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Potential for Use of Methylene Blue Index testing to Enhance Geotechnical Characterization of Oil Sands Ores and Tailings

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Abstract

Geotechnical engineers have traditionally limited their classification and behavior characterization of clays to Atterberg limits determination and calculation of an associated clay "activity" that relates the plasticity of a clay to the percentage of clay size particles present in a given sample. This paper explores the possibilities for use of methylene blue index testing to enhance geotechnical understanding of the impact of the cation exchange capacity of clays present in oil sands ores and both solid and fluid components of the tailings stream. The paper provides a basic description of the methylene blue index test procedure most commonly used for characterization in the oil sands industry, discusses requirements for obtaining consistent test results, and explores how the test has been used to enhance geotechnical characterization of clays in other areas. Potential for developing correlations between methylene blue index test results and other geotechnical parameters or index tests used to characterize solid phase and fluid fines oil sands tailings is also discussed.

Introduction

Background

During the second CONRAD Clay conference held in Edmonton Alberta in March 2011, clay scientists, tailings rheologists, and geotechnical engineers presented various perspectives on why clay minerals were important factors in Alberta Oil Sands (hereafter oil sands) operations and tailings management considerations. Clay scientists devoted much of their presentations to discussing the variability that could exist in clay structures present in both oil sands ores and tailings and the impact of possible cationic substitutions on the spacing, overall charge, and behavior of clay particles in bitumen extraction processes and tailings streams. The common message from clay scientists at this conference was that although clay particles generally represented a small percentage of oil sands process ores or tailings by weight, the impact of water chemistry on clay particles was critical to understanding observed tailings properties (Mikula 2011).

The main geotechnical presentation at the workshop (prepared by John Sobkowicz and Jeremy Boswell (2011)) focused on describing clays from a traditional geotechnical perspective in which the impact of various clays on soil behavior is understood in terms of plasticity quantified using Atterberg limit determination. The presentation described the percentages of clay required to be present for clay behavior to dominate overall soil behavior from a geotechnical engineering perspective. It was observed that the percentages of clay cited as those required to have an adverse effect (from a geotechnical perspective) were significantly higher than the percentages indicated by the clay scientists at the workshop. The presentation included a brief discussion about clay activity but generally underscored the negative impacts of high clay content (clay content in excess of 15%) and high plasticity on geotechnical performance of solid tailings in the closure landscape (Sobkowicz and Boswell 2011).

In general, geotechnical engineers base their designs on material behavior instead of ionic composition. However, the presentation acknowledged the impact of the exchangeable ion present on the plasticity exhibited by various clay species, many of which are found in oil sands ores (Sobkowicz and Boswell 2011).

This author contends that failure of geotechnical engineers to understand the impacts on physical behavior associated with the nature of clay minerals present in oil sands ores and tailings or the highly ionic environments in which oil sands tailings streams exist will limit advancement of engineering designs using amended and un-amended oil sands tailings streams in which clay mineral behavior drives overall observed material behavior. Moreover, identification and subsequent determination of the plasticity behavior of mixed layer clays (Illite-Smectite) which are common in oil sands ores is considered to be an important addition to existing plasticity charts. Use of test methods to provide increased understanding of the behavior of clay minerals present (especially in fluid/non-settling tailings where clay minerals are concentrated and on which Atterberg limit testing is not possible) could be very helpful in the development and refinement of engineering models of mature fines tailings (MFT) and overall management of fine tailings.

This view is consistent with the views of clay scientists present at this workshop who suggested that understanding the nature of the clays present was critical to understanding observed tailings behavior, especially in the fluid phase. The geotechnical presentation was also limited to a discussion of the impact of clay minerals on “solid” oil sands tailings and did not present any discussion about the role of clays (and their behavior in highly ionic environments in which residual bitumen was present) continues to present significant challenges to tailings management considerations (most notably MFT) within oil sands industry.

This paper explores the background of methylene blue adsorption testing, how test procedures have been applied in oil sands industry, and discusses limitations of current test methods. The paper also reviews traditional geotechnical assessment of clays and explores ways in which traditional methods have limited understanding of clays in the management of oil sands tailings. Use of MBI results to characterize clay minerals in other geotechnical applications are discussed in addition to an exploration of how this test may enhance geotechnical characterization of oil sands ore and tailings, inform closure planning, and facilitate engineering design of closure landforms in the oil sands.

