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Long-term Consolidation of Two New Polymer Treatments of Oil Sands Fluid Fine Tailings

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ABSTRACT

This paper examines the effects of two new polymers (cationic and neutral) on the consolidation behaviour of FFT compared to A3338 polymer treatment. Seven large strain consolidation experiments were completed, two for each polymer type and one control sample of untreated FFT. Furthermore, the material properties of untreated and treated FFT were analyzed. Results indicate that at the end of self-weight consolidation, a demonstrably higher dewatering efficiency of the neutral polymer on FFT was observed relative to the cationic and anionic polymers determined by the change in void ratio of each treated specimen. At each load step, the hydraulic conductivity and compressibility of FFT treated using the neutral and cationic polymers were higher compared to the anionic polymer and control sample. Moreover, at a given solids content, the shear strength of the new polymer treatments was an order of magnitude higher than the anionic polymer. Below a solids content of 35 %, the neutral polymer produced about twice the shear strength of FFT treated with the cationic polymer, which is attributed to the distinct structure the neutral polymer creates following treatment.

RÉSUMÉ

Cet article examine les effets de deux nouveaux polymères (cationiques et neutres) sur le comportement de consolidation des résidus miniers fluides par rapport au traitement du polymère anionique A3338. Sept essais de consolidation à grande contrainte ont été réalisés, deux pour chaque type de polymère et un échantillon témoin de résidus non traités. Les propriétés des matériaux des résidus traités et non traités ont également été analysées. Les résultats indiquent qu'à la fin de la consolidation du poids propre, une manifestation de déshydratation efficace plus élevée a été observée sur les résidus traités avec le polymère neutre par rapport aux polymères cationiques et anioniques. Cette manifestation a été déterminée par le changement d'indice des vides de chaque traitement de polymère. À chaque étape de charge, la conductivité hydraulique et la compressibilité des résidus traités à l'aide des polymères neutres et cationiques étaient plus élevées par rapport au polymère anionique et aux résidus non traités. De plus, à une teneur en solides donnée, la résistance au cisaillement des nouveaux traitements des polymères était d'un ordre de grandeur supérieur à celle du polymère anionique. En dessous d'une teneur en solides de 35%, le polymère neutre a produit environ deux fois la résistance au cisaillement des résidus traités avec le polymère cationique, ce qui est attribué à la structure distincte que le polymère neutre crée après le traitement.

1 INTRODUCTION

Surface mining of oil sands in Northern Alberta has been in operation for over five decades. The bitumen extraction process produces tailings, consisting of sand, silt, dispersed clay, residual bitumen and process water. Deposition of the tailings material in a surface storage facility allows the sand to settle out near the discharge point, while fluid fine tailings (FFT) at less than 10% solids content accumulate farther away. Within a few years, FFT settles to a solids content of 30 to 35 % with little to no effective stress (Beier et al. 2013) and remains unconsolidated for decades afterwards due to dispersed clay. The total volume of legacy and new FFT now exceeds 1.2 billion m^3 (AER, 2019) and occupies a storage footprint of over 250 km^2. The growing inventory of FFT and the slow rate of consolidation pose a significant challenge to both reclamation efforts and the physical stability of tailings impoundments. Directive 085 of the tailings management framework limits the volume of FFT that mine operators can deposit to reduce liability and environmental impacts (AER 2017, Alberta

Government 2015). The policy also requires operators to develop and implement technologies to create reclaimable FFT deposits within 10 years of the life of mine. These technologies must aim to reduce volumes, and increase the density and strength of FFT deposits through dewatering.

Many tailings dewatering technologies have been researched at bench and field pilot scales, and several of them are currently in commercial use, including chemical treatments (Sobkowicz 2012). Aggregation of fine tailings particles using polyacrylamide-based polymers in in-line flocculation and tank thickening operation is found to increase the settling and consolidation rates of FFT (Znidarčić 2016, Yao 2012, Jeeravipoolvarn 2010). Polymer treatment (PT) also has applications in other dewatering technologies, such as centrifugation, rim ditching and atmospheric fines drying, where FFT is first flocculated to improve the dewatering efficiency.

