Influence of pipeline transport on sedimentation and consolidation of flocculated Fluid Fine Tailings (fFFT)

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ABSTRACT

This study evaluated the effects of pipeline transport on the dewatering and settling behaviors of polymer-amended Fluid Fine Tailings (FFT). An advanced Couette rheometer was utilized to simulate the in-pipe shear rates and shear durations that flocculated FFT could experience when transported in different pipe diameters and for different travel distances. The obtained results showed that the pipeline shear could reduce the short term dewaterability of flocculated FFT. However, certain amounts of pipeline shear increased the magnitude of dewatering over weeks to months. Despite the improved long term performance of the sheared flocculated FFT samples, pipeline shear did reduce the value shear strength at a given density. The developed torque force during flocculation provided an effective in-real time indicator of the quality of the produced flocculated FFT samples. It could also assist on predicting the performance of the flocculated FFT materials after deposition.

RÉSUMÉ

Cette étude a évalué les effets du transport par pipeline sur les comportements d'assèchement et de sédimentation des résidus fins fluides modifiés au polymère (FFT). Un rhéomètre avancé de Couette a été utilisé pour simuler les taux de cisaillement dans la conduite et les durées de cisaillement qu'une FFT floculée pouvait subir lors du transport dans différents diamètres de conduite et pour différentes distances. Les résultats obtenus ont montré que le cisaillement du pipeline pouvait réduire la déshydratation à court terme de la FFT floculée. Cependant, certaines quantités de cisaillement dans les pipelines ont accru l'importance de la déshydratation au fil des semaines et des mois. Malgré l'amélioration des performances à long terme des échantillons de FFT floculés cisaillés, le cisaillement du pipeline a réduit la valeur de la résistance au cisaillement à une densité donnée. La force de couple développée au cours de la floculation a fourni un indicateur efficace en temps réel de la qualité des échantillons de FFT floculés produits. Cela pourrait également aider à prédire la performance des matériaux FFT floculés après le dépôt.

1 INTRODUCTION

The water-based extraction of bitumen from oil sands is accompanied with production of significant amount of Fluid Fine Tailings (FFT). Treatment is required to minimize the footprint of these tailings to render tailings deposits reclaimable within regulatory mandated schedules (AER 2017).

In tank and Inline flocculation are two common tailings treatment techniques used in oil sand industry. Both are based on polymer flocculant blending with raw FFT to enhance binding of clay particles into larger flocs (Farinato and Dubin 1999; Gregory 1989; Moudgil and Somasudaran 1988, 1994). Some of the main difficulties associated with flocculation are managing the optimum polymer dosage, mixing time and energy, and effects of pipeline shear. Flocculated FFT is shear sensitive material where the exposure to intensive shearing post flocculation could deteriorate its performance (Pelssers et al. 1989; Yeung et al. 1997; Owen et al. 2008). Previous studies reported negative impacts of excessive mixing on dewatering and settling behaviors of flocculated FFT. 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.

Weiss et.al (2018) stated that the flocculation process would start with gel formation which subsequently would be subjected to shear conditioning during pipeline transport. A moderate pipeline shear was found useful by breakdown the flocs and enhancing water release, however prolonged shear time may lead to substantial decrease in dewaterability. Giving its benefit, clear guidelines on the optimum pipeline shear is not available.

Webster et. al. (2016) suggested adopting an inline instrumentation technique for quality control of the produced flocculated FFT. The applicability of such technique in a field setting depends on its capacity of providing in real time measurements and feedback that allow for adjustment of the process inputs to address for any change in the raw FFT properties.

The current study examines the effects of different pipeline shear conditions on the evolution of dewatering and settling behaviors of flocculated FFT over time. It also evaluates the strength behavior of the deposited flocculated FFT after the exposure to different scenarios of pipeline shear rates and shear durations. A simple technique for in-real time assessment of the quality of the flocculation is also introduced.

2 MATERIALS

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 was 31% and the liquid limit was 60%. 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 (rFFT) was 1050 mg/L, electrical conductivity was 1590 μS/cm, while the dominant cations were sodium at 340 mg/L. Typical 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 200 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 APPARATUS

An advanced Couette rheometer was used in this experiment for processing the raw Fluid Fine Tailings (rFFT) with the polymer solution for producing flocculated Fluid Fine Tailing (fFFT) following in-line flocculation procedure. The Couette rheometer, subsequently, was utilized to impose various pipeline shearing conditions (i.e., shearing rate and duration) on the flocculated samples for simulating pipeline shear scenarios.

