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Evaluation of Polymer Feed Rate, Polymer Dose, and Mixing Duration for Flocculation Optimization of Clayey Tailings with Various Solid Contents

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ABSTRACT
Fluid Fine Tailings (FFTs) are clayey type of tailings produced during bitumen extraction from oil-sands ore. FFTs are often treated with synthetic polymer for transforming their dispersed structure into flocculated structure such that their dewatering and settling tendency is improved. The flocculation quality, however, is influenced by the several input parameters into the process of flocculation including the mineral composition of the FFTs, the flocculant concentration, the feed rate of flocculant, and the shear rate and shear time of mixing. In this study, real time assessment of the effects of several input parameters on the flocculation quality of FFTs was conducted. The study tested FFTs with various solid contents ranged between 30 and 35% (w/w) treated with a synthetic polymer at feed rates ranged between 5 and 36 ml/sec. The flocculation process was conducted in an Advanced Couette Rheometer and controlled via an innovative feedback Torque Force-based Technique (TFT). The preliminary results showed that the faster the polymer feed rate the better the flocculation. This coincided with better immediate dewatering, longer-term dewatering, and longer-term settling behaviors. The TFT showed a strong potential for real time optimization of polymer feed rate, polymer dose, and mixing duration for flocculation improvement of FFTs with various solid contents.

RÉSUMÉ
Les résidus fins fluides (FFT) sont des résidus argileux produits lors de l'extraction du bitume du minerai des sables bitumineux. Les FFT sont souvent traitées avec un polymère synthétique pour transformer leur structure dispersée en structure floculée de sorte que leur tendance à la déshydratation et à la décantation est améliorée. Cependant, la qualité de la floculation est influencée par les différents paramètres d'entrée dans le processus de floculation, y compris la composition minérale des FFT, la concentration de floculant, la vitesse d'alimentation du floculant et la vitesse de cisaillement et le temps de cisaillement du mélange. Dans cette étude, une évaluation en temps réel des effets de plusieurs paramètres d'entrée sur la qualité de floculation des FFT a été réalisée. L'étude a testé des FFT avec divers contenus solides variant entre 30 et 35% (p / p) traités avec un polymère synthétique à des vitesses d'alimentation comprises entre 5 et 36 ml / s. Le processus de floculation a été effectué dans un rhéomètre Couette avancé et contrôlé via une technique innovante basée sur la force de couple (TFT). Les résultats préliminaires ont montré que plus la vitesse d'alimentation du polymère est rapide, meilleure est la floculation. Cela a coïncidé avec une meilleure déshydratation immédiate, une déshydratation à plus long terme et des comportements de sédimentation à plus long terme. Le TFT a montré un fort potentiel d'optimisation en temps réel de la vitesse d'alimentation du polymère, de la dose de polymère et de la durée de mélange pour l'amélioration de la floculation des FFT avec divers contenus solides.

1. INTRODUCTION

Fluid Fine Tailings (FFTs) is a byproduct generated when recovering useful and precious minerals and metals, such as bitumen from oil-sand ores, using mineral processing and hydrometallurgical processes (Wang et al. 2014). After selective extraction and beneficiation of the bitumen and other useful materials, the mill refuses and residuals are combined to form the tailings stream. In most cases the tailings are discharged in the form of a slurry into engineered impoundments known as tailings ponds where solids and process water separate under gravity. Given sufficient time, the nearly solids-free supernatant can be recycled into the extraction process to minimize freshwater consumption and reduce waste volume. However, the tailings deposits would still contain significant amount of liquid water besides sands, fine particles (silt and clay), and residual unrecoverable bitumen.

Despite the quickly settling tendency of the sand particles in tailing ponds, the fine clays, residual bitumen, and process water constitute a stable three-phase suspension, called Mature Fine Tailings (MFTs), that does not appreciably settle over time (Sobkowicz, 2013: Beier et al., 2013). Treatment, therefore, is required to minimize the footprint of these tailings by rendering tailings deposits reclaimable within regulatory mandated schedules (AER 2017).

The use of polymers or polymer-coagulant combinations is quite a common treatment method to improve the dewatering and consolidation properties of fine-grained tailings, including fine fluid tailings from the oil sands industry (Hogg, 1999; Agarwal, 2002; Tripathy and De, 2006; Beier et al., 2013; Vajihinejad and Soares, 2018; Vajihinejad et al., 2019). Common types of flocculants include polyacrylamide (PAM), poly (diallyldimethyl ammonium chloride) (PDADMAC), polyethylene oxide (PEO), and chitosan-based polymers. Polymers are usually combined with either centrifuge, inline, or in tank flocculation where polymers promote aggregation of clay particles into larger flocs (Farinato and Dubin, 1999; Gregory, 1989; Somasundaran, 2018; Moudgil and Somasundaran, 1994). Some of the main difficulties associated with flocculation are managing the optimum polymer dosage, mixing time and energy, polymer feed rate, and effects of pipeline shear during hydraulic transport post flocculation (Pelssers et al., 1989; Yeung et al., 1997; Owen et al., 2008; Bara et. al., 2013; Derakhshandeh et al., 2016).