The long-term dewatering performance of tailings treatments is essential to achieving physical stability and reclamation targets. Laboratory studies have demonstrated the effect of anionic polymer treatment on the consolidation and strength characteristics of FFT (Wilson et al. 2018, Znidarčić 2016, Beier et al. 2013, Jeeravipoolvarn 2010). These studies have shown a decrease in density (or increase in void ratio) with a corresponding increase in hydraulic conductivity of FFT after polymer treatment (Reid and Fourie 2018). It is also found that polymer addition increases the undrained shear strength of FFT considerably (Reid and Fourie 2018, Beier et al. 2013).

The drive to explore new ways to improve existing technologies is at the core of recent research. Enhancement of polymers to optimize FFT dewatering is receiving considerable attention in the industry (COSIA, 2019). This paper explores the effect of two newly developed polymer flocculants on the long-term consolidation behaviour of FFT. These new polymers are described as cationic and neutral based on their net charge. Large strain consolidation and shear strength tests were conducted on FFT treated with the new polymers and compared with those of anionic polymer treated FFT and raw FFT.

2 MATERIALS

2.1 Polymers

Three polymer flocculants were used in the experimental study. Two of these flocculants are new cationic and neutral polymers, designed to improve the dewatering performance of FFT. The third polymer is FLOPAM A3338 manufactured by SNF, an existing anionic polyacrylamide flocculant. The polymers were received in dry solid condition. Prior to treatment, the polymers were hydrated in 500ml glass beakers to create polymer solutions that are miscible with FFT. The specified concentrations in Table 1 were achieved by separately adding 500ml of deionized water to 2 g of the cationic polymer, 2 g of anionic polymer and 1 g of neutral polymer respectively, and mixing at 200 rpm for 5 minutes, and then at 125 rpm for 55 minutes using a mixer. After mixing, the polymer solution was set aside for a maturation period of at least 15 minutes before use. Table 1 details the concentrations of the polymer solutions used in the tailings treatment.

Table 1. Polymer solution concentrations and dosage

Polymer	Mass of polymer per 500 mL solution (g)	Concentration (%)	Treatment Dosage (g/ton)
Neutral	1.0	0.2	8000
Cationic	2.0	0.4	4000
Anionic	2.0	0.4	800

2.2 Oil Sands Tailings

For this study, 40 L of FFT from a tailings pond in Northern Alberta were sourced from Carleton University. Upon delivery, the FFT were homogenized and characterized to determine basic material properties. In all experiments conducted, FFT was used as the control sample.

For each treatment, a predetermined mass of FFT was treated based on the solids content and the polymer dosage. The dosages specified by the designer for the new polymer treatments are given in Table 1. An anionic polymer dosage of 800 g/ton was adopted from other research conducted on similar FFT (Salam et al. 2018). Based on these dosages, the required volume of the hydrated polymer was determined and added to FFT. As specified in the design mixing protocol, the anionic, cationic and neutral polymer treatments were stirred at 315 rpm in a vessel in batches of 2 litres using a propeller-type mixer for 10 s, 1.5 min and 2.5 min, respectively.

3 METHODS

3.1 Tailings Characterization

Untreated and polymer-treated FFT were characterized for basic material properties in accordance with ASTM and accepted testing procedures. Geotechnical index tests were performed on homogenized tailings samples to determine the initial solids content, particle size distribution, and Atterberg limits. In addition, the bitumen content and specific gravity of the untreated FFT were analyzed.

