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Prediction of Water Content and Normalized Evaporation from Oil Sands Soft Tailings Surface Using Hyperspectral Observations

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Abstract

The paper addresses the challenge of measuring water content and evaporative fluxes from oil sands soft tailings surfaces using hyperspectral observations. Hyperspectral time-series laboratory observations were collected from four different Mature Fine Tailings (MFT) samples displaying variations in swelling potential and bitumen concentration. The samples were allowed to evaporate from an initial state of water saturation to an air-dried state. From these data, several spectral features were evaluated to predict water content and normalized evaporation rate from the optically sensed portion of the tailings surface ($< a \text{ few } 100\mu\text{m}$). For the samples tested, the best estimate of moisture content was achieved using the Normalized Soil Moisture Index (NSMI) index ($R^2 = 0.97$). The absolute reflectance at 1920 nm was found to be the best spectral estimator of normalized evaporation ($R^2 = 0.97$) with the NSMI index also being of value ($R^2 = 0.95$). In both instances, the NSMI index may be of value for estimations attempted in the field. In the case of tailings management, the remote estimation of moisture content and evaporation could help to assess the drying process, to determine when the deposit has stopped drying at the surface as part of a decision when the next lift should be deposited. In future efforts, the models obtained from this laboratory investigation will be assessed for their applicability in field settings and validated using concurrent sampling.

Keywords: Oil sands, Tailings, Mature Fine Tailings, Hyperspectral data, Moisture content, Evaporation.

Introduction

The oil sands of northern Alberta comprise the third largest proven reserves of petroleum in the world (Alberta Energy 2014). Oil sands are a natural unconsolidated mixture of sand, clays and other minerals, water, and bitumen, a viscous petroleum high in residuals and asphaltenes. Bitumen must be separated from the solids and water so that it can subsequently be upgraded and refined into petroleum products, primarily transportation fuels. Depending on the depth of the oil sand deposits, bitumen extraction is done either by in-situ or surface mining methods. Bitumen does not flow naturally through a deposit, due to its high viscosity at ambient temperatures. In-situ production entails extracting bitumen from underground deposits by injecting steam and solvents to reduce viscosity and allow flow within an artificially created reservoir. Surface mining is done for deposits with overburden of less than approximately 75 meters (National Energy Board 2004). In surface mining, the ore is conditioned with reagents in warm water and agitated to separate bitumen from the oil sand matrix and to aerate bitumen droplets. Aerated bitumen then floats to the top of a separation vessel. The bitumen-rich froth is then diluted with a solvent and put through additional separation steps to reduce the amount of water and fine solids in the bitumen. Non-aqueous bitumen extraction processes are in development; but they have not been commercially implemented. The water-based separation process requires about two barrels of water for each barrel of bitumen produced, resulting in large volumes of tailings, comprising mostly water with sand, silt, clay, and residual bitumen. When the tailings are discharged into the tailings pond, the coarse sand particles settle to the bottom quickly, forming a beach and trapping some fine solids in interstices. The remaining fine solids settle slowly. This mixture naturally densifies to about 30 wt% fines/fines-plus-water within a few years in a settling basin, forming Mature Fine Tailings (MFT) (MacKinnon 1989). Released water clarifies fairly quickly and is recycled in the extraction process. The MFT remains saturated for

decades because of its very slow natural consolidation rate (Kasperski 1992; MacKinnon 1989), and so it has essentially no bearing strength (FTFC 1995).

One of the long-term goals in tailings management is to remove the water from solids so that a trafficable load-bearing surface can be produced (with an undrained shear strength significantly greater than 10 kPa) for terrestrial reclamation (BGC Engineering Inc. 2010). Water removal from saturated tailings is the process of densifying and consolidating tailings. The separation of water from MFT is thus an operational and environmental challenge of tailings management.

In the past few decades, several engineering techniques have been proposed and tested to accelerate water removal and increase the performance of the consolidation process of MFT. The composite tailings or consolidated tailings (CT) process combines gypsum as a coagulant with MFT mixed with tailings sand, which acts as a charge to accelerate densification (FTFC 1995; Boratyniec 1998). Thickened tailings processes (TT) use flocculants to form agglomerates in MFT that will settle more quickly and in appropriate conditions to form dense (dewatered) deposits that develop sufficient shear strength to be covered with reclamation material (Scott et al. 2008). New processes use beaching of flocculated tailings in thin lifts to promote faster desiccation, or the process employs centrifugation of flocculated tailings to produce a dense paste deposit with sufficient bearing strength to support a load (Mikula et al. 2009).