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 shaft in order to prevent the formation of a slip layer around the bobbin (Figure 1a). This baffling is believed 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) equal to 21 mm. This gap makes the ratio between the radius of the bobbin to the radius of the cup equal to 0.63 which may not satisfy the narrow gap assumptions. However, a moderate-gap condition was meant to avoid severe flocs sheardown which may not be experienced in a typical pipeline due to the existence of a lubricated layer on the pipe wall.

The Couette rheometer is equipped with a Multimeter that provided a power consumption reading to an accuracy of 0.1 Watt. Knowledge about power consumption by the Couette rheometer at a given rotational speed can enable calculating the exerted torque force at any time using the following equation:

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

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

Using the Couette rheometer was aimed at imposing predetermined shear rates and shear durations similar to those generated in a pipeline during transport of fFFT. Assuming a Newtonian fluid, laminar flow, and fully sheared conditions, the shear rate in circular section pipes can be estimated as:

$$\gamma^{\cdot} = \frac{8U}{D} \qquad [2]$$

where: U is the pipe internal diameter (m) and D is the flow velocity (m/sec).

The flocculated FFT is a shear sensitive Non-Newtonian fluid that may experience turbulent flow at some stages of the flocculation and pipeline transport. However, Equation 2 was selected for its simplicity.

Shear rate in the Couette rheometer for Newtonian fluids is a function of radius of the cup, radius of bobbin, and the rotational speed of the bobbin and can be expressed as follow:

$$\gamma^{\cdot} = \frac{N_B * R}{9.549 * (R_c - R_b)} \qquad [3]$$

$$R = \frac{R_c + R_b}{2} \tag{4}$$

where: N_B is the bobbin rotational speed in (rpm); R_c and R_b are the cup and the bobbin inner and outer radius (m) including baffles respectively.

For a pipeline with a certain internal diameter and flow rate, the shear rate in the pipe can be calculated using Equation 2 and then substituted in Equation 3 to calculate the bobbin rotational speed in (rpm) that is needed for generating the corresponding shear rate in the Couette rheometer. In other words, the pipeline shear conditions were modeled in the Couette rheometer by the shear rate, i.e., the bobbin rotational speed, and the duration of the shear time. Similar work on oil sands fFFT was conducted by Derakhshandeh et al. (2016).

4 EXPERIMENTAL PROGRAM

4.1 Flocculation

The fluid fine tailing was amended with anionic polymer flocculant type A3888 at an optimum dosage of 800 ppm. This treatment is known as flocculation which is desired to enhance aggregation of the colloidal particles within the FFT into larger flocs, thus, a greater density. Therefore, the flocs would tend to settle in the suspension under gravity and separate from the water in tailings leading to larger solid content, smaller void ratio, and greater strength (Salam et al., 2016).

Flocculation in this study was conducted in the Couette rheometer following in-line flocculation procedure. The used Couette rheometer had the capacity of flocculating 1400 ml of FFT each round. The flocculation started with placing the FFT sample into the cup, then positioning the bobbin on a designed base in the center of the cup to allow free rotation around the vertical axis of the Couette rheometer. After setting the rotational speed of the Couette rheometer to 250 rpm, the mixing process was initiated and continued for 40 seconds before the optimum polymer dosage was added to the sample at a polymer to tailing rate of around 1.5%/s. The feed of the polymer was facilitated via syringes and injected at the mid height of the Couette rheometer through two small tubes of 5 mm diameter attached to the inner surface of the cup. To control the quality of flocculation, a new criterion was adopted in this study based on the torque development during flocculation. Conducting many trial tests, it was noticed that the power consumption by the Couette rheometer during flocculation gradually increased until reaching a peak value after which the power reading started to decline referring to initial FFT flocculation followed by a stage of deflocculating as more mixing was continued after the peak. The power measurement technique seemed to enable determining the optimum time required for best flocculation beyond which more blending would result in an over-sheared sample, thus, flocs sheardown. Using this technique, well flocculated samples were often obtained at the maximum torque reading that corresponded to an optimum mixing time ranging between 20 and 25 seconds after polymer injection.

Several well flocculated samples were produced and divided into two groups. The first group of samples was evaluated right after flocculation, while the second group of samples was assessed after being exposed to different pipeline shear conditions modeled by the Couette rheometer.

