work, new control strategies are in place to ensure that the material is placed at the highest possible density and yield stress that the positive displacement pumps can deliver to the deposition site.

2 TEST CAMPAIGN

A comprehensive test campaign was developed to determine the reasons for the change in material behaviour. The CTP Mine essentially re-processes the older tailings resources produced since kimberlite was first mined in Kimberley, more than 100 years ago. The old tailings resources contain widely varying quantities of weathered kimberlite with high fractions of smectite and kaolinite clays and these affect the rheology of the re-processed ore. The test programme therefore had to include different host ores, and had to answer the following questions:

- What is the reason for the change in rheology in the system?
- What is the effect of the different ore types on the flow behaviour?
- What can be done to increase the density and rheology of the thickened tailings?

2.1 Sampling Points

In order to determine the reasons for the change in rheology in the system, the material properties were measured at different locations along the pipeline after the system had been operating under steady state conditions for a period of time. The paste tailings system comprises the following main elements:

- Five deep cone paste thickeners, each fitted with a re-circulation loop and underflow centrifugal pump.
- A central holding tank that all five thickeners discharge into.
- Centrifugal charge pumps, used to transfer paste from the central holding tank to the suction of the piston diaphragm positive displacement pumps.
- Piston diaphragm positive displacement pumps to transfer paste to the deposition site via a high pressure pipeline.
- Two discharge risers (one operating, one standby) at the tailings facility.

Figure 1 shows schematically where sample points were installed along the system, as follows:

- Sampling points 1 and 2 measured the change across the thickener number 5 underflow pump.
- Sampling points 3 and 4 measured the change across a charge pump.
- Sampling points 5 and 6 measured the change across a positive displacement pump.
- Sampling points 7 to 10 measured changes along the tailings disposal pipeline.

It is important to note that samples were only taken from thickener 5. This material is likely to be similar, but not identical, to the mixed material in the sump that receives underflow from five thickeners simultaneously. In practice, there will be a slight variation in the material in each thickener due to potential preferential feed conditions in the launder splitter box, and variations in flocculant etc.

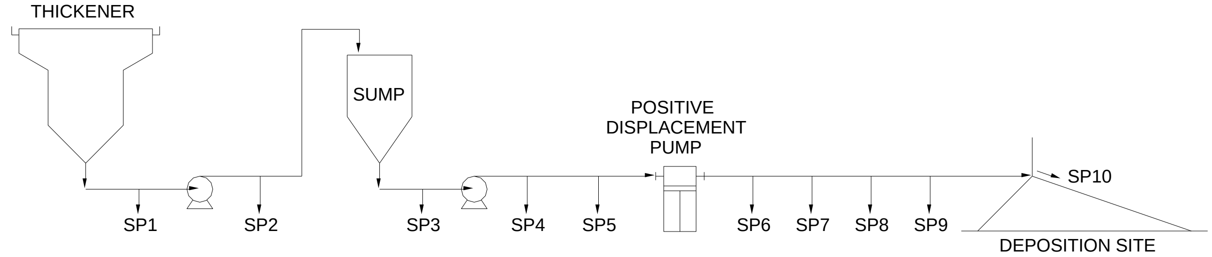

Figure 1 Sample point locations

2.2 Test Procedures

Tests were conducted for different ore feeds and under different operating conditions over a two week period, so as to obtain an indication of the variability of the material properties and process conditions during normal operations. For a typical test, samples were taken as follows:

- The system was operated under stable conditions for approximately 45 minutes in an attempt to obtain as uniform a slurry as possible throughout the system.
- During this period flow and pressure variations from the control system were recorded to check for anomalies in operation.
- Samples were collected from the low pressure sample points 1 to 4 during operation.
- The positive displacement pumps were shut down so that samples 5 to 10 could be collected in a safe manner.

For each sample collected, the following data were measured:

- Solids concentration, determined by oven drying a sample.
- Particle size distribution using standard wet sieving.
- Slump using a 300 mm tall ASTM slump cone.
- Flow curve at sampled concentration for samples 'as collected' and in the fully sheared state.

Where required, thickener overflow water was used to dilute samples to measure the change in rheology of a specific sample as a function of solids concentration.

2.2.1 Viscometer

The flow curves for the samples were obtained using a capillary viscometer. The viscometer consists of a 3.7 litre sealed vessel which can be pressurised and a measurement tube through which the slurry sample is discharged. The discharge rate varies from a maximum value to zero during the test. The flow rate and pressure loss within the tube are calculated from the variation in the measured vessel pressure using calibrated pressure transmitters. There is no mechanical shearing of the slurry during the measurement process except for the slurry flowing through the tube. This makes the instrument ideal for testing partially sheared slurry. This information is used to generate a pseudo-shear diagram or flow curve (a plot of wall shear stress versus bulk shear rate) from which the slurry rheology is determined. The internal diameter of the measurement tube used for the test series was 9.8 mm.