Clay Characterization

Clays are scientifically defined as hydrous phyllosilicates composed of layers of tetrahedral sheets and octahedral sheets with the capacity for the substitution of one cation on the interlayer surface for another without changing the shape of the atomic structure (Kaminsky 2011). Geotechnical engineers take great care when inclusion of clays in foundation materials cannot be avoided because of the recognition that soil behavior is influenced by a range of factors that often lie outside the scope of engineering controls e.g. subsequent wetting, or large specific surface areas of clays that are described as “sensitive” (e.g. expansive/”quick” clays and loess).

Clay mineralogy in Athabasca oil sands ores and the associated process streams is known to vary not only across the Athabasca oil sands deposit but even within the ore being mined at a single mine site (Kaminsky 2008, Omotoso and Mikula 2004). In order of frequency of occurrence, the follow clay minerals have been identified in oil sands ores and tailings streams: kaolinite, illite, mixed layer clays (kaolinite-smectite and illite-smectite), chlorite, smectite, and vermiculite (Kaminsky 2008, Kaminsky 2011). Omotoso and Mikula (2004) also suggested that the settling and consolidation of MFT was significantly affected by the presences of minor concentrations of smectite, amorphous oxides with high surface areas, and residual organic coatings on solids.

In addition, several of the technologies proposed to reduce MFT inventories involve polymer addition and utilization of thickening technologies (Jeeravipoolvarn 2010). Effectiveness of these processes relies on the successful manipulation of clay behavior (Omotoso and Mikula 2004). Identification and quantification of clay minerals in oil sands tailings streams is therefore considered “critical” to the development of adequate engineering models (Omotoso and Mikula 2004).

The potential for engineering properties to be influenced by much more than particle size has been acknowledged by several geotechnical engineers (Terzaghi et al. 1996, Mitchell 1993, Day 2006). It has also been observed that most of the clay minerals in oil sands ore and tailings streams were in the clay size fraction (<2μm) with clay minerals in the clay size fraction being the most active and problematic (Kaminsky 2011). Furthermore, where clay behavior is thought to govern overall material behavior, it has been suggested that even better understanding of the effect of clays on observed physical behavior is required (Terzaghi et al. 1996).

Moreover, where wide variability exists characterization should at a minimum include both particle size and plasticity characterization (Terzaghi et al. 1996).

Atterberg limits determination provides an indication of the amount and type of clay minerals present. Classic plasticity charts, as seen in Figure 1 and Figure 2 also provide an indication of clay reactivity which in turn provides an indication of cation exchange capacity. Said differently, clays with increasing liquid limit and high plasticity index indicate clays that have high activity, and correspondingly high cation exchange capacity (Kaminsky 2008). As such, the intention of this paper is not to suggest that Geotechnical engineers change the bases of their design criteria but suggests our design considerations could potentially be enhanced by a more complete understanding of the clay minerals and their interaction with salts and bitumen as encountered in oil sands ores and tailings streams.

Cation Exchange Capacity

Cation Exchange Capacity (CEC) is the quantity of cations (positively charged ions) that a clay mineral can accommodate on its negatively charged surface. Clay ion exchange is also identified to be rapid, reversible, and selective (Kaminsky 2011). Furthermore, the effect of the exchangeable ion present on the plasticity behavior exhibited by clay minerals has been widely acknowledged by both geotechnical engineers and soil scientists (Boswell and Sobkowicz 2011, Terzaghi et al 1996, Chiappone et al. 2004.). Observed impacts on clay mineral behavior based on cations present suggests that the ionic environment to which clay minerals in oil sands tailings are exposed is not a trivial consideration especially in fluid phase tailings where clay minerals predominate. Said differently, while it is understood that high cation exchange capacities have the potential to impact release water chemistry of MFT (Omotoso and Mikula 2004), physical behavior is also influenced by the CEC of the clay minerals present. As such, it is the opinion of this author that not only would understanding of the geotechnical engineering properties of oil sands clay minerals be enhanced by better identification/classification of the nature of clay minerals present using methylene blue index (MBI) testing, but the concept of CEC, which is directly measured using MBI testing, will enhance overall understanding about thresholds at which the presence of various clay minerals have an effect on observed material behavior, particularly in the management of tailings waste streams.

