

Experimental Study of Consolidation Behavior of Mature Fine Tailings Treated with Microbial Induced Calcium Carbonate Precipitation

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ABSTRACT

Mature fine tailings (MFT) are by-products from oil sands extraction processes and pose a challenge to the geo-environmental community. Large impoundments are required to store MFT due to physical characteristics of the material, namely the high volume of the water in tailings and large-strain consolidation behavior. Microbial induced calcium carbonate precipitation (MICP) treatment has been previously demonstrated to effectively accelerate the dewatering process of the MFT; however, the change to the consolidation behavior of the MFT after MICP treatments has not been examined. In this paper, slurry consolidometers are constructed to evaluate the compressibility and permeability properties of MFT after MICP treatment. The presented test results indicate MICP can help accelerate the settlement of MFT by developing the soil skeleton with a minimal decrease in permeability.

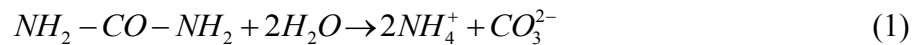
INTRODUCTION

The Clark hot water extraction process (Clark and Pasternack 1932) has been used to extract bitumen from oil sands in Alberta, Canada for decades, but in return this produces large quantities of tailings that consist of sands, fines, water and residual bitumen. Generally, mature fine tailings (MFT), which are considered a stable suspension, are formed after two to five years of disposal of fluid fine tailings into tailings ponds (Farkish and Fall 2013). With the extensive dispersed clay, low permeability and residual bitumen, studies have predicted that it will take decades or a hundred years for the MFT to reach an appropriate strength and solid content for terrestrial reclamation (Liang et al. 2015; Wong et al. 2008). The 400 million cubic meters of tailings may be increased to over one billion cubic meters by 2020 (Farkish and Fall 2013).

Researchers have made significant effort to speed up the settlement process of MFT because of the facts mentioned above. Several strategies have been advocated: freeze-thaw and dry cycling methods, composite tailings, and flocculants combining with thickeners or centrifuges approaches (Botha and Soares 2015; Farkish and Fall 2013; Proskin et al. 2010; Reis et al. 2016). Biological amendments have also been used to increase the solid contents and degrade organic matter in pore water (Siddique et al. 2014; Yu et al. 2018). Liang et al. (2015) found that microbial induced carbonate precipitation (MICP) could help increase the strength of MFT from 20.34 Pa to 789.8 Pa after 24 h of treatment.

MICP is a sustainable biological ground improvement technique that can provide cohesive bonds between soil particles through microbial metabolism (DeJong et al. 2006). Among different bio-mediated soil improvement approaches, typically *Sporosarcina pasteurii* is selected for ureolytic-driven MICP treatment on soils (Al Qabany and Soga 2013). The chemical reactions related to MICP are shown below (Eqs (1) and (2)) (Stocks-Fischer et al. 1999). Bacteria provide the urease as a catalyst to hydrolyze the urea. The products of the urea

hydrolysis are ammonium and carbonate. With the available calcium in the solution, the calcium carbonate can be precipitated under alkaline conditions.



The standard consolidation test is limited by small strain behavior and constant permeability and compressibility assumptions. However, MFT, like other slurries, undergo large settlements and nonlinear compression behavior. It is necessary to apply the large-strain consolidation theory on the MFT to estimate the consolidation behavior. The governing equation of large strain consolidation reveals the hydraulic conductivity-void ratio relationships and effective stress-void ratio relationship is presented as Eq (3) (Gibson et al. 1967).

$$\pm \left(\frac{\rho_s}{\rho_f} - 1 \right) \frac{d}{de} \left[\frac{k(e)}{1+e} \right] \frac{\partial e}{\partial z} + \frac{\partial}{\partial z} \left[\frac{k(e)}{\rho_f(1+e)} \frac{d\sigma'}{de} \frac{\partial e}{\partial z} \right] + \frac{\partial e}{\partial t} = 0 \quad (3)$$

where ρ_s and ρ_f are densities of the fluid and solid phases, e is the void ratio, $k(e)$ is the hydraulic conductivity, z is material coordinate, σ' is effective stress and t is time.