3.2 Large Strain Consolidation (LSC) Test

Untreated and treated FFT were examined in a single-drainage large strain consolidation testing program to determine their consolidation characteristics under incremental loading conditions. For each type of flocculated FFT, both original (S1) and duplicate (S2) samples were analyzed. The untreated FFT sample was used as the control sample in this investigation. After treatment, fresh samples were poured into standard 200 mm high by 150 mm diameter LSC Plexiglas cells with a porous stone overlaid by a filter paper placed inside the cell. Further mixing of the original neutral PT sample in the LSC cell to record the settling time resulted in some degree of floc shearing. The samples were allowed to consolidate under self-weight, which is generally estimated to occur at approximately 0.1 kPa effective stress. Once excess pore pressures had dissipated, the samples were subjected to surcharge loads.

The LSC equipment comprised a regulated pressurized air Bellofram seated on a loading frame through which incremental loads were applied to the sample in the cell in a multi-step fashion. Measurements of the settlement were taken with a linear variable differential transformer (LVDT), while the Bellofram air pressure regulator and the pore water pressure outlet in the sample were equipped with pressure transducers. Figure 1 shows the typical LSC testing apparatus utilized for the experimental work.

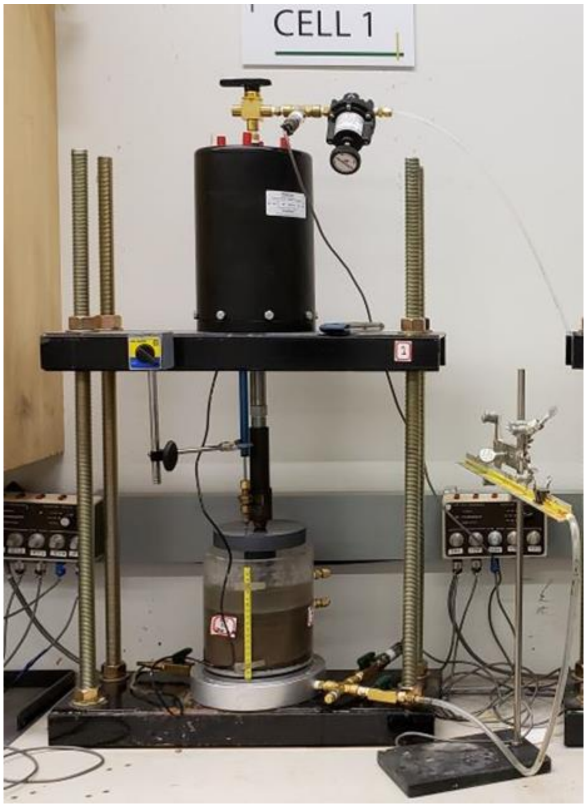

Figure 1. The Large strain consolidation testing apparatus.

Following self-weight consolidation, effective stresses ranging from 0.3 kPa to 900 kPa were incrementally applied to the samples. For effective consolidation, each newly applied load was approximately twice the previous load. Due to air fluctuation at low pressures, effective stresses less than 10 kPa were imposed on the samples using dead weights. When excess pore pressure has entirely dissipated, and vertical deformation is infinitesimal, consolidation was considered completed for a load step.

3.3 Hydraulic Conductivity Measurement

At the end of each load step, the saturated hydraulic conductivity of the sample was measured with the aid of the attached constant head permeability setup shown in Figure 1. The setup consists of a transparent glass tube connected to a bottom outlet port of the LSC cell by a transparent flexible tube. The glass tube is horizontally suspended on a graduated clamp at a height to establish a hydraulic gradient across the LSC sample. The hydraulic conductivity is calculated from the measured upward flow velocity and the hydraulic gradient across the sample.

3.4 Shear Strength Measurement

After the constant head permeability test, a laboratory vane shear test was conducted to measure the undrained shear strength of the samples at each load step. In this test, only the duplicate samples were examined to allow the effect of sample disturbance to be evaluated. Only the peak undrained shear strength was measured to minimize floc disturbance. Soft consistencies (less than 8 kPa) were analyzed with a Brookfield DV3T rheometer to obtain the peak yield stress at a shearing rate of 0.1 rpm, while a motorized laboratory vane shear apparatus was used for testing stiffer consistencies per ASTM D4648-16. Standard vane sizes and torque springs (for vane tester) were employed in the shear strength measurement. Based on the rotation angle, the measured torque is correlated to the undrained shear strength by applying the corresponding spring and vane calibration factors.