Atterberg Limits Testing

Atterberg Limits testing provides an indication of both the amount and nature of clay minerals present in a soil through observed behavior. The test method is described in a procedure developed by the American Standards of Testing Materials (ASTM) D4318 (ASTM 2010). The test involves addition of distilled water (from which both ions and all other impurities have been removed) to the soil samples being evaluated. When this test method is applied to oil sands ores and tailings, questions arise about how the effects of residual bitumen or the presence of ions in tailings streams affect the results obtained. Furthermore, care is required to indicate test result constraints– e.g. indicate how clay minerals tested and the nature of their origin - found in naturally occurring ores, actual un-amended tailings streams, polymer amended or in-line thickened tailings, or other altered tailings waste streams.

It should also be noted that conventional plasticity charts were never intended to provide indications of all clay mineral behavior. At a minimum these charts should be expanded to include data for the main clay mineral types found in the oil sands indicated earlier in this paper. Moreover, it was never anticipated that use of this test method would constitute the limits to which clay behavior could be characterized and understood by geotechnical engineers. Indeed, Terzaghi et al. (1996) recommended investigations of statistical relations between Atterberg Limits and other physical properties of cohesive soils be developed to broaden the scope of conclusions that can be drawn using results of the limit tests. Mitchell (1993) also provided the following recommendation, *"On large projects where unusual behavior is encountered, compositional data are useful for interpretation of observations. Influence of material composition and structure are not always adequately reflected in usual classification properties and more direct evaluation of their significance is needed."*

Methylene Blue Testing

Methylene blue (MB) is a cationic dye that has been used to identify redox reactions for a wide range of applications in the fields of chemistry and biology. In the field of clay chemistry, the adsorption of methylene blue to the edges, external surfaces, and accessible interlayer regions of clay minerals dispersed in an aqueous solution is often used to measure CEC and specific surface area of clay minerals (Omotoso 2011, Bergaya 2006). In the oil sands, MB adsorption testing is widely used to measure clay activity in process ores, froth, and tailings streams (Omotoso 2011). The methylene blue adsorption index (MBI) is determined through a laboratory procedure in which a solution of methylene blue made with de-ionized water (typically 0.006M) is titrated in 1 mL increments into an aqueous solution in which the sample being assessed has been well dispersed. Titration continues until a permanent blue halo indicates the presence of the methylene blue cation. The MB cation displaces Na^+, Ca^{2+}, K^+, and Mg^{2+} cations located on the surfaces of clay particles allowing estimation of the specific surface area of clay minerals present (Meisina 2006). It is also important to note that MB will exchange with any inorganic cation present on clay surfaces in a fully dispersed system (Omotoso 2011).

Test Procedure

The Association fraçaise de Normalization (AFNOR) and the American Society for Testing Material (ASTM) have both published test procedures using methylene blue to provide a semi-quantitative evaluation of the activity of a geomaterial based on the type and quantity of clay materials contained (Chiappone et al. 2004). In laboratories processing ore and tailings samples from the oil sands to determine clay activity, the ASTM test procedure (ASTM C387-99

Standard Test for Methylene Blue Index of Clay) is the procedure most commonly used (Kaminsky 2008).

The potential for large errors in results from MB adsorption testing has been acknowledged by ASTM and has led to skepticism on the part of some in the industry about the reliability of test results using MB adsorption test methods. These errors likely result from the absence of a single way of confirming that test samples have been completely dispersed prior to the start of the titration (Omotoso 2011). Moreover, leading clay scientists actively engaged in research in the oil sands have acknowledged that thorough dispersion of the clay sample in solution is critical to exposing all available clay surfaces and obtaining repeatability in test results (Omotoso 2011, Mikula 2011). Additional stirring in combination with ten minute intervals of sonication in an ultrasonic bath (subjection of the sample in solution to sound waves) have been used to enhance sample dispersion (Kaminsky 2008).