3 TEST RESULTS

3.1 Particle Size Grading

The measured particle size grading of a typical test series is given in Figure 2. There is a variation in the measured data, and this needs to be considered in the interpretation of the results. In general, the results showed that samples 1 and 3 were the coarsest and that samples 7 to 10 were finer compared to the rest of the samples. Samples 2 and 4 are taken from sample points on the centrifugal pump discharge side and are therefore likely to be well mixed and probably are deemed representative of the typical size grading.

It is unlikely that the slurry will physically degrade so rapidly in the system and the differences in measured size gradings can be attributed to a number of factors, including differential settling and solids stratification along the pipeline under laminar flow conditions, sample collection from the tapping points with high residual pressures, or variations in thickener underflow product. For practical and safety reasons, sample points in the high pressure pipeline were taken by opening the existing high pressure tee pieces installed as unblocking tees in a vertical orientation. This meant that should there have been any laminar flow settling, samples at the bottom of the pipe will be coarser than samples at the top of the pipe. Table 1 shows the range of four sets of particle size envelope data measured over a two week period, clearly indicating the variability of the tailings properties.

Table 1 **Measured material properties envelope**

Test Series	1	2	3	4
d90 particle size	749 µm	614 µm	482 µm	826 µm
d85 particle size	616 µm	459 µm	356 µm	690 µm
d50 particle size	182 µm	49 µm	-	151 µm
Average slurry pH	8.5	9.0	8.7	8.7

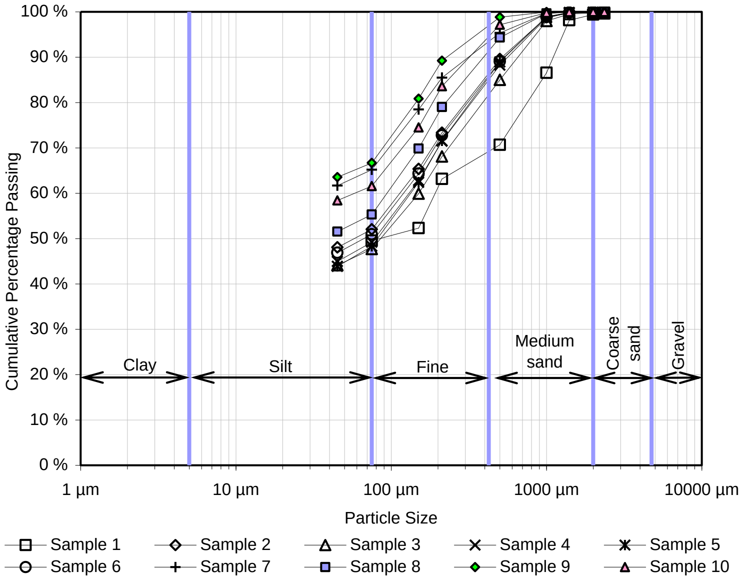

Figure 2 **Typical measured size grading from a single set of tests**

3.2 Measured Slump Data

Slump tests provide a quick visual test on the samples collected and can be used to show general trends, as well as to provide a qualitative indication of slurry consistency. A standard 300 mm high (12 inch) slump cone was used for all the tests as specified in ASTM, C 143/C 143M “Standard Test Method for Slump of Hydraulic-Cement Concrete”.

The slump data provided the initial insight into variations in slurry properties along the pipeline, as shown in Figure 3 for a typical data set. From Figure 3, there are some immediate important observations, most importantly the change in slurry density / solids concentration, along the pipeline, and the fact that sample points 1 and 2 have a slump of approximately 225 mm, compared to the remaining samples that have a slump of about 250 mm. This data was typical for samples collected during normal plant operation, and an immediate concern was the effect of dilution, as densities changed from 1.52 to 1.39 t/m^3.

