Evaluation of thermal properties of oil sand fluid fine tailings

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ABSTRACT
Syncrude Canada Ltd. has developed the first end pit lake in the oil sands region at their Mildred Lake Mine site. The end pit lake, referred to as Base Mine Lake, was constructed within a mined-out pit, and incorporates 186 Mm^3 of fluid fine tailings (FFT) below an 8 m water cap. Fluid fine tailings are deposited at elevated temperatures, and act as a heat source to the overlying lake. The thermal properties of the FFT must be defined to evaluate the long-term thermal regime within the tailings and lake. Samples were collected from Base Mine Lake at various depths. Select samples were chosen to represent a range of oil contents, and pore water salinity. Water was added or removed from each sample to create multiple tailings sub-samples of varying water content. Thermal conductivity and volumetric heat capacity of each sub-sample was measured with a KD2 Pro Probe, and this dataset was analyzed to determine the influence of water content, oil content, and salinity on the thermal properties of FFT. Thermal conductivity and volumetric heat capacity values were similar to those estimated using theoretical relationships for the thermal properties and water content, when volumetric oil content was taken into consideration.

RÉSUMÉ
Le premier lac de kettle dans la région des sables bitumineux de l'Athabasca a été développé par Syncrude Canada Ltd. dans le site minier de Mildred Lake, à 40 km au nord de Fort McMurray. Ce lac de kettle, appelé lac Base Mine, a été créé dans une mine épuisée. Il incorpore 186 Mm3 de résidus fins fluides en dessous d'une couche d'eau de huit mètres. Les résidus sont déposés à des températures élevées et constituent une source de chaleur pour le lac qui les recouvre. Afin d'évaluer l'évolution à long terme du régime thermique dans les résidus fins fluides, il faut définir les propriétés thermiques de ces résidus. Des échantillons de résidus fins fluides ont été recueillis dans le lac Base Mine à différentes profondeurs et à différents endroits. Des échantillons représentatifs ont été choisis pour montrer l'éventail des teneurs en hydrocarbures et de la salinité de l'eau interstitielle. De l'eau a été ajoutée ou retirée de chacun de ces échantillons pour créer de multiples sous-échantillons de résidus à teneur en eau variable. La capacité de conductivité thermique et de chaleur volumique de chacun des sous-échantillons a été mesurée avec une sonde KD2 Pro et cet ensemble de données a été analysé pour déterminer l'influence de la teneur en eau, de la teneur en hydrocarbures et de la salinité sur les propriétés thermiques des résidus fins fluides. Les valeurs de capacité, de conductivité thermique et de chaleur volumique étaient similaires à celles qui avaient été estimées en utilisant les rapports théoriques pour les propriétés thermiques et la teneur en eau, quand la teneur volumique en hydrocarbures entrait en ligne de compte.

1 INTRODUCTION

Oil sands mining activities have disturbed more than 700 km^2 of boreal forest in northern Alberta (Audet et al., 2015). Additionally, the process used to extract bitumen from the mined oil sands ore produces large volumes of by-product materials (Gosselin et al., 2010). One of these by-products is a dense fluid with dispersed, suspended solids (Siddique et al., 2007), referred to as fluid fine tailings (FFT). Oil sands operators are establishing a range of strategies to return affected areas to a natural state, while incorporating by-products like FFT into the reclaimed landscape. One of these strategies is the creation of end pit lakes: lakes formed within depleted mine pits. There are currently thirty end pit lakes proposed for the Athabasca oil sands region, half of which will incorporate FFT below the lake water (Prakash et al., 2011). The first end pit lake (Base Mine Lake) was developed by Syncrude Canada Ltd. (Syncrude) with 186 Mm^3 of FFT stored below the lake water. The feasibility of isolating FFT from the overlying water and establishing a sustainable biological community in the lake have yet to be fully evaluated.

The thermal regime within the end pit lake water is central to establishing a sustainable lake ecosystem. Fluid fine tailings are relatively warm compared to natural groundwater temperatures in the region. Therefore, the FFT will act as a heat source to the overlying lake, and may affect the thermal regime within the water. In order to evaluate the movement of heat from the FFT to the lake, the thermal properties of the FFT must be defined.

