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ETD technology

Laboratory study of application performance and associated geotechnical characteristics for polymer-assisted tailings deposition of oil sands MFT

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Rheomax® ETD technology is based on the application of a family of polymer chemistries developed by BASF for the mining industry; with the objective of enhancing the de-watering and immobilization of mineral slurries during hydraulic deposition.

The laboratory study is focused on oil sands mature fine tailings (MFT), investigating the influence of polymer chemistry, dose and conditioning time on the behavioural characteristics of polymer-treated deposits. Subsequent geotechnical characterization of the polymer-treated deposits provides an alternative means by which to investigate the relative effectiveness of each polymer treatment under a number of potential process conditions. This paper reports on the findings of the investigation.
1. Introduction

The goal of polymer treatment of oil sands mature fine tailings is to improve tailings performance upon deposition in tailings storage facilities. The performance parameters of interest include early dewatering of the tailings to improve water recover and reuse in mining operations, reduction of storage volume and shear strength increase to facilitate land reclamation.

It is desirable to optimize polymer chemistry and dosage to achieve the most beneficial performance of tailings in the tailings storage facilities. Field trials provide the ultimate proof of success for any treatment technology, but are typically time-consuming and can be very expensive. Alternatively, laboratory investigation and numerical modeling techniques can be used to screen several possible polymer chemistries and identify the most promising options. These can then be verified in full-scale field trials. This paper describes such a laboratory testing program and associated modeling efforts.

Several polymer chemistries are first evaluated for optimal dosage and conditioning. The evaluation parameters include net water release and yield stress achieved for each chemistry. The consolidation characteristics of these samples are then determined in the Seepage-Induced consolidation test. The characteristics consist of void ratio – effective stress (compressibility) relationships and void ratio – hydraulic conductivity (permeability) relationships. These relationships are then used in modelling the consolidation process of tailings treated with three different polymer chemistries upon deposition. Three deposition scenarios were evaluated: a thin lift (1 m thick), thick lift (10 m thick) and a deep pour (50 m deep). Cumulative water release with time for each case is normalized with respect to the maximum water release of an untreated material in a deep pour configuration. The comparison of these results provides a rational base for the evaluation of the three polymer chemistries and disposal scenarios.
2. Slurry characterisation, polymer preparation and testing procedures

2.1 Slurry characterisation

Using a suitable mixer fitted with a marine impeller, the slurry was agitated in a baffled container until homogeneous. The slurry was sampled and characterized for pH, density, solids content (% w/w and % w/v), clay content (by methylene blue titration) and particle size distribution (laser).

Prior to particle size determination, any bitumen present in the slurry was removed. This was done by taking 400 ml of slurry, transferring into a 600 ml beaker and, with gentle mixing, approximately 100 ml of kerosene was added. This mixture was agitated for one hour, after which time the kerosene phase was decanted and the remaining slurry was suitable for analysis.

2.2 Polymer preparation

A 400 ml polymer solution of a 0.5% wt/vol concentration was prepared by weighing 2 grams of the dry polymer into a weighing boat onto a four-figure balance, while insuring that the mass of the product is ±0.001 g of the desired value.

The 2 grams of dry polymer was then transferred to a clean and dry 500 ml Nalgene bottle. 5 ml of acetone was added to "wet" the polymer. The polymer and acetone slurry was gently mixed and allowed to stand for approximately one minute before 395 ml of process water was added.

After the process water was added and the bottle resealed, the polymer was shaken vigorously for at least one minute. The bottle was then transferred onto a rotating wheel and further conditioned for at least 2 hours.

All polymer solutions were disposed of 48 hours after preparation.

2.3 Laboratory testing

Approximately 300 g (weighed to 1 decimal place) of homogeneous slurry was placed into a 600 ml beaker, covered and conditioned with a torque-dependent mixer, fitted with a flat-blade impeller, for a predetermined time and speed, which had been qualified in a previous laboratory study on the same batch of slurry-polymer samples.

While conditioning the slurry with the beaker immobilized, the polymer solution was injected into the slurry. For each sample, this was performed at the same location in the vortex created by the flat-blade impeller. After the polymer had been added, the timer for the conditioning began immediately.

The samples were conditioned to a point of optimum net water release (NWR). During conditioning, the slurry torque slowly increases for a time and then slowly starts to decrease as the optimum structure formed by the polymer addition begins to shear thin.