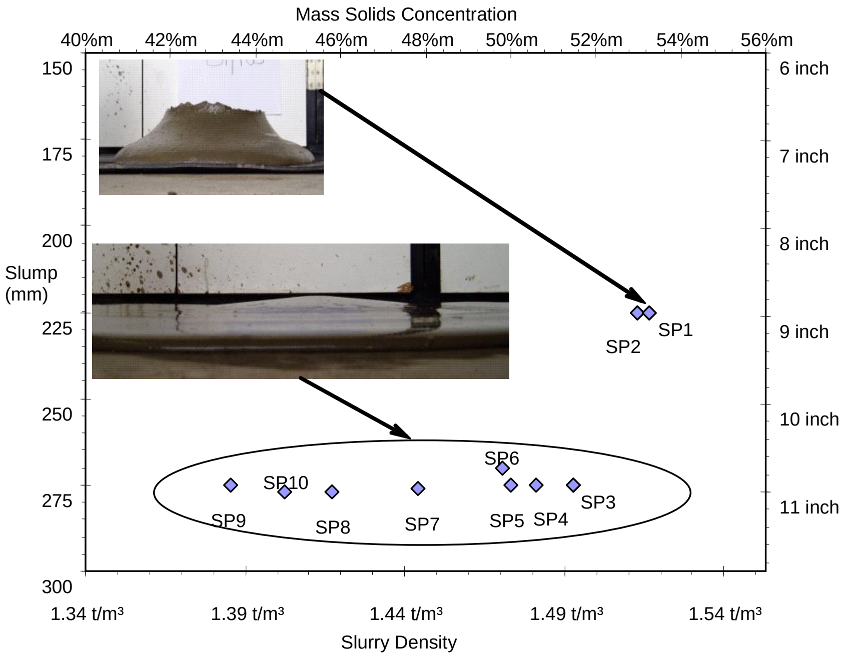

Figure 3 **Slump – as collected slump data during normal operation**

Further tests were done when the dilution valves in the system were manually isolated, and this data is shown in Figure 4. This also shows a change in density along the system from 1.55 to 1.44 t/m^3, however it is not as marked as in Figure 3, and samples points 1 to 6 have more or less similar densities. The change in density from samples points 7 to 10, those along the pipeline, do not follow a consistent trend, and could be due to the samples being drawn from the vertical unblocking tee pieces, and solids stratification along the pipeline.

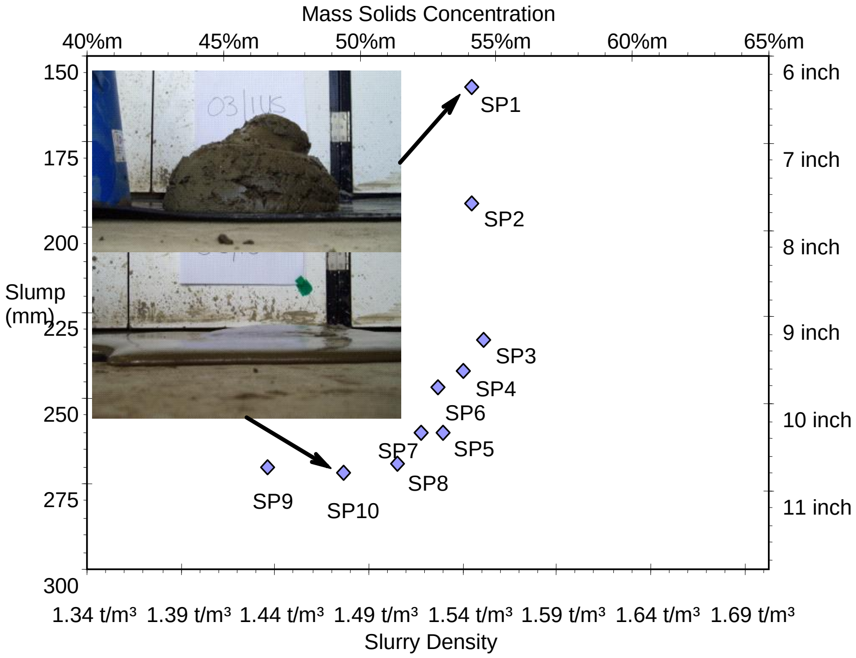

Figure 4 **Slump – as collected slump data with manual isolation of dilution valves**

3.2.1 *Influence of shear on slump*

Considering Figure 3 and 4, which both show that the thickener underflow density is consistently high, the change in slump from sample points 1 to 6 cannot be ascribed only to dilution, as in Figure 4 there is a rapid change in slump from 160 mm to 250 mm at a constant slurry density.

This change in slump is ascribed to the change in shear history of the slurry as it passes through the system, and is clearly seen in Figure 5 that shows the effect of shear on slump for sample point 1 taken from Figure 4. For the same sample at the same solids concentration, the slump changes from 159 mm to 255 mm when the sample is properly sheared. This is discussed further when analysing the change in measured flow curves along the pipeline system.

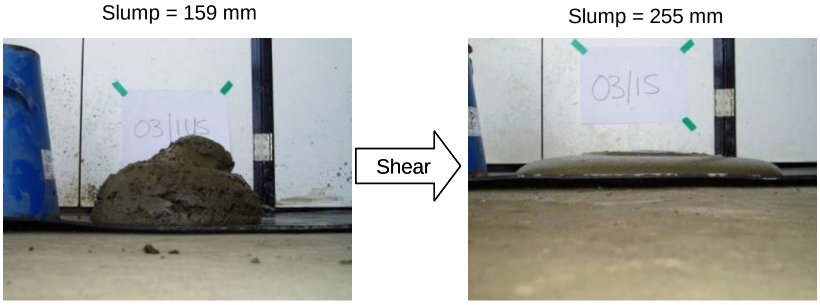

Figure 5 **Change in slump for sample point 1 in Figure 4 as a result of shear**

3.3 Measured Flow Curves

3.3.1 *Typical data*

Figure 6 shows the measured flow curves for the data shown in Figure 3. There is a significant decrease in the measured flow curves from sample points 1 to 4, compared to the change in flow curves between sample points 5 to 10. There is a variation in solids concentration between sampling points that will partially account for the change in measured flow curves.

