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USE OF PIPELINE PRESSURE GRADIENTS TO MONITOR INLINE POLYMER FLOCCULATION OF OIL SAND FINE TAILINGS

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ABSTRACT: In Canada's oil sands industry, the processing and storage of fluid fine tailings is important because it directly impacts land usage and reclamation, water and thermal energy requirements as well as environmental stewardship and mine sustainability. A key technology used for this purpose is inline flocculation, wherein existing inventories of fluid fine tailings are withdrawn from tailings storage facilities and mixed with polymer flocculants. These flocculated tailings can be then sent through additional process stages (e.g. evaporation, centrifugation, filtration) to promote dewatering and improved geotechnical characteristics of the resulting deposits. The polymer type, dosage and inline mixing conditions primarily dictate the efficacy of the inline flocculation process. Presently, numerous measurements are taken to establish flocculation performance. Some of these require samples to be collected and analyzed, meaning that such measurements cannot be used for real-time process control. Others, such as online FBRM (focus beam reflectance measurement), can be used for real-time process control but are often challenging and expensive to deploy in a commercial operation. The present study represents a preliminary assessment of the use of pressure measurements to monitor flocculation performance using a pilot-scale inline flocculation rig. Tests were conducted at different flow rates and polymer injection rates/concentrations. The test rig was fitted with 4 differential pressure sensors positioned at different axial locations. The pressure gradients measured just downstream of the inline mixer were primarily dictated by the production, and subsequent break-up, of the shear-sensitive floc structures and thus were highly sensitive to changes in polymer dosage at any given fluid tailings feed rate. A relationship among conventional performance metrics (e.g. floc size from FBRM) and maximum pressure gradient measured downstream of the mixer was observed, i.e. the same optimal polymer dosage was indicated by conventional measures and peak pressure gradient.

KEY WORDS: Tailings, polymer-dosed flocculation, pipeline flow, non-Newtonian

NOTATION

CST	Capillary Suction Time (s)
CWR	Clay-Water Ratio (-)
DP	Differential Pressure (Pa)
FBRM	Focused Beam Reflectance Measurement
P	Pressure (Pa)
Q_{FT}	Feed tailings flow rate (L/min)
Q_{PS}	Polymer solution flow rate (L/min)
z	Axial position (m)
μ_p	Bingham plastic viscosity (Pa·s)
ρ	Fluid or mixture density (kg/m^3)
τ_y	Yield stress / Bingham yield stress (Pa)

1. BACKGROUND

In the mining and mineral processing industry, billions of tonnes of fluid tailings are stored in dedicated containment areas, often referred to Tailings Storage Facilities, or TSFs (Wang et al., 2014; Coffey et al., 2021). Because the nature of the solids present in these tailings, i.e. particles that are very fine (submicron to ~ 44 μm in size) and typically surface-active, solid-liquid separation is difficult and thus the fluid tailings contain substantial quantities of water that need to be reclaimed and reused within the process (Masliyah et al., 2004; Wang et al., 2014). Moreover, the design, operation and management of TSFs pose many challenges from capacity limitations to more serious issues such as containment breaches (Coffey et al., 2021). Clearly, tailings management is a global issue especially as the need for rare earth metals continues to grow (Liang et al., 2022).

In Canada, the mining and extraction of extra-heavy crude oil, known as bitumen, requires about 3m^3 water for every 1m^3 bitumen produced (Masliyah et al., 2004) and stored fluid tailings volumes were 1 345 Mm^3 in 2021 (Alberta Energy Regulator, 2021). Consequently, processing of fluid tailings to reduce accumulated volumes, provide clarified water for reuse in the process and produce reclaimable tailings deposits is of paramount importance. Numerous technologies are used to for this purpose, including filtration, electrofiltration and centrifugation (Wang et al., 2014). Each of these technologies requires the fluid tailings to be pretreated to promote fine-particle aggregation, enhance solid-liquid separation and promote dewatering. Presently, in-pipe mixing of fluid fine tailings with a dilute polymer solution, known as inline flocculation, is the method of choice (Wells et al., 2011; Wang et al., 2014, Pougatch et al., 2021). The success of the inline flocculation depends primarily on (Pougatch at al., 2021) efficient mixing of the polymer solution into the fluid tailings; polymer adsorption onto the fine particles; and the balance of floc (aggregate) formation and growth with floc breakdown due to shear exposure. From an operational perspective, the aforementioned conditions are affected by the fluid tailings properties, polymer properties and dosage, the mixing device used to introduce the polymer solution into the fluid tailings, the hydrodynamics downstream of the mixer, and the downstream residence time (or shear exposure) (Wells et al., 2011; Gillies et al., 2012; Neelakantan et al., 2018).