The MBI test method which follows is presented in expanded detail in Kaminsky 2008. When samples from oil sands operations are tested the MBI test should be performed on dried, Dean Stark extracted solids (i.e. solids from which bitumen has been removed) using the methods described in Kaminsky (2008). Once the mass of the dried sample to be tested has been measured, the sample (usually less than 5g) is typically dispersed into 50 mL of sodium hydrogen carbonate ($NaHCO_3$) to which approximately 2 mL of 10% w/w of sodium hydroxide (NaOH) has been added. Once the sample has been dispersed, 2 mL of 10% v/v sulphuric acid (H_2SO_4) is added. Titration commences in 1 mL intervals with fresh methylene blue solution once the pH of the dispersed solution containing the sample is confirmed to be below 3 using a pH meter. After each MB addition, a sample of the titrated mixture is transferred using a disposable pipette onto Whatman #4 filter paper and the droplet examined for the presence of a blue halo. Once a hint of a blue halo appears, the mixture is stirred and a second drop of mixture transferred on to the filter paper to see if the halo remains present after the second drop. A persistent blue halo indicates completion of the titration and the volume of MB required to titrate the dispersed solid recorded. MBI (an estimate of CEC) and surface area of the clay particles are calculated using the equations of Hang and Brindley (1970) as follows:

$$MBI\left(\frac{meq}{100g\ solids}\right) = \frac{(\textbf{vol. MB x normality of MB})}{weight\ of\ solids\ (g)} x\mathbf{100} \qquad \textbf{(1)}$$

where:

vol. MB is the volume of MB used in the titration, and the normality of MB is the concentration of the MB solution used (0.006 M typical).

$$Surface\ Area\left(SA, \frac{m^2}{g}\right) = MBI\ x\ SA_{mb}\ x\ 0.060\frac{2m^2}{g} \qquad \textbf{(2)}$$

where:

MBI is calculated in Equation 1, SA_{mb} is the surface areas of a methylene blue molecule (1.3 nm^2/molecule), and 0.0602 m^2/g is Avogadro's constant.

Geotechnical Assessment of Clays in the Oil Sands

In the oil sands industry, the term "fines" refers to materials having an equivalent spherical diameter less than 44µm. Most geotechnical engineers outside of the oil sands industry define fines as the material fraction with equivalent spherical diameter less than 75 µm (ASTM 2011).

The heightened focus received by fines in the oil sands likely stems from the general observation that good processing ores (ore producing high bitumen recoveries) generally cause minimal problems during extraction processes and contain lower quantities of fines than ores having higher quantities of fines which generally create greater challenges to bitumen liberation and extraction processes. While these observations are generally true, the use of the term fines to describe the portion of the ore complicating both extraction processes and tailings management conceals the wide variability that exists in both oil sands ores and in the types, structure, and activity of clay minerals present in these ores. This focus on the role of fines is confirmed by the definitions used in the language adopted by the industry to describe ore grade and ore processability. A "good processing" ore is ore considered to have bitumen content in excess of 10% by weight with fines content less than 20%. Poor processing ores are considered to have bitumen content less than 10% by weight, and over 20% fines. In addition, ore described as having "high" fines content is described as containing in excess of 18% fines while ore with "low-fines" content is described as containing less than 6% fines (Kasperski 2001).

It is likely that the increased focus given to fines stemming from general bitumen extraction observations has influenced geotechnical considerations about the role of fines on observed geotechnical behaviors of oil sands tailings. This influence is evident in ternary diagrams developed by Shahid Azam and Don Scott (Azam 2005) in which oil sands tailings slurry behavior is characterized in terms of sand content, water content, and fines content. The effect of pervasive "fines focus" is also likely evident in the use of cutoffs for considering the potential geotechnical impact of clays to levels in excess of 10 % as presented by Sobkowicz and Boswell (2011). As such, geotechnical characterization of materials in the oil sands has primarily been limited to the assessment of oil sands ores and tailings solids where it is believed that standard geotechnical test methods specified by ASTM can be applied. Typical geotechnical characterization of oil sands tailings includes determination and assessment of the following: Atterberg limits (plasticity), soil structure (assessment of soil fabric and matrix stability), drained and undrained strength, permeability, coefficient of consolidation, and compressibility (Sobkowicz and Boswell 2011). However, it should be noted that it is unclear whether standard ASTM material test methods being applied to oil sands tailings are being completed on samples from which bitumen has been removed since the presence of bitumen will likely affect the results obtained from several of the test methods initially developed to be completed on soil samples containing solids, water, and air.