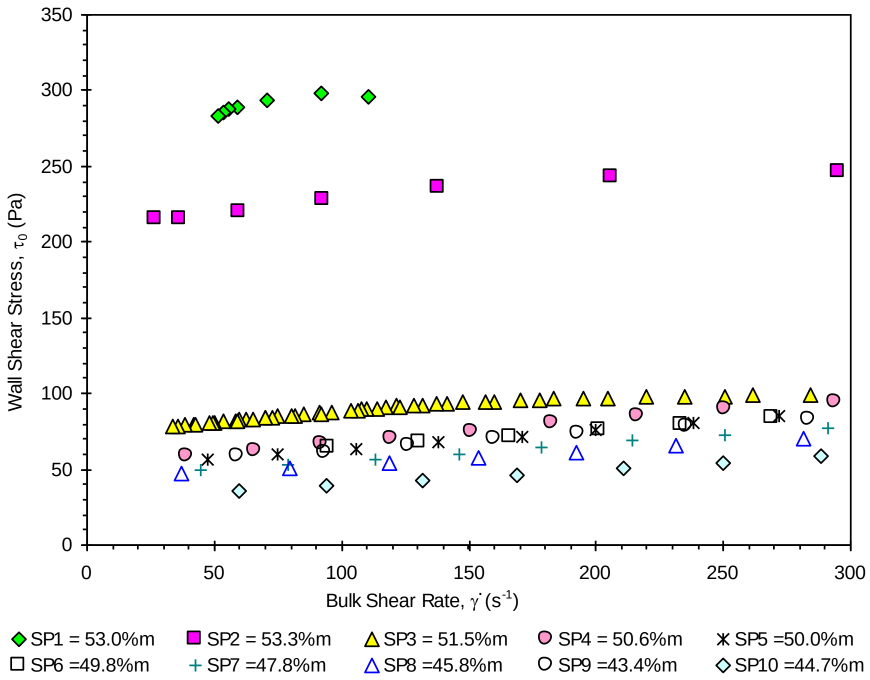

Figure 6 **Flow curves measured during normal operation**

Figure 7 shows the measured flow curves for the same data shown in Figure 4 with the dilution valves manually isolated. The flow curves show a similar change in shear stress from sample points 1 to 10, however there is an increase in slurry concentration from sample points 2 to 3. This means that the slurry concentration in the collection tank (the combined underflow from all the thickeners) is higher than thickener 5 underflow concentration at the time of sampling. The measured flow curve for sample point 2 is still significantly higher compared to sample point 3, even though there is an increase in slurry concentration.

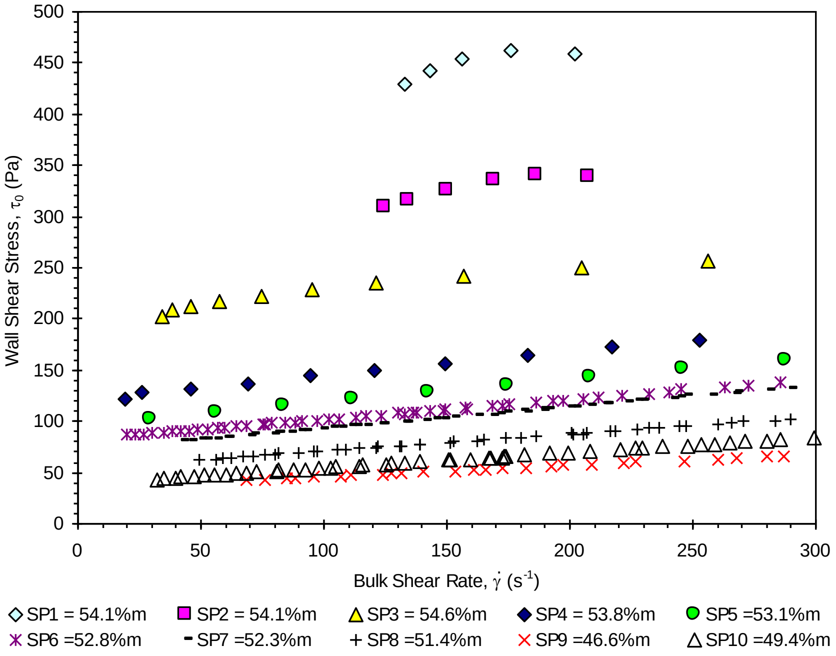

Figure 7 **Flow curves measured for samples collected with manually isolated dilution valves**

4 ANALYIS OF DATA

4.1 Effect of Shear

Samples were tested 'as received' and these are considered partially sheared as the samples have been subjected to shear in the system, as well as during the collection and testing procedures. Data was recorded on the 'as received' samples, and once complete, the samples were agitated for a period of five minutes using a low speed mixer. These samples are referred to as fully sheared, as tests done after further agitation had no additional effect on the flow curve.