Since so many factors affect the inline flocculation process, it is critical to be able to assess its performance. Some of the current assessment methods (Revington et al., 2011; 2018 COSIA Tailings Report, 2019) involve the withdrawal and collection of samples at various axial positions downstream of the polymer-fluid tailings mixing point, followed by laboratory analysis, e.g. yield stress (τ_y), final clay-to-water ratio (CWR) after dewatering, methylene blue index (MBI). Additionally, the 'Capillary Suction Test' (CST), which is used an indicator of the longer-term tailings deposit performance (Gray, 2015; Gumfekar et al., 2019)), can be conducted using a subsample of the flocculant-dosed tailings. The primary deficiency with each of these performance indicators is that a sample (or samples) must be collected and then analyzed, meaning it could be hours (or days) before the results are known. This approach is clearly not useful for real-time process monitoring and control. The only online techniques that are regularly used are to insert a focus beam reflectance measurement (FBRM) or particle vision and measurement (PVM) device into the flow downstream of the mixing point. It has been demonstrated that variations in FBRM results typically track with operating changes (Gumfekar et al., 2019; 2018 COSIA Tailings Report) but it is not proven that the floc sizes or size distributions reported by an FBRM are quantitatively meaningful in flocculated oil sand tailings applications. Moreover, there are known to be issues with probe fouling due to the presence of bitumen (Saraka et al., 2019). The purpose of the present study, then, is to determine if differential pressure measurements made downstream of the mixing location could be used as a flocculation performance indicator.

2. METHOD

Figure 1 provides a basic overview of the pilot-scale, flocculated tailings flow line located at the Coanda Research and Development Corporation facility in Edmonton, Canada. The piping is 50mm (nominal) diameter and 33 m in length. As shown in the diagram, the fluid tailings and the dilute polymer solution are fed, using different pumps, to the polymer injection device (Revington et al., 2011). Each of the feed lines is equipped with a flow meter, such that the total flow downstream of the injector is the sum of the two feed flow rates (fluid tailings + polymer solution). Downstream of the injector, there are a number of pressure transmitters, differential pressure sensors and sampling ports. Note that Figure 1 does not show all the sensors or sampling locations on the line; those relevant to the present study are described in Table 1. The positions of the differential pressure sensors are listed relative to the injector. The spacing between the high- and low-pressure sides of each sensor is 1.00 m. The position of the sampling point nearest to each DP cell is also listed in Table 1. The FBRM is located just 0.6 m from the pipe discharge, i.e. 32.4 m downstream of the injector.

Table 2 shows the run conditions completed as part of this study. The fluid tailings properties / composition were held constant for all 4 runs: specifically, the density was 1200 kg/m^3, with measured Bingham fluid properties of τ_y = 2 Pa and μ_p = 0.007 Pa·s. Note that within each run, the fluid tailings flow rate is held constant and the polymer injection flow rate is varied, such that a range of polymer dosages in the mixed, flocculant-dosed tailings could be studied. For this study, polymer dosages from 1200 to 2200 ppm were tested. In this paper, we focus on Runs 1109 and 1110, where the MFT flow rate was roughly doubled (from 103 to 219 L/min) while the polymer flocculant type and dosage were fixed.