4.2 Pipeline Shear Modeling

Flocculated FFT is usually shipped via pipelines to the tailings ponds for final deposition. Depending on the flow rate, the internal pipe diameter, and the transport distance, the flocculated FFT may experience various shear rates and shear time during pipeline transport. To evaluate the effect of pipeline shear on dewaterability and settling behaviors of flocculated FFT, four field-pipeline shear conditions were modeled and examined. The shear rates were calculated using Equation 2 based on two different flow rates of 662 m^3/hr and 2648 m^3/hr and two field-scale pipe sizes of 609.6 mm (24″) and 762 mm (30″) (Table 2).

Table 2. Calculated shear rates based on field-scale pipeline transport system

Flow Rate (Q)	Pipe Dia. (D)	Cross Section Area	Velocity $\left(U = \frac{Q}{A}\right)$	Shear rate $\left(\Upsilon = \frac{8U}{D}\right)$
m^3/hr	in	(m^2)	m/sec	s^{-1}
662	30	0.456	0.403	4.23
662	24	0.292	0.630	8.27
2648	30	0.456	1.614	16.94
2648	24	0.292	2.521	33.09

The calculated shear rates were modeled in the Couette rheometer through the rotational speed of the bobbin. For each shear rate, the corresponding rotational speed was determined based on the Couette rheometer geometry using Equation 3. Table 3 shows the conversion from in-pipe shear rate to the rotational speed of the bobbin in the Couette rheometer expressed in round per minute.

Table 3. Calculation of shear duration for different pipeline transport distances

´Y	R_b	R_c	N_B	U	Transport time	
					0.5 km	1km
S^-1	m	m	rpm	m/sec	min	min
4.23	0.038	0.059	18	0.40	20	41
8.27			35	0.63	13	26
16.94			72	1.61	5	10
33.09			141	2.52	3	6

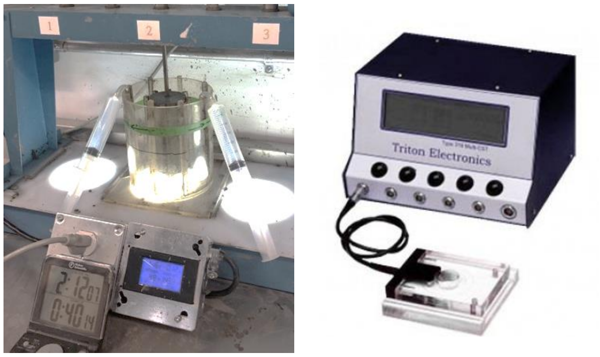
For modeling the pipeline shear, the flocculated samples in the second group were sheared in the Couette rheometer at rotational speeds of 18, 35, 72, and 141 rpm simulating pipeline shear rates of 4.23, 8.27, 16.94, and 33.09 s^{-1} respectively. The shear time in the Couette rheometer was dependent on the shear rate and transport distance. For a given transport distance, smaller shear rates (i.e., slower flow speeds or wider pipe diameter) would result in a longer transport time. In this experiment, two different transport distances were adopted (i.e., 500 m and 1000 m) to investigate the effect of moderate and prolonged pipeline shear durations. The change in torque during modeled pipeline shear conditions was recorded for evaluating the impact of pipeline shear on the strength of the flocculated FFT.

4.3 Testing and Evaluation

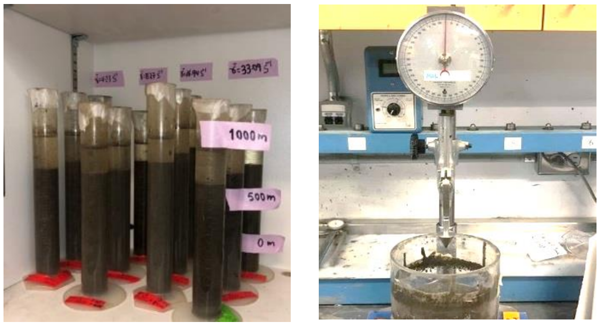
The test samples were prepared at various conditions including:

- Flocculated, but not transported samples,
- Flocculated and sheared samples for residence time corresponding to 500 m.
- Flocculated and sheared samples for residence time corresponding to 1000 m.