4.4.1 Centrifugal pump data

Figure 8 shows the data collected for sample points 1 and 2 before and after shearing. Sample 1 is collected from the suction side of the thickener underflow pump, and sample 2 from the discharge side. The effect of the centrifugal pump shear is seen to reduce the yield stress from approximately 250 Pa to 200 Pa, and further shearing produces a fully sheared material with a yield stress of about 125 Pa. The solids concentration is the same for both samples.

Figure 9 shows sample point 3 and sample point 4 partially and fully sheared flow curves. Sample point 3 is on the suction side of the collection tank underflow pump and sample point 4 is from the pump discharge. There is a significant difference between the partially and fully sheared sample, however the two fully sheared data sets do not collapse on the same flow curve due to the difference in solids concentration due to gland service seal water.

Figures 8 and 9 are from the same test series, however Figure 9 slurry is the combined slurry from all five thickeners so cannot be compared directly to the slurry from thickener 5 only, shown in Figure 8.

These two data sets demonstrate that shear in a centrifugal pump reduces the yield stress of the slurry by a considerable margin; however the pump does not fully shear the material. The bulk of the shear reduction is believed to be due to a breakdown of the inter-particle floc structure at the high impeller tip speeds found in a centrifugal pump. Subsequent measurements on the fully sheared material showed no further change in the flow curve and there was no re-formation of the floc structure. The material is considered to exhibit an irreversible reduction in yield stress.

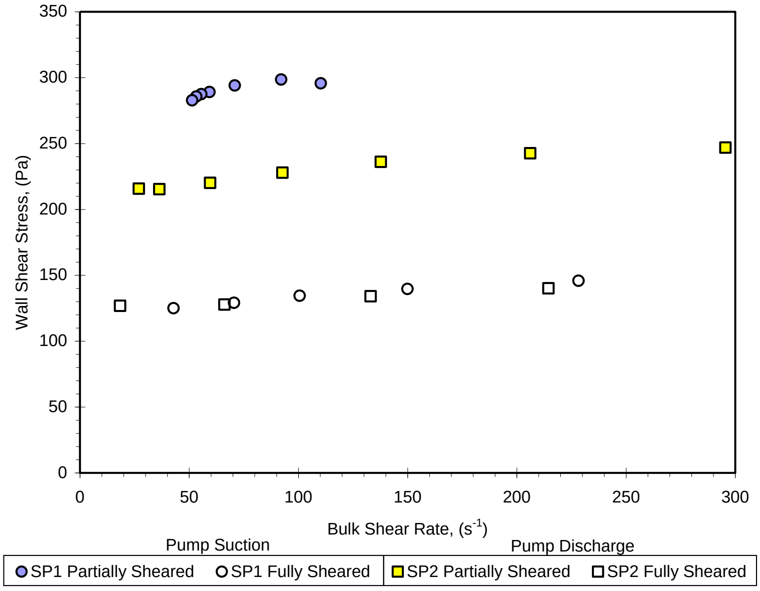

Figure 8 **Comparison of partially and fully sheared sample between sample points 1 and 2, the suction and discharge of thickener 5 underflow pump (53% m)**

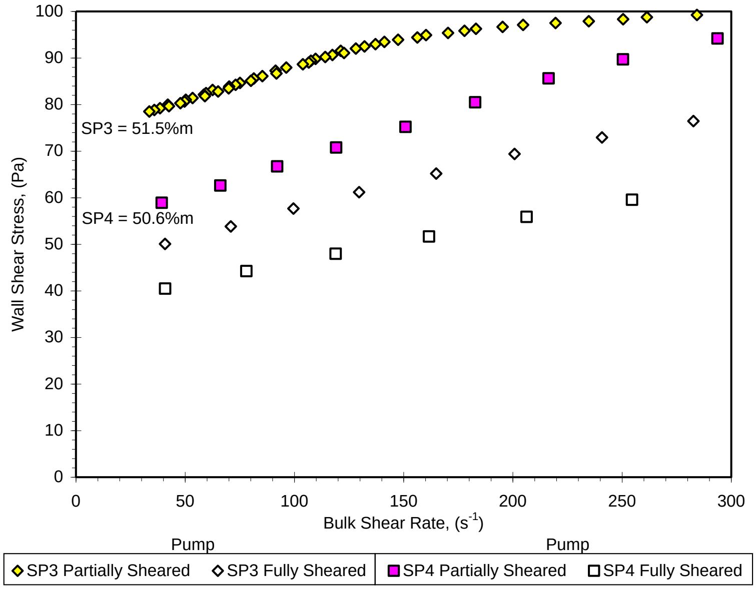

Figure 9 **Comparison of partially and fully sheared sample between sample points 3 and 4, the suction and discharge of the collection tank underflow pump**