A sampling program was completed in July 2014 at Base Mine Lake to retrieve FFT samples at various depths. Laboratory testing of these samples was performed to assess the physical composition of the FFT, as well as its particle size distribution, electrolytic conductivity, and thermal properties. Theoretical relationships for thermal conductivity and volumetric heat capacity were developed for the FFT. These relationships were compared to laboratory results to assess the effects of oil content and salinity on the thermal properties of FFT.

1.1 Site Description

Base Mine Lake is located in one of the original mine pits at Syncrude's Mildred Lake Mine site, 40 km north of Fort

M[c]Murray. Base Mine Lake was filled with FFT from 1994 to 2012, with approximately 186 M m^3 of tailings in the pit when filling ceased. Base Mine Lake was commissioned as an end pit lake in November 2012. At this time, the average lake water depth was 8 m. Fresh water is pumped into the lake to maintain a water surface elevation of 308.5 metres above sea level (masl). Base Mine Lake covers an approximate area of 8 km^2 and is the large body of water in Figure 1.

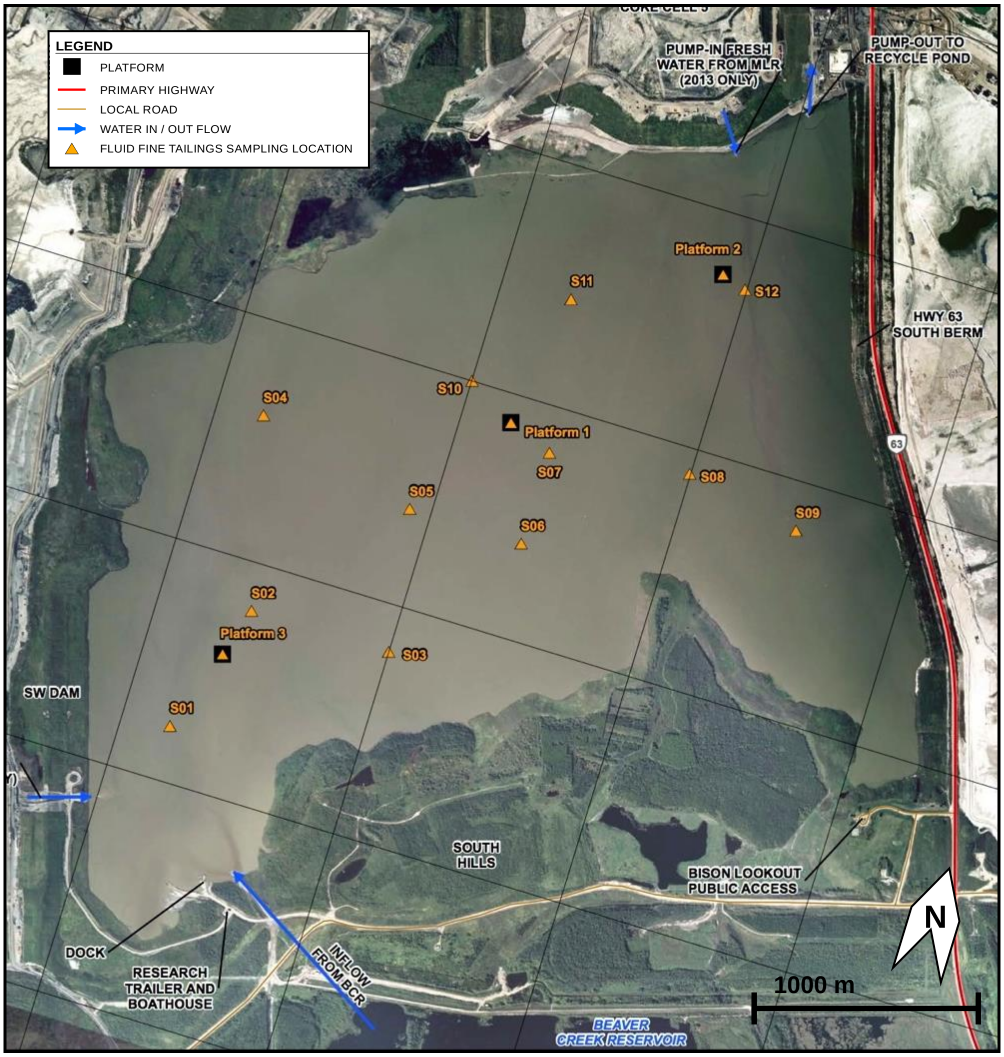

Figure 1. The Base Mine Lake site and selected monitoring locations

1.2 General Properties of Fluid Fine Tailings

Fluid fine tailings are a dense fluid with dispersed solid particles that contribute 30% to 35% to its initial weight (corresponding to a void ratio between 4 and 6). Fluid fine tailings exhibit slow settlement rates due to the addition of dispersants during bitumen extraction, and naturally occurring surfactants present in the ore that are released during heating (Jeeravipoolvarn, 2009; Chalaturnyk et al., 2002). Fluid fine tailings undergo most dewatering during the first few years after discharge (Siddique et al., 2011); however, high water contents persist, taking many years to significantly dewater and eventually consolidate (Kasperski and Mikula, 2011). In addition to these high water contents and disperse clay particles, the FFT has residual bitumen, is relatively warm (between 11°C and 19°C), and the associated pore water has elevated concentrations of total dissolved solids (TDS).