4 RESULTS AND DISCUSSION

4.1 Tailings properties

Table 2 presents the initial properties of FFT as received and after flocculation. With a solids content of 30.5% and bitumen content of 2.4%, the untreated FFT had an initial void ratio of 5.17 and a specific gravity of 2.27. The initial solids contents of the anionic, cationic and neutral polymer treated FFT after flocculation are given in Table 2. The difference in void ratio results from the volume of hydrated polymer added to FFT during treatment.

Figure 2 shows the particle size distribution of treated and untreated FFT (bitumen included) analyzed using the hydrometer test method (ASTM D4221 – 18, D422-63). The treated tailings were analyzed without adding a dispersant, while FFT was examined under dispersed and non-dispersed conditions. In both conditions, the fines content (<44 microns) of the FFT was 94% with a sand-to-fines ratio (SFR) of 0.06. The two distributions were similar, suggesting that the as-received condition of FFT was dispersed. The fines content and SFR of the cationic and anionic PTs are provided in Table 2.

Table 2. Initial properties of tailings

Material	Solids content (%)	Fines content (%)	Sand-to-fines ratio (SFR)	Void ratio
Untreated FFT	30.5	94	0.06	5.17
Neutral PT	13.7	NM	NM	14.25
Cationic PT	23.6	92	0.09	7.44
Anionic PT	28.9	72	0.39	5.63

Note: NM, not measured

Table 3. Atterberg limits

Material	Liquid limit (%)	Plastic limit (%)	Plasticity index (%)
Untreated FFT	52	30	22
Neutral PT	82	46	36
Cationic PT	76	44	31
Anionic PT	78	39	38

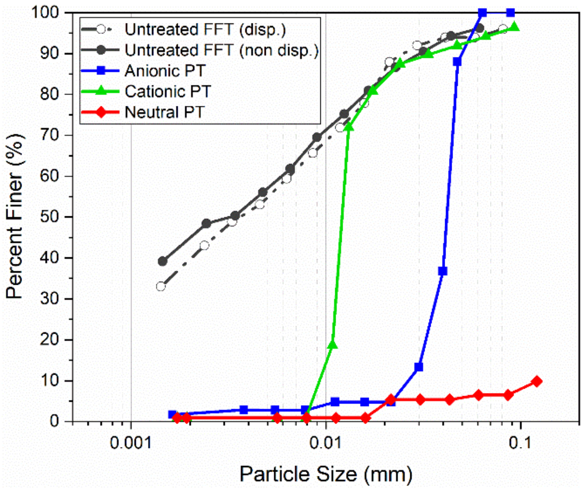

Figure 2. The particle size distribution of tailings: dispersed and non-dispersed FFT; non-dispersed polymer treated FFT.

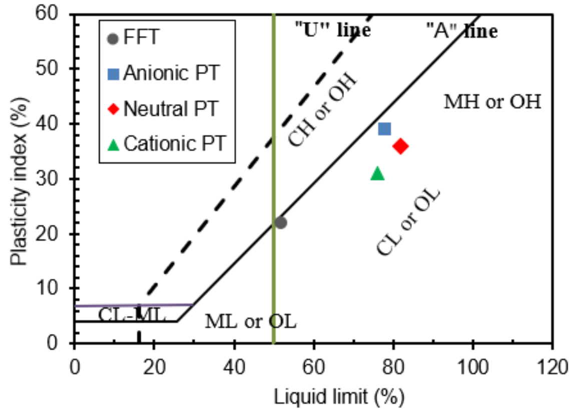

Figure 3. Plasticity chart of untreated and polymer treated FFT.

The cationic polymer appears to have aggregated particles finer than 11 microns, whereas the average floc size of the anionic PT was about 40 microns. The floc sizes of the neutral PT were much larger, and the hydrometer measured only the approximate sizes of fine suspended flocs. Appropriate digital imaging techniques are being employed to analyze the complete floc size distribution of the neutral PT.