The dewaterability, settling behavior, and strength of these samples were then evaluated using different types of tests including Capillary Suction Time (CST) for immediate dewatering, Graduated Cylinder Test for settling and longer-term dewaterability, Fall Cone Test for undrained shear strength, and the Multimeter readings for estimating torque force (Figure 1).



a. Couette rheometer b. CST test



c. Graduated cylinder d. FCT

Figure 1. Couette rheometer and test types used for dewaterability, settling, and strength evaluation of processed tailings.

5 RESULTS AND DISCUSSIONS

5.1 Effect of Pipeline Shear on Immediate Dewaterability

The Triton Type 319 Multi-purpose Capillary Suction Time (CST) is a commonly used type of test for the assessment of resistance to filtration (Figure 1b). It was utilized in this study to assess the effect of pipeline shear on the immediate dewatering of the test samples. The CST test evaluates the readiness of the test sample to release its water under a suction force applied by a CST filter paper in contact with the sample. Given the constant suction properties of the filter paper, the test sample that has a larger flocs size, thus, a larger interparticle pore size, would tend to saturate the predefined filter paper area in shorter time. A higher CST value, therefore, indicates poor immediate dewaterability. The CST test was performed immediately on samples post flocculation at zero residence time, samples exposed to pipeline shear for a residence time corresponding to 500 m length, and samples exposed to pipeline shear for a residence time corresponding to 1000 m length.

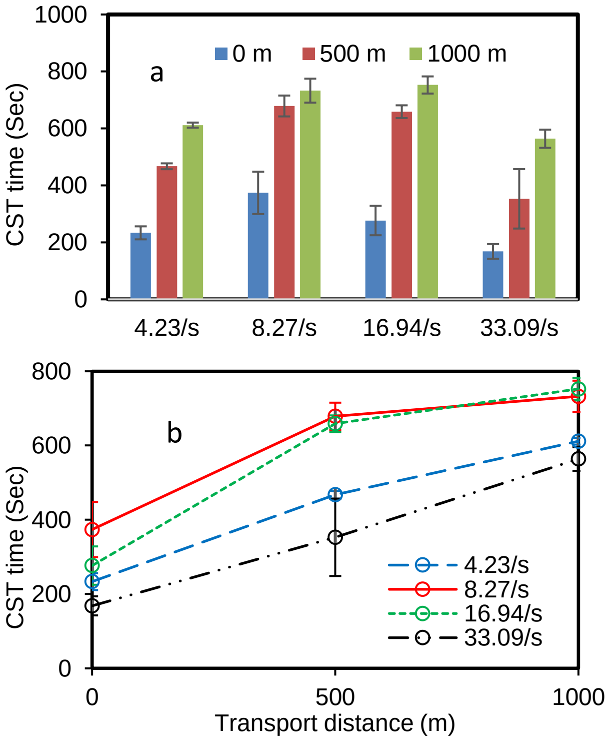


Figure 2. Variation of CST time with different shear rates and shear durations

The test results showed that a shorter CST value was recorded for the non-sheared flocculated FFT samples. As the flocculated FFT being sheared simulating pipeline transport, the CST value significantly increased with increasing transport distance, i.e., the duration of shear time (Figure 2a). This refers to a greater immediate dewaterability for the flocculated FFT samples that undergo shorter travel distance. The results from Figure 2b demonstrated that transporting at the lowest and highest tested shear rates appear to had less impact on the immediate dewaterability by showing lower CST values. However, the variation in the initial CST values (for non-sheared samples) refers to different initial flocculation quality. This, may have contributed to the observed differences in CST values after shearing. To eliminate this effect, the CST values for the sheared samples were normalized by their initial CST values to obtain meaningful comparison and better understand the effect of different shear rates. The normalized CST values were presented in Figure 3 for different transport distances.

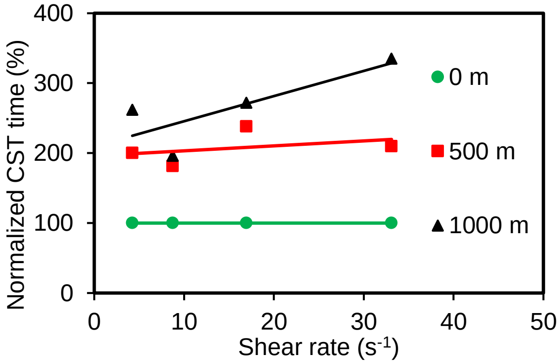


Figure 3. Effect of different shear rates on immediate dewaterability

The normalized CST values still support the conclusion of the negative impact of prolonged travel distance on the immediate dewaterability of the flocculated FFT samples. However, they provided different image from what was drawn from Figure 2b regarding the impact of different shear rates. Normalized CST values, indeed, suggested slight tendency of reduction in immediate dewaterability as the shear rates were increased. This tendency became more pronounced for the flocculated FFT samples that experienced longer travel distance.