Once conditioning time was recorded, the beaker was removed from the stirrer and any remaining slurry left on the impeller was carefully scraped back into the beaker. The yield stress of the treated material was immediately recorded using a Haake Rheometer.

The mass of the beaker and treated material was recorded and the polymer-treated sample was transferred onto a 1 mm mesh sieve, fitted with a base. The mass of the empty beaker was also recorded.

Once the treated material had been transferred onto the sieve, the deposition investigation began. Data points were taken over a range of post-deposition times, in which the weight of the sieve and contents and water volumes in the base pan were recorded. (N.B. between readings, each test sample was covered to minimize evaporative losses). Using a Brookfield Rheometer fitted with a V-73 half vane, the yield stress of the deposit was measured and recorded at each time interval.

2.4 Seepage-induced consolidation testing protocol

Where polymer-treated slurries were prepared for SIC investigation, the protocol outlined in section 2.3 above was followed. However, in this instance, once prepared, rather than transferring the sample onto a mesh sieve, the treated slurry was transferred directly into the SIC cell. The testing procedure for the SICT on MFT is described by Znidaric et al (2011) and Esthepo et al (2013). In this test program, the procedure was somewhat modified to better capture consolidation behavior of treated samples at low effective stresses (below 1 kPa). Small step load increments were applied to the samples and the hydraulic conductivity was measured directly at each step. This modification prolonged the required testing time significantly, but provided improved data quality for the consolidation behavior of samples in the low effective stress range.
3. Test results, data interpretation and discussion

Section 3 consists of four subsections detailing test slurry characterization: polymer-treated tailings deposition, each containing data tabulation; graphical interpretation of polymer-treated application performance and discussion of relative and absolute performance.

3.1 Slurry characterisation

Table 1: MFT slurry characterisation

<table>
<thead>
<tr>
<th>Bitumen (%wt/wt)</th>
<th>Solids (%wt/wt)</th>
<th>Water (%wt/wt)</th>
<th>Clay (%wt/wt)</th>
<th>pH</th>
<th>Density</th>
<th>SFR</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>28.8</td>
<td>70.1</td>
<td>92</td>
<td>8.1</td>
<td>1.21</td>
<td>&lt;0.02</td>
</tr>
</tbody>
</table>

3.2 Water analysis

Table 2: Principle soluble cations identified in test slurry

<table>
<thead>
<tr>
<th>Sodium (mg/l)</th>
<th>Calcium (mg/l)</th>
<th>Magnesium (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>~800</td>
<td>~10</td>
<td>~20</td>
</tr>
</tbody>
</table>

3.3 Discussion of slurry characteristics

The Mature Fine Tailings (MFT) slurry used in this program of test work is typical of that found in a number of Canadian industrial operations, in that it has a sand to fines ratio (SFR) of less than 0.02, a measurable bitumen content and a total solids content of approximately 30%wt/wt. Likewise, the soluble metal ions present in the water in significant quantities are in line with those found in such industrial processes. The only variable that might be said to be high is the proportion of clay within the mineral solids, measured at 92%. However, this was deemed to be advantageous to the work program, as the high clay content would support greater differentiation between different polymer treatments.

3.4 Polymer-treated tailings deposition

Table 3: Application performance ranking for polymer-treated slurry

<table>
<thead>
<tr>
<th>Polymer</th>
<th>Dose (gpt)</th>
<th>24 hr NWR (%wt/wt)</th>
<th>24 hr Yield stress (Pa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>C</td>
<td>4</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>E</td>
<td>3</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>F*</td>
<td>1</td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>

Rank 1 – Lowest value and rank 4 – Highest value
* Polymer F = Untreated MFT slurry
3.5 Discussion – application performance polymer-treated slurry

The application performance data, in terms of the 24hr NWR vs polymer dose for three different polymer types, is illustrated in Figure 1. Treatment systems applying polymers A and C produce comparable optimum 24hr NWR performance. However, polymer C required a 35% higher polymer dose (1400 vs 1035 gpt respectively) to achieve this performance.

Relative to polymers A and C, polymer E produced an inferior optimum 24hr NWR performance, releasing only 18% of the available water from the deposited slurry, although it required a lower dose than polymer C to produce this value.