4.4.2 Positive displacement pump data

Figure 10 shows partially and fully sheared flow curves across a positive displacement pump, sample point 5 is taken before the positive displacement pump suction and sample point 6 is taken at the pump discharge. There is no change in solids concentration between these sample points. The flow curves show that there is no additional shear occurring through the positive displacement pump as the partially sheared flow curve is almost exactly the same before and after the pump. Both samples tended to the same fully sheared condition. The data shows that a piston diaphragm type positive displacement pump does not shear the material significantly as the slurry velocity gradients within the pump are low.

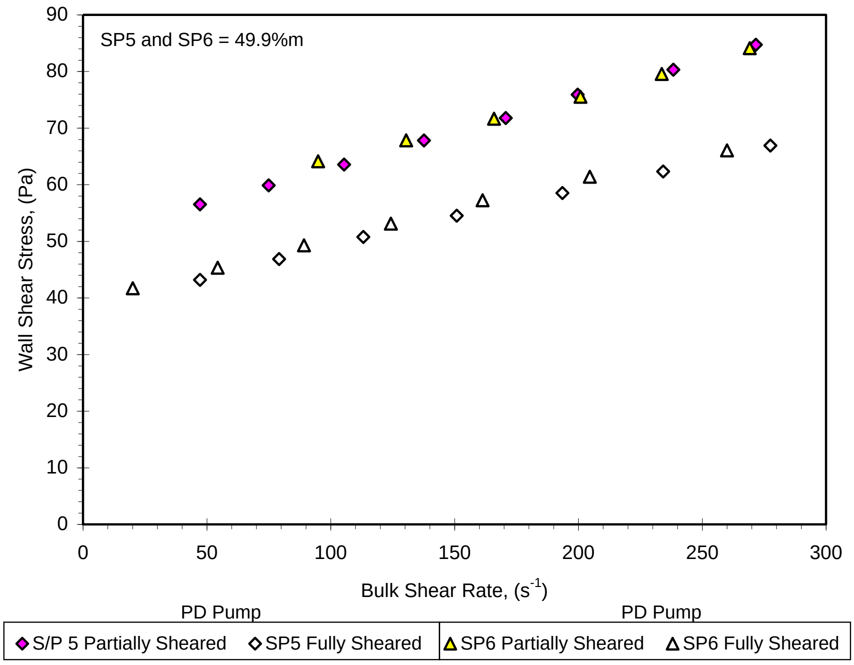

Figure 10 Partially and fully sheared sample across the positive displacement pump

4.4.3 *Pipeline data*

From the positive displacement pump to the deposition site there is some shear occurring in the pipeline from the pump discharge to the riser, as shown in Figure 11. It is seen that the sample collected at the discharge is close to fully sheared, as further shearing results in a small change in the measured flow curve.

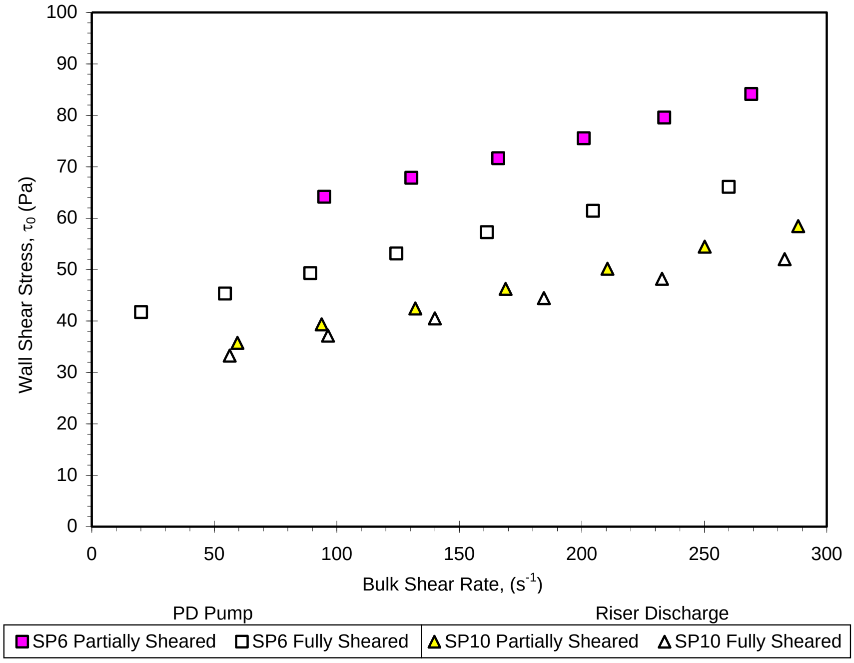

Figure 11 Partially and fully sheared sample during normal operation from positive displacement pump discharge to deposition site