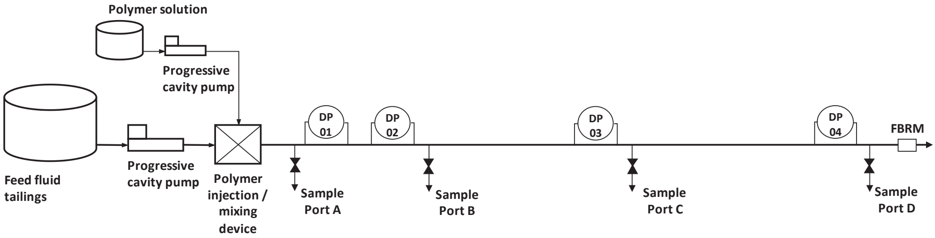

Fig.1 A PFD-style illustration of the pilot-scale, flocculated tailings flow line located at Coanda Research and Development Corporation.

Table 1

Locations of differential pressure sensors and nearest sampling ports (see Figure 1)

DP sensor	Distance downstream from injector (m)	Nearest sampling port	Location relative to the nearest DP sensor
01	2.44	A	0.43 m upstream
02	4.58	B	1.05 m downstream
03	16.7	C	1.22 m downstream
04	29.2	D	1.22 m downstream

Table 2

Run conditions evaluated during the current study

Test No.	Fluid tailings feed flow rate (L/min)	Polymer concentration in injected solution (wt %)	Final polymer flocculant dosages in flocculated tailings (ppm)
1109	103	0.25	1200, 1400, 1600, 1800, 2000, 2200
1110	219	0.25	1200, 1400, 1600, 1800, 2000, 2200
1111	372	0.25	1200, 1400, 1600, 1800, 2000, 2200
1112	108	0.65	1200, 1400, 1600, 1800, 2000, 2200

Pressure loss and flow data were collected at a frequency of 10 Hz and time-averaged over intervals where the test conditions were constant, as shown in Figure 2. Signals from the FBRM were analyzed and the mean floc size reported for the same time interval over which the pressure loss and flow data were constant. Samples were collected and analyzed, and the measured Capillary Suction Time (CST) and Final Clay Water Ratio (CWR) of a settled bed were determined. Briefly, a CST test determines how quickly a given amount of water flows into an absorbent filter paper because of capillary action (Gray, 2015). It is designed to give an indication of the ability to filter the flocculated tailings, and a lower value of CST (in seconds) suggests better filtration (water removal) is possible. It should be noted that other sample analyses were conducted but these are not reported here.

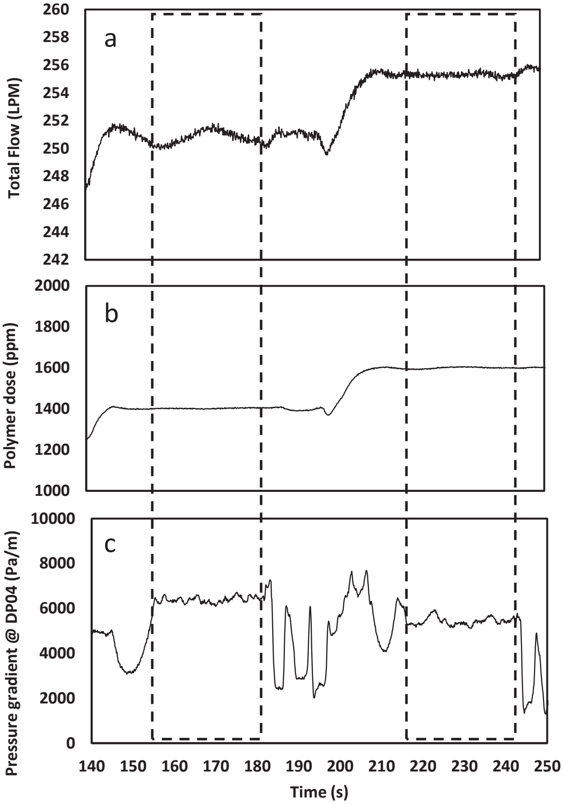

Fig.2. Measured test conditions during a portion of Test 1110: (a) Total flow rate, i.e. feed tailings + polymer solution combined flow (L/min); (b) polymer dosage in flocculated tailings (ppm); (c) pressure gradient measured at DP04 (Pa/m). The dotted rectangles show the intervals over which time averages were taken for subsequent analysis.