In terms of maximising 24 hr NWR while minimizing the dose of polymer applied, polymer A offered the most effective treatment overall, releasing 26% of the available water from the deposit within 24 hrs while requiring only 1035 gpt to achieve this.

When viewed in terms of the original four polymer treatment systems (see Table 3 for details) evaluated, it can be seen that in terms of 24 hr NWR, polymer E results provided the least effective treatment while polymers A and C produced the second and third highest performance.

As mentioned in section 2.3, each individual application test was conditioned for sufficient time to visually establish the maximum water release for each test. Recording these times and relating their values with polymer type and dose produces some interesting trends.

It was not overly surprising to see that extended conditioning times were required to maximize the effective performance of higher polymer doses and, with lower polymer doses, the conditioning times for the various polymers converge (see Figure 2).

What was interesting was that the three polymer samples displayed discrete response profiles. This was obvious in the case of polymer C which, for a given polymer dose, produced its optimal performance with a significantly shorter conditioning time than either polymer A or E. Such factors can be extremely important when considering scale-up operational applicability. Should polymer C be applied under the same conditioning system as polymer A, it is likely to be over sheared, resulting in loss of liberated water back into the treated slurry (Wells et al 2012).

### Table 4: Key performance data for three selected polymer treatment systems

<table>
<thead>
<tr>
<th>Polymer</th>
<th>Dose (gpt)</th>
<th>Conditioning (sec)</th>
<th>24 hr NWR (%wt/wt)</th>
<th>24 hr Yield stress (Pa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1035</td>
<td>9.5</td>
<td>26.2</td>
<td>472</td>
</tr>
<tr>
<td>C</td>
<td>1400</td>
<td>11.2</td>
<td>26.6</td>
<td>1044</td>
</tr>
<tr>
<td>E</td>
<td>1200</td>
<td>12.8</td>
<td>18.2</td>
<td>1398</td>
</tr>
</tbody>
</table>

Figure 1: Effect of polymer type and dose on NWR performance after 24 hr drainage

Figure 2: Effect of polymer type and dose-optimum conditioning time

As mentioned in section 2.3, each individual application test was conditioned for sufficient time to visually establish the maximum water release for each test. Recording these times and relating their values with polymer type and dose produces some interesting trends.
When viewing the relationship between deposit yield stress vs solids content treatment for the most effective dose and the associated conditioning time for named polymers (see Figure 3), it was apparent that different polymer treatments could result in significantly different profiles.

To produce a deposit strength of 1 kPa, polymer E was required to achieve 38%wt solids while polymers A and C required a significantly higher solids content: 52 and 46%wt solids respectively. Such differences in deposit yield stress for a given solids content can have implications on ranking the performance of polymer-treated tailings.

Polymer E was a prime example of this. When its performance was viewed in terms of polymer dose required to achieve maximum 24 hr NWR, it was the least effective of the three products evaluated. However, considering the performance in terms of the deposit strength gain for a given solids content, polymer E was significantly more effective.

It might be expected that a treatment system requiring greater polymer dosage would result in a deviation in the relationship between deposit yield stress and solids content, in that with increasing polymer dose, yield stress would increase for a given solids content. Evidently, from the three polymers considered in this work, where polymer A was applied at 1035 gpt while polymers C and E were applied at 1400 and 1200 gpt, the relationship between yield stress for a given solids content did not correlate with polymer dose.

As part of the application test protocol described in section 2.3, the torque profile of the slurry was noted from the time of polymer addition until optimum visual water release occurred. Within this period of time, the peak yield stress and the conditioning time required to achieve this value were documented for each individual polymer type and applied dose (see Figure 4).

Using the polymer doses previously identified to achieve maximum 24 hr NWR, 1035 gpt polymer A, 1400 gpt polymer C and 1200 gpt polymer E, replicate tests produced an average peak yield stress and associated conditioning time with accompanying 95% confidence intervals.

The three polymer-treated slurries produced statistically different peak yield stress values of 225, 317 and 414 Pa for 1035 gpt polymer A, 1400 gpt polymer C and 1200 gpt polymer E respectively. Again, peak yield stress did not correlate with applied polymer dose and likewise did not correlate with the 24 hr deposit yield stress.