Pipeline transport post to flocculation could impose different shear conditions that negatively impacts the immediate dewatering. This could be attributed to the deflocculating and flocs sheardown of the flocculated FFT, which may have resulted in smaller pore size and less immediate water release.

5.2 Evolution of Dewaterability and Settling Behaviors of Sheared and Non-sheared fFFT Samples

Four non-sheared samples, four sheared samples at the defined shear rates and for modeled transport distance of 500 m, and four sheared samples at the defined shear rates and for modeled transport distance of 1000 m were deposited in 100 ml graduated cylinders to observe the evolution of dewatering and settling behaviors over time.

After 24 hours of deposition, the non-sheared samples (i.e., 0 m transport distance) released the largest amount of process water ranged from 5 to 15 % of the total volume of the deposited samples. The released amount of water in this short term, however, decreased with increasing the transport distance. The samples sheared for a modeled transport distance of 500 m showed percentage water release ranged from 1.5 to 9.5 %, while the modeled transport distance of 1000 m resulted in the least water release recording a range of 1 to 3.7 %. This observation supported the results obtained from the CST tests which suggested lower immediate water release with increasing the duration of pipeline shear (Figure 4).

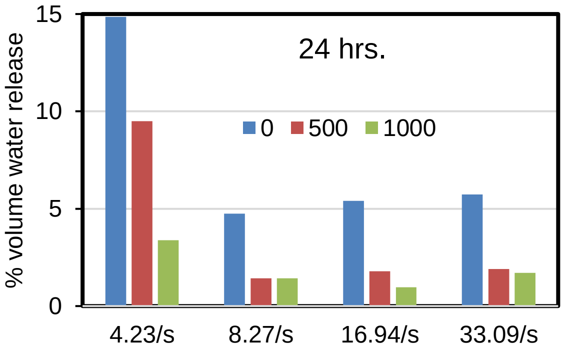
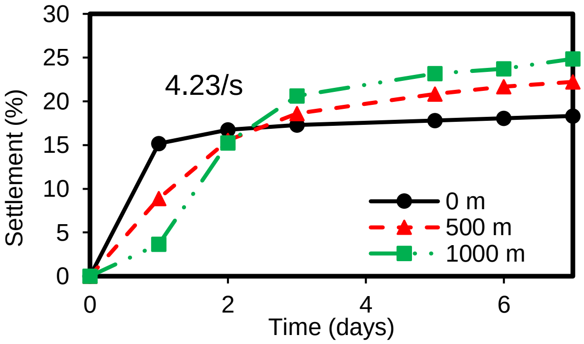


Figure 4. Percentage of water release 24 hrs. post deposition

After seven days of sedimentation in graduated cylinders, the non-sheared samples showed reduction in their settling tendency over time compared to the sheared samples (Figure 1c). For all different shear rates, the sheared samples developed larger settlement percentage compared to non-sheared samples (Figure 5). Increasing the pipeline shear duration, indeed, seemed to enhance the settlement especially for the samples that were sheared at the shear rates of 4.23 s^{-1} and 33.09 s^{-1}.