The variation of the mineral composition of the raw FFTs and the shear sensitivity characteristic of the flocculated FFTs require in-real time management of optimum polymer dose and optimum mixing time for obtaining acceptable levels of dewatering at efficient polymer doses. Therefore, technologies that can control dewatering efficacy immediately after the mixing of the polymer into the tailings stream are potentially of a great value (Salam et al., 2016). There is also a need for optimization technologies that can adjust and correct the polymer dose and mixing duration in real-time.

Previous studies reported negative impacts of excessive mixing on dewatering and settling behaviors of flocculated FFTs. Demoz and Mikula, (2011), for example, reported an optimum mixing energy and time after which more mixing would reduce dewatering and minimize settlement. Bara et al., (2013) showed decreased yield stress and increased Capillary Suction Time (CST), after shown a short period of peak values, due to increased post-flocculation shear duration.

Derakhshandeh et al., (2016) and Aldaeef and Simms, (2019) studied the effect of pipeline shear on dewaterability, settlement, and strength behaviors of flocculated FFTs. In both studies, a Couette shaped rheometer was used to simulate the shear rates and shear durations experienced in pipeline settings. The studies showed that excessive shearing, either during flocculation or during pipeline transport post flocculation, could decrease the immediate dewaterability and reduce the strength gain overtime. However, Aldaeef and Simms (2019) reported that, moderate pipeline shearing showed to enhance the longer-term settling percentage compared to non-sheared samples. Aldaeef and Simms, (2019), furthermore, used the Couette rheometer for simulating the inline flocculation. Their preliminary results showed that the torque force exerted by a Couette shaped static mixer during flocculation can be used as an indicator for real time flocculation optimization.

Webster et al. (2016) developed a lab-scale control scheme for dynamic inline flocculation for enabling control over mixing intensity and flocculant dosage based on the clay content, density of FFTs, and properties of polymer. The control system would select the optimum polymer dose and mixing speed based on stored database from 150 laboratory flocculation experiments conducted on several FFTs with various clay contents and densities. The control system corresponded well to the increase in clay content and density by promptly increasing the mixing speed and polymer feed. However, the final dewatering and yield strength results were somewhat scattered.

There have been clear evidences that excessive shearing after an optimum state of flocculation would have negative impact on dewaterability and strength behavior of flocculated FFTs, nevertheless, the optimum mixing time has still been uncaptured using the current flocculation protocols implemented in practice. Most of the used flocculation protocols lack practical technologies that can provide real time optimization over the polymer-tailings mixing duration, polymer dose, and polymer feed rate for optimum flocculation.

The current study introduces a new technique for real time optimization of polymer-tailings mixing duration and polymer dose. The study also evaluates the influence of polymer feed rates on flocculation quality using the introduced optimization technique. In addition, the paper investigates the capacity of the introduced optimization technique in defining the optimum polymer dose for FFTs with various solid contents.

2. Material

2.1 Oil-sands Tailings

Oil-sands tailings samples were collected from a tailings pond in Northern Alberta, Canada, and shipped to Carleton University in Ottawa, Canada. Various laboratory tests and analyses were performed to determine the physical, mineralogical, and chemical characteristics of the raw fluid fine tailings. The initial solids content from oven-dried samples was 31% and the liquid limit was 60% determined from Fall Cone tests. The sands to fine ratio (SFR) was 0.25. The clay content obtained from the Methylene Blue Index (MBI) analysis ranged from 28% to 32%. According to the X-ray diffraction (XRD) results, the composition of the clay fraction was 68-72% Kaolinite and 28-32% Illite. Total Dissolved Solids (TDS) in the pore water collected from the raw fluid fine tailings (rFFTs) was 1050 mg/L, electrical conductivity was 1590 μS/cm, while the dominant cations were sodium at 340 mg/L. These and other material characteristics of the tailings used are listed in Table 1.

