Assessment of Water Removal from Oil Sands Tailings by Evaporation and Under-drainage, and the Impact on Tailings Consolidation

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Abstract

Canada is reported to have one of the largest oil reserves in the world, with 97% of these reserves being related to oil sands. One key issue that challenges the oil sand companies is the large amount of tailings generated during the process of oil separation from mined sands, and the requirement of large surface areas for tailings storage. The problem is aggravated by the fact that oil sand tailings typically take a long time to consolidate, with limited reduction in volume and gain of strength over time. It appears to be a consensus that maximizing water removal from the tailings is critical to solve this problem.

This paper presents the results of laboratory drying column tests developed to evaluate the role of evaporation and under-drainage in the removal of water from oil sand tailings. The tests suggested that evaporation plays a major role in the process of water removal, while under-drainage is marginally beneficial. As a consequence, evaporation appears to be responsible for significant volume changes in the long term.

Introduction

One of the largest oil reserves in the world is located in the Province of Alberta in Canada, with the vast majority of these reserves being related to oil sands. A common problem faced with fine tailings from the oil sand industry is that the process of tailings consolidation takes a long time to complete. The consequence is that there is need for the storage of large volumes of tailings at low solids contents with inherent financial and environmental implications.

Scott et al. (2004) described the monitoring of a 10-metre high standpipe filled with fine oil sands tailings that had been observed for over 20 years. The tailings material settled about 30% over the monitoring period, but little variation was observed in the solids content profile except for the lower 2 metres of the standpipe. The authors concluded that the tailings was, in fact, creeping and not consolidating.

The problem appears to be related to several factors including: chemicals added during the extraction process such as dispersing agents, residual bitumen, and the impact of tailings gradation and mineralogy. Combined, these processes affect several geotechnical and hydraulic properties of the tailings (e.g. hydraulic conductivity, specific gravity, Atterberg limits, coefficient of compressibility and undrained shear strength), which cause a delay to the tailings consolidation process (Jeeravipoolvarn 2010. Miller G. et al, 2010a, and 2010b, Scott et al 2004).
Maximizing water removal from oil sands tailings is required to accelerate tailings consolidation and gain in shear strength. Therefore, it is very important to understand the role of evaporation and under-drainage in the process of water removal so a deposition strategy can be defined. Numerical models have typically been used to assess water removal from tailings (e.g. Simms et al., 2010, Junqueira et al., 2009, Simons et al. 2007), but there are model limitations associated with large volume changes and lack of laboratory information about under-drainage and evaporation with which the models can be calibrated.

The study described in this paper was developed to measure water loss from oil sands tailings associated with evaporation and under-drainage using laboratory drying column tests. In addition, the tests also provided the means to evaluate the impact of water loss on the process of tailings consolidation and gain in shear strength for different lift thicknesses.

Besides generating direct results and indicating trends of tailings dewatering, the results of this type of test can be further used to calibrate numerical models aimed to predict water loss under different field scenarios.

**Materials and Methods**

Columns tests were performed to assess the role of under-drainage and evaporation in the dewatering process of thickened oil sands tailings deposited with different thicknesses. The material tested consisted of fine-grained thickened tailings generated at the Total E&P Canada (Total) 2010 Tailings Thickening Pilot. The tailings were composed of about 26% sand, 57% silt, and 17% clay sized particles. The silt and sand fractions were mostly quartz, while the clay fraction consisted primarily of Kaolinite and Illite. The material used in this study had residual bitumen content of less than 5%.

Three different test types were conducted for a period of about 10 weeks: a) Evaporation columns (E), b) Drainage columns (D) and, c) Evaporation plus Drainage columns (E+D). The evaporation columns allowed water removal from the tailings associated with evaporation only. The drainage columns had tailings placed on top of a saturated sand drainage layer, and the top of the columns were covered to prevent evaporation. The evaporation plus drainage columns, measured water removal from the tailings associated with both evaporation and under-drainage.

The columns were constructed using clear acrylic pipes, had a diameter of 15.24 cm, and total heights varying between 20 cm and 120 cm. Thickened tailings material with an initial solids content of 55% was placed into the columns at initial lift thicknesses of 20 cm, 40 cm, and 100 cm. The drainage layer, when present, was 20 cm thick and was maintained fully saturated for the duration of the tests.