The Atterberg limits of the tailings are provided in Table 3. The untreated FFT had a liquid limit of 52% and a plasticity index of 22%, which fall within the typical range for FFT (Beier et al. 2013). The anionic, cationic and neutral polymer treatments of FFT resulted in higher liquid limits and plasticity indices. The plasticity chart in Figure 3 shows reduced plasticity in the treated FFT. It is evident from these results that the polymer treatments significantly increased the liquid limit and plastic limit of FFT.

4.2 Compressibility

The effect of the polymer treatments on the compressibility of FFT was examined from consolidation settlements of the tailings samples. The void ratio of the tailings was calculated from the measured deformation at the end of consolidation. Figure 4 shows the void ratio-effective stress relationships that define the compressibility of the tested samples. The void ratio of the neutral PT reduced from an initial 14.25 to 4.95 (31% solids) after self-weight consolidation. This occurred within 10 hours after treatment, with no further settlement observed. The void ratios of the cationic PT and anionic PT after self-weight consolidation were 6.06 (27% solids) within 11 days and 4.17 (35% solids) after 47 days, respectively. Conversely, the untreated FFT attained a void ratio of 3.66 (38% solids) after 8 weeks. Table 4 presents the total consolidation time of the tailings samples for the range of effective stresses tested. The larger part of the self-weight consolidation was dominated by hindered settling of particles in suspension at different rates based on particle/floc sizes in each treatment. The change in the void ratio of the tailings after self-weight consolidation indicates the amount of initial water released.

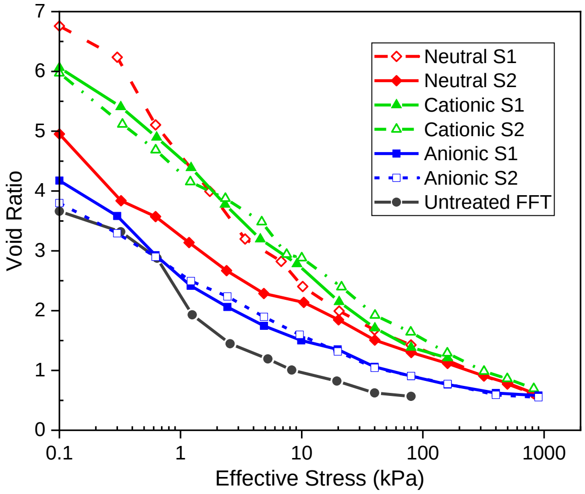

Figure 4. Void ratio-effective stress relationships for untreated and polymer amended FFT.

Table 4. LSC consolidation time

Material	Range of effective stress (kPa)	Total consolidation time (weeks)
Untreated FFT	0 – 80	51
Neutral PT	0 – 900	17
Cationic PT	0 – 900	26
Anionic PT	0 – 900	44

With incremental effective stresses from 0.3 kPa to approximately 900 kPa, a final void ratio of 1.20 (65% solids) was achieved in the cationic PT at 160kPa, after which no further compression was observed. Further compression was observed in the duplicate sample of the cationic PT until a final void ratio of 0.70 (77% solids). The reason for this difference in the final void ratio is unknown, but may be attributed to further compression due to the closure of the holes created in the sample after the vane shear tests. With or without vane shear testing, the neutral PT and anionic PT had final void ratios of 0.63 (78% solids) and 0.58 (80% solids), respectively, with measured settlements under each load. Figure 4 also shows the convergence of the compressibility curves of both optimum and overmixed neutral PT samples at an effective stress of 10 kPa. Similarly, the compressibilities of the cationic and neutral PTs converge under a vertical effective stress of 20 kPa.