Polymers A and E required comparable slurry conditioning times to achieve their respective peak yield stress, approximately 6 seconds while polymer C required a statistically longer time of 8 seconds. Once again, it is perhaps surprising that the time each polymer required to achieve peak slurry yield stress did not correlate with the time each required to achieve optimum visual water release.
3.6 Polymer-treated tailings consolidation test work

The measured consolidation characteristics for the polymer-treated samples A, C and E and for the untreated MFT (sample F) are presented in Figures 5 and 6. The figures show for each sample the directly measured values as well as the fitted curves used in the numerical modeling of the disposal scenarios. The model parameters for each sample are given in Table 5 along with the void ratio corresponding to zero effective stress.

Table 5: SIC test parameters and zero effective stress void ratio for slurry samples

<table>
<thead>
<tr>
<th>Polymer</th>
<th>Compressibility</th>
<th>Permeability</th>
<th>Zero effective stress</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
<td>B</td>
<td>Z</td>
</tr>
<tr>
<td>A</td>
<td>4.18</td>
<td>0.271</td>
<td>0.5</td>
</tr>
<tr>
<td>C</td>
<td>4.08</td>
<td>0.275</td>
<td>0.5</td>
</tr>
<tr>
<td>E</td>
<td>3.35</td>
<td>0.242</td>
<td>0.1</td>
</tr>
<tr>
<td>F</td>
<td>3.08</td>
<td>0.233</td>
<td>0.103</td>
</tr>
</tbody>
</table>

Parameters A, B, Z, C, and D are used in expressions 1 and 2 to characterize the compressibility and permeability relationships of the material.

1) \( e = A(\sigma' + Z)^B \)

2) \( k = C e^D \)

where \( e \) is void ratio, \( \sigma' \) is vertical effective stress and \( k \) is hydraulic conductivity.

The effects of polymer treatment were apparent from the graphs and the void ratio values at zero effective stress. First, it was noted that the addition of polymer always increased the initial void ratio of the slurry. In some cases, however, a portion of that water was released almost instantaneously in the initial process and the void ratio at zero effective stress was lower than the zero effective stress void ratio of untreated MFT. This was the case for polymers A and C, where the zero effective stress void ratios were lower than for sample F. In the case of polymer E, the void ratio at zero effective stress remained higher than for the untreated MFT. This was because the created structure was stiff enough to prevent sedimentation prior to any increase in the effective stress. This observation was consistent with the findings of laboratory tests summarized in Table 4 where polymer E had a higher yield stress and lower NWR than polymers A and C. Second, the compressibility curves demonstrate that the structure of treated samples was stiffer and produced smaller volume changes for the same stress increments than in the untreated material. The increase in stiffness was particularly visible in the low effective stress range, below 1 or 2 kPa. Third, the polymer treatment significantly increased hydraulic conductivity of the slurry at high void ratios, up to two orders of magnitude. However, as the void ratio decreased the differences in hydraulic conductivity between treated and untreated material diminished. The increases in stiffness and hydraulic conductivity would significantly shorten consolidation times while the increased stiffness alone will somewhat reduce the storage capacity of any tailings facilities.
3.7 Discussion of deposition scenarios analyses

The consolidation properties listed in Table 5 were used in the numerical 1-d consolidation model CONDES to evaluate several possible disposal scenarios for oil sands MFTs. Program CONDES (Yao et al 2001) implements a numerical solution to the nonlinear finite strain consolidation-governing equation for any combination of initial and boundary conditions, including both consolidation and desiccation effects.

Three disposal scenarios were considered for the purpose of evaluating field performance of both polymer-treated and untreated MFT. The three scenarios included:

- a thin lift of 1 m in thickness
- a thick lift 10 m thick
- and a 50 m deep pour

In order to compare the effectiveness of each scenario in all three cases, the same quantity of tailings was considered. The 50 m deep pour was assumed to have an area of 1 m², the 10 m thick lift an area of 5 m² and the 1 m thin lift and area of 50 m². Of course, any common multiplier of these areas would produce exactly the same results. To facilitate easy comparison, all results were normalized by the maximum value of the 50 m deep pour. It is also noted that for all four slurries, the same quantity of dry tailings was considered so that a proper comparison could be made. Due to the variability of the void ratios at zero effective stress, the nominal heights for the three scenarios had to be slightly changed for each slurry so that the total quantity of solids in all cases remained the same. The results are presented in terms of cumulative water release over time as a percentage of total (final) water released from the 50 m deep pour of the untreated MFT.