Water removal from the columns associated with evaporation was measured in terms of change in mass by weighting the columns three times a week. For the drainage and drainage plus evaporation columns, under-drainage was collected through a drainage outlet, and outflow volumes were periodically monitored by measuring the mass of water flowing out of the columns. The mass of under-drainage water was deducted from the total column mass so weight loss associated with evaporation could be accurately tracked.

Volume changes were monitored during the tests in terms of settlements by periodically measuring the heights of the tailings lifts in each column.

For the drainage plus evaporation columns (D+E), a set of tensiometers was installed in the upper section of the columns to monitor the evolution of suction during the tests. The tensiometers were inserted horizontally into the columns at depths of 5 cm, 10 cm and 15 cm from the tailings surface. The tensiometer’s ceramic tip was 0.5 cm in diameter and 2 cm in length.
In the end of the tests, the tailings were progressively removed from the columns, with measurements of suction, vane shear strength and moisture contents taken at different depths within the tailings profile.

Table 1 summarizes the configuration of the drying column tests, and Figure 1 shows the 40-cm drainage plus evaporation column in the beginning of the test. All the other columns had similar configurations as shown in Figure 1, with the difference that tensiometers were not installed in the drainage-only and evaporation-only columns, and the evaporation-only columns did not have a drainage layer at the bottom of the column.

**Table 1: Summary of column tests**

<table>
<thead>
<tr>
<th>Column</th>
<th>Lift thickness (cm)</th>
<th>Test duration (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Evaporation</td>
<td>20 and 40</td>
<td>76</td>
</tr>
<tr>
<td>Drainage</td>
<td>20 and 40</td>
<td>76</td>
</tr>
<tr>
<td>Drainage plus Evaporation</td>
<td>20, 40 and 100</td>
<td>65 to 72</td>
</tr>
</tbody>
</table>

**Figure 1: 40-cm drainage plus evaporation column test. Drainage layer and outflow collection system at the bottom, with tailings and tensiometer on top.**

**Tests Results**

**Drainage Columns and Evaporation Columns**

The primary objective of the drainage columns and the evaporation columns was to provide a means to assess which process would be more important to remove water from the tailings. The 20-cm and 40-cm high columns had the same geometry, were filled with the same material, and had the same test duration. Figure 2 shows the evolution of water loss from the drainage columns and the evaporation columns in terms of total mass.
As seen in Figure 2, total water loss from the evaporation columns (E20 and E40) was much higher than water removed from the drainage columns (D20 and D40). Water loss through evaporation occurred at a relatively constant rate, while the rate of under-drainage progressively reduced with time. The major role of evaporation in removing water from the tailings, compared to under-drainage, is reflected in the average daily water loss as shown in Figure 3.

For the 40-cm high evaporation column (E40), the rate of evaporation remained between 20 g and 25 g per day during the entire test period. For the 20-cm high evaporation column (E20), the rate of daily evaporation was between 25 g and 30 g for over 50 days, with further reduction to values between 20 g and 25 g of water a day to the end of the test.

Figure 2: Evolution of water loss through evaporation (E) and under-drainage (D) for the 20-cm and 40-cm columns.

Figure 3: Average daily water loss through evaporation (E) and under-drainage (D) for the 20-cm and 40-cm columns.
For the drainage columns (D20 and D40), the rate of daily water loss decreased progressively, from over 30 g of water a day in the beginning of the tests to about 5 g a day after about 75 days of tests. As seen in Figure 3, under-drainage rates from the 40-cm high drainage column (D40) were greater than the 20-cm high column (D20) for about 50 days but, from day 50 to the end of the tests, the rate of water loss via under-drainage was similar for both columns, with average daily water loss value of 5 g a day. This suggests that increasing the thickness of the tailings lift would not necessarily generate much higher water loss via under-drainage in the long term.

Reduction in the drainage rates of all columns was likely related to reduction in the hydraulic conductivity at the lower portion of the tailings. For thicker lifts, the density of the lower portion of the tailings will tend to become higher as water drains out. As a consequence, the tailings hydraulic conductivity at that portion will decrease, thereby reducing the rate of under-drainage.

In addition to tailings densification, another factor that might have affected water removal via under-drainage was downward migration of bitumen. For all columns, a darker layer of bitumen was observed moving down progressively. At the end of the tests, bitumen was observed in the interface between the tailings and the drainage layer, which could have reduced the permeability of the interface zone and affected under-drainage rates.