3. RESULTS AND DISCUSSION

For each of the test conditions and final flocculant dosages described in Table 2, pressure gradients were analyzed over the periods where relatively steady readings were obtained. Figure 2 shows an example of these periods where the pressure gradients and flow rates were stable. Also, as mentioned above, FBRM signals and flocculated tailings samples were collected during these periods. Recall that within each run, the feed tailings flow rate was kept constant while six different final flocculant dosages were tested. The first objective was to evaluate how the pressure gradients varied with distance downstream of the injector for each test, and Figure 3 illustrates this result for Run 1110 (Q_{FT} = 219 L/min) and final flocculant dosages of 1200 – 2000 ppm. In Figure 3, the four different DP cell measurements are normalized by the DP04 value (for a given run). It can immediately be seen that the normalized pressure gradients at DP03 are close to unity, meaning there is little axial variation of pressure gradient over the last 20m of the loop. Figure 3 also shows that the pressure gradients at DP01 and DP02 are noticeably higher than those measured at DP04, such that the normalized pressure gradients at these positions are, in some cases, as much as 3.5 times greater than those measured downstream at DP04. It is also immediately apparent that normalized pressure gradients at the two locations just downstream of the injector, DP01 and DP02, vary quite significantly with final flocculant dosage; in other words, the flocculant dosage has a notable effect on the pressure gradient at these positions. Considering DP01, for example, the lowest normalized pressure gradient is associated with a flocculant dosage of 2000 ppm, while the highest value was observed for the 1600 ppm test. The other normalized DP01 measurements for the other flocculant dosages (1200, 1400, 1800ppm) fell between the aforementioned bounds. It should be noted that the 2200 ppm test was not included on this figure as it was essentially identical to the 2000 ppm data points. The variation of pressure gradient at DP01 and DP02 with flocculant dosage appears to be related to the key processes required to produce good-quality flocculated tailings: in particular, the extent of mixing between the feed tailings and the polymer solution, and the particle aggregation and the formation of flocs. If the mixing is relatively poor, or if the formed flocs are quickly broken down, one would expect pressure gradients that vary little with axial position, e.g. 2000 ppm in Figure 3. If the mixing is effective and particle aggregation / floc formation occurs, then the mixture yield stress will increase significantly (Gillies et al., 2012) and the pressure gradients downstream of the injector should be higher than those measured near the end of the pipe, where flocs have broken down and the resulting mixture yield stress is greatly reduced (Gillies et al., 2012). It should be noted that although the results are not shown here, plots showing the variation of normalized pressure gradient with axial position for the other tests (1109, 1111, 1112) gave similar trends as those shown in Figure 3 (for Run 1110).

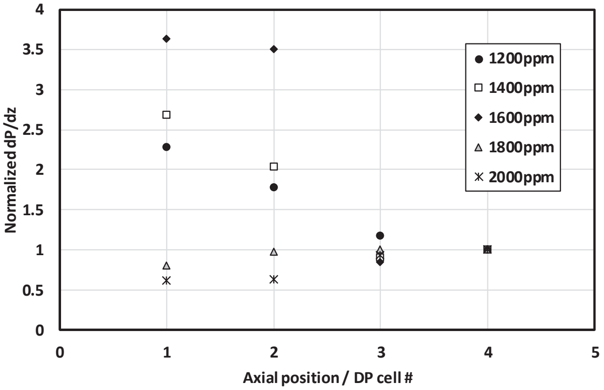

Fig.3. Variation of frictional pressure gradient with axial position, normalized using the pressure gradient measured near the pipe loop discharge (DP04): Test 1110, Q_{FT} = 219 L/min.