Flocculating and drying of MFT has been tested by several oil sands operating companies (COSIA/OSTC 2012). The method typically employs the deposition of layers of in-line flocculated MFT into drying cells where the lifts are allowed to de-water to a solids content with negative pore pressure that - under the right conditions - yields a consolidated soil that meets the specified shear strength requirements. The duration of the drying time required depends on: i) the rate of evaporation associated with the climatic conditions for

each day throughout the spring, summer and fall seasons, ii) precipitation, iii) the degree of drying and associated values of total suction at the surface of the MFT for each lift, iv) the thickness of the lift, and v) the soil property functions of the MFT (i.e. Soil-water characteristic curve and hydraulic conductivity functions). Optimization of the drying operation with respect to the key cycling parameters of lift thickness and drying time requires real-time quantification of the actual rate of evaporation at the surface of the tailings, which in turn depends on atmospheric forcing conditions as well as the water content and associated total suction at the surface of the MFT as the material progresses through each evaporation cycle.

The present work investigates the potential of using remote sensing methods to develop techniques for the estimation of water content and evaporative fluxes from the optically sensed portion of the tailings surface (<a few 100 μ m). Hyperspectral time-series laboratory observations are collected from MFT samples that are allowed to evaporate from an initial state of water saturation to an air-dried state. From these data several spectral features are evaluated to predict water content and normalized evaporation rate. The ability to quickly measure the water content and evaporation flux of tailings surfaces from a standoff distance could allow for estimation of drying progress of treated tailings without physical sampling campaigns (which are laborious and expensive) (Lipsett et al. 2014). Simple surveying of the surface of a treated area may provide insights into the effectiveness of tailings processes that allow decisions on scheduling the deposition of new lifts, and when placement of reclamation material can be done.

Background

Potential evaporation (PE) can be defined as the maximum rate of evaporation from a pure water surface under a given climatic condition. The term was first introduced by

Thornthwaite (1948) who developed a method to calculate PE based on mean monthly temperature. The rate of evaporation from a water surface can be simply computed using the well-known Dalton's equation (Gray 1970):

$$(1) \quad E = f(u)(e_s - e_a)$$

where E is the rate of evaporation (mm/day), $f(u)$ is transmission function which depends on the mixing characteristics of the air above the evaporating surface, e_s is the saturation vapour pressure of water at the surface temperature (kPa), and e_a is the air vapour pressure in the atmosphere above the water surface (kPa). According to Dalton's equation, evaporation can be described by Fick's Law as a function of the difference between the vapour pressure of the evaporating surface and that of the air above it. The application of Dalton's equation to calculate the evaporation in field settings can be challenging mainly because of difficulties in: i) determining the temperature of the evaporating surface and thus the saturation vapour pressure (Gray 1970), and ii) evaluating the transmission function, which needs to be established empirically (Gray 1970) or on the basis of rigorous aerodynamic profiles and eddy diffusion similarity theory (Wilson et al. 1997). Although Dalton's equation often remains indeterminate, it is the basis of the widely used Penman method (Penman 1948) in which the energy balance and the net radiation available to the evaporating water surface are used to resolve the difficulty associated in determining the surface temperature. Penman also presented a method based on measurement of the mean wind speed to determine the transmission function. The Penman method, however, assumes that water is always freely available to the surface and thus is applicable for the estimation of evaporation from a saturated soil surface. Accordingly, the actual evaporation (AE) from a soil surface is approximately equal to the potential evaporation from a free water surface as long as the soil

is fully saturated (Penman 1948). However, as the surface begins to dry and becomes unsaturated, the Penman model becomes inaccurate in the estimation of actual evaporation due to soil suction forces.

Traditional models developed for the calculation of potential evaporation provide an overestimation of evaporation when applied to unsaturated soil surfaces, because the basic assumption in these models is that water is freely available to the surface (Morton 1985; Granger 1989a). Numerous efforts have been implemented to evaluate the actual evaporation (AE) from unsaturated soil surfaces. It has been shown that AE begins to decrease when the availability of water becomes limited and the soil is no longer saturated (Gray 1970; Morton 1975; Brutsaert 1982). Fig. 1(a) shows the typical relationship between normalized evaporation (AE/PE) defined as the ratio of actual evaporation to the potential evaporation and water availability for sand and clay soil surfaces, after Holmes (1961) and Gray (1970). AE/PE equals unity for both sand and clay soils when the soil surface is saturated or the water content is high. The normalized evaporation starts to decline when water availability decreases. The behaviour of curves in Fig. 1(a) is not constant for different soils; and it depends on the water availability, soil texture, and drying rate (Wilson et al. 1997). Empirical models have been developed to estimate the evaporation from unsaturated soil surfaces (Hillel 1980; Yanful et al. 1993), because of the difficulty in determining the soil characteristics that control the evaporation from unsaturated soils.