4.3 Hydraulic Conductivity

Constant head permeability measurements were taken during consolidation to assess the effect of the changing void ratio on the saturated hydraulic conductivity of the untreated and treated FFT. Figure 5 shows the measured hydraulic conductivity as a function of effective stress. The hydraulic conductivity at a given stress was averaged for five to ten measurements with a coefficient of variation ranging between 0.02 and 0.23. Over the range of effective stresses analyzed, the average hydraulic conductivities decreased by about four orders of magnitude for the cationic and anionic PTs and five to six orders of magnitude for the neutral PT. The lowest hydraulic conductivity was recorded in the untreated FFT.

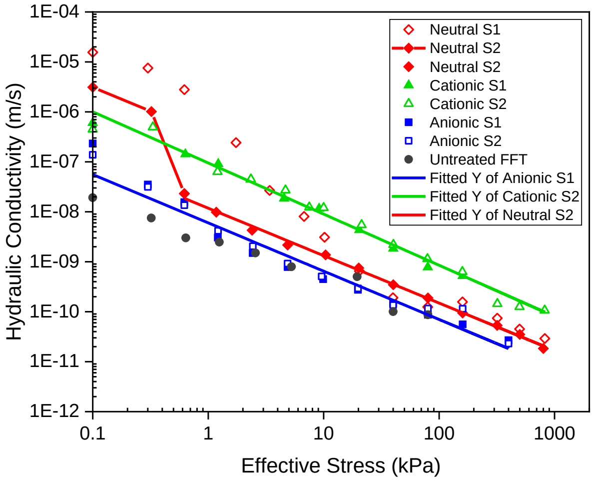

Figure 5. Hydraulic conductivity-effective stress relationships of untreated and polymer amended FFT.

The observed trend for the saturated hydraulic conductivity in the neutral PT indicates a relatively higher value at low effective stresses (less than 0.3kPa), where the pore spaces between the large flocs permit higher fluid flow through the tailings. There is a sudden reduction of about two orders of magnitude in the hydraulic conductivity when the effective stress exceeds 0.3kPa. This may suggest the collapse of the large pores due to floc compression under increased load, forcing fluid flow through the floc microstructure. Figure 5 indicates considerable differences between the hydraulic conductivities of the various treatments at any given effective stress, with the cationic PT exhibiting the highest values. It is noted, however, that the void ratio achieved in each tailings type at a given effective stress is different.

Figure 6 illustrates the hydraulic conductivities of the different tailings as a function of the void ratio. This figure shows that at void ratios greater than 3.8, the hydraulic conductivity of the neutral PT was an order of magnitude higher compared to the other treatments. The cationic and anionic PTs exhibited somewhat similar hydraulic conductivities within experimental error at void ratios higher than 2.8. Below a void ratio of 3.8, the hydraulic conductivity of the neutral PT significantly reduced, as previously described, to rates similar to that of the anionic PT. At lower void ratios, the hydraulic conductivity of the cationic PT is three times higher compared to the other treatments.

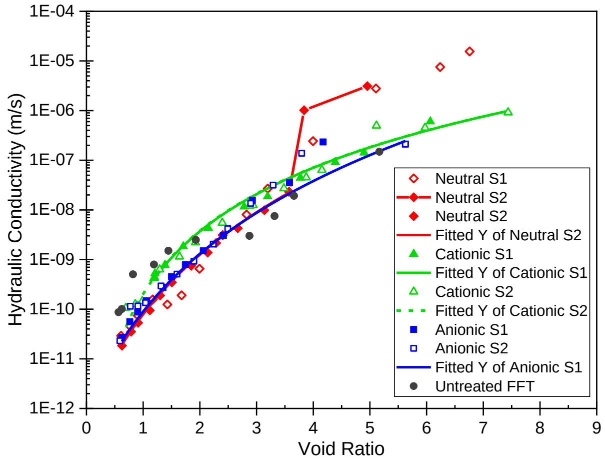

Figure 6. Hydraulic conductivity-void ratio relationships of untreated and polymer amended FFT.