Table 1: Physical properties of the raw fluid fine tailings parameters

Characteristic	Ave. Value
Initial solids content (%)	31
Initial water content (%)	220
Hydrocarbons content (%)	1.4
Initial wet density (g/cm^3)	1.20
Initial void ratio	5.1
Specific gravity	2.12
Liquid limit (%)	60.0
Plastic limit (%)	27.0
Plasticity index (%)	33.0

2.2 Polymer Stock Solution

Polymer A3338 (SNF), an anionic polyamide based flocculent, was used to prepare the polymer amended oil-sands tailings samples. In a plastic weighing dish, 4 g of A3338 polymer (for the preparation of 0.4% polymer stock solution) was weighed using an analytical balance (Fisher Scientific, Sartorius AG Germany, LE225D) and decanted into a 1500 mL glass beaker and completed to 1000 mL with deionized water. The polymer solutions were stirred using a jar tester (Phipps and Bird, USA) at 250 rpm for 5 minutes and at 125 rpm for the following 55 minutes. Then, the polymer solution was mixed with a hand blender for 10 seconds and left for maturation for 1 hour.

3. DESCRIPTION OF APPARATUS

An advanced Couette rheometer was fabricated and used to simulate the inline flocculation in laboratory on the raw Fluid Fine Tailings (rFFT). The Couette rheometer consists of an outer stationary cylinder (cup) encompassing an inner cylinder (bobbin) which is rotating at a controlled rotational speed. The height of the cup and the bobbin are 150 mm and 110 mm respectively. The inside surface of the cup and outside surface of the bobbin were baffled with thin acrylic strips along their shafts in order to prevent the formation of a slip layer around the bobbin during flocculation (Figure 1). The baffles are also meant to minimize the wall slip occurrence and enhance the application of a uniform shear force throughout the flow region. The diameters of the cup and the bobbin including the baffles are 118 mm and 76 mm making the gap in the Couette rheometer (i.e., the difference between the inside radius of the cup and the outside radius of the bobbin including the baffles) equal to 21 mm. The used Couette rheometer has the capacity to process flocculation for 1400 ml of FFTs.

The Couette rheometer has been previously used for studying the effect of pipeline shear on mineral slurries including oil-sand tailings (Derakhshandeh et al., 2016; Aldaeef and Simms, 2019). The Couette rheometer was used to simulate the shear rates and shear durations experienced in pipeline settings through the rotational speed of the bobbin in a given Couette rheometer geometry. In addition to pipeline shear simulation, Aldaeef and Simms, (2019) used the Couette rheometer for simulating the inline flocculation. Their preliminary results showed that the torque force exerted by the Couette shaped static mixer during flocculation can be used as an indicator for flocculation optimization.

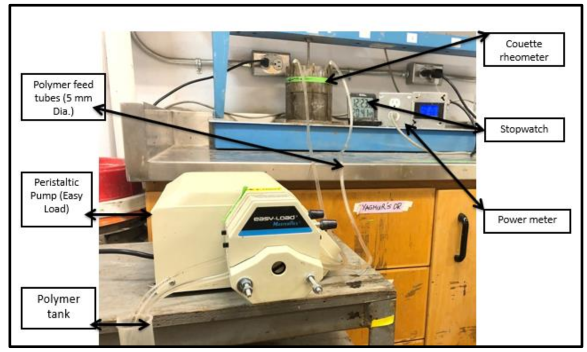

Figure 1. Configuration of the Couette rheometer and the experimental set up.

In their previous work, Aldaeef and Simms, (2019) upgraded the Couette rheometer with a multimeter device to read power consumption in-real time during flocculation and during modeling of pipeline transport. They reported a direct correlation between the power consumption and torque force exerted by the Couette rheometer for a given rotational speed which was expressed as follow:

$$\tau = \frac{P}{0.105 * N_B} \qquad [1]$$

where: τ is the torque force (N.m); P is the power (W); N_B is the rotational speed of the Bobbin (rpm).

information about the torque force change during the flocculation is found to be the controlling key index in their earlier study. The utilized advanced Couette rheometer in this study has been improved further by including an automized polymer injection scheme via an incorporated peristaltic pump. This has enabled a well-controlled polymer feed rate for flocculating a certain amount of rFFTs (Figure 1). This advanced Couette rheometer scheme was then utilized for conducting the following tasks:

a. Optimizing the flocculation process via the torque-force based technique by controlling the polymer-tailings mixing duration,
b. Studying the effect of various polymer feed rates on the quality of the optimized flocculated samples and identify the optimal polymer feed rate,
c. Using the optimal polymer feed rate and the torque-force based technique for real time determination of optimal polymer dose,
d. Using the optimal polymer feed rate and the torque-force based technique for real time determination of optimum polymer dose for FFTs with a different solid content.