Atterberg limits are still understood by geotechnical engineers to "reflect both the amount and type of clay minerals in a soil" (Sobkowicz and Boswell 2011). However, it is important to remember that Atterberg limits were developed in the early 1900s by Albert Atterberg, a Swedish soil scientist, to distinguish between different types of silts and clays and were not intended to provide conclusive indications of all clay types (especially of clay polytypes or mixed-layer clays) (Holtz and Kovacs 1981). Atterberg's methods were later refined by Arthur Cassagrande, a civil engineer who made important contributions to the field of soil mechanics in geotechnical engineering (Holtz and Kovacs (1981) and Mitchell (1993)). Cassagrande indicated that many clay properties like dry strength, compressibility, reaction to shaking tests, and the Atterberg Limits are correlated using the Plasticity Chart as shown on Figure 1 and Figure 2 (Cassagrande 1932). Conventional Plasticity Charts were developed using data from very homogeneous and extensively studied clay mineral deposits outside the oil sands (Terzaghi et al 1996). Furthermore, it is important to note that Atterberg Limit tests were never envisioned identify clay types. However, these charts provide an indication of CEC due to the relationship that exists between CEC, plasticity, and clay activity. Table 1 summarizes this relationship which generally indicates that clay minerals of increasingly high plasticity generally exhibit higher CEC values.

Activity is a measure used by geotechnical engineers to consider the effect of the clay minerals present on soil behavior (Skempton 1953). Mathematically, clay activity is calculated by dividing the plasticity index (PI) by the clay size fraction (taken as the percentage by weight of particles finer than 2 μm) (Terzaghi et al. 1996). Activity therefore provides an indirect indication of the type of clay minerals present. . Clay minerals with high plasticity also generally have higher activity and corresponding high CEC i.e. they tend to plot in the upper right hand region of an expanded plasticity chart – high liquid limit and high PI. The higher the clay activity, the more important the influence of the clay fraction on material properties. Mitchell (1993) indicates that these materials are more susceptible to changes in factors like the type of exchangeable ions present, and pour fluid composition. This confirms a vital link between activity and CEC.

Table 1: Common Clay Minerals found in Oil Sands Ores[1]

Clay Mineral Types[2]	Relative Plasticity	Activity	CEC (meq/100g)
Kaolinite	Low	0.5	3-15
Illite	Low	0.5-1	10-40
Mixed Layer (Kaolinite – Smectite, Illite-Smectite)	(Med- High)[3]	(1-7)	(3-100)
Chlorite	Low	0.5-1	10-40
Smectite	High	1-7	85-150
Vermiculite	Medium	(1-7)	100-150
Reference clay mineral: Montmorillonite	High	(1-7)	80-150

Notes:

1. Activity and CEC values not inferred were obtained from Mitchell (1993).

2. Clay minerals are listed in order of frequency of occurrence in Athabasca oil sands ores.

3. Values in parentheses are inferred. Actual values should be determined testing completed on actual oil sands ore and tailings samples.

PI is calculated as the difference between the liquid limit and plastic limit of the tested sample using the procedure for Atterberg limits determination. The percentage of clay size particles is calculated by hydrometer testing as the dry weight of the soil sample having an equivalent spherical diameter less than 2 µm (Mitchell 1993, Peck et al. 1974, Kaminsky 2011). Again, it is unclear whether clay content in the solids is determined absent from the effects of bitumen interaction as the original methods were developed for natural soils containing solids, water, and air and did not account for viscous effects contributed by organic matter or hydrophobic affects associated with bitumen. However, as seen on the conventional plasticity chart for classification of fine-grained soils (Figure 1) and the location of common clay minerals (Figure 2), classification is generally limited to identification of predominant clay constituents like Kaolinite, and Illite, and does not account for the presence of mixed layer clays containing high activity smectite common in both oil sands ores and tailings.