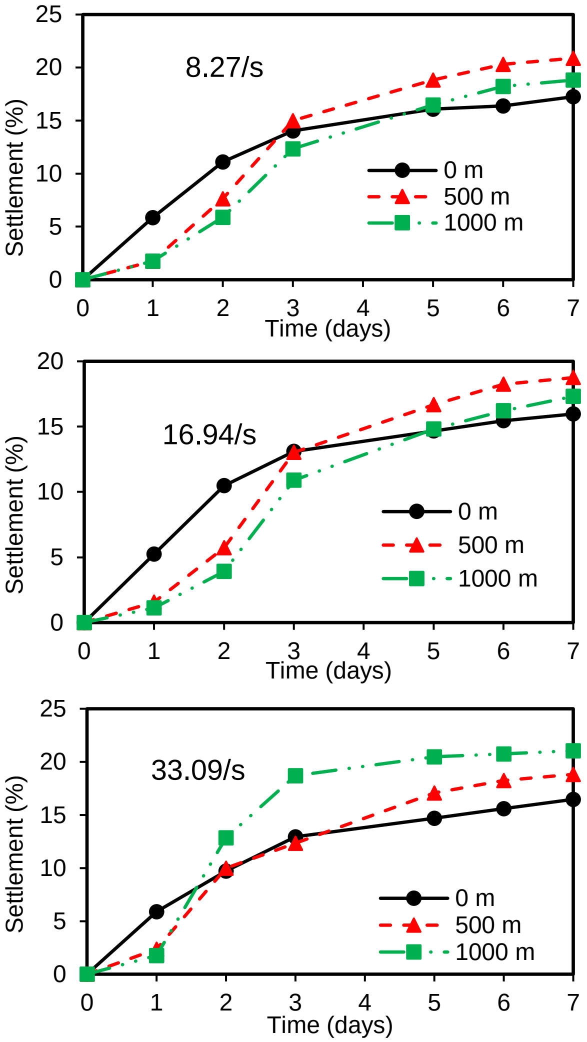


Figure 5. Percentage of settlement for non-sheared samples and sheared samples at various pipeline shear conditions

This alternation in settlement and dewatering behaviors over time may be attributed to different structures that the test samples tended to develop following to the exposure to various pipeline shear durations. From visual inspection, it was noticed that the flocculated FFT (i.e., non-sheared samples) developed larger flocs which probably would settle faster under its larger self-weight resulting in larger immediate water release. However, this may have subsequently led to larger interparticle pore size that over time limited the tendency of the non-sheared samples to exhibit increased settlement rate. This was also suggested by Hogg, (2000) and Rattanakawan and Hogg (2000). Increasing the pipeline shear duration, on the other hand, caused deflocculating and reduced flocs size. 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, the sheared samples would, eventually, exhibit larger settlement which would increase with decreasing the flocs size, thus increasing the pipeline shear duration. This conclusion, however, should be limited to pipeline shear conditions tested in this study.

5.3 Development of Undrained Shear Strength of Sheared and Non-Sheared Flocculated FFT Samples

Four sheared samples and four control samples (i.e., Non-sheared samples) were collected in air-tight acrylic columns with diameter of 140 mm and height of 150 mm and used for undrained shear strength evaluation using Fall Cone Test (FCT) (Figure 1d). Each of the sheared samples was exposed to different shear rates (i.e., 4.23 s^{-1}, 8.27 s^{-1}, 16.94 s^{-1}, and 33.09 s^{-1}) but similar modeled transport distance of 1000 m. FCT has long been used for determining liquid limit and plastic limit of cohesive soils (Sherwood and Ryley, 1970). Lately, FCT became a widely used technique for measuring undrained shear strength (Zreik, et. al 1995; Rajasekaran & Rao, 2004). It uses simple semi-empirical equation proposed by Hansbo (1957) for correlating the depth of the cone penetration (d), falling under its self-weight (mg) to the undrained shear strength (Cu) as follows:

$$Cu = k\left(\frac{m*g}{d^2}\right) \qquad [5]$$

where: Cu is undrained shear strength in Pa; k is a dimensionless surface roughness factor of the cone which used herein as 1.33 for semi-rough surface; g is acceleration of gravity (m/s^2); m is the mass of the cone (kg); d is the depth of penetration in (m).

The test samples underwent weekly FCT and for around a month (Figure 6). The results demonstrated that the sheared samples developed significantly less strength over time compared to the non-sheared samples. The exposure to the modeled pipeline shear seemed to degrade the flocs size and caused flocs sheardown post flocculation. After one week of sedimentation, the non-sheared sample showed an average undrained shear strength of 400 Pa, while the sheared samples did not develop any strength even after two weeks of sedimentation except the samples that were sheared at 16.93 s^{-1} which showed an average strength of 200 Pa after 10 days.