Efforts have also been made to develop models on the basis of the soil variables that control evaporation from unsaturated soil surfaces (Barton 1979; Hammel et al. 1981; Granger 1989b; Wilson et al. 1994). Wilson et al. (1997) found that the decline in actual evaporation from unsaturated soil surfaces happens when the total suction exceeds the value of approximately 3000 kPa. As the total suction increases the evaporation decreases to reach zero. The relationship between total suction and AE/PE was found to be consistent for all the

soil types and independent of water content, texture, and mineralogy, as illustrated in Fig. 1(b). According to Wilson et al. (1997), if the soil, water, and air temperature are approximately the same, then AE/PE can be computed as:

$$(2) \quad \frac{AE}{PE} = \left[\frac{\exp \left[\frac{\psi g W_v}{RT} \right] - h_a}{1 - h_a} \right]$$

where ψ is total suction expressed as equivalent matric suction (head) and has a negative value (m), g is acceleration due to gravity (m/s^2), W_v is the molecular weight of water (0.018 kg/mol), R is the universal gas constant (8.314 J/(mol.K)), T is the soil temperature (K), and h_a is the relative humidity of the air. Although Eq. (2) provides a good mean to estimate AE/PE, measuring total suction and temperature of the soil surface is still required.

In general, to provide good estimates of evaporative fluxes, both climatic parameters and soil properties must be measured, which is a difficult task in field applications. Therefore, the objective of this paper is to evaluate the potentials of remote hyperspectral technology in estimation of normalized evaporation and moisture content in which there is no need to measure soil and climatic properties. The spectral models are developed by performing evaporation tests and collecting spectral time series in the laboratory. A range of tailings samples are examined to assess the robustness of spectral estimators against the tailings composition.

Materials and Methods

Sample suite

A suite of 4 MFT samples was provided by a major oil sands operator in northern Alberta. The samples were characterized for Methylene Blue Index (MBI), bitumen content, solid content, and particle size distribution (PSD) (Table 1). MBI is an indicator of the swelling potential of the tailings and depends on the type and relative abundance of clay minerals and their total content in the sample. According to Da Silva et al. (2014), a typical MFT is predominantly comprised of approximately 40 wt% quartz, 30 wt% kaolinite, 10 wt% illite and contains traces of siderite, albite, microcline, greigite, pyrite, dolomite, calcite, tenorite, halite, rutile, and anatase. In addition, pore water of MFT contains nearly 12 (mg/L) Ca^{2+} and has a pH of approximately 8, both of which play a significant role in the dispersion and flocculation of MFT (Da Silva et al. 2014). The samples were exposed to the evaporation tests to assess the sensitivity of the spectral measurements to the sample composition. Each sample was stirred to create a homogenous mixture before conducting the experiments in April 2014, as the samples had segregated after long-term storage in their polyethylene storage containers. Air-dried condition of the samples examined is shown in Fig. 2(a).

Experimental approach

The experimental approach was selected to derive a prediction of MFT moisture content and AE/PE from the optically sensed portion of the tailings surface (<a few 100 μm) using hyperspectral observations. The evaporation tests were conducted using the experimental setup developed by Wilson et al. (1997). Spectral time-series data were collected for MFT samples at variable moisture conditions to determine the spectral metrics of greatest sensitivity and to derive predictive models. Each evaporation test was performed using two identical circular evaporation pans (polystyrene petri dish), with 150 mm diameter,

to measure AE and PE concurrently. One pan contained a thin layer of MFT to measure the actual evaporation rate (AE) and the second contained water to measure the potential evaporation rate (PE). Each container was put on a scale to continually monitor the mass change of the MFT sample and water, to determine the moisture content and actual and potential rates of evaporation.

Two identical 50 W quartz halogen lamps were used to illuminate each of the containers and thus to create an identical heat source over each container. Two thermocouples were embedded in the perimeter of each petri dish to monitor the temperature of tailings and water. Air temperature and relative humidity were also measured using a digital relative humidity and temperature sensor.

