A Column Experiment to Study the Drying Behaviour of Mature Fine Tailing

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***Abstract*—Oil sands in Alberta have been excavated to extract bitumen over the past five decades. Continual accumulation of fine tailing and high risk of failure associated with constructed dams are considered as a serious problem for this industry. Recent regulatory changes have forced this industry to investigate on more effective technologies to control and reduce this inventory. Multi-lift deposition of oil sand tailings could be appropriate solution in order to meet regulatory requirement. However, this approach could not be viable if the addition of more lifts compromise the developed strength in the former layers. Moreover, hydraulic and mechanical properties that are strongly coupled, can affect geotechnical behavior of deposited tailing. In this study, the evolution of coupled hydraulic and mechanical properties of mature fine tailing (MFT) has been studied by means of column experiment under atmospheric condition. The results obtained have shown that, by adding the second lift, former lift initially lost the suction developed in this layer; but this effect was not permanent and over a 30 days period, recovered to prior values. Strongly coupled hydraulic and mechanical behavior is due to several mechanisms, such as evaporation, drainage, and self-consolidation, suction and crack development. Based on the obtained data, two-lift deposition can be considered as an efficient reclamation plans to minimize dedicated disposal areas (DDAs).**

***Index Terms*—tailings, oil sand, environment, drying, multi-lift deposition**

I. Introduction

Oil sand extraction processes in Northern Alberta began five decades ago. This industry produces large volumes of tailings with high water content, and managing mine tailings has been a perplexing challenge for active operators. Oil sand tailings (known as “whole tailings”) are a by-product of mining operation. The tailings are a mixture of water, clay, silt, sand and residual hydrocarbons, salt and soluble organic compounds. They also include solvents added during the mine extraction process [1]-[5]. The standard industry practice until now has been pumping the tailings into very large tailing ponds. In tailing ponds, sands as the heaviest part settle to bottom. Water goes to the surface and can be recycled. The middle layer known as Mature Fine Tailing (MFT) is comprised of about 30% solid and takes centuries to solidify [1], [2]. For every unit volume of bitumen recovered, there are 7 to 8 volume units of MFT that need to be handled, and 10 volume units of water either recycled or make up is required. About 3 cubic meters of water per cubic meter of bitumen is trapped in tailing pond [4]. This water is responsible for continually rising pond volume; and removing the entrapped water is essential to improve traffic ability of the deposit for reclamation of dedicated disposal areas [4], [5].

As an initial step in reducing the inventory of fluid tailing, the Energy Resource Conservation Board (ERCB) developed new tailings management regulations and released on 2009. Application of the ERCB’s Directive 074 has motivated active operators to review current technologies and techniques and has driven them to investigate alternative technologies and process, innovation and collaboration to manage and for reclamation of oil sand tailings [5], [6]. The key requirement of Directive 074 is that DDA must be formed and managed to guarantee formation of trafficable deposition. One of the most important criteria that must be achieved is a minimum undrained shear strength of 5 kPa for MFT deposited in the previous year. Also, previous year deposited MFT that does not meet 5 kPa must be removed or remediated [5]. Thin-lift drying is defined as deposition of MFT in thin lifts (200-300 mm) to get dried and achieve the required strength under atmospheric conditions. However, this technology cannot be beneficial and applicable if additions of the new lifts eliminate developed strength of underlying layers. Hydraulic and mechanical properties that are strongly coupled, are involved in multi-lift drying of MFT. The understanding of these coupled behaviors is crucial for the successful application of the multi-lift or thin lift drying technology in oil sand industry. To date, our understanding of the mechanical and hydraulic variation that occur in multi-lift MFT under atmospheric drying is limited. Hence, the objective of the present study is to assess the HM processes and behaviors of thin-lift raw MFT under atmospheric drying by conducting column experiments.

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TABLE I. PHYSICAL PROPERTIES OF THE RAW MFT

Parameter	Average value
Initial solid content (%)	45
Initial water content (%)	121.7
Initial bulk density (g/cm^3)	1.31
Initial void ratio	3.44
Liquid limit (%)	51.2
Plastic limit (%)	37.2

II. EXPERIMENTAL PROGRAM

A. *Material*

Raw MFT sample was obtained from an oil sand tailings pond located in northern Alberta (Canada). Based on XRD results, 18% clay, 81% silt and 1% sand were measured in the MFT sample. According to Atterberg test results that can be seen in Table I, Activity was 0.77 which corresponds to a normal clay [6]. Based on ASTM D854, specific gravity was measured 2.36 that is lower than that of the other clay type material. Low specific gravity of bitumen that is equal to 1.03 is responsible for the low specific gravity of MFT [2].