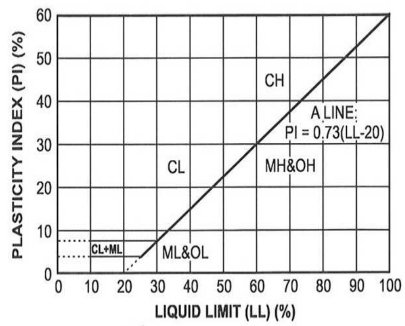

Figure 1: Plasticity Chart from Unified Soil Classification System (source: Mitchell (1993)

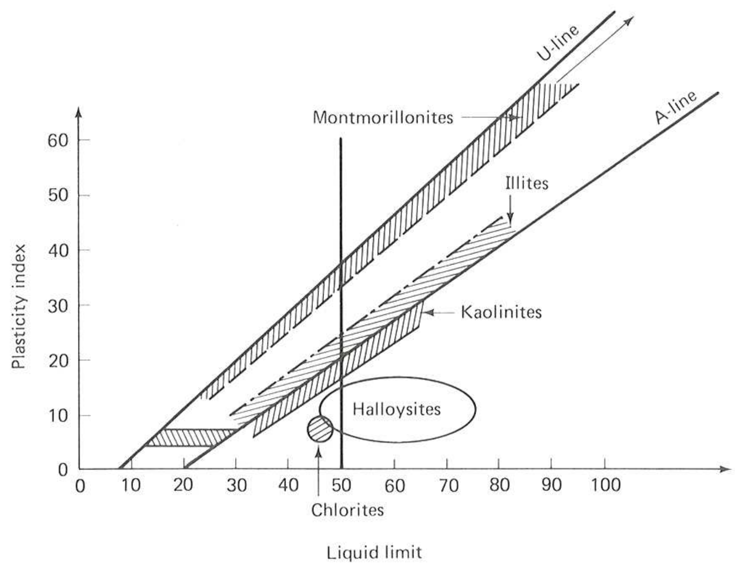

Figure 2: Location of Common Clay Minerals Plasticity Chart (source: Holtz and Kovacs (1981)

It is also important to note that the activity ranges provided for various clay minerals calculated using PI do not allow for unique identification of clay minerals. As an example, Allophones, Attapulgite, Illite, Kaolinite, and Halloysite, could all exhibit an activity of 0.5, and Illites and Smectites could be indicated by an activity of 1 (Sobkowicz and Boswell 2011). Furthermore, it would be helpful for geotechnical engineers to enhance understanding of how the activity of clay minerals factored into geotechnical engineering design considerations in oil sands tailings management.

As a result, while Atterberg limits facilitate discussion about soil plasticity, the following limitations may exist in the current application of this test method to characterization of oil sands tailings: 1) the ability of this test to clearly and consistently identify and distinguish the presence of mixed layer clays requires additional investigation; 2) geotechnical characterization has been inadvertently limited to soil-like tailings streams since methods to geotechnically characterize fluid fine tails have not been standardized; 3) the true cation exchange capacity or potential for clay structures to be affected by isomorphic substitution is not explicitly considered; and 4) the long-term ionic and associated physical stability of clay minerals has not been assessed. These considerations gain heightened importance especially if it is true that the CEC of clays in the fluid phase determine tailings properties and that water chemistry is important to defining fluid phase tailings properties (Mikula 2011). CEC considerations also receive added importance when the use of polymers and process aids are considered to flocculate fine tailings in order to create tailings materials that initially appear more manageable but consist of a chemically or physically unstable structure.