The evaporation experiments were started when tailing samples were initially saturated and continued until the samples were completely air dried. The mass and temperature of MFT and water, the temperature and relative humidity of air, and the spectra of MFT were simultaneously measured every 4 minutes, as drying took place. Each experimental trial took 2-2.5 hours. Fig. 2(b) shows the experimental setup used to conduct the evaporation tests.

The MFT samples were made as thin as possible due to two reasons: 1) to minimize the effect of water content below the evaporating surface as the total suction at the soil surface controls the evaporation characteristics of AE/PE, and 2) to minimize decoupling between spectral measurements and tailings bulk properties, as the reflectance is a surface phenomenon collected from a few hundred microns in depth. Extensive effort was exerted to create a thin layer of tailings with a uniform thickness. Approximately 20 g of tailings was poured onto the petri dish and then a plastic spoon was used to gently spread the materials over the entire pan and create a thin sample of uniform thickness. Thickness uniformity was

assessed qualitatively by visual inspection. The tailings were not viscous and some spreading occurred naturally.

Tailings samples with known varying degree of swelling potential (determined with MBI) and residual bitumen were tested to assess the robustness of spectral estimators against the tailings composition. Spectral features, such as absolute reflectance and absorption depth, were derived from the collected spectral time series. Linear regression analysis was used to link the spectral features to the moisture content and the normalized evaporation. Coefficients of determination (R^2) were calculated to assess the accuracy of the spectral models. A summary of the evaporation tests is provided in Table 2.

Collection of optical measurements

Reflectance spectra of MFT surfaces were obtained using an ASD Fieldspec 3 Max spectrometer with a spectral range of 350-2500 nm, and a nominal spectral resolution of 1 nm. In this paper, however, focus was on the Short Wave Infra-Red (SWIR) region that extends from 1000 to 2500 nm.

Illumination of the sample was provided by a 50W lamp positioned at an incidence angle of approximately 20° . The radiance spectrum from the sample was collected with the ASD pointing at a normal viewing angle to the sample surface and sensing a sample footprint almost equal to the petri dish diameter (150 mm). A spectrum was acquired at each time interval of 4 minutes and was the result of averaging 25 measurements, a process that took less than 3 seconds. To obtain a reflectance spectrum, the sample radiance spectrum was normalized to that of a standard white reference panel measured at the beginning of the experiment. Example reflectance spectra of the wet and dry MFT1 sample are shown in Fig. 2(c).

Spectral metrics evaluated

The reflectance spectra collected from the tailings samples during evaporation are affected by variations of the samples water content over time. Using the time series data (AE/PE, moisture content and reflectance spectra) different spectral metrics were compared in terms of their ability to estimate the water content and normalized evaporation of MFTs. The spectral features examined comprised absolute reflectance values, absorption depths, and the normalized soil moisture index (NSMI) (Haubrock et al. 2008). To determine appropriate wavelengths at which to examine absolute reflectance, a correlation analysis was performed between the absolute reflectance at all SWIR bands and water content and normalized evaporation, taking all the samples into account. The depth of absorption features attributable to water and centered at 1450 and 1925 nm was evaluated as a potential spectral metric for moisture content and evaporation estimation. For this purpose, the depth of the absorption band at 1450 nm and at 1925 nm were calculated using the continuum removed spectra between 1375 and 1550 nm and 1850 and 2150 nm. Lastly this study examined the normalized soil moisture index (NSMI) suggested by Haubrock et al. (2008). NSMI is calculated as the normalized difference of the absolute reflectance at 1800 and 2119 nm wavelengths. This index has proved to be a good water content estimator for a range of natural soils.

Calculation of moisture content and AE/PE

The gravimetric water content (GWC) at each time step of the experiments was calculated by measuring the weight of the sample and comparing it to the weight of the dried solids obtained at the end of the test.

$$(3) \quad GWC = \frac{W_{sample} - W_{solids}}{W_{sample}} \cdot 100$$

where W_{sample} and W_{solids} are the weight of the sample (water plus solids) and weight of dried solids, respectively. The normalized evaporation, AE/PE, was calculated using the changes in mass of the tailings and water measured at each time interval.

Results

Behaviour of water content and AE/PE over time

Figs. 3(a) and 3(b) show the moisture content and AE/PE with respect to time for all samples tested in this study. The offset between the behaviour of MFT1 and other samples is due to the lower initial water content of this sample.