B. *Experimental Program*

Four Plexiglass columns with inner diameter of 25 cm and height of 55 cm were manufactured. They include one column for monitoring and the last sampling after 30 days and three columns were allocated for sampling at different elapsed times of 5 days, 10 days and 20 days. A three cm layer of sand is used as a drainage layer at the bottom of the columns that is separated from the tailing by a perforated plate. A coarse filter paper was used to cover perforated plate which could hold the tailing and prevented the tailing to clog the drainage path. Surface of each column is exposed to ambient condition. To simulate the wind, a fan on top of each column was placed. These fans were adjustable and equal distance from the tailings' surface was set after addition of each lift. Monitoring column was equipped with eight sensors. Four MPS-2 and four 5TE sensors were installed at four different heights of 5, 15, 35 and 45 cm. MPS-2 can monitor soil water potential in the range of 0-500 kPa. Moreover, for measuring the evolution of the temperature, Electrical Conductivity (EC) and Volumetric Water Content (VWC) of the drying MFT, 5TE sensors were placed at these four different heights.

III. RESULT AND DISCUSSION

A. *Evaporation*

Soil evaporation process can be divided into three phases [7], [8]. Initially (stage I), external factors such as temperature, humidity and wind speed control the evaporation rate. In phase II, rate of evaporation is controlled by soil hydraulic properties and decline in the rate is the result of development of a drying zone [7], [9]. In phase III, the evaporation rate decreases gradually to reach a residual value in which liquid and vapor phases are discontinuous and evaporation is limited by vapor diffusivity [7], [8]. Understanding of evaporation in mature fine tailings is important because by monitoring the evaporation rate, the suction developed within the MFT can be determined, and consequently its effect on the strength can be predicted. Fig. 1 shows the evaporation rate and accumulative water lost by evaporation in a 30-day period. The first phase of evaporation depends on the room temperature and relative humidity. As discussed above, the test comprised drying an initial layer for 5 days before adding a second layer and another 25 days of drying after loading the second lift. Evaporation rate was initially 1.14 kg/hr.m^2 and reached 0.48 kg/hr.m^2 after 5 days (before loading the second lift). Evaporation rate showed a high increase by casting the second lift and gradually decreased and finally reached a relatively stable condition after 30 days in the residual phase (around 0.13 kg/hr.m^2). Accumulative water loss was measured around 13 kg on the 30th day. Decline in the rate of evaporation could be attributed to the formation of the crust formed on the surface of the tailing that resisted against water flow.

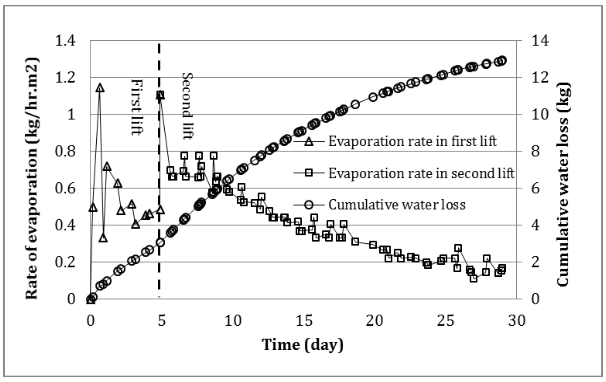

Figure 1. Actual rate of evaporation and cumulative water loss (by evaporation) for the first and second lift.

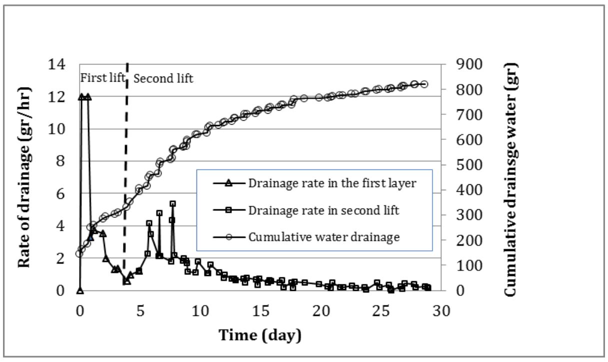

Figure 2. Rate of drainage and cumulative water loss (by drainage) for the first and second lift.

B. *Drainage*

Fig. 2 illustrates the results of the measurement of drainage rate and accumulative drainage. Within the first days after loading each lift, the rate of drainage was higher and it levelled to very small rate during the last 10 days. Maximum rate of drainage (12 g/h) was measured during the first day when accumulative drainage was around 160 gr. After loading the second lift, the rate of drainage reached 5gr/hr (in the second and third days after casting the second load) and then had a decreasing trend until the end of the test period. Development of cracks after the first days of each load caused water molecules to move upward to the evaporation boundary rather than drainage. These results indicate that regardless of the height of the tailing, evaporation is a dominant mechanism for removing water from MFT in comparison with drainage. Similar observations were made and reported by Junqueira *et al*. [10].