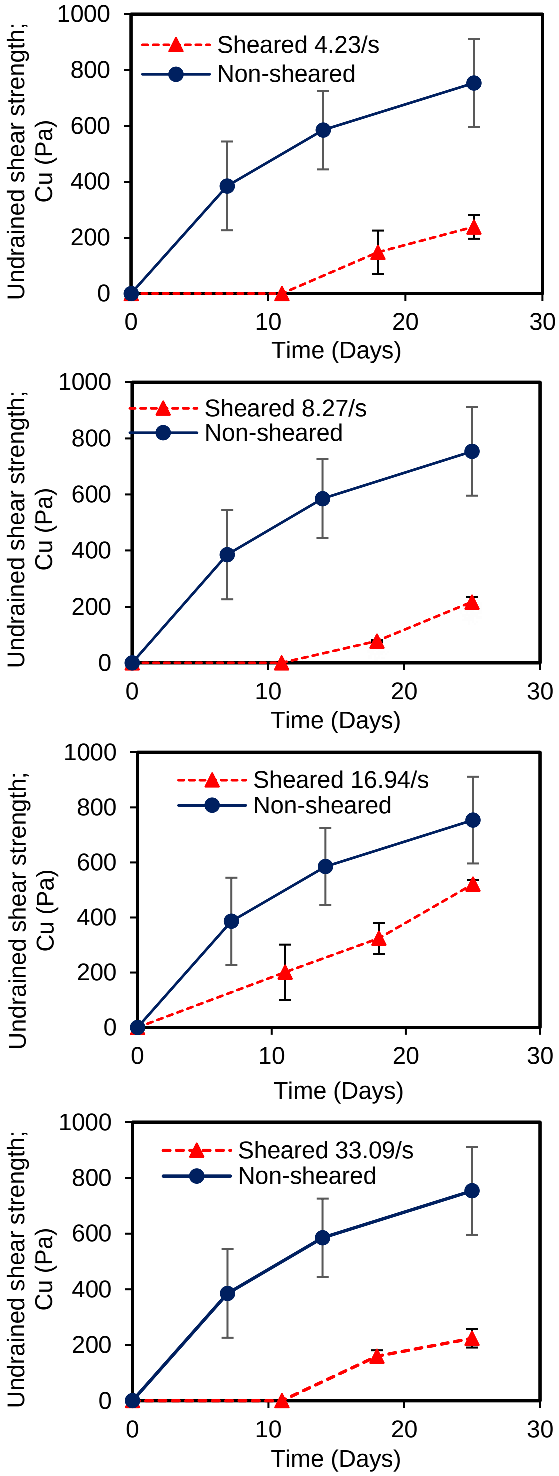


Figure 6. Effect of pipeline shear on strength behavior of flocculated FFT.

By the end of the test, the sheared samples have gained an average undrained shear strength between 250 and 500 Pa. In contrast, non-sheared samples have developed stronger profile recording 750 Pa. despite better dewaterability and larger settlement, sheared samples developed smaller strength compared to non-sheared samples. This could be attributed to the smaller flocs size that the increased shear durations have caused. Smaller flocs size seemed to have less shear strength and tend to deform under smaller shear forces.

5.4 Innovative Quality Control Technique for Improved Flocculation

Through the current experiment, a strong relationship was detected between the quality of the flocculation and the developed torque force during flocculation. The flocculated samples that developed larger torque force always exhibited better immediate dewaterability and settling behavior. Those samples, furthermore, demonstrated better performance even after pipeline shear such as the sample sheared at 4.23 s^{-1}. Optimizing the flocculation process for obtaining well flocculated samples seems to contribute to the improvement of dewatering and settling behavior after deposition.

Figure 7 demonstrates the evolution of torque force observed during the process of flocculation for two different FFT samples. The curves showed that the torque reading increased dramatically from 0 to around 0.35 N.m corresponding to the starting of the Couette rheometer. The initial torque force increase could be linked to the energy needed to rotate and blend the raw FFT in the cup. The torque reading, after that, decreased slightly as the mixing process continued for 60 seconds for homogenizing the FFT sample before adding the flocculant. The polymer flocculant was then injected. Subsequently, the torque force exhibited dramatic development reaching maximum values of around 0.6 N.m. It was noticed that the peak torque often occurred between 15- and 25- seconds post polymer injection. The peak torque is believed to be associated with formation of large flocs size which seems to require greater energy from the Couette rheometer to move them around. After the peak, a small extra mixing time led to sharp reduction in the torque force. This reduction could be attributed to over shearing and flocs sheardown.