A yearly FFT monitoring program has been conducted at Base Mine Lake since the end pit lake was commissioned. Solids content measured through the FFT increased gradually with depth, as illustrated in Figure 2. Two of the locations show substantially greater solids contents near the bottom of the mine pit, potentially indicating the presence of under-drainage in these locations (S08, S09). The variability in measured solids content between locations is likely due to the different deposition times of FFT in each location as those closer to the FFT discharge point have had greater time for dewatering to occur and would exhibit higher solids contents with depth.

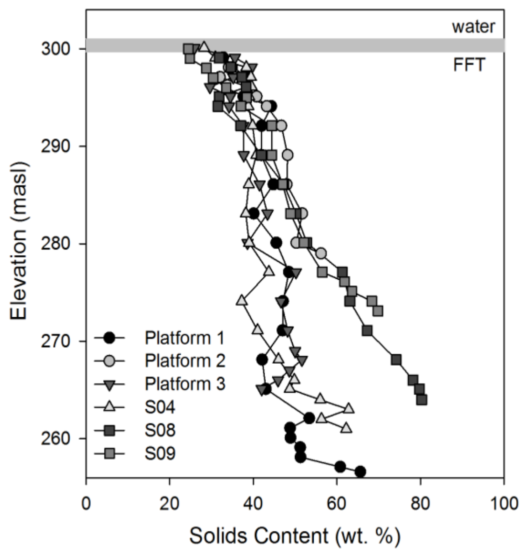

Figure 2. 2014 FFT solids content with depth at several monitoring stations

1.3 Thermal Properties Relationships

The thermal conductivity and volumetric heat capacity of a soil depend on its water content and solids density (Cosenza et al., 2003; De Vries, 1963); however, salt concentration and organic matter may also influence the thermal properties (Abu-Hamdeh and Reeder, 2000). Therefore, the residual bitumen and salts present in FFT must be considered when evaluating its thermal properties.

General relationships for the thermal properties of soils were altered to incorporate an oil term. The theoretical relationship for thermal conductivity, established by Cosenza et al. (2003), was adjusted to:

$$\lambda = \lambda_s^{[\%s]} \cdot \lambda_w^{[\%w]} \cdot \lambda_o^{[\%o]} \quad [1]$$

where λ is the thermal conductivity of FFT (W/m/K), λ_s is the thermal conductivity of the FFT solids (W/m/K), λ_w is the thermal conductivity of the pore water (W/m/K), and λ_o is the thermal conductivity of oil (W/m/K). The thermal conductivity of each component is raised to the power of the percent that component contributes to the total sample volume, where $[\%s]$ is the volumetric solids content, $[\%w]$ is the volumetric water content, and $[\%o]$ is the volumetric oil content. In order to include the affects of salinity in the above equation, the thermal conductivity of the FFT pore water can be adjusted to represent water with elevated TDS.