In Figure 4, the measurements collected at DP01 for the different final flocculant dosages are compared, as this is the location where the maximum normalized pressure gradients were observed in Figure 3. It can be seen that the maximum pressure gradient occurs at a flocculant dosage of 1600 ppm. The next highest dP/dz occurs at 1400 ppm, with the other dosages yielding substantially lower values. Because of the way the tests were conducted, though, the total flow rate (i.e. $Q_{FT} + Q_{PS}$) increases with each final flocculant dosage: the feed tailings flow rate is kept constant but Q_{PS} must be increased to achieve the desired dosage.

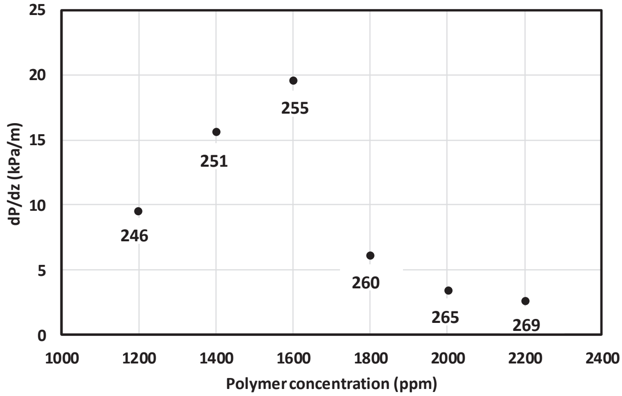

Fig.4. Variation of measured pressure gradient at DP01 with polymer dosage and total flow rate for Test 1110 (QFT = 219 L/min).

The variation of total flow with dosage is indicated in Figure 4: the total flow is 246 L/min at 1200 ppm and increases to 269 L/min to achieve the 2200 ppm dosage. It is reasonable to ask, then, if the variation seen in measurements at DP01 is affected by flow rate, or if it is primarily dictated by polymer dosage and the consequent mixing / floc formation / breakdown processes.

Figure 5 provides a significant clue as to the relative unimportance of flow rate on the pressure gradient measurements. In Figure 5a, a pressure gradient flow curve for a Bingham fluid having the properties $\rho = 1200$ kg/m^3; $\tau_y = 80$ Pa and $\mu_p = 34$ mPa·s is shown. Recall that the density of this Bingham fluid matches that of the feed tailings, while the selected Bingham rheological parameters come from careful measurements made by Gillies et al. (2012) on a similar flocculated tailings mixture. While the actual properties of the flocculated tailings flowing through the section of pipe downstream of the injector where DP01 is located are not known, and expected to be nonhomogeneous and changing rapidly with axial position, these values can be viewed as a reasonable approximation for flocculated tailings where the feed and polymer solution have been well-mixed, and assuming significant floc growth followed by some shear-related breakdown (Gillies et al., 2012). The range over which the flow rate varies during Run 1110 is also indicated in Figure 5a. Figure 5b shows the predicted increase in frictional dP/dz over this flow rate range for the Bingham fluid described in Figure 5a. As Figure

5b shows, the change in pressure gradient because of the change in flow rate is less than 1.5%. In other words, for a given test, it is clear that polymer dosage is the primary independent parameter.

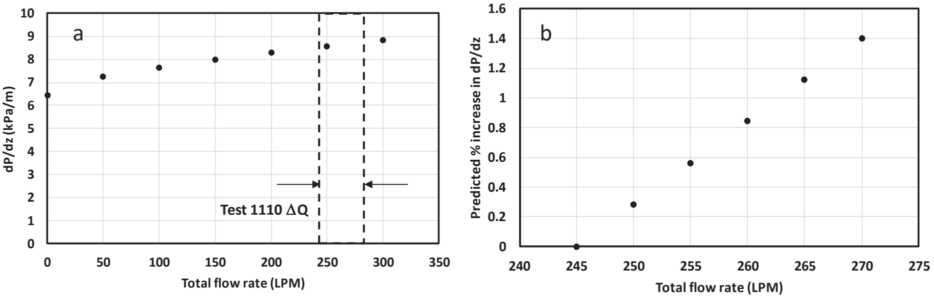

Fig.5. Predicted pressure gradient changes based on flow rate only, for flow of a Bingham fluid (ρ = 1200 kg/m^3; τ_y = 80 Pa; μ_p = 34 mPa·s) in a pipe D = 0.05 m: a) Flow curve showing the flow rate range for Run 1110; b) per cent increase in frictional pressure gradient with flow rate for Run 1110.