The behaviour of curves shown in Fig. 3(b) is similar to those shown in Fig. 1(a) given by Holmes (1961), except that AE/PE has been plotted as a function of time rather than water availability. According to Holmes (1961), when the soil is saturated or the water content is high, the AE is equal to PE and thus the normalized evaporation (i.e. AE/PE) equals unity for the clay and sand soils. For the samples tested in this study, however, the normalized evaporation is greater or less than unity as seen in Fig. 3(b). This deviation from unity is mainly attributed to decoupling between the water and soil temperature as the aerodynamic condition above the water and tailings containers was the same during each experiments. Knowing the temperature of the tailing and water, the potential evaporation can be corrected and thus the normalized evaporation. The potential evaporation is adjusted using the tailings temperature (i.e. the potential rate of evaporation is calculated at the tailings temperature using the Dalton's equation). Nevertheless, due to the bias existing between the actual tailings temperature and its temperature measured by the thermocouples, it was not

possible to correct the normalized evaporation using the tailings temperature. This temperature discrepancy is due to embedding the thermocouple in the perimeter of the tailings container so that it is not seen by the spectrometer sensor. The tailings temperature measured with the thermocouple is thus not fully representative of the average temperature of the entire sample. Therefore, to correct the normalized evaporation for each curve, the average of the AE/PE was calculated before the AE/PE starts to decline from its constant behaviour and all the data values were divided by this average value. Fig. 3(c) shows the corrected normalized evaporation versus time. AE/PE is approximately unity for all the samples at the start of the evaporation tests. These corrected normalized evaporation values were then used for further analysis.

Relationship between AE/PE and water content

The AE/PE versus gravimetric water content is shown in Fig. 3(d). All the curves show a similar behaviour and one comparable to that shown in Fig. 1(a) by Holmes (1961). When the water content is high, all the samples continue to evaporate at a near potential rate and then start to decline as the availability of water is decreased. The normalized evaporation reaches zero when each sample becomes air dried. For all samples examined in this study, the normalized evaporation declines at a water content of approximately 30 wt%. This drop in evaporation at a water content of 30 wt% is in close agreement with the results obtained by Wilson et al. (1997) for Regina Clay samples. The slight variation in behaviour between the samples is attributed to the variations in the composition and thickness of the samples, as well as relative humidity of the air at the time of each experiment.

Relationship between spectral features and water content

Absolute reflectance

The correlation coefficient between water content and absolute reflectance for each SWIR wavelength is shown in Fig. 4(a). In general, reflectance in the SWIR has a high negative correlation with water content. The highest correlation was observed at 1985 nm. Plots of water content versus absolute reflectance at 1985 nm for all the samples are shown in Fig. 4(b). The behavior of the 1985 nm reflectance above approximately 30 wt% water content is significantly affected by specular reflection where water is present within the field of view. Below 30 wt% moisture content, the data define two groups formed by MFT samples 1 & 3 and samples 2 & 4. The separation between these groups appears to be mainly due to non-uniform drying patterns rather than the composition of the samples. The effects of specular reflection and non-uniform drying patterns on the reflectance spectra are expanded upon in the Discussion section. Although MFT samples 1 & 3 show almost the same behaviour below 30 wt%, MFT3 shows a lower reflectance than MFT1 below 10 wt% water content because of its higher bitumen concentration. It can be concluded that when the sample is wet (above 10 wt% moisture content), the impact of bitumen on the reflectance is insignificant; but it lowers the reflectance when the sample surface dries (below 10 wt% water content). Also, it is observed that below approximately 5 wt% moisture content, the behavior of the reflectance at 1985 nm is nonlinear. This reflects the progressive loss of sensitivity of the spectral measurement to the dehydration process when the surface is dry. Deeper parts of the sample likely then loose moisture due to the progressive development of fractures. If one were to use the reflectance at 1985 nm for imagery acquired outdoors (e.g. tailings illuminated by sunlight), the presence of water vapor in the intervening atmosphere would severely impact the quality of the spectral measurements. Consequently, the reflectance at 2205 nm was also examined (Fig. 4(c)) as it is minimally impacted by

atmospheric effects. As can be seen in Fig. 4(c), the behaviour of graphs is similar to the 1985 nm reflectance except for having a smaller range of variation (0.1 to 0.3 compared to 0.05 to 0.33 in case of 1985 nm reflectance). Because the variation of both the 1985 nm and 2205 nm reflectance above 30 wt% water content is affected by specular reflection from the water surface, the potential of these spectral features was evaluated only below 30 wt%. To account for the nonlinear behavior of the reflectance at 1985 nm and 2205 nm below 5 wt% moisture content, second-order polynomials were employed to fit the data. R^2 values of 0.95 and 0.94 were achieved for reflectance at 1985 nm and 2205 nm, respectively. Although both these features are of value for the estimation of water content in the laboratory, only the reflectance of 2205 nm is of value for outdoor scenarios due to its robustness against atmospheric conditions.