4.4.4 *Yield stress reduction in the system*

There is a significant change in yield stress through the system due to a combination of shear and dilution. Figure 12 shows the change in partially sheared slurry yield stress through the system during normal operation. The contribution to changes in yield stress are summarised as follows:

- Shear across the thickener charge pump shows a decrease of ± 60 Pa yield stress, from 250 Pa to 190 Pa.
- Dilution and blending from all thickeners in the collection sump has the most significant effect on the yield stress, dropping slurry density from 1.54 to 1.44 t/m³, and the yield stress from ± 190 Pa to ± 70 Pa at the sump discharge.
- Shear in the collection sump centrifugal pump further decreases the yield stress to about 45 Pa.
- Shear in the pipeline results in a final yield stress of about 25 Pa.

These results cannot be used as an absolute indication of the influence of different process equipment on the slurry. The reason for this is that as the slurry is sheared along the pipeline it is becoming less sensitive to further shear i.e. partially sheared slurry flowing through a centrifugal pump for the first time may have a 50% reduction in yield stress, whereas the same slurry on the second pass through the same pump will have a smaller reduction in yield stress. The results do, however, show that there is a change in slurry properties through the system, resulting in this example in a tenfold decrease in yield stress from the thickener underflow to the deposition site.

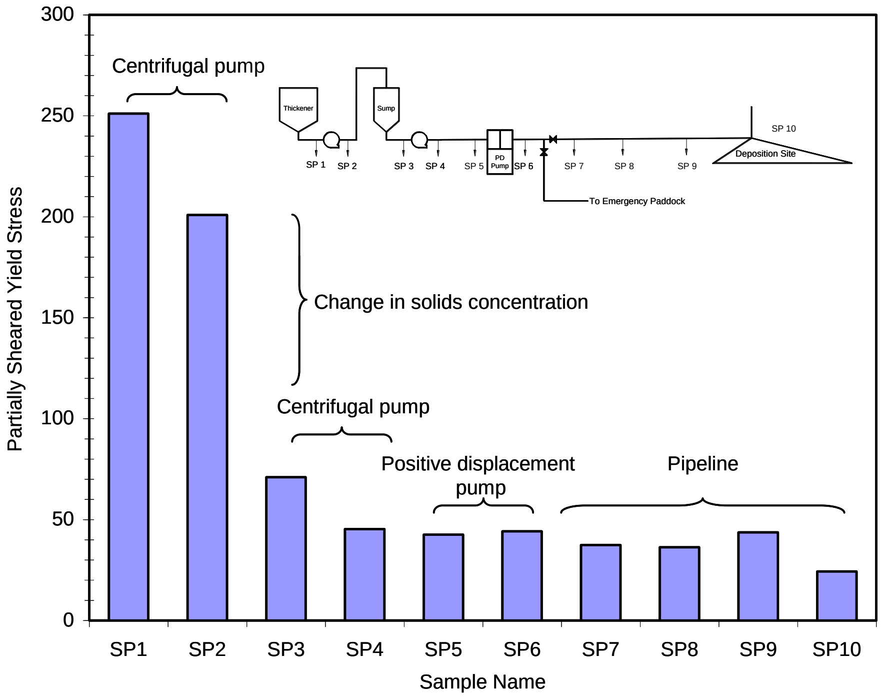

Figure 12 **Change in partially sheared yield stress throughout the system**

4.4.5 *Yield stress comparison between partially and fully sheared samples*

Figure 13 compares the partially and fully sheared slurry yield stress data as a function of concentration. The partially sheared slurry has higher yield stress values for the same concentration compared to the fully sheared slurry, which is to be expected. This is an important consideration when assessing the original control philosophy that did not account for the effect of shear (Houman and Johnson, 2003). The original yield stress design envelope is shown in Figure 14 compared to the partially sheared data, which is what the system now produces. It is seen that at lower solids concentrations there is reasonable agreement, however at higher solids concentrations the partially sheared data has very much higher yield stresses than the original design conditions.