Figure 7 presents the comparison of cumulative water release for all three deposition scenarios, for both untreated and a polymer-treated material. In both cases, the thin lift deposition produced the fastest water release but also the lowest total amount of released water. It was also noted that the water release rate for the treated material was an order of magnitude faster where the polymer was used than for the untreated material. It would take about 50 years of consolidation time to release all the water from just one meter-thick layer of untreated material. Thicker layers would require consolidation times measured in centuries if not millennia. On the other hand, for the polymer-treated material, the consolidation time of the 1 m thick layer is within a year and about 10 years for a 10 m thick layer.
Figure 8 compares cumulative quantities of released water for three polymer-treated slurries A, C and E with the untreated MFT (F) for a 1 m thick layer. Polymer E produced the fastest water release but the total amount was limited to about 50% of the total water release available in the 50 m tall column of untreated material. Polymers A and C had comparable water release rates and their total release volumes were of the order of 40% of the available water.

It was noted that these analyses were completed by assuming no drainage at the bottom of each layer. If subsequent material is added to the thin lift, its consolidation time will be different: most likely longer, as initial water will be squeezed from the first lift causing an upward gradient through the second layer. All possible field scenarios, including desiccation, can be analysed using program CONDES, and an optimal disposal strategy can be developed when consolidation characteristics of polymer-treated MFT are correctly determined. Once promising strategies have been developed, the model predictions can be validated by instrumented field tests.

Figure 7a: Normalized cumulative water release with time for untreated slurry

Figure 7b: Normalized cumulative water release with time for slurry treated with polymer E

Figure 8: Comparison of normalized cumulative water release for A, C and E polymer-treated slurries and untreated (F) MFT
3.8 Discussion of deposition scenarios analyses vs application performance analyses

Reviewing the performance data discussed in sections 3.2.1 & 3.2.2, it is clear that the performance of polymers A and C was superior to that of polymer E and of the untreated sample F, where 24hr NWR was concerned. When comparing the rankings from 3.2.1 Table 3 with the CONDES outputs from Figure 8 (tabulated in Table 6), the respective polymer rankings did not align. Polymers E, then C then A showed the best performance in terms of water release under the field conditions discussed in section 3.4.2.

Table 6: 24 hr NWR application rankings vs CONDES output rankings

<table>
<thead>
<tr>
<th>Polymer</th>
<th>24 hr NWR (%wt/wt)</th>
<th>CONDES</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>C</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>E</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>F</td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>

It should be noted that where 24 hr NWR was measured, ranking of performance was based on test data in contrast to CONDES, in which rankings were derived from test data, then worked through a finite strain numerical model. It was the authors’ view that this method of assessment, although limited in some ways as described in this study, did provide an insight into polymer/soil relationships that otherwise would not be achievable if looking at consolidation data in isolation.

With the above in mind, the first obvious difference in this comparison was the timescale used. Whereas in section 3.2.1 polymer performance was measured at 24 hrs with almost no effective stress, in section 3.4.2, timescales of years were used with incremental increases in effective stress. In the shorter timescales, it was clear that polymer A provided the highest net water release, followed by C, E and then, as one would expect, F. However, when longer timescales are applied, the polymer rankings are changed and polymer E ranks highest, followed by C, A and then again F.
Polymers application testing and consolidation testing was undertaken on different polymer-treated MFTs. Field conditions were then applied to the test data using a numerical model to assess the suitability of each method. Polymer performance from both application testing and CONDES values were ranked and compared in order of water release. Based on this study, it was clear that the optimized thin lift application conditions for named polymers cannot be applied to other methods of polymer-treated tailings deposition.

Even within a given application test method, it should not be assumed that all polymers will display their optimum application performance under the same test conditions. Although not an exhaustive investigation, the application test work performed for this evaluation has shown that although they are all effective, each product has its own discrete set of application conditions to achieve optimum performance (24 hr NWR).

Should the primary performance indicator change (to say 24 hr deposit yield stress) then (1) product ranking will change and (2) it cannot be assumed that the previously identified application conditions will result in optimal performance for the new targeted response. Furthermore, testing criteria, modeling inputs and conditioning regimes should all be aligned with site drivers for the application in which the chemistry was designed to be used.

4. Conclusions
References


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