The theoretical relationship for volumetric heat capacity was established by De Vries (1963) as the sum of the volumetric heat capacities of the individual components of a soil. Similar to the theoretical relationship for thermal conductivity, the volumetric heat capacity relationship was altered to include a term for the volumetric heat capacity of oil, such that:

$$C = c_s \cdot \rho_s \cdot [\%s] + c_w \cdot \rho_w \cdot [\%w] + c_o \cdot \rho_o \cdot [\%o] \quad [2]$$

where C is the volumetric heat capacity of FFT (kJ/m^3/K), c_s is specific heat capacity of the FFT solids (kJ/kg/K), c_w is specific heat capacity of the pore water (kJ/kg/K), and c_o is the specific heat capacity of oil (kJ/kg/K). The density of the FFT solids is represented by ρ_s (kg/m^3), ρ_w is the density of the pore water (kg/m^3), and ρ_o is the density of oil (kg/m^3). As with the theoretical relationship for thermal conductivity, the effects of salinity can be incorporated into [2] by altering the specific heat capacity and density of the FFT pore water to represent water with elevated TDS.

2 METHODOLOGY

ConeTec Investigations Ltd. obtained FFT samples at 3 locations (Platform 1, Platform 3 and S08) using a pneumatic piston sampling system during the 2014 FFT monitoring program. A sample chamber with a pneumatic piston was positioned at the desired depth, the cable-actuated ball-valve on the chamber was opened, and the pneumatic piston was slowly retracted to allow FFT to enter the chamber. The ball valve was closed when the chamber was full, the sample system was brought up to the surface, and the collected sample was transferred to a high-density polyethylene bottle. The electrolytic conductivity of each sample was measured with a YSI Pro30 conductivity probe immediately after the sample was collected. This process was repeated at multiple depths at each location. Every sample was divided into two parts so that samples could be sent to both Syncrude and the University of Saskatchewan for analysis.

2.1 Initial Laboratory Testing at the Syncrude Research Facility

Syncrude conducted laboratory testing to determine the physical characteristics of the FFT samples at their research facility in Edmonton. The Dean and Stark extraction method was used to assess the oil, water and solids content of each sample (Dean and Stark, 1920). Dry solids obtained from this process were analyzed with a Coulter LS 13 320 laser diffraction particle analyzer to determine the particle size distribution of each sample (after ASTM, 2015; ASTM, 2014).

2.2 Thermal Properties Analysis

The physical characteristics of the FFT samples (determine by Syncrude) were utilized to select samples for thermal properties analysis at the University of Saskatchewan. Seven FFT samples were chosen to represent a range of oil contents, with oil values varying from 1.9% to 9.5% by volume. These samples were chosen so that the other characteristics (electrolytic conductivity, water content and particle size distribution) were fairly similar. Three additional samples were chosen to represent a range of salinities, with conductivity values from 850 to 1700 μS/cm. The selected samples and their properties are listed in Table 1.

Table 1. Summary of FFT samples for thermal analysis.

Variable	Sample Location	Oil Content (% volume)	Conductivity µS/cm
Oil	Platform 1 - 10.5 m	1.9	1020
	S08 - 10.5 m	3.0	850
	Platform 1 - 40.5 m	3.7	900
	Platform 3 - 34.5 m	4.6	860
	Platform 1 - 9.5 m	5.1	950
	Platform 1 - 12.5 m	6.4	990
	Platform 3 - 28.5 m	9.5	860
Salinity	S08 - 10.5 m	3.0	850
	Platform 3 - 16.5 m	2.5	1310
	Platform 3 - 19.5 m	2.9	1700

The volumetric water content of the samples listed in Table 1 ranged from 71.1% to 81.3%. The particle size distributions for these samples are provided in Figure 3. The electrolytic conductivities of the selected FFT samples appear to be slightly elevated; however, they are within the typical conductivity range of freshwater streams (Rundle et al., 1998).

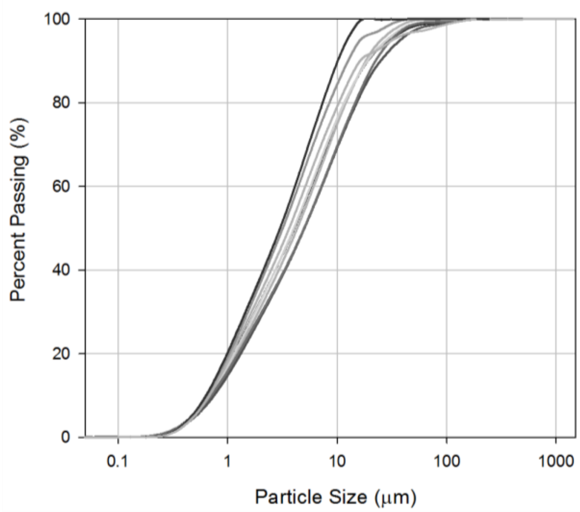

Figure 3: Particle size distribution of the selected FFT samples

Each sample was divided into four sub-samples for thermal properties analysis. Water was added to or removed from each sub-sample to create a range of water contents. This was done to evaluate the effects of volumetric water content, in addition to volumetric oil content and salinity, on the thermal conductivity and volumetric heat capacity of FFT.