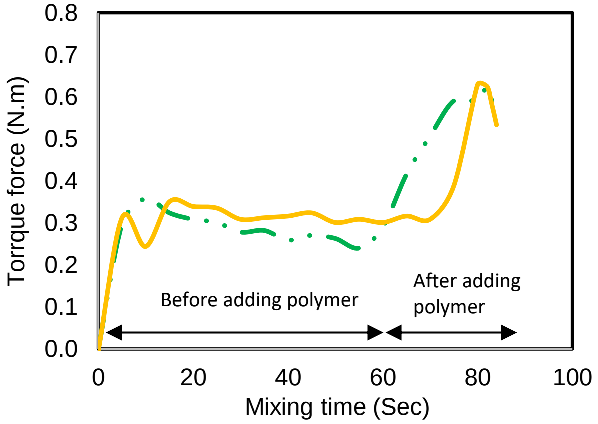


Figure 7. Torque development during flocculation.

To further investigate the relationship between flocculation quality and the developed torque force, the maximum torque readings during flocculation was plotted against the CST values and the 7-days settlement percentages of several flocculated non-sheared samples (Figure 8a&b).

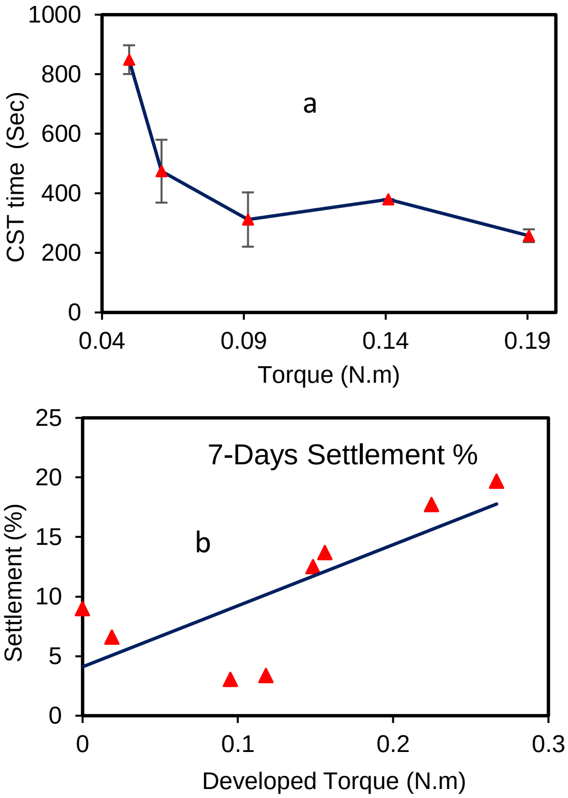


Figure 8. Assessment of immediate dewarting and settling behavior based on developed torque force.

The CST readings decreased significantly with increased torque force indicating better immediate dewatering (Figure 8a). The longer-term performance also showed an improved settling behavior for the samples that developed greater torque readings during the process of flocculation (Figure 8b). Although the flocculated samples were treated with identical polymer dosages, yet they developed different torque forces. This difference was mostly driven by the way the polymer was added during flocculation. Better flocculation was always attained when the polymer was injected at depth in the Couette rheometer and in a moderate flow rate. The samples that received the polymer on the surface and in one shot usually resulted in a small torque force and less flocculation quality.

Using the torque force as an indicator on the quality of flocculation seems to be a promising technique that can help control the flocculation process. For a given mixer geometry and mixing tank volume, the maximum torque force corresponding to the optimum flocculation can be defined and set as a reference. The process inputs can then be adjusted to always maintain the developed torque force close to the reference value. Couette rheometers may also be positioned in bypasses along the pipeline to track the changes in the torque force which may be compared to another optimum reference torque force obtained at the downstream.

6 CONCLUSION

This study demonstrates that pipeline shear slightly reduces the immediate dewatering of flocculated FFT. The reduction tendency becomes more pronounced under higher shearing rates and longer shearing durations. However, pipeline shear enhances the longer-term dewatering and settling behavior despite the significant reduction in shear strength of the flocculated FFT following to pipeline shear. Although longer-term settling percentage shows no sensitivity to the increased shear rates, it increases with increasing shear duration, i.e., pipeline transport distance, within the boundaries of this model study. The developed torque force during flocculation process can provide indication on the quality of the produced flocculated samples. It could be a promising technique for real time assessment of flocculation process and an effective indicator of post deposition performance of flocculated FFT.

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