4. EXPERIMENTAL PROGRAM

4.1 Flocculation

Different from other flocculation protocols (Mizani, 2017; Salam et al. 2017; Salam et al. 2018), the flocculation process of raw Fluid Fine Tailings (rFFT) in this study was conducted in the advanced Couette shaped rheometer and optimized by the torque force-based technique.

A patch of flocculated samples was prepared at various polymer concentrations using the torque force-based technique flocculation protocol. To process flocculation, a certain amount of rFFT was calculated such that a total volume of the flocculated samples would be always constant at 1400 ml for each flocculation trial. Maintaining constant volume of the test samples would normalize the effect of sample volume on the torque readings. The mixing speed in the Couette rheometer was selected as 250 rpm and kept the same for all of the flocculation trials. The flocculation started with placing the rFFT sample into the cup, then positioning the bobbin on a designed base in the center of the cup to allow free rotation about the vertical axis of the Couette rheometer. After setting the rotational speed of the Couette rheometer at 250 rpm, the mixing process was initiated and continued for 60 seconds to ensure a homogenizing of the rFFTs sample before the desired polymer dosage was added. The polymer stock solution was then injected at a defined feed rate while observing the change in the torque force. The torque force-based technique enabled monitoring the exerted torque force during flocculation such that the optimum mixing time is defined, thus avoiding an excessive mixing duration such that an overshearing during flocculation is prevented.

To study the effects of polymer feed rates on flocculation quality, the feed of polymer stock solution of A3338 type of polymer was conducted using the peristaltic pump in several automized flow rates selected randomly including 5 ml/sec, 10 ml/sec, 15 ml/sec, and 36 ml/sec. The polymer volume for each flow rate was fixed corresponding to 800 ppm polymer concentration. The predefined polymer volume was pumped from a polymer tank using the peristaltic pump via two 0.5 mm-diameter tubes attached to the inner surface of the cup of the Couette rheometer and located at the med height of the cub. Controlled polymer flow feed is meant to mimic the actual practice for in-line flocculation conducted in field (Webster et al. 2016).

Representative specimens were taken from each flocculated sample at each polymer feed rate for the evaluation of immediate dewatering using the Capillary Suction Time (CST) test. Shorter CST value indicates better immediate dewaterability, which is expected for the best flocculated sample, thus optimal feed rate. The CST values for each feed rate was plotted versus the recorded torque force to study the validity of the torque force-based technique for feed rate and flocculation optimizations.

After determining the optimal feed rate, this feed rate was then used for flocculation with various polymer doses to determine the optimum polymer dose in-real time using the torque-force based technique. Polymer doses ranged between 100 ppm and 1200 ppm were tested for obtaining the best flocculated samples based on short- and longer term dewaterability behavior. The short-term dewaterability behavior was assessed based on the CST value while the longer-term dewaterability behavior was evaluated from settlement percentage in graduated cylinder. CST values and settlement percentage for each polymer dose were compared with the maximum developed torque force recorded at the optimal mixing duration identified in real time for each dose to evaluate the applicability of the torque-force based technique in identifying the optimum polymer dose in-real time.

Another patch of flocculated samples was prepared from a rFFTs with solid content of 35% (compared to the previous patch of flocculated samples with solid content of 31%) to evaluate the influence of solid content on optimum polymer dose. The flocculated samples in this patch were prepared with polymer doses ranged between 400 ppm and 1200 ppm at the predefined optimal feed rate and optimized with the torque-force based technique.

5. RESULTS AND DISCUSSION

5.1 Effects of polymer feed rate on shor-term dewaterability

Figure 2 illustrates the change in the developed torque force over time during flocculation corresponding to different feed rates. Polymer feed started at time zero and followed slight reduction of the developed torque force. The reduction of the force torque was more pronounced for the samples that were polymer-fed at slower feed rates. The reduction in the torque force could be attributed to the reduction in the mixture density as the polymer stock solution was injected and before the fine particles started to agglomerate and forming larger flocs. Shortly after, the developed torque forces recovered and started to increase sharply until reaching peak values. It can be noted that the time needed for the torque force to recover was longer for the samples that were flocculated at slower feed rates. This behavior may be attributed to that at slower feed rate there have been no sufficient polymer to enhance the flocculation. However, as the total volume of the polymer was injected into the sample, the fine particles find sufficient polymer volume to start agglomerating and forming larger flocs, thus, required larger energy by the Couette rheometer to continue mixing the thicker flocculated structure.