In terms of settlements, tailings in the evaporation columns experienced higher settlements compared to tailings subjected to under-drainage only as seen in Figure 4. The evolution of settlements in the columns followed the patterns observed for water loss. As the tailings were initially fully saturated, volume changes were directly related to the volume of water removed from the tailings. For the evaporation columns, additional volume change occurred associated with development of negative pore-water pressures (suction) in the upper portion of the tailings that caused the material to shrink.

![Figure 4: Evolution of settlements for the 20-cm and 40-cm drainage-only and evaporation-only columns.](image)

**Drainage plus Evaporation Columns**

The main purpose of the drainage plus evaporation drying column tests was to assess the impact of lift thickness in the process of water loss associated with evaporation and under-drainage at the same time.
The evolution of water loss with time through evaporation and under-drainage is shown in Figure 5. Similarly to what was observed for the evaporation-only and drainage-only columns, the evaporation plus drainage columns indicated that, for all lift thicknesses, evaporation was more effective than under-drainage to remove water from the tailings. Likewise, evaporation removed water at a near constant rate, while the rate of under-drainage reduced progressively with time.

As discussed before, reduction in the drainage rates of all columns was related to reduction in the hydraulic conductivity at the lower portion of the tailings, and possibly to downward migration of bitumen that could have affected the hydraulic conductivity of the drainage layer.

Figure 6 shows total water loss through evaporation and under-drainage for the 20 cm, 40 cm and 100 cm thick lifts, as well as estimated amounts of water in the tailings in the beginning of the tests. The results indicate that evaporation was the dominant process of water removal from all columns. The tests also showed that the ratio of total water loss to the initial amount of water in the tailings becomes lower as the lift thickness increases.

The increase in water loss from thicker lifts was always less than the associated increase in initial water amounts in the tailings. The increase in lift thickness initially generated higher water loss via under-drainage, but it had little impact in water loss through evaporation, which was identified as the most important component in the process of water removal observed during the tests.

Figure 7 shows the evolution of settlements measured for the evaporation plus drainage columns. The 100-cm thick lift showed total settlement about 1.6 times greater than the 20-cm lift, even though the lift thickness was initially five times greater. Likewise, the 40-cm lift initially had twice the thickness of the 20-cm lift, but total settlement was only 1.3 times greater.

The tests indicated that increases in volume change and water loss were not proportional to the increase in lift thickness, suggesting that deposition of tailings in thinner lifts would have better performance in terms of volume change in the long term compared to thicker lifts.
Figure 6: Total water loss through evaporation and under-drainage for the Evaporation plus Drainage columns.

Suction in the tailings was measured for all drainage plus evaporation columns at depths of 5 cm, 10 cm and 15 cm below the tailings surface. The results showed that suction developed mostly for the upper 10 cm of the tailings. Suction values varied between 40 kPa and 70 kPa near the surface of the tailings, but values decreased to less than 10 kPa about 15 cm below the tailings surface. No suction was measured below that level.
The development of suction might be important because some gain in shear strength can occur associated with suction, but the column tests suggested that only a limited portion of the tailings would benefit from additional shear strength associated with suction.

The profiles of solids content and undrained vane shear strength measured from the different drainage-plus-evaporation columns in the end of the tests are shown in Figure 8. For all columns, the solids content in the upper portion of the tailings was higher than measured at the lower portion above the drainage layer.

The 20-cm thick lift showed the profile of highest solids content among all lift thicknesses. The measured undrained shear strength varied from about 20 kPa on top of the tailings to 5 kPa at the bottom.

The 100-cm thick lift showed increase in solids content mostly for the upper and lower 10 cm of tailings. In fact, about 70% of the tailings stored in the 100-cm column (from depths of 20 cm to 80 cm), remained with solids content close to the as-placed value of 55%. Undrained shear strength was above 5 kPa only for the upper 10 cm of tailings, and little shear strength (about 2.1 kPa) was gained at the bottom of the tailings.

For the 40-cm thick lift, the very middle portion of the tailings showed the lowest value of solids content of about 61%. Solids content increased in the upper and lower portions associated with water removal by evaporation and under-drainage.

![Figure 8: Final solids content and undrained vane shear strength profiles measured from the evaporation plus drainage columns.](image)

The final solids content and shear strength profiles measured from the different columns suggest that thinner lifts would experience quicker increase in solids content, and gain strength throughout the lift with time. As the lift becomes thicker, only the upper portion would be subjected to meaningful increase in solids content, although some increase in solids content would occur at the bottom of the lift associated with under-drainage. The test indicated that, the thicker the lift, the larger the extent of tailings that would remain with low solids content and no significant shear strength for a long time.
Solids Content and Undrained Shear Strength

The Energy Resource Conservation Board of the Province of Alberta (ERCB) approved the Directive 074 in 2009, which establishes that oil sands tailings must present minimum undrained shear strength of 5 kPa within a year after tailings deposition. It is therefore important for the oil sand industry to identify the minimal amount of solids content required for each type of oil sands tailings to reach this target value.

