International Journal of Mining Science and Technology 27 (2017) 203–209

Contents lists available at ScienceDirect

International Journal of Mining Science and Technology

journal homepage: www.elsevier.com/locate/ijmst

A column study of the hydro-mechanical behavior of mature fine tailings under atmospheric drying

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ARTICLE INFO

Article history:
Received 19 January 2016
Received in revised form 12 March 2016
Accepted 14 August 2016
Available online 2 February 2017

Keywords:
Tailings
Oil sand
Environment
Drying
Multi-lift deposition

ABSTRACT

In this paper, the hydro-mechanical behavior and physical properties of mature fine tailings (MFT) under atmospheric drying are investigated through a column study. In the study, evaporation takes place in the development of suction in the upper parts of the column and increasing suction leads to higher strength in the tailings. After 5 days, the suction in the first lift is around 17 kPa in the upper part of the column. When a second lift is added, the first lift initially loses strength but over a 30 days' period, the strength is recovered to its prior value and suction in the second lift reaches 500 kPa. The vane shear strength values show a substantial increase in the strength of the MFT after 30 days under atmospheric drying and drainage. The 90% strength found in the column exceeds the threshold (5 kPa). The hydraulic-mechanical properties of the deposited tailings are closely coupled due to several mechanisms, such as evaporation, drainage, self-consolidation, suction and crack development. The findings of this study will provide a better understanding of the placement behavior of multiple lifts of MFT and thus contribute to reclamation design standards and reduce the use of dedicated disposal areas.

1. Introduction

Oil sand extraction processes in northern Alberta produce large volumes of tailings with high water content. The tailings (known as "whole tailings") are a mixture of sand, silt, clay, and a small amount of bitumen. For each barrel of synthetic crude oil produced, around two tons of ore must be processed, which results in the production of around 1.8 t of solid tailings and about 2 m^3 of waste water [1]. After deposition, the fine tailings (<45 μm) settle to about a 30% solid content (water content of 186–233%) within 2 years and are then referred to as mature fine tailings (MFT). Extensive clay dispersion from the extraction processes due to sodium hydroxide (NaOH) causes chemical interactions among the clay, water and residual bitumen which lead to a significant reduction of the hydraulic conductivity and consolidation of the MFT [2,3]. The average solid content of MFT has increased from 30.6% to 41.8% in approximately 26 years [2] and full consolidation of untreated tailings could take up to thousands of years [1,3] which require consideration of their long-term storage in constructed containments. The continuing accumulation of MFT is therefore causing substantial economic and environmental concerns [4].

Applying practical methods to manage and reduce MFT has been an ongoing challenge for the oil sands industry. The industry has developed several types of technologies to manage MFT. For instance, composite tailings or consolidated tailings (CT) were used by Suncor and Syncrude. However, CT have a number of challenges associated with the process. Any deviation from the sand to fine ratio (SFR), which is approximately 4:1, could produce segregated material that would not be trafficable and cannot be reclaimed [3]. An increasing trend in this industry is to manage the fine tailings stream by using chemical additives. Polymer solutions are injected into transfer pipelines and the flocculated mixture is discharged in thin layers to form a gently sloping beach. Flocculants are added in a thickening process to create thickened tailings, which allow them to spread in layers and consolidate [5]. However, chemically amended tailings may exhibit shear-sensitive and metastable behavior after deposition, unless mitigative measures are applied [3].

In 2009, the implementation of Directive 074 by the Energy Resources Conservation Board (ERCB) compelled operators to review their current technologies and techniques, and investigate alternative technologies and processes to manage oil sand tailings and their reclamation [6–7]. The key requirement of Directive 074 was that oil sands operators were to deposit a substantial percentage of their annual production of fine tailings in designated disposal areas (DDAs). The DDAs must be constructed in a manner

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http://dx.doi.org/10.1016/j.ijmst.2017.01.023
2095-2686/

that guaranteed trafficable deposits [4,6]. However, a promising alternative approach to effectively manage MFT instead is through atmospheric drying (thin-lift drying). Thin-lift drying consists of depositing MFT in thin lifts to dry and achieve the required strength under ambient conditions. The benefits of thin-lift drying are most marked when utilizing multi-lifts in order to reduce dedicated disposal area (DDAs). However, this technology cannot be applied and related benefits cannot be realized if additions of new lifts eliminate the developed strength of the underlying lifts. The multi-lift drying of MFT involves very complex hydraulic (H; e.g., evaporation, fluid flow, suction) and mechanical (M; e.g., strength increase/decrease, deformation, cracking) processes which also strongly interact with each other. An understanding of these HM processes and the HM behavior of thin-lifts of MFT is crucial for the successful application of the multi-lift or thin lift drying technology. To date, our understanding of the HM processes that occur in multi-lifts of MFT and the HM behavior of the deposition of multiple lifts of MFT under atmospheric drying is limited. Hence, the objective of this study is to assess the HM processes and behaviors of raw MFT deposited in thin-lifts under atmospheric drying by conducting column experiments.