The thermal conductivity and volumetric heat capacity of the sub-samples were measured with the KD2 Pro thermal properties probe (Decagon Devices Inc.). Electrolytic conductivity of each sub-sample was measured with a ThermoScientific Orion Star conductivity meter. Once laboratory analysis was complete at the University of Saskatchewan, sub-samples were sent to Syncrude to determine the oil, water and solids contents using the Dean and Stark extraction method, as previously discussed.

3 RESULTS

Laboratory results for the physical characteristics of FFT sub-samples showed that the addition or removal of water from each sub-sample caused a shift in the volumetric oil content and electrolytic conductivity. The volumetric oil content and conductivity of all sub-samples were plotted over volumetric water content in Figure 4. As the volumetric water content increased, both oil content and conductivity of the FFT sub-samples decreased. Sub-samples created from the same original FFT sample did not represent a uniform oil content or salinity, as altering one variable (e.g. water content) affected the other properties.

Sub-samples with a volumetric water content less than 80% had substantially higher electrolytic conductivities than those originally determined by Syncrude (listed in Table 1). This increase in conductivity indicated greater TDS in the FFT pore water, and may correspond to an increase in pore water density. However, Millero et al. (1973) determined that a conductivity value of 4000 µS/cm produced a water density only 0.2% greater than that of distilled water.

Higher concentrations of TDS may also affect the thermal conductivity and specific heat capacity of the pore water. Millero et al. (1973) calculated a 0.3% decrease in the specific heat capacity of freshwater at 20°C when its conductivity was increased to 4000 µS/cm. In addition, Caldwell (1974) found that there was a limited difference in the thermal conductivities of freshwater and seawater at 20°C. Therefore, the observed increase in electrolytic conductivity was expected to have a negligible impact on pore water density, specific heat capacity and thermal conductivity of the FFT samples.

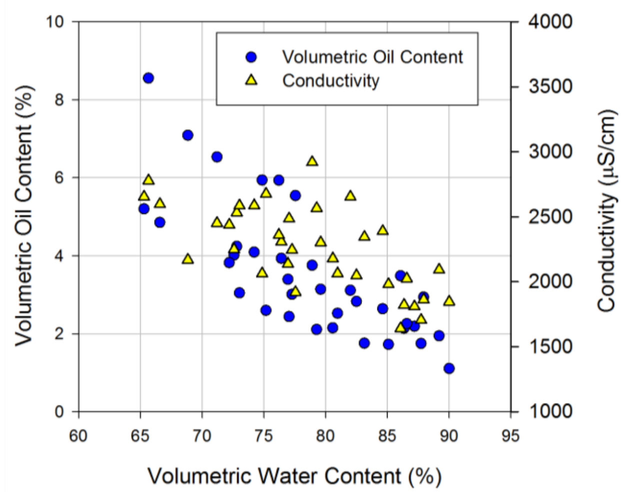

Figure 4: Change in volumetric oil content and conductivity with volumetric water content

3.1 Influence of Oil and Water Content

The thermal conductivities of the oil content samples (each with 4 sub-samples) are displayed in Figure 5. The thermal conductivity of each sub-sample was plotted with a symbol size representative of its associated volumetric oil content. Trend lines for the theoretical relationship between thermal conductivity and volumetric water content are also included in Figure 5. These trends were calculated for various volumetric oil contents using equation [1] and the parameter values listed in Table 2.