Absorption depth

Figs. 4(d) and 4(e) show the changes in absorption depths at 1450 nm and 1925 nm with respect to water content for each sample, respectively. Both of these features appear to be sensitive to the changes in water content for the entire moisture regime, with a slight decline in sensitivity of 1450 nm depth below 8 wt% moisture content. The absorption depth at 1925 nm, however, shows a higher range of variation than the 1450 nm band depth. The range of variation for the 1925 nm depth is roughly from 0 to 0.7 compared to 0 to 0.35 in case of 1450 nm depth. Similar to absolute reflectance at 1985 nm, samples form two populations in 1925 nm absorption depth attributed to the non-uniform dehydration. The 1450 nm absorption depth, on the other hand, seems to be more robust against the pattern of dehydration (Fig. 4(d)). In general, both features are insensitive to the tailings composition including bitumen. R^2 values of 0.96 and 0.95 were obtained by fitting a second-order polynomial considering the entire set of data points for 1450 nm and 1925 nm absorption

features, respectively. Such a polynomial accounts for the changes in the data patterns as the sample goes from encompassing standing water to loosing standing water at a moisture content of approximately 40 wt%. This pattern is observed for the band depth at 1450 nm, 1925 nm and the NSMI results of the next section.

Although there is a strong correlation between the absorption bands at 1450 nm and 1925 nm and water content, both spectral regions would be of diminished value for the analysis of imagery acquired outdoors due to the strong absorption of sunlight by water vapor in the intervening atmosphere.

NSMI

The relationship between NSMI and water content for each tailings sample is shown in Fig. 4(f). The data shown in this figure suggest that NSMI shows a good level of robustness against tailings composition. Furthermore, it is sensitive to the variation in water content for the entire moisture regime. R^2 of 0.97 was achieved by fitting a second-order polynomial to the data. This high R^2 value and the fact that this index is not affected by the atmosphere make NSMI an appropriate water content estimator in field condition.

Relationship between spectral features and AE/PE

Since for all the tailings samples examined, the AE/PE was approximately unity above 30 wt% water content, the relationship between spectral features and AE/PE was evaluated below this moisture level.

Absolute reflectance

A correlation analysis was performed between AE/PE and the absolute reflectance at SWIR wavelengths, as shown in Fig. 5(a). Although reflectance in the SWIR generally has a

high correlation with AE/PE, the highest correlation value was observed at 1920 nm. Since 1920 nm is located at the centre of the water absorption band, absolute reflectance at 2205 nm was also examined. Figs. 5(b) and 5(c) show plots of AE/PE versus absolute reflectance at 1920 nm and 2205 nm for all the samples, respectively. Both features show a similar pattern with respect to AE/PE; the absolute reflectance increases with decreasing evaporation. The absolute reflectance at 2205 nm, however, shows a less range of variation than the 1920 nm. The range of variation for the 2205 nm reflectance is roughly from 0.15 to 0.29 compared to 0.1 to 0.32 in case of 1920 nm. Both features show a good level of robustness against the tailings composition. However, it seems that absolute reflectance at 2205 nm is more affected by bitumen concentration. The sample MFT3 shows generally a lower reflectance at 2205 nm than the other samples, but this behaviour is not evident in the 1920 nm diagram until the evaporation regime of less than 0.1. The behaviour can be explained by the presence of more bitumen in sample MFT3. Since both the 1920 nm and 2205 nm reflectance values showed a nonlinear trend with respect to the AE/PE, second-order polynomials were employed for model development. This nonlinear behaviour (also observed in sections below) is presumably associated with the nonlinear relationship between AE/PE and total suction (Fig. 1(b)). R^2 of 0.97 and 0.95 were obtained for the absolute reflectance at 1920 nm and 2205 nm, respectively. R^2 values of greater than 0.9 indicate that absolute reflectance can be considered to be capable of measuring normalized evaporation from oil sands tailings. Atmospheric effect is, however, an obstacle for the use of 1920 nm reflectance under the field conditions.