The time needed for injecting the total volume of polymer was shorted at higher polymer feed rates ranging between 2 seconds for the feed rate of 36 ml/sec and 12 seconds for the feed rate of 5 ml/sec. Therefore, the samples flocculated with higher polymer feed rates received sufficient polymer volume in a shorted time, thus started to flocculate sooner after the end of polymer feed. Beyond the peaks, the torque force experienced a rapid reduction. This reduction in the developed torque force was attributed to flocs sheardown due to excessive mixing time. To maintain the flocs at the optimal size, the flocculation procedure was terminated as soon as a declining in the developed torque force was observed.

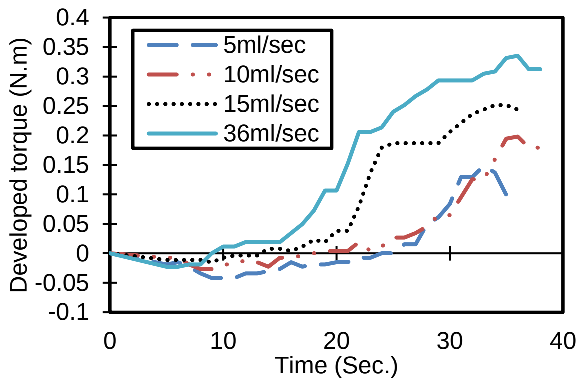

Figure 2. Evolution of torque force during flocculation with various polymer feed rates.

The peak torque force, furthermore, was greater for the samples that were flocculated at higher feed rates following systematic increase trend. The lower developed peak torque force recorded for the samples that was polymer-fed at slower polymer feed rates may be attributed to the de-flocculation and flocs sheadown that seemed to have happened during flocculation and before the total polymer volume was injected. Therefore, there was only smaller amount of the polymer stock solution (the effective polymer volume) that was responsible for the flocculation. This polymer feed volume may have not been sufficient enough to recover the deflocculated flocs, thus, resulting in a poorer flocculation quality and yielding a smaller peak torque force value at the end of the process. In contrast, the shorter polymer feed time attendant to the faster polymer feed rates may have led to receiving the total volume of the polymer stock solution shortly after the initiation of polymer feed. Therefore, there was sufficient amount of effective polymer volume to flocculate most of the fine particles within the rFFTs before any de-flocculation could have happened. In order to investigate the correlation between polymer feed rate and peak torque force, the immediate dewaterability behavior determined from CST test was evaluated for the flocculated samples at each feed rate and plotted against the developed torque force at the end of flocculation (Figure 3).

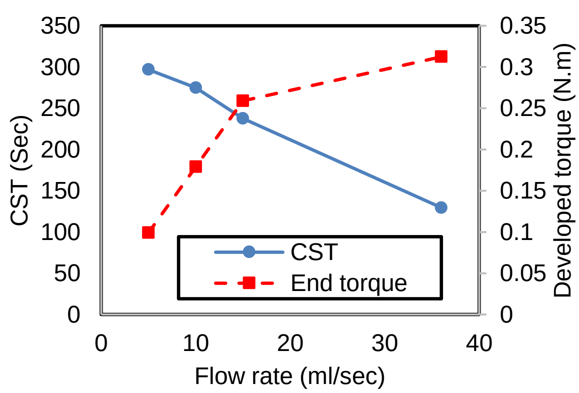

Figure 3. Changes in CST and torque force with the change of polymer feed rate during flocculation.

From the illustration in figure 3, it can be seen that the CST values demonstrated a systematic reduction as the polymer feed rate was increased. Shorter CST value often indicates better immediate dewaterability. As such, the highest tested polymer feed rate of 36 ml/sec would be considered optimal compared to the other evaluated polymer feed rates as it corresponded to the lowest CST value in this study. The reduction in CST value happened simultaneously with the increase in the peak torque force. The higher developed torque force was attributed to the greater amount of large flocs formation at the end of flocculation. The development of larger flocs sizes would probably lead to forming larger interparticle voids which, on the other hand, tend to scarify their contained water under smaller suction forces applied by the filter paper of the CST, thus, resulting in a larger immediate water release. Forming largest flocs sizes, would also explain the highest peak torque force value recorded at the end of flocculation when higher polymer feed rate was conducted.