At this point, it has been established that the measured pressure gradient at DP01 (or DP02) is dictated by flocculant dosage, and thus gives an indication of conditions where mixing and flocculation are better than other conditions (see, for example, Figure 4). It is therefore reasonable to compare the peak measured pressure gradient at DP01 with more conventional performance indicators, such as Capillary Suction Time (CST), final clay-water-ratio (CWR) in a settled bed and mean floc size obtained from the FBRM. These comparisons were made and are shown here for two tests, Runs 1109 and 1110, in Figure 6. The left-hand series of plots shows, for Run 1109, the peak pressure gradient measured at DP01, the average CST result (averaged from 3 repeats), the mean floc size from the FBRM, and the final CWR. The right-hand series of graphs show the same performance indicators for Run 1110. In both tests the samples were obtained from Port A, which is just upstream of DP01 (see Table 1). The optimal flocculant dosage for Run 1109 was determined to be 1400 ppm, and was 1600 ppm for Run 1110, and these are shown with the dotted arrows in Figure 6. These optima were determined from a range of lab assessments and performance indicators, including CST, mean floc size and final CWR, before the present study was conducted; in other words, and as Figure 6 shows, the peak pressure gradient measured at DP01 also indicates the same optimum. Although not shown here, similar findings were obtained for Runs 1111 and 1112. It is interesting to note that the individual conventional performance indicators (CST, mean floc size, CWR) are not unanimous in their description of the optimum condition. Samples from the other ports were also analyzed for CST and CWR, and those results compared to the peak pressure gradients, but gave poorer general consensus of the optimal dosage, and thus poorer correlation with the peak pressure gradient at DP01.