2. Experimental program

2.1. Material

2.1.1. Mature fine tailings

Raw MFT were taken from an oil sand tailings pond located in northern Alberta, Canada as the sample. The physical, mineralogical and chemical characteristics of the sampled tailings were determined by conducting various laboratory tests. Fig. 1 depicts the grain size distribution curve of the MFT used. The tested MFT contain about 18% clay, 81% silt and 1% sand. The liquid limit (LL) and plastic limit (PL) of the MFT are 51.2 and 37.2, respectively [4]. So, the plasticity index (PI) is equal to 14 and activity (A) is 0.77 which corresponds to a normal clay. According to the X-ray diffraction (XRD) results, the mineralogy of the clay component is kaolinite and illite. The average specific gravity was measured to be 2.36, which is lower than that of the other types of clays. Bitumen is found in tailings in the forms of free and adsorbed bitumen. The specific gravity of bitumen is about 1.03 and results in a lower recorded specific gravity of the MFT compared with other natural clay soils [2]. Typical material characteristics of the raw MFT used are listed in Table 1.

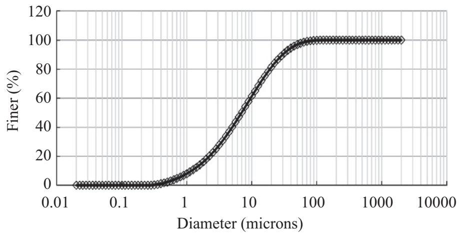

Fig. 1. Grain size distribution of MFT used in study.

2.2. Developed experimental setup

Fig. 2 presents a schematic diagram of the developed experimental set up of columns in this study. In total, four columns were manufactured, with one column for monitoring purposes and the last sampling after 30 days (Column a) and three columns for sampling at different elapsed times of 5 days (Column d-only one lift), 10 days (Column c) and 20 days (Column b). The columns, made of Plexiglas with an internal diameter of 25 cm and height of 55 cm, were used as the framework for analysis. A 3 cm layer of sand was used as the drainage layer at the bottom of the columns which was separated from the tailings with a perforated plate. Coarse filter paper covered the perforated plate in order to hold the tailings and prevent them from going into the drainage layer. The top of the columns remained open and was exposed to the environment. There was also a fan placed on top of each column in order to simulate wind at the site. The placement of the fans could be adjusted so as to provide equal distance from the tailings surface after the addition of each lift.

Table 1
Physical properties of raw MFT.

Parameter	Average value
Initial solid content (%)	45
Initial water content (%)	121.7
Bitumen content (%)	18.37
Initial bulk density (g/cm^3)	1.31
Initial void ratio	3.44
Specific gravity	2.36
Liquid limit (%)	51.2
Plastic limit (%)	37.2
Plasticity index (%)	14.0

2.3. Column instrumentation and monitoring

The monitoring column was equipped with various sensors, including four MPS-2 sensors, four 5TE sensors, and a dial gage for measuring the settlement. MPS-2 is capable of measuring the soil water potential in the range of 0 to −500 kPa with an accuracy of ±0.25 kPa and a resolution of 0.1 kPa. This sensor can also record the temperature in the range of −40 °C to 60 °C with an accuracy of ±1 °C. The 5TE sensor measures the electrical conductivity (EC) in the range of 0–23 ds/m with an accuracy of 10%. This sensor also measures the volumetric water content (VWC) in the range of 0–100%. In total, eight sensors were installed at heights of 5, 15, 35, and 45 cm from the bottom and connected to a data logger to record and collect the data. To measure the self-weight settlement as well as the shrinkage from drying due to evaporation, a dial gage was installed at the top immediately after casting the second lift. The filling strategy was carried out as follows: two stages of fillings with a thickness of 25 cm would be casted, with the first filling at the start of the experiment and five days later for the second filling. That is, five days after casting the first lift, the second lift was added. Each column was allocated to one specific period of elapsed time. After each elapsed time (5, 10, 20, and 30 days) the columns were dismantled and samples were taken from four different heights. The design locations of the sensors, filling sequence and location of obtained samples are illustrated in Fig. 2.

The mass of water lost in each column by evaporation was obtained by measuring the mass of the column on an approximately daily basis by using a scale (OHAUS Defender) with a readability of 0.01 kg. The initial mass of soil was recorded before evaporation was permitted. The mass of the container and tailings was measured and compared with the initial mass. The difference in mass was attributed to the mass of water lost by evaporation and drainage.

2.4. Experimental test program

In addition to the column monitoring program and procedure described above, extensive laboratory tests were conducted on MFT samples extracted from different heights of the columns at different elapsed times. The extracted samples were subjected to mechanical tests (vane shear strength) and physical property anal-