5.2 Effects of polymer feed rate on longer-term dewaterability and settlement behaviors

Flocculated samples at the various polymer feed rates were deposited in graduated cylinders to evaluated the longer-term dewaterability and settlement behavior (Figure 4). After one hour of sedimentation, the results showed that the settlement percentage increased with increasing the polymer feed rate recording 1.2 % for 5 ml/sec and 9 % for 36 ml/sec. This short-term settlement observation agreed with the short-term dewaterability determined from CST results as demonstrated in Figure 3. As the time progressed, however, the flocculated samples with polymer feed rates of 5 ml/sec and 10 ml/sec demonstrated grater increase settlement rates compared to samples that were flocculated with 15 ml/sec and 36 ml/sec polymer feed rates. The settlement percentage stayed the highest for the sample that was polymer-fed at 36 ml/sec until day 2 post deposition. At the day 4, the settlement percentage of the sample flocculated at 10 ml/sec became the greatest. The settlement percentage of the sample flocculated at 5 ml/sec, in addition, was approaching the value of settlement percentage for the sample flocculated at 15 and 36 ml/sec.

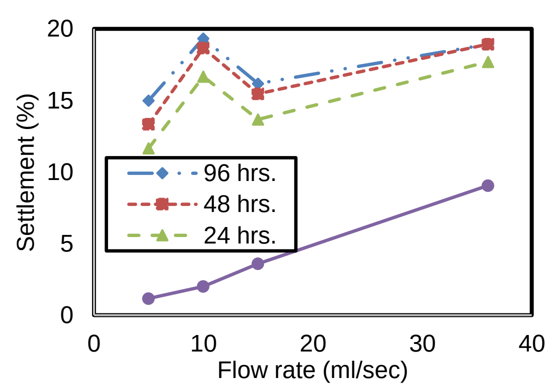

Figure 4. Evolution of percent of settlement for samples flocculated with different polymer feed rates.

As aforementioned, the sample flocculated with polymer feed rate of 36 ml/sec showed the highest peak torque force which was attributed to the larger flocs size formation. In short-term, heaver flocs would tend to settle faster and yield higher settlement percentage as recorded at 1hour time post deposition. Their larger flocs size however, would subsequently lead to larger interparticle pore size that over time limited the tendency of exhibiting an increased settlement rate. the samples that were polymer-fed at slower polymer feed rate, in contrast, may have experienced deflocculating during the flocculation process that may have reduced their flocs sizes. Smaller flocs, therefore, would tend to show slower settlement rate due to their smaller self-weight, thus less immediate dewaterability. However, their smaller size would allow them to pack in smaller volume over time yielding smaller interparticle pore volume as they continue to settle. Therefore, they would eventually exhibit larger settlement percentage as recorded for the sample flocculated with 10 ml/sec at the day 4 of sedimentation. Similar behavior was reported by Aldaeef and Simms, (2019).

5.3 Determination of optimum polymer dose in real-time following the optimized flocculation protocol and using the torque-force based technique (TFT)

Capillary Suction Time (CST) test has often been used for determination of the optimum polymer dose based on the immediate dewatering behavior of flocculated FFTs. However, this technique happens off-line and requires sampling post flocculation, thus not applicable for real time assessment. In this section, the optimum polymer dose was evaluated indirectly and in-real time using the torque force-based technique (TFT). The determined optimum polymer doses using the TFT were compared with those determined using CST results for validation. The TFT was also used to optimize the mixing duration such that an excessive mixing duration is avoided, thus eliminating flocs sheardown after flocs formation.

Various polymer doses of A3338 polymer type including 400 ppm, 600 ppm, 800 ppm, 1000 ppm, and 1200 ppm were used to prepare flocculated samples at polymer feed rate of 10 ml/sec and controlled with the torque force feedback technique. During flocculation, the evolution of the developed torque force for each polymer dose was recorded over time and illustrated in Figure 5.

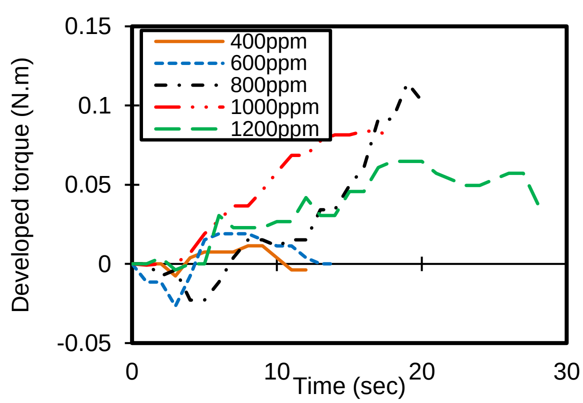

Figure 5. Evolution of torque force during flocculation with various polymer doses.