C. Suction Evolution

Fig. 3 shows the evolution suction with time in the monitoring column. The initial MFT suction was around 0 kPa at the height of 5 cm and 15 cm (first layer). In Fig. 3, on the right hand side, the suction evolution is presented for early 10 days after MFT casting. Five days after filling the first lift (before adding the second lift), suction developed and reached to around 16 kPa at 15 cm height. After adding the second lift, developed suction in this height showed a sharp decrease reaching almost zero but it reached to same suction right before adding the second lift (almost 20 kPa) on the day 30^{th}. Suction reduction after loading the second layer is attributed to the drainage of water from the upper lift to the lower part of the column (due to gravity) and recovered after 25 days. Upon approaching to the surface, due to the effect of evaporation, the maximum suction was achieved. According to Fig. 3, suction at heights of 45 cm and 35 cm diverged between days 7 and 8 (days 2 and 3 after loading the second lift). Suction reached more than 500 kPa in depth of 35 cm and 45 cm after 17 days and 12 days, respectively. After this time, cavitation of the sensors occurred. While, at the bottom (5cm), suction meter installed in this depth showed the lowest suction values during the test period. On the one hand, drainage of water from the upper part to lower part and on the other hand not to have close access to evaporation boundary prevented suction and thus strength to be developed in the level. By starting phase II drying, the rate of evaporation becomes a function of total suction and water content rather than environmental condition [11]. Vapor flow is dominant in dry zone while liquid flow is dominant in layers below.

D. Un-Drained Shear Strength of Mature Fine Tailings and Solid Content Evolution.

To meet Directive 074 requirements, it is necessary to reduce MFT water content. As a consequence, solid content increases that lead into higher strength. Un-drained vane shear strength test was conducted on the samples for different heights at defined elapsed times. Fig. 4 presents the variation in strength against different heights after 5, 10, 20 and 30 days. It can be understood that the strength increases with the time. Evaporation leads to a dense soil matrix and vane shear strength increased accordingly. In addition, suction development within the column has a significant impact on mechanical properties of the tailing. Fig. 1 to Fig. 4 show hydro-mechanical coupled relationship. It can be concluded that increase in suction increases the strength.

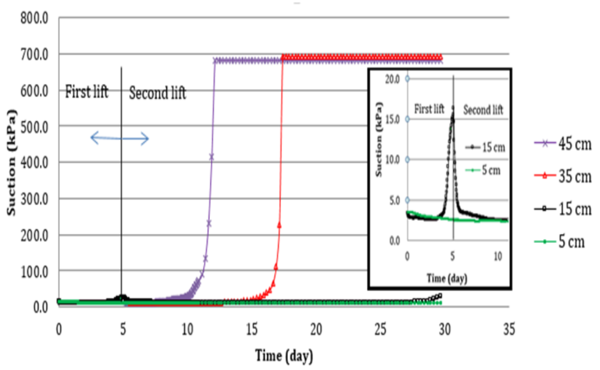

Figure 3. Evolution of suction with time and column height

Taken samples from the bottom of the columns showed the minimum strength in all the elapsed times. The second lift drains its water (because of gravity) through the lift beneath and accumulation of drained water resulted in a lower strength at the bottom. For all of the elapsed times (all figures below), significant growth in strength for the samples close to the top of the columns was observed. Vane shear strength of the upper part of the first lift after five days and before casting the second lift was around 10 kPa. Evaporation is the main responsible mechanism in this height for suction development and subsequent strength increase. Suction could not develop well in the first lift within the first 5 days. Only top layer (15 cm) reached around 10 kPa and the rest of the column that was not exposed to environment had much lower strength. After filling the column with the second lift, strength felt to around 1 kPa. This reduction is due to water drainage from the fresh layer that eliminates developed suction and resulted in strength reduction within the next 20 days. At the end of the test period, after 30 days, cracks could be extended to deeper depths and developed suction (caused by the evaporation) increased vane shear strength in this depth (15 cm) to around 7 kPa. Developed suction at day 30 at height of 15 cm can be seen in Fig. 3. The strength of the top portion of the columns (35 cm and 45 cm) reached to more than 2 MPa after 20 days.