4.4 Undrained Shear Strength

The peak undrained strength of the tailings was measured using a laboratory vane shear apparatus and a rheometer. Two to three strength measurements were taken for each load step. Figure 7a relates the average undrained shear strength of the tailings to the effective stress with the range of measured shear strengths indicated by the error bars. In general, the undrained shear strength of the tailings increased exponentially with effective stress. Figure 7a shows that the shear strengths of the cationic and anionic PTs are similar at any given effective stress, within experimental error. Beyond effective stress of 10 kPa, the shear strength of the neutral PT exceeds that of the other treatments by approximately 40 percent. Jeeravipoolvarn (2010) suggests that the effect of flocculation is more evident at low effective stresses, where void ratios are high. Figure 7b focuses on the short-term strength gain at effective stresses below 20 kPa. The measured shear strengths at effective stresses less than 10 kPa indicate a relatively high initial strength and rapid strength gain in the neutral PT compared to the cationic and anionic PTs. Therefore, the results in Figure 7 agree with observations made by previous researchers on the effect of flocculation on shear strength as a function of effective stress (Wilson et al. 2018, Jeeravipoolvarn 2010).

In relation to void ratio or solids content, as shown in Figures 8 and 9, distinct differences in the undrained shear strength of the tailings are observed. The results indicate that, at a given void ratio, the shear strength achieved in both the neutral and cationic PTs is about an order of magnitude higher than that of the anionic PT and two orders of magnitude higher compared to that of untreated FFT. At void ratios greater than 3.5, the shear strength of the neutral PT was distinctly higher compared to the other treatments. This may be attributed to the floc structure created by chemical bonding between the polymer and clay particles. The flocs of the neutral PT appear to be the most resistant to shear at higher void ratios. Compared to the anionic PT, the cationic PT also exhibits a higher shear strength at low effective stresses, despite its relatively fine flocs. Table 5 summarizes the consolidation properties of the tailings at specific shear strengths.

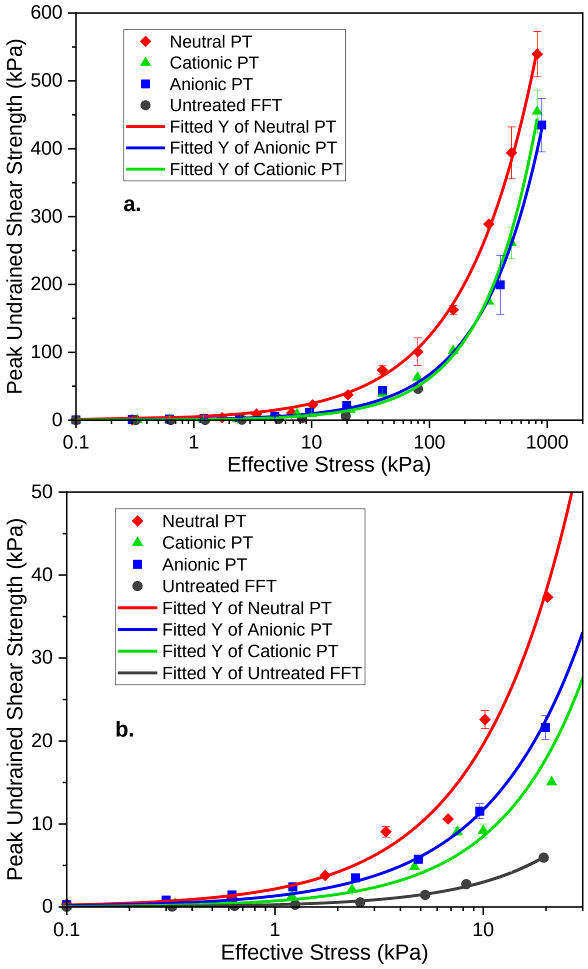

Figure 7. Peak undrained shear strength-effective stress relationships of untreated and polymer amended FFT: a) effective stresses up to 900 kPa; b) effective stresses below 20 kPa.