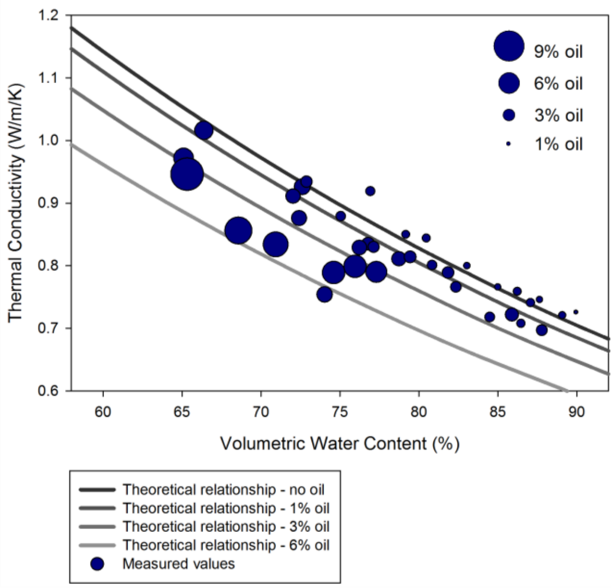

Figure 5: Measured thermal conductivities compared to theoretical trends for multiple volumetric oil contents

The theoretical curves illustrate the negative relationship between oil content and thermal conductivity. The measured volumetric oil contents generally followed the theoretical trends, as sub-samples with lower oil contents fall along the theoretical trend line calculated for no oil, and sub-samples with greater oil contents are between the theoretical trend lines for 6% and 9% oil by volume. There are a few sub-samples that appear out of place; for example, the sample with the greatest volumetric oil content, approximately 9%, appears to have a thermal conductivity that is too high for the associated water content.

Theoretical thermal conductivity values of each sub-sample were estimated using equation [1] and the physical composition of the sample (oil, water and solids contents). Measured thermal conductivities were plotted over the theoretically derived values in Figure 6. The data points follow the 1-1 line, confirming that the theoretical equation provided a reasonable fit for the measured values. However, most of the measured thermal conductivities are greater than the theoretically derived values, suggesting that equation [1] may cause a slight underestimation in the thermal conductivity of FFT.

Table 2. Assumed parameter values for theoretically derived thermal conductivity and volumetric heat capacity.

Parameter	Assumed Value	Reference
λ_s	3 W/m/K	Li et al., 2015
λ_w	0.6 W/m/K	Incropera and DeWitt, 2002; Caldwall, 1974
λ_o	0.15 W/m/K	Cerventes-Espinosa et al., 2012; Wu et al., 2005; Elam et al., 1989; Bogatov et al., 1976
c_s	0.7 kJ/kg/K	Liu and Si, 2011
c_w	4.182 kJ/kg/K	Incropera and DeWitt, 2002; Millero et al., 1973
c_o	1.8 kJ/kg/K	Cerventes-Espinosa et al., 2012; Plantier et al., 2008
ρ_s	2650 kg/m^3	Li et al., 2015
ρ_w	1000 kg/m^3	Millero et al., 1973
ρ_o	950 kg/m^3	Liu et al., 2005

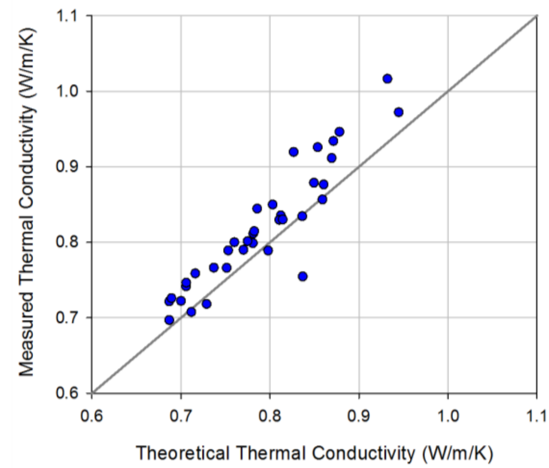

Figure 6: Comparison of measured and theoretical thermal conductivity values

Volumetric heat capacities of the oil sub-samples are plotted in Figure 7. Theoretical trends for volumetric heat capacity were calculated for several volumetric oil contents using the parameter values provided in Table 2 and equation [2]. Theoretical relationships for the oil contents illustrated in Figure 7 appear to be similar because: (1) when the oil content increases, the solids content must decrease for a given volumetric water content; and (2) the volumetric heat capacity of the FFT solids (1.86 MJ/m^3/K) is similar to the volumetric heat capacity of oil (1.62 MJ/m^3/K). Thus, when the solids are exchanged for an equal volume of oil, the total volumetric heat capacity only experiences a slight downward shift, as evident in Figure 7.