Fig. 5 shows the impact of solid content on the strength of mature fine tailing. To meet the regulations set by ERCB (Directive 074), sufficient water removal from the MFT is required. Dewatering could increase solid content and consequently strength increases. Initial solid content was measured around 45% (void ratio 2.9-3.4). Solid content increased from initial value to around 58%, 72%, 98% and 99% after 30 days for the depths of 5 cm, 15 cm, 35 cm and 45 cm, respectively. Evaporation, drainage and self-weight consolidation could be effective mechanisms for this trend. MFT showed very low strength at solid content less than 55%. According to Fig. 5, the MFT should be dewatered to around 70% solid content to meet directive 074. This findings is in agreement with Beier *et al*. (2013)'s results.

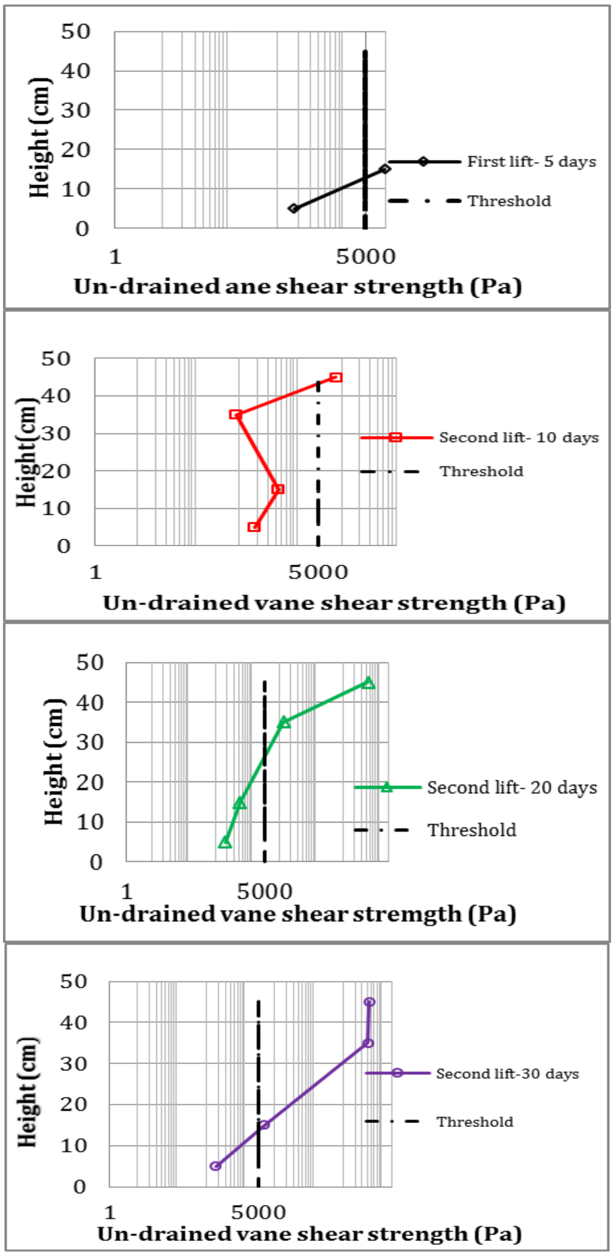

Figure 4. Changes in un-drained vane shear strength for four different elapsed times.

IV. Conclusion

This paper deals with the study the simultaneous evolution of the mechanical, hydraulic and physical properties of raw MFT under atmospheric drying. The results obtained show that vane shear strength is highly variable within elapsed time and column height. Multi-lifting deposition had two negative effects on the developed strength within the former lift. Water drainage from the upper part due to gravity can affect developed suction within the former lift. In addition of water drainage, second lift covers the evaporation boundary for the former lift. However, this effect was not permanent and strength and suction recovered and exceeded the previous value (values in absence of the second lift). Moreover, strong coupled HM behavior shows that coupled relationship between suction and strength exists in the column. Comparison between evaporation and drainage show that evaporation is the dominant mechanism in dewatering process rather than drainage. This study revealed that the coupled HM behavior of multi-layer MFT deposits is important for an effective management of MFT to reduce DDA and following Directive 074.

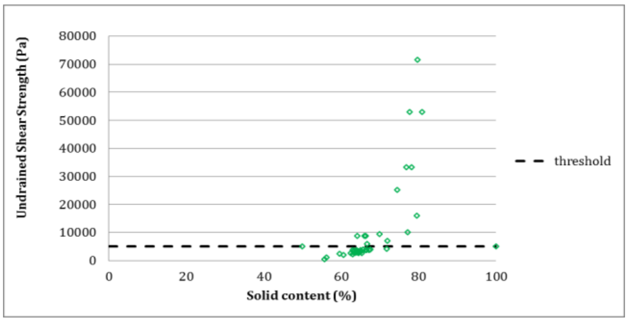

Figure 5. Evolution of strength with solid content

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