Absorption depth

The changes in band depths at 1450 nm and 1925 nm with changes in AE/PE are shown in Figs. 5(d) and 5(e), respectively. In both cases, the depth decreases with decreasing

evaporation. For the absorption depth at 1450 nm, the sensitivity of the feature is lost below an AE/PE value of 0.4, a behavior that is not observed for the absorption depth at 1925 nm. As can be seen in Figs. 5(d) and 5(e), these absorption depths are not sensitive to the composition of tailings. Moreover, the absorption depths appear not to be affected by bitumen concentration as the sample with more bitumen content (MFT3) does not show a distinct behaviour. Second-order polynomials were used to model the variations of evaporation with variation of absorption depths at 1450 nm and 1925 nm. R^2 values of 0.94 and 0.96 were calculated for the 1450 nm and 1925 nm absorption depths, respectively. Although these spectral features are successful in prediction of evaporation from the tailings surface under the laboratory conditions, they are not applicable on the spectral data collected in the field due to the effect of the atmosphere on these absorption bands.

NSMI

The values of NSMI were calculated and plotted for all the samples examined. Fig. 5(f) shows the relationship between the NSMI and normalized evaporation. Between AE/PE evaporation rates of 0.2 to 0.8, this index seems to be insensitive to the tailings composition. However, above 0.8 and below 0.2 evaporation rate, the index starts to show some variations. In particular, when the rate of evaporation is very low (below 0.1), NSMI appears to be sensitive to the samples composition including the bitumen concentration. An R^2 value of 0.95 was achieved by fitting a second-order polynomial to the data. As the NSMI is not affected by the atmospheric conditions, it can be a good estimator of normalized evaporation (AE/PE) when using the field data.

Discussion

Field applications

The predictive models developed in this study are intended to apply to hyperspectral data acquired in field settings by imaging the MFT tailings and sensing the top few hundred microns of the surface. Thus, the spectral sensing is able to estimate moisture content and AE/PE from the very top surface of the tailings. This is valuable information for tailings management and could help to assess when the deposit has stopped drying at the surface as part of a decision process to determine when the next lift should be deposited. In addition, the moisture content and normalized evaporation at the surface can contribute to the estimation of the water profile under the surface using empirical models, a topic of future research.

Estimation of total suction at the tailings surface

The results of this study demonstrate the capability of remote hyperspectral technology for the estimation of normalized evaporation. Since there exists a relationship between the normalized evaporation and the total suction (i.e. matric suction plus osmotic suction) as described by Wilson et al (1997) that is independent of water content and soil composition, one can estimate the total suction for the top few hundreds of microns of the surface by measuring the normalized evaporation from hyperspectral observations. According to Eq. (2), to measure the total suction, it is required to measure the normalized evaporation, surface temperature of the soil, and relative humidity of the air. The normalized evaporation can be estimated using the hyperspectral data as presented in this study. Long Wave Infra-Red (LWIR) hyperspectral data, on the other hand, can be used to estimate the surface temperature of the soil in field applications. Therefore, by employing the SWIR and LWIR hyperspectral technology, measuring the total suction of the surface in field applications is feasible. It should be noted that the established relationship between normalized evaporation

and total suction was demonstrated for thin soil sections as described by Wilson et al. (1997). Nevertheless, special care and attention must be used when applying the relationship to soil columns or for field applications since spatial variation, both vertically and horizontally, in water content and total suction occur. In other words, uniform drying in natural systems should not be expected.

Effect of specular reflection

The behaviour of the 1985 nm and 2205 nm reflectance with varying water content in the high moisture regime (approximately above 20 wt% moisture content) appeared to be counterintuitive. As can be seen in Figs. 4(b) and 4(c) the initial decrease in water content results in an increase in reflectance as expected. But a peak in reflectance is then observed nominally around 40 wt% moisture content where reflectance is higher than expected (a hump in the curves). The expected pattern in reflectance resumes at lower moisture content (e.g. 20-30 wt%). Our investigations revealed that this unexpected behaviour is attributable to the contribution of specular (e.g. mirror like) reflections from the water surface in domains of the sample undergoing the onset surface exposure from the water film. It is an ephemeral phenomenon that disappears as the sample dries. This phenomenon was documented using a series of photos (Fig. 6) taken at a normal view to the MFT sample (the same position as the sensor) during a dehydration experiment. As can be seen in these photos, the sample surface is initially covered by a continuous water film that progressively thins. The photo at 50.4 wt% water content displays the first evidence of specular reflection (areas with very high reflection) in the left part of the sample. The presence of these reflections are attributed to the formation of surface microtopography as drying occurs that provided localized mirror like bright returns. Their extent increases in subsequent photos for lower moisture content but they clearly have begun to wane for the photo at 39.1 wt% moisture content as standing water

has largely disappeared. This phenomenon is the cause for the observed increase in the absolute reflectance at 1985 nm and 2205 nm, as the water content decreases to approximately 20-30 wt% moisture regime.