After polymer injection, the developed torque fore exhibited slight reduction followed by sharp increase until reaching a peak value which was previously proved to be the optimum mixing duration. Subsequently, the developed torque force started to decline which may refer to the end of flocculation and the initiation of flocs de-flocculation. As such, the mixing procedure was terminated as soon as a torque force declining was observed. Therefore, the TFT was able to define the optimum mixing duration in-real time which could be considered an important innovation in the flocculation practice of oil-sand tailings. Additionally, the TFT seemed to have distinguished the optimum polymer dose amongst the tested polymer concentrations. In Figure 5, it was noticed that the peak torque force value increased with increasing the polymer dose until recording the maximum peak torque force for the polymer dose of 800 ppm. Increasing the polymer dose to 1000 ppm and 1200 ppm resulted in reducing the peak torque value to be lower than the value recorded for the 800-ppm polymer dose. Based on the aforementioned discussion, the highest peak torque should be corresponding to the best flocculated sample. In order to confirm that, the peak torque force value recorded for each polymer dose was plotted against the CST results obtained form specimens taken at the end of flocculation of each polymer dose (Figure 6).

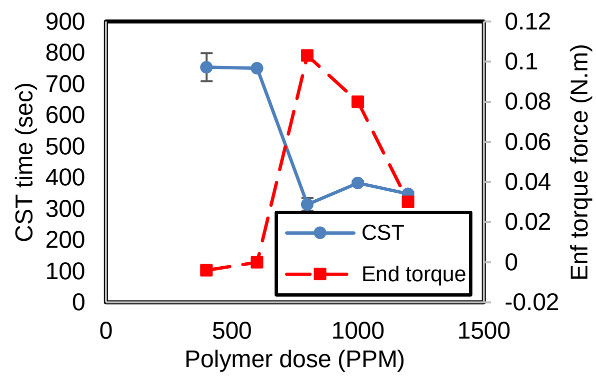

Figure 6. Changes in torque force and CST value corresponding to the change in polymer dose.

As the polymer dose was increased, the CST value decreased until recording the lowest CST reading for the polymer dose of 800 ppm, which, on the other hand, corresponded to the largest exerted torque force value. Given that the lowest CST value refers to the best immediate dewaterability in the short-term, the polymer dose of 800 ppm would be considered the optimum polymer dose amongst the evaluated polymer concentrations in this study. This finding prove that the torque-force based technique (TFT) not only was able to identify the optimum mixing duration but the optimum polymer dose in-real time. This conclusion highlights the usefulness of the introduced new technique in optimizing the FFTs flocculation in-real time with strong potential application for inline flocculation practices.

5.4 Effect of solid content of FFTs on optimum polymer dose determination using TFT

Physical properties and mineral composition of Fluid Fine Tailings (FFTs) have been reported to vary from patch to patch possibly due to the composition variation of the oil-sands ore itself. Such unstable state of composition imposes challenges when determining the optimum polymer dose and optimum mixing duration for optimum flocculation. Many research studies (e.g., Salam et al, 2016; Webster et al., 2016; Revington et al., 2018) attempted to developed techniques that can adjust the polymer does in-real time to maintain the flocculation at optimum, however, some shortcomings existed. TFT, in contrast, has shown superiority for in real-time optimization of polymer dose and mixing duration for a given FFTs as it has been demonstrated in this study. However, the applicability of TFT for flocculation optimization of FFTs with different physical properties and/or mineral composition is still unknown. This section is devoted to evaluate the applicability of TFT for flocculation optimization of FFTs with a different solid content. The raw FFTs used in this study was let to self-consolidate in a 20-liter capacity bucket for 2 months to increase its solid content. After this time, the supernatant water was removed and the remaining solid and contained water were mixed thoroughly for homogenizing. Subsequently, samples were taken for oven-drying test to determine the new solid content. The solid content increased from the initial value of 31% (w/w) reported in Table 1 to 35 % (w/w) after self-consolidation. TFT was then used for flocculation optimization of the FFTs with the new solid content. The flocculation was conducted using A3338 polymer type with polymer dose ranged between 400 ppm and 1200 ppm to determine the optimum polymer dose that corresponding to the best immediate dewaterability as determined from CST results.

The evolution of the developed torque force was recorded during flocculation using each polymer dose and plotted over time (Figure 7). The maximum peak torque force value for this FFTs was recorded for the polymer does of 1000 ppm. This may refer to that the 1000 ppm have produced the best flocculated sample, thus corresponding to the optimum polymer dose. This polymer dose was greater than the optimum polymer dose of 800 ppm recorded for the FFTs with solid content of 31%. Increasing the solid content of the FFTs seems to have led to increasing the optimum polymer dose by a margin of 200 ppm. The torque-force based technique (TFT), surprisingly, was able to correspond to the change in the solid content and adjust the polymer dose to be always at the optimum level.