The measured volumetric heat capacities were plotted against theoretically derived values in Figure 8. The results illustrated in Figure 8 indicate a reasonable correlation between theoretical and measured volumetric heat capacities, as the data points fall along the 1-1 line. However, the measured values showed greater deviation from the theoretical ones as volumetric water content decreased in both Figures 7 and 8.

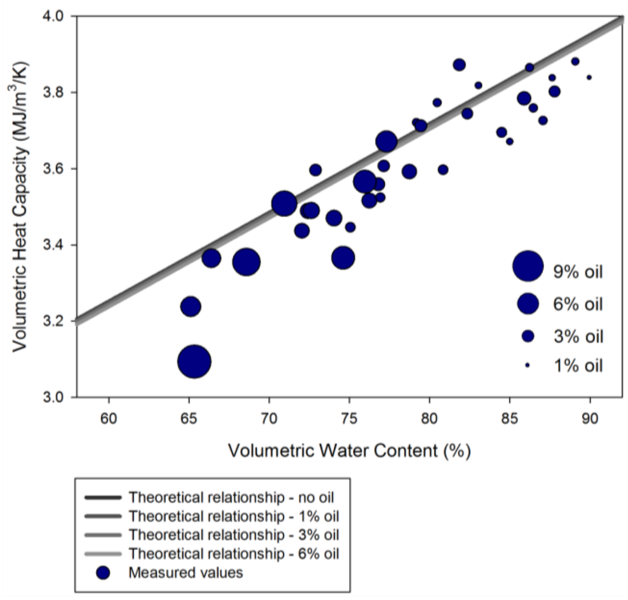

Figure 7: Measured volumetric heat capacities compared to theoretical trends for multiple volumetric oil contents

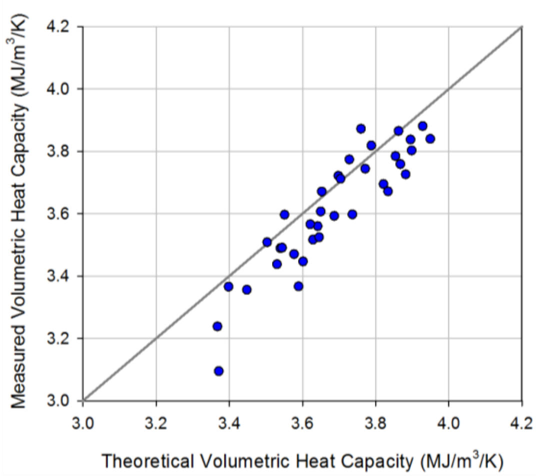

Figure 8: Comparison of measured and theoretical volumetric heat capacities

3.2 Influence of Salinity

The thermal conductivities of the three salinity samples (each with 4 sub-samples) are provided in Figure 9, and the volumetric heat capacities are plotted in Figure 10. Each value was plotted with a symbol size representing the measured electrolytic conductivity of that sample. The theoretical relationships for FFT with volumetric oil contents of 0% and 3% are also illustrated in Figures 9 and 10. This was the expected range in volumetric oil content of the selected salinity samples.

The measured thermal conductivities and volumetric heat capacities fall along the theoretical trend lines, with the exception of one point on the thermal conductivity plot (Figure 9). This data point had a measured volumetric oil content of 4.1%, while the other salinity samples exhibited oil contents between 1.7% and 3.1%. Therefore, the observed discrepancy in the thermal conductivity of this data point was due to the influence of oil present in the sample. There were no observed outliers in the volumetric heat capacity results, as oil content was determined to have less of an effect on volumetric heat capacity in the previous section. The electrolytic conductivities of the sub-samples exhibited a relatively small variation, so it was difficult to distinguish any trends in the plotted results that would provide insight on the influence of salinity on the thermal properties of FFT.