Effect of non-uniform drying pattern

It was observed during the experiments that non-uniform drying pattern of the samples introduces variability in spectral measurements. The non-uniform drying pattern on the sample surface is mainly attributed to non-uniform sample thickness and illumination. Although the footprint of the spectrometer was adjusted to cover the whole sample area, it was observed that the central part in the field of view contributes more to the final spectra collected than the edge. As a result, for instance, a sample at certain moisture content with wet central part shows a lower reflectance and deeper water absorption band than a sample at the same moisture content with dry central part. Fig. 7 shows all the samples examined in the evaporation tests at 20 wt% moisture content. The central part of MFT samples 2 & 4 is wetter than the central part of MFT samples 1 & 3, resulting in a lower reflectance and deeper water absorption depth at 20 wt% moisture content. This explains the offset between the behaviour of the MFT samples 1 & 3 and MFT samples 2 & 4 in Fig. 4.

Stability assessment of the spectrometer

A test performed in the laboratory to assess the stability of the ASD instrument showed that by warming up the instrument for about 2 hours, the instrument would be stable enough and there is therefore no need to measure the white panel frequently during the experiment. Thus, normalization of each measurement to that of a standard white reference panel for calculation of reflectance was only conducted at the beginning of each experiment. It should be noted that measuring the white panel during the experiment could introduce

errors in measuring the actual evaporation rate as the tailing container needed to be replaced by the panel in order to measure the white reference panel spectrum. This disturbance could cause fluctuations in the rate of evaporation.

Conclusions

This paper investigated the use of SWIR hyperspectral remote sensing data for estimating the moisture content and normalized evaporation of oil sands soft tailings surfaces. Measurements of the moisture content and the exchange of water between the soil surface and the atmosphere are of importance for many geotechnical problems. In the case of tailings management, the remote estimation of moisture content and evaporation helps to assess the drying process, to determine when the deposit has stopped drying and to decide when the next lift should be deposited.

All SWIR spectral features examined were of value for the estimation of water content and normalized evaporation of the MFTs. For the estimation of moisture content, the best result was achieved using the NSMI index ($R^2 = 0.97$). The absolute reflectance at 1920 nm was found to be the best spectral estimator of normalized evaporation ($R^2 = 0.97$) with the NSMI index also being of value ($R^2 = 0.95$). However, NSMI appears to be sensitive to the sample composition including the bitumen concentration when the evaporation rate is very low. In both instances the NSMI index may be of value for estimations in the field while the reflectance at 1920nm may not due to its sensitivity to atmospheric conditions.

The samples examined in this study were obtained from a single mine and were processed using the same tailings operation technology. Future work could incorporate samples from different mines and tailings process to assess the robustness of our findings to tailings composition. The long term goal is to develop a new tool to monitor moisture content and evaporation over a wide range of tailings and generate real-time maps of tailings

properties. In future efforts, the models obtained from this laboratory investigation will be assessed for their applicability in field settings and validated using concurrent sampling. Developing such a remote mapping capability offers a key enabling technology to assess key characteristics of tailing deposits as a supplement to standard geotechnical testing and sampling campaigns.

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93x52mm (300 x 300 DPI)

Fig. 7. Photographs of samples at 20 wt% moisture content.
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Table 1. Characteristics of MFT samples examined.

Sample No.	Solids (wt%)	Bitumen (wt%)	MBI (meq/100g)	PSD (wt%)		
				< 2 μm	< 44 μm	< 74 μm
MFT1	52.16	3.5	2.3	8.90	70.83	83.23
MFT2	46.55	4.0	2.3	9.97	71.65	83.53
MFT3	44.66	4.3	3.5	10.71	82.78	91.53
MFT4	47.96	3.3	3.4	8.39	72.09	83.59

Table 2. Summary of key evaporation test parameters.

Sample No.	Initial water content (wt%)	Test duration (min)	Mean room air temperature (°C)	Mean relative humidity of air (%)
MFT1	47.84	108	23.25	22.5
MFT2	53.45	136	24.10	21.4
MFT3	55.34	120	24.30	21.9
MFT4	52.04	140	23.20	35.3

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