Figure 9 shows measurements of undrained vane shear strength taken in the end of the drying columns tests. The measurements suggest that, for the tailings type tested in this study, the minimum value of solids content required for this tailings to gain 5 kPa undrained shear strength would be approximately 77%, or about 30% gravimetric moisture content. The average initial solids content of the tailings was 55%.

![Figure 9: Evolution of undrained shear strength with increase of solids content measured in the end of the drying column tests.](image)

Table 2 summarizes the average daily water loss measured from the evaporation plus drainage columns, and provides an estimate of time that would be required for the tailings to reach at least 77% solids content under the laboratory conditions.

The average temperature in the laboratory during the tests was about 18°C, and the average potential evaporation rate was about 1.6 mm/day. Under this condition, it would take about 54 days for a 20-cm thick lift of tailings to increase solids content from initial 55% to the target 77%. In fact, after 71 days of test, the 20-cm thick lift stored in the evaporation plus drainage column was the only layer that had solids contents above 77%, and undrained shear strength higher than 5 kPa.

For the 40-cm and 100-cm thick lifts however, the initial amount of water in the tailings was much higher. As a consequence, it would take about 107 and 193 days, respectively, for the solids content to reach the target value of 77%, considering the average rates of water loss measured in the laboratory. Neither the 40-cm lift nor the 100-cm lift had reached this target value of solids content in the end of the tests after about 71 days.
Table 2: Estimated time for solids contents to rise from 55% to 77% under the laboratory conditions.

<table>
<thead>
<tr>
<th>Lift Thickness (cm)</th>
<th>Initial Amount of Water (g)</th>
<th>Average water loss via under-drainage (g/day)</th>
<th>Average water loss through evaporation (g/day)</th>
<th>Total average water loss (g/day)</th>
<th>Required water loss for 77% solids</th>
<th>Estimated time for 77% solids</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>2334</td>
<td>7.3</td>
<td>20</td>
<td>27.3</td>
<td>1482</td>
<td>54</td>
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<tr>
<td>40</td>
<td>4954</td>
<td>9.9</td>
<td>19.4</td>
<td>29.3</td>
<td>3145</td>
<td>107</td>
</tr>
<tr>
<td>100</td>
<td>12676</td>
<td>15.4</td>
<td>26.3</td>
<td>41.7</td>
<td>8048</td>
<td>193</td>
</tr>
</tbody>
</table>

Conclusions
Drying column tests were conducted under controlled laboratory conditions to evaluate the role of evaporation and under-drainage in the process of water removal from oil sands tailings, and to assess the impact of water loss in the process of tailings consolidation and gain in shear strength. The study also evaluated the impact of lift thickness.

The trends observed during the column tests suggest that evaporation plays a major role in the process of water removal from the tailings investigated in this study. During the tests, water removal from the tailings through evaporation occurred at a nearly constant rate, while the rate of under-drainage progressively reduced with time.

Densification of the bottom portion of the tailings in all columns, and migration of residual bitumen into the drainage layer are factors that might have affected the rates of under drainage with time. These processes would be expected to occur in real tailings deposition areas.

The column tests showed that thinner lifts (i.e. 20-cm and 40-cm thick lifts) had better performance in terms of overall water loss, settlements, and gain in shear strength with time. The 100-cm thick lift had the worst performance among all columns.

In the end of the tests, the 20-cm thick lift had final solids content above 78%, and shear strengths higher than 5 kPa within the entire lift. The 40-cm and 100-cm thick lifts showed higher solids content mostly for the top and bottom portions of the layers, with the middle portion remaining with solids content close to the initial values. For the 100-cm thick lift, the majority of the tailings remained with low solids contents and had no shear significant strength in the end of the test.

The drying column tests performed in this study under laboratory condition, and using one type of thickened oil sands tailings, suggest that thinner lifts would have better performance in terms of tailings consolidation and gain in shear strength compared to thick lifts.

References


Scott, D. J. and Chalaturnyk, R. J., 2004. Fine tailings decrease in volume by creep compression. 57th Canadian Geotechnical Conference, Quebec City.