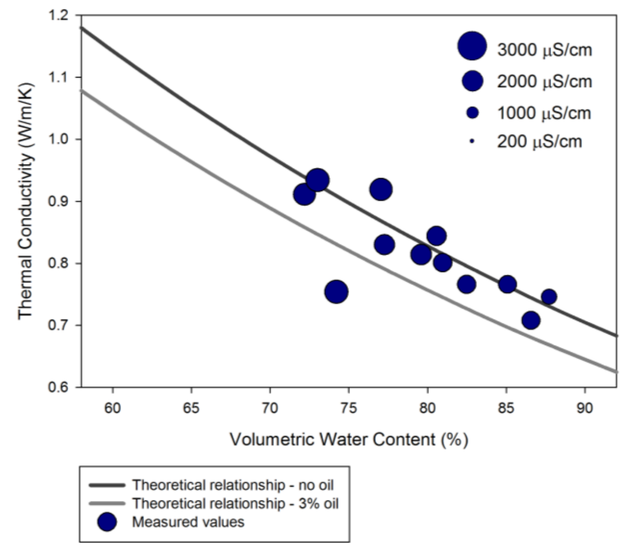

Figure 9: Measured thermal conductivities for FFT samples selected to assess salinity effects

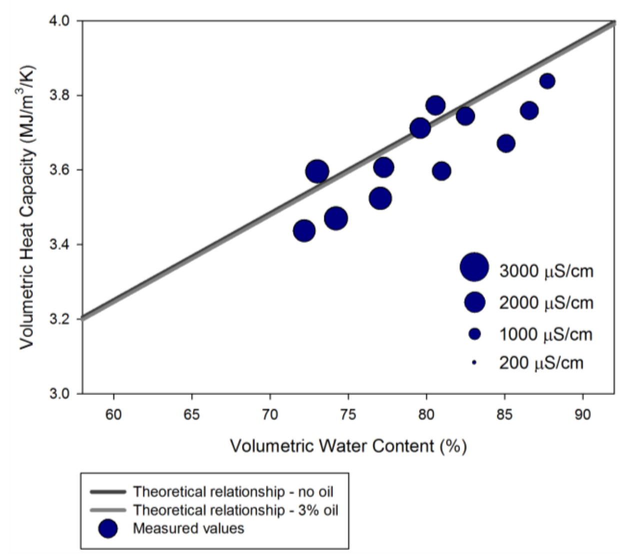

Figure 10: Volumetric heat capacities of FFT samples selected to assess salinity effects

4 DISCUSSION

Laboratory testing provided insight on the relationship between oil content and the thermal conductivity of FFT, as greater volumetric oil contents generally produced lower thermal conductivities. On the other hand, no substantial shift was observed in the volumetric heat capacity of FFT when oil content varied. The laboratory results also confirmed the importance of water content on both thermal conductivity and volumetric heat capacity of a soil. The approximate shifts in thermal conductivity and volumetric heat capacity of FFT, over the observed range in oil and water contents, are provided in Table 3. Water content was found to have a relatively greater impact on both thermal conductivity and volumetric heat capacity of FFT. However, volumetric oil content was also an important factor for the thermal conductivity of FFT.

Table 3. Relative importance of water content and oil content on the thermal properties of FFT.

Variable	**Measured Range** (% by volume)	**Effect on Thermal Properties** (% change)
Water Content	65.3% – 90.0%	λ: - 35% C: + 15%
Oil Content	1.1% – 8.6%	λ: - 20% C: < - 1 %

Salinity effects on the thermal conductivity of the FFT were difficult to assess because the conductivity values did not vary significantly between the selected salinity samples. However, salinity was expected to have a minimal effect on the thermal properties of FFT given the observed electrolytic conductivity range, and previous testing completed by Caldwell (1974), and Millero et al. (1973).

The theoretical relationship established for the thermal conductivity of FFT provided a good fit for values measured in the laboratory. However, the theoretical relationship slightly underestimated the thermal conductivity values, as illustrated in Figure 8. This underestimation indicates the presence of systematic error in the theoretical approximation of thermal conductivity. This error could be due to the use of incorrect values for the thermal conductivity of the FFT solids and/or oil. The assumed values were selected based on the thermal conductivities of similar materials (with the referenced studies listed in Table 2). Future testing should be completed to determine the thermal conductivity of the individual component of FFT (solids and oil).

The theoretical relationship for volumetric heat capacity also provided a good fit for the measured data. Contrary to the thermal conductivity results, the theoretical relationship for volumetric heat capacity may cause a slight overestimation, as the measured values generally fall below the theoretical curve. An evaluation of the specific heat capacity of the individual components of FFT should be evaluated, and laboratory tests should be conducted to verify the specific gravity of the FFT solids. Finally, the FFT solids should be analyzed to determine the mineralogical composition of FFT and its variation in Base Mine Lake, as this may also influence to the thermal properties of FFT.

ACKNOWLEDGEMENTS

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