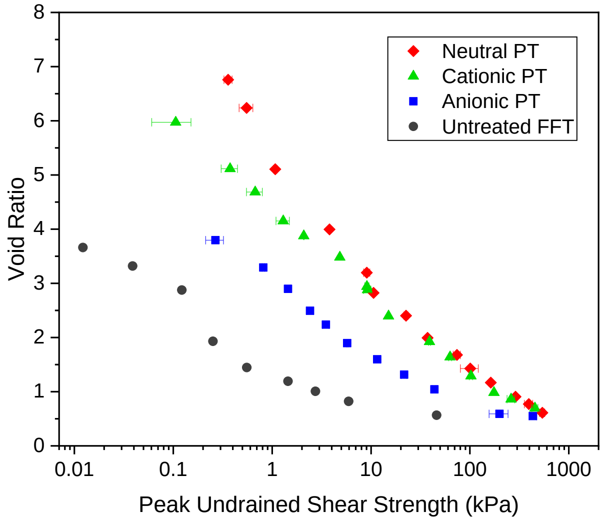

Figure 8. Void ratio-peak undrained shear strength relationships of untreated and polymer amended FFT.

Table 5. Consolidation properties of treated and untreated FFT at specific shear strengths

Treatment	5 kPa shear strength			10 kPa shear strength		
	Effective stress (kPa)	Void ratio	Hydraulic conductivity (m/s)	Effective stress (kPa)	Void ratio	Hydraulic conductivity (m/s)
Untreated FFT	19.5	0.80	$8.0\text{x}10^{-10}$	40.0	0.70	$1.0\text{x}10^{-10}$
Neutral PT	0.7	3.50	$2.0\text{x}10^{-8}$	1.9	2.80	$6.0\text{x}10^{-9}$
Neutral PT (overmixed)	2.4	3.50	$7.0\text{x}10^{-8}$	6.0	2.80	$8.0\text{x}10^{-9}$
Cationic PT	3.0	3.50	$3.0\text{x}10^{-8}$	8.0	2.80	$1.1\text{x}10^{-8}$
Anionic PT	4.0	1.80	$9.0\text{x}10^{-10}$	10.0	1.50	$4.4\text{x}10^{-10}$

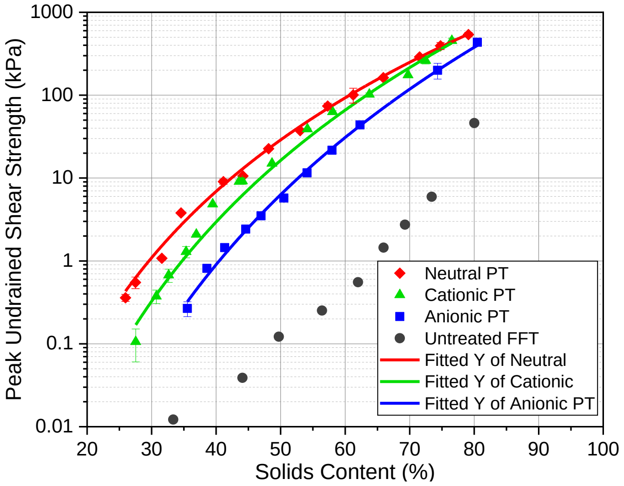

Figure 9. Peak undrained shear strength-solids content relationships of untreated and polymer amended FFT

5 SUMMARY AND CONCLUSIONS

Fluid fine tailings were flocculated using two newly developed cationic and neutral polymers and an existing anionic polymer. The polymer treatments significantly altered the material properties of FFT. The neutral PT is sensitive to shear, especially after settling.

Large strain consolidation tests conducted on the flocculated tailings showed improved compressibility and hydraulic conductivity by the new polymers with demonstrable shear strength gain at given effective stress and void ratio. The higher hydraulic conductivity and considerable strength gain of the cationic PT over the long term make it a comparatively better option for reducing reclamation timelines.

The consolidation behaviour of FFT is strongly influenced by material properties and floc structure after polymer addition. Further evaluation of the long-term dewatering performance of these new polymer treatments is being conducted in ongoing modeling research.

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