Enhancement of Physical Characterization of Oil Sands Ores and Tailings

Use of MBI elsewhere in Geotechnical Characterization of Clays

Test methods described by the Association Française de Normalisation (AFNOR) and the American Society for Testing and Materials (ASTM) have been used by geotechnical engineers throughout the industry to characterize clay minerals and to assess the clay content of drilling fluids or clay-amended soils. Meisina (2006) describes use of methylene blue adsorption test using AFNOR standards to further characterize clay minerals present in weathered clayey soils considered to be responsible for the occurrence of shallow landslides. In this reference the study combined with completion of intensive field mapping and laboratory testing that included MB adsorption testing in addition to determination of water content, unit weight, degree of saturation, grain size distribution, and Atterberg limits for the materials of interest using ASTM methods (Meisina 2006). Collection of this data facilitated better characterization of the clay minerals present and allowed for identification of distinct clay units within the studied soil profiles. MB testing has also been used to provide quality control during the installation of bentonite liners during installation of natural covers (Alther 1983).

Chiappone et al. (2004) compared results from clay mineral characterization using both the AFNOR and ASTM methods. The research described in this study was performed to identify methods for the characterization of swelling clay minerals that were "faster and cheaper" than X-ray diffractometry (XRD) or Brunauer-Elmer-Teller (BET) analysis (Chiappone 2004). Specifically, MB adsorption test methods were applied to identify the presence of high activity clay minerals in the southeast Piedmont region of Italy where landslides are often triggered by large rainfall events. The comparative tests were conducted at the geotechnical lab of the Polytechnic University in Torino, Italy on homogeneous (mostly clayey) materials and heterogeneous materials (mostly marly materials with fine-grained clastic sediments). Based on the results obtained from the limited study, the following conclusions were drawn: 1) the ASTM procedure was considered suitable for obtaining information in cases where only the clayey fraction was tested; 2) the ASTM standard was considered suitable for tests performed on fine-grained homogeneous materials; and 3) the AFNOR procedure in which the blue value of soil index (V_B) is determined, was recommended to be used to perform tests on heterogeneous materials (Chiappone et al. 2004).

SRK Consulting has also used the Methylene Blue Test Kit developed by OFI Testing Equipment Inc. of Houston Texas to establish a field-based laboratory in which the rate of bentonite application to amend sandy material during liner installation could be tested as part of the project's QA/QC procedure. While the basic test procedure provided with the OFITE test kit was slightly modified to account for the dry solids being tested (the original test procedure is specified for use with drilling fluids), the simplicity of the method and its inclusion of repeated opportunities to confirm full dispersion of the sample allowed for consistent and repeatable results to be achieved.

Use of MBI to Enhance Geotechnical Characterization of Oil Sands Ores and Tailings

Kaminsky (2008) and Omotoso (2011) indicate that the typical clay minerals found in oil sands ores and tailings are Kaolinite, Illite, mixed layer clays (Kaolinite-Smectite and Illite-Smectite), Chlorite, and Smectite. Work by Omotoso et al (2006) also indicates that the composition of the minus 2 micron fraction of oil sands ores and tailings can be dominated by both Kaolinite (up to 67% in ores, and up to 79% in tailings) and mixed layer clays (up to 93% in ores, and up to 74% in tailings). Results of this work also indicated that up to 57% of the minus 2 micron fraction in tailings could be composed of non-clay minerals. The later finding confirms the reality that not all minerals with an apparent spherical diameter less than 2 microns are clays. Kaminsky (2011) also provides a reminder that while clay minerals in the clay size fraction tend to exhibit the greatest activity, Kaolinite and Illite can exist in the form of minerals ranging in size between 2 microns and 45 microns.

As indicated earlier in this paper, MBI titration procedures are generally used to provide an indication of the cation exchange capacity and specific area of clay minerals in process ores. However, through drying of Dean Stark extracted solids from tailings streams, MBI determinations have also been completed on oil sands tailings. In the early 1980s Amar Sethi developed an empirical relationship correlating MBI to clay content (Omotoso 2011). Based on MBI testing that has been completed and compared to results of clay content determined using centrifugation techniques, strong correlation was observed (Omotoso 2011). The importance of dispersion of samples to be tested was also reiterated by Omotoso (2011). Work completed by Canmet ENERGY also indicated that the specific surface of minerals in the clay sized fraction in two MFT samples tested was largest for Kaolin-smectite and Illite-smectite minerals (Mikula 2011).