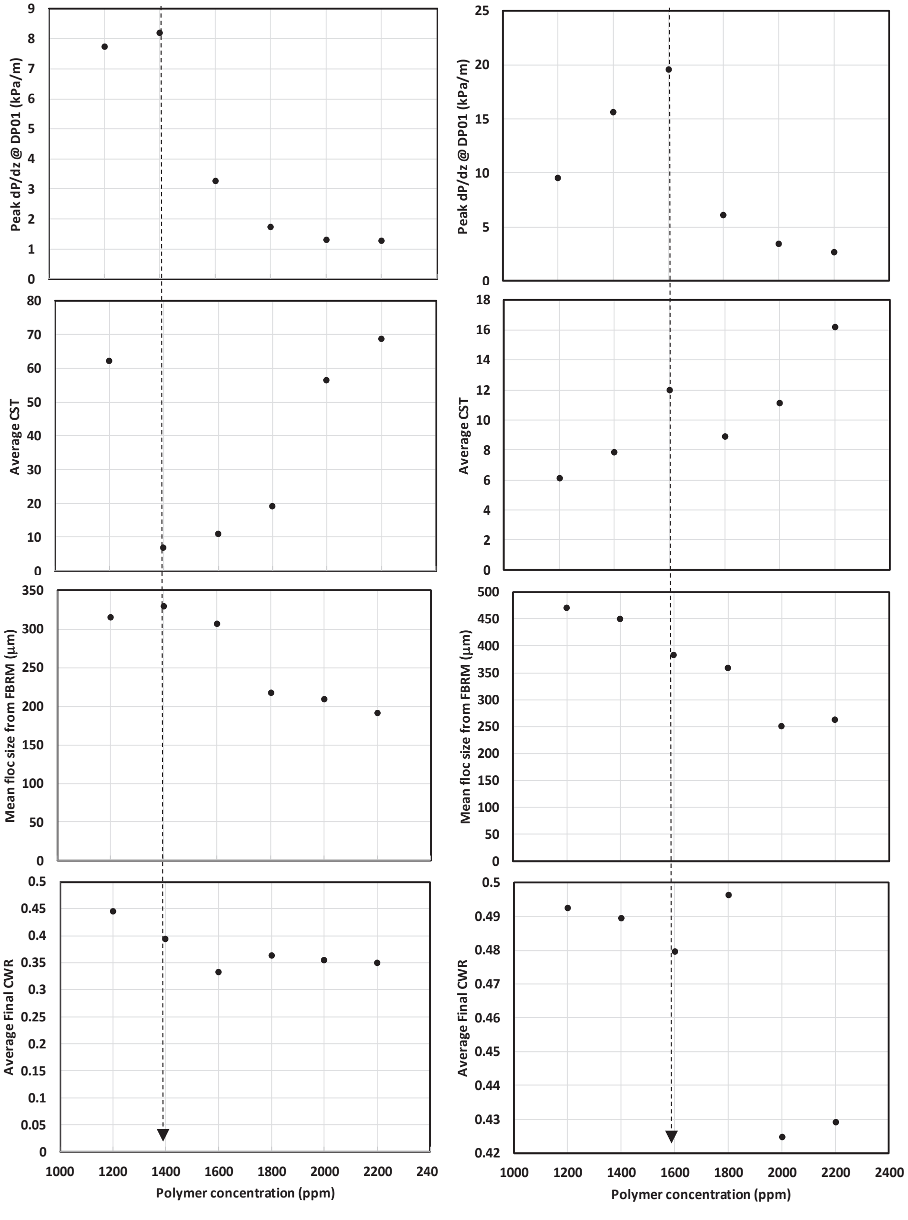

Fig.6. Comparison of conventional key performance indicators (CST, mean floc size, Final CWR) against the peak pressure gradient measured at DP01 for Run 1109 (left) and Run 1110 (right). The optimal dosage for each run, determined without the pressure gradient measurements, is indicated by the dotted arrows.

4. SUMMARY AND RECOMMENDATIONS

In the inline flocculation of tailings, a relatively dilute fine-particle tailings stream is mixed with a dilute polymer solution to promote particle aggregation (“flocculation”) and eventually improved dewatering and consolidation properties. Inline flocculation requires efficient mixing of the polymer solution and fine tailings streams, polymer adsorption onto the fine particles, and floc (aggregate) formation and growth. Continued mixing / shearing will cause floc breakdown which negatively impacts the downstream separation processes (e.g. centrifugation, filtration). It is therefore necessary to assess when optimal operating conditions have been achieved, and typically, a combination of inline measurements (e.g. FBRM) and offline sample analyses (e.g. CST, CWR) is used to identify this optimum. In this study, we have conducted a preliminary analysis of the use of a series of pressure gradient measurements, located downstream of the mixing point, to determine the optimal operating conditions.

It has been clearly shown that there is a significant variation of frictional pressure gradient with axial position downstream of the mixing point. With the 50 mm (diameter) by 33 m (length) flocculated tailings flow loop used for this study, it was found that a constant pressure gradient is obtained about 20 m downstream of the mixing point – or sooner, depending on feed tailings flow rate and polymer dosage. For a given feed tailings flow rate, the pressure gradient measured at the DP cell 2.4 m downstream of the mixing point (DP01) varied significantly with polymer dosage in the flocculated mixture. It was found that the peak (maximum) pressure gradient measurement at DP01 occurred at the optimum polymer dosage, with this optimum assigned based on the combination of conventional performance indicators, i.e. CST, mean floc size, final CWR.

Based on the positive correlation found here between the peak pressure gradient and the optimal dosage, further tests should be done at both the pilot and commercial scale to determine how robust this indicator (peak pressure gradient downstream of the injector) is in determining the optimal mixing and polymer dosage conditions. It is also recommended that the inline FBRM be relocated so that it is significantly closer to the mixing location. In the present pilot-scale flocculated tailings line, the FBRM is located near the end of the pipe, far from the mixing point; based on the variation of pressure gradient with axial position, the FBRM should provide a better indication of optimal conditions if it is a few meters from the mixing point, i.e. physically near DP01.

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