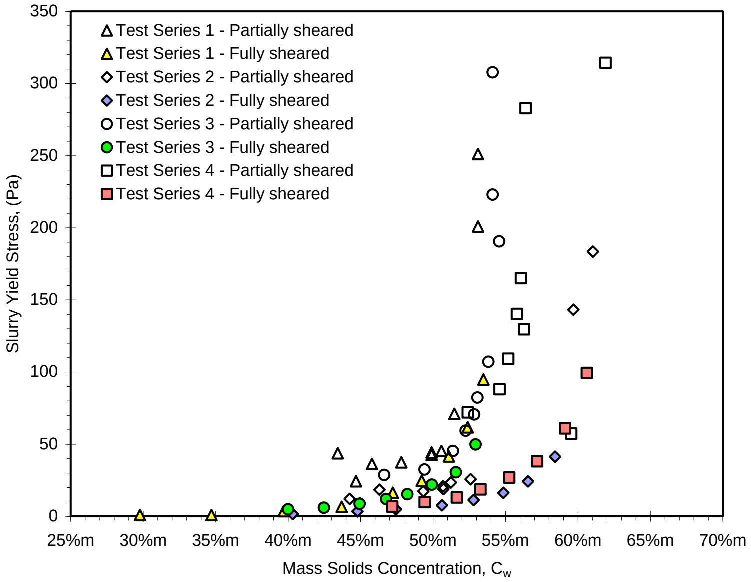

Figure 13 **Yield stress as a function of solids concentration for partially and fully sheared data**

The original control system limited the yield stress values to the 1998 correlations shown in Figure 14 in the thickener re-circulation pipeline by adding dilution water to reduce the yield stress to acceptable limits. This was determined by measuring the flow rate and pressure drop in the thickener re-circulation pipeline. Should yield stress values of 300 Pa be calculated by the control system, dilution water would be added until a yield stress of approximately 150 Pa was obtained, shown as no. 1 in Figure 14. As this was added into the thickener re-circulation loop, the consequence of shear in the underflow pump and the dilution, no. 2, is only seen downstream when the material enters the collection sump after further pumping and shearing. This results in a considerably lower yield stress than the target value. To rectify this, the control system now focuses on material that is as fully sheared as possible and minimises the amount of dilution water added.

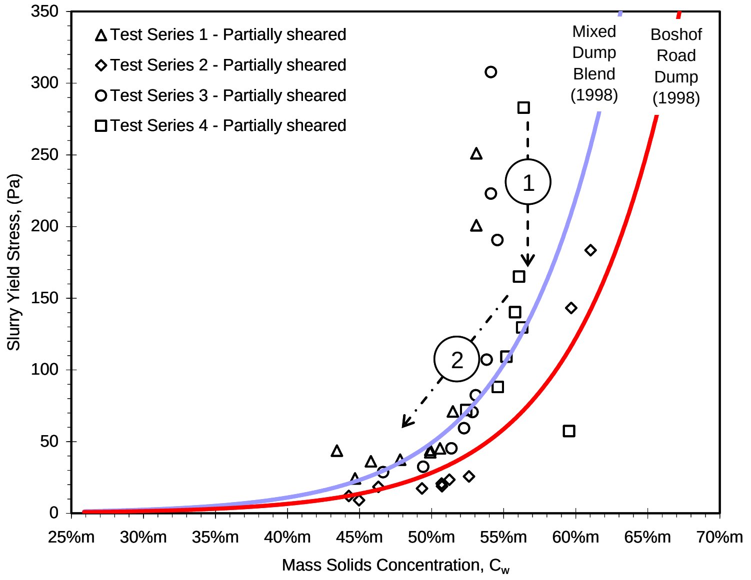

Figure 14 **Comparison of 1998 design rheology with current yield stress measurements**

5 CONCLUSIONS

The site specific conclusions of this study for the Combined Treatment Plant are:

- The thickeners are capable producing a very viscous paste product with yield stresses in excess of 200 Pa, however this material is sheared and diluted from the thickener underflow pump to the deposition site to a point where the yield stress can be as low as 25 Pa. This significantly impacts the deposition site beaching angles.

- The effect of shear in the system is most significant in the initial preparation stages that utilise centrifugal pumps for thickener underflow and for transferring material from the collection sump to the positive displacement pumps.
- The new control system minimises dilution and allows the effect of shear to be maximised prior to delivery to the positive displacement pumps so that material at the highest possible density is delivered to the positive displacement pump in as fully a sheared condition as possible.

This study highlights some important general conclusions that need to be considered when designing preparation, pumping and deposition systems for viscous materials:

- Centrifugal pumps have a noticeable effect on the rheology of shear sensitive materials; however, a single pass through a centrifugal pump does not fully shear the material.
- Positive displacement pumps, due to the low slurry velocity gradients within the pumps, do not have a marked effect on shear sensitive materials.
- It is important to quantify slurry shear history during pilot plant test work and trials as there can be significant changes in the material delivered to the deposition site than to what was measured during pilot plant trials that did not properly shear the material.

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