Conclusions

The geotechnical definition of soil activity provides an indication of the effect of the clay minerals present on the overall plasticity of the soil. However, use of this data in combination with CEC data might enable additional confirmation of the clay minerals present, and provide an indication as to how the physical stability of engineering structures designed with these materials will be affected by continued exposure to water, organic solvents, or other ions present in process water (which can exhibit variation from a single plant's output and across various operations). Observation that a soil's plasticity index increases as the cation exchange capacity of the material increases suggests that CEC could enhance understanding of observed physical behavior associated with the clay minerals present. It should also be noted that the ratio of CEC to the size of the clay sized fraction has already been utilized as another way to define clay activity (Olson et al. 2000).

As oil sands ores and tailings can exhibit wide variability at a single site and between various oil sands operations the CEC of clay minerals is not insignificant and directly impacts the behavior of clay minerals in ore processing and in fluid and solid tailings phases. Furthermore, clay minerals are highly susceptible to impact from the chemical compounds to which they are exposed throughout the bitumen extraction process. Since the oil sands environment is largely influenced by chemical manipulation, geotechnical engineers should be mindful of the origins of Atterberg limit determination in soil science and recognize that the test currently provides limited information about complex clay minerals that are often impacted by the complex ionic environments to which they are subjected in bitumen extraction processes. In addition, the need for consistent methodology to ensure sample dispersion should not discourage geotechnical engineers from consideration of MBI data since the need for consistent laboratory procedures is no less important for completion of Atterberg limits determination which are understood to be fundamental to current geotechnical understanding of clay behavior in the soil like component of oil sands tailings. MBI data also provides geotechnical engineers with greater knowledge about the surface area of the clay minerals present and information about their potential availability for cation exchange or chemical reactivity.

The ability for geotechnical engineers to assess the long-term geotechnical stability of oil sands tailings is directly tied to their ability to understand the factors impacting the behavior of clay minerals present in oil sands tailings and potential changes that might occur due to the ionic nature of the environments in which these tailings exist. Understanding of the suspension, settlement and consolidation behaviors in tailings impoundments could also be deepened. The potential also exists to correlate CEC data with results from index testing completed using Cone Penetrometer testing. This allows for development of correlation data at actual project scales e.g. ability to characterize materials present as well as behavior observed within an entire tailings impoundment. Finally it is hoped that incorporation of this data will enhance geotechnical engineers' ability to reliably incorporate tailings solids into landforms that maintain geotechnical stability throughout closure and post closure project phases. Furthermore, assessment of the impact of "ionic buildup" associated with process water recirculation should be investigated.

Results of this work could directly impact the ability to implement more effective tailings management strategies. It is recommended that MBI testing be included in the standard suite of analyses completed to characterize both oil sands ores and tailings. Such testing would also advance understanding of how ionic environment impacts the behavior of these minerals in both the fluid and soil-like tailings phases. Strong correlation between results of MBI tests completed on well dispersed samples of oils sands clay minerals and XRD results suggests that MB adsorption tests could be effectively used to assess the CEC of clay minerals in froth from the primary and secondary extraction phases, fine fluid tailings, and in treated tailings streams producing tailings solids including composite tailings, tailings produced by Suncor's Tailings Reduction Operations (TRO) process, and thickened tailings (Omotoso 2011). Use of this data could allow for possible development of correlations between CEC and index data obtained from CPT profiles generated in tailings impoundments containing both fluid fines and treated tailings solids.

Geotechnical engineers working in the oil sands are not exempt from understanding the basic chemical environments to which oil sands ores have been subjected, or from deepening their appreciation for the role which chemical interactions with clay minerals have on their ability to engineer closure landforms that are geotechnically stable in the long-term. It is believed that collection of MBI data will enhance initial understandings of clay activity currently provided by Atterberg Limit tests and provide more comprehensive geotechnical characterization of oil sands material behavior. Collection of this data will also enable possible development of correlations between the CEC of tailings and other measured geotechnical characterization of treated tailings solids like compressibility, permeability, drained and undrained strength thereby enabling this data to inform geotechnical engineering design of closure land forms. Finally, while most information could likely be privileged and confidential, it would also be helpful to explore whether MBI is used in the characterization of clays in uranium and kimberlite mining since clay mineralogy also plays a significant role in operations and tailings management considerations for these industries.

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