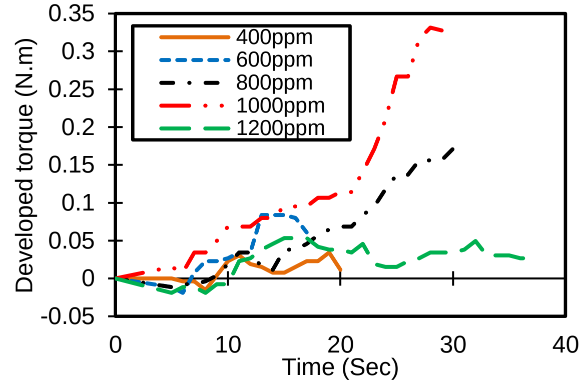

Figure 7. Developed torque force during flocculation with various polymer doses (solid content of 35%).

To confirm that 1000 ppm was the optimum polymer dose for the FFTs with solid content of 35 %, the CST results and the peak torque force were obtained and plotted for each polymer dose and presented in Figure 8.

The CST readings declined from 1149 seconds to 161 seconds when the polymer dose was increased from 400 ppm to 1000 ppm. The CST readings increased to 710 second as the polymer dose was increased to 1200 ppm. The CST results, therefore, indicate that the 1000 ppm was the optimum polymer dose for the FFTs with 35 % solid content. To evaluate the applicability of TFT in capturing the optimum polymer dose, the torque forces at the optimum mixing time were recorded for each polymer dose and compared with the CST results. The peak torque force increased sharply as the polymer dose was increased reaching a maximum peak torque force value of 0.33 N.m for the polymer dose of 1000 ppm. The peak torque force decreased to 0.03 N.m as the polymer dose was increased to 1200 ppm.

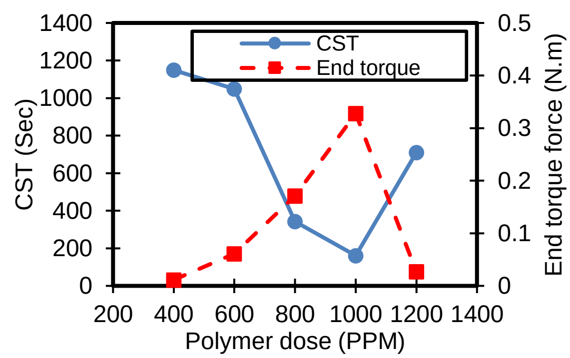

Figure 8. Optimized flocculation using TFT and the corresponding CST results and peak torque forces for various polymer doses (solid content 35%).

Considering the hypothesis of the torque-force based technique, the max peak torque force should correspond to the optimum polymer does as discussed earlier. The obtained results from CST and peak torque force both agreed about the optimum polymer dose which confirmed the applicability of TFT in defining not only the optimum polymer dose but the optimum mixing duration for the best flocculation of FFTs materials regardless of their solid contents. The increase in solid content would usually be coincided with increase in clay content for a given volume of rFFT, thus required higher polymer volume for optimum flocculation. This was found true as the optimum polymer dose increased from 800 ppm to 1000 ppm when the solid content increased from 31% to 35%. TFT was able to track this change and corresponded well to the increase in solid content by adjusting the optimum polymer dose to the right value. Moreover, TFT was able to sense the increase in solid content by demonstrating a higher maximum peak torque force at the respective optimum polymer dose. The maximum peak torque force recorded 0.11 N.m when the solid content of FFTs was at 31% compared to 0.33 N.m for FFTs with 35% solid content. FFTs with higher solid content would exhibit higher density, thus impose larger load on the Couette shaped mixer which would require greater energy and, thus, larger torque force for mixing.

6. CONCLUSION

This study introduced an innovative technique for inline and in-real time optimization of flocculation of Fluid Fine Tailings (FFTs) through an optimized polymer-tailings mixing duration, polymer feed rate, and polymer dose. The findings of this study can be summarized in the following bullets:

1- Feeding the predefined polymer volume at a faster rate produced optimal flocculation with better immediate dewaterability and settlement percentage. From the longer-term observations, however, polymer feed rate seemed to have less impact on the settlement percentage.
2- The introduced TFT optimization technique showed a strong potential of producing high quality flocculated FFTs by optimizing the mixing duration and the optimum polymer dose in-real time.
3- TFT showed a great applicability in maintaining optimum flocculation for FFTs with different solid contents by adjusting the polymer dose and the mixing duration to be always at optimum. This highlights the great potential of the TFT as an in-real time technique for flocculation optimization for materials with a changeable composition such as FFTs.

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