To solve the equation numerically, a constant parameter C_F or $g(e)$ presented in Eq (4) has been defined to represent the coefficient of consolidation for large strain (Been and Sills 1981; Gibson et al. 1967).

$$C_F = g(e) = \frac{k(e)}{\rho_f(1+e)} \frac{d\sigma'}{de} \quad (4)$$

The void ratio-effective stress and hydraulic conductivity-void ratio relationships expressed as Eqs ((5) and ((6) were also used for numerical evaluation (Bartholomeeusen et al. 2002; Hawlader et al. 2008; Jeeravipoolvarn et al. 2009). Hawlader et al. (2008) mentioned that the void ratio-effective stress relationship would reach a steady state which can be expressed by the line of end of primary consolidation (EOPCL). The void ratio on the EOPCL, e_f , can be also represented in a format of Eq ((5). In Eqs ((5) and ((6), A and B are constant compressibility parameters, C and D are constant hydraulic conductivity parameters.

$$e = A\sigma'^B \quad (5)$$

$$k = Ce^D \quad (6)$$

MICP treatment method may become a useful tailings disposal technique; therefore, large-strain consolidation tests were conducted to elucidate the fundamental consolidation behavior and the development of the MICP treated MFT structure. Because of the chemicals involved in MFT treatment (Eqs (1) and (2)), it is also interesting to compare the different influences of the chemical induced precipitation (CIP) and MICP on the consolidation process of MFT.

MATERIALS AND METHODS

Test materials: MFT was obtained from Syncrude Canada Ltd in Alberta, Canada. To have a homogenous suspension, the tailings were stirred for 30 min before use. Water content of MFT was 220% (ASTM D2216) and the specific gravity of the sample was 1.98. The residual bitumen in MFT can be removed by toluene (Fisher). The mass of bitumen in MFT was calculated by the mass difference of dry MFT samples between toluene washed dry MFT samples (Holowenko et al. 2000). The bitumen content was defined as the mass of bitumen divided by mass of toluene washed dry MFT samples. Specific surface area (SSA) was tested using the methylene blue spot test of the dry soil samples (Yukselen et al. 2006). Tailings particle size distribution, Atterberg

limits, specific gravity and pH were tested using sieve analysis (ASTM D6913), the Casagrande cup and rolling method (ASTM D4318), water pycnometer (ASTM D854) and pH strips (Fisherbrand), respectively, and the obtained properties of the MFT are presented in Table 1. The method of cultivation of *Sporosarcina pasteurii* (ATCC 11859) suspension and incubation of the growth media followed previous studies (e.g., Feng and Montoya 2016). Ammonium carbonate and calcium chloride were purchased from Alfa Aesar and Fisher, respectively.

Table 1. Physical properties of MFT

Property	Test result
Water content (%)	220
Bitumen content (%)	13
Sand content (%)	54.3
Fines content (%)	45.7
Specific surface area (m ² /g)	122
Liquid limit	57
Plasticity index	23
Specific gravity	1.98
pH	8.0

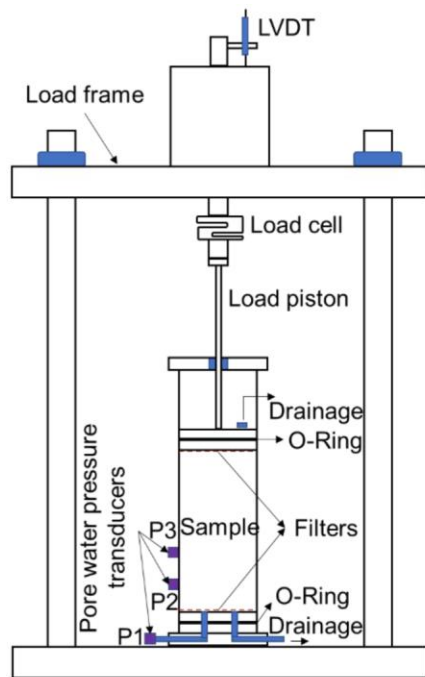
Test details: To evaluate the difference between CIP and MICP on the consolidation behavior of MFT, a chemical consolidation group (CC) and biological consolidation group (BC) were used. To maintain the same chemical components and ionic strength of the pore water, the recipe for the CC group was selected to have equivalent concentrations of ammonium and carbonate when the urea was fully hydrolyzed in BC group. The recipes of the test groups can be found in Table 2. Before the consolidation tests, the chemicals and bacteria were mixed with the tailings for 5 min by using a magnetic stirrer.

Table 2. Test groups and treatment solution recipes

Name	Description	(NH ₄) ₂ CO ₃ M	Urea M	CaCl ₂ M	<i>S. Pasteurii</i> mL/100 mL MFT
Control	MFT				
CC	MFT+(NH ₄) ₂ CO ₃ +CaCl ₂	0.25		0.075	
BC	MFT+Urea+CaCl ₂ + <i>S. Pasteurii</i>		0.25	0.075	25

Test equipment and protocol: Large-strain consolidation device (Fig. 1) was constructed following He et al. (2017). Three pore water pressure transducers (GeoTac-Trautwein) were installed at 0 cm (P1), 3 cm (P2) and 6 cm (P3) to measure the excess pore water pressure during the consolidation process. A layer of high-density polyethylene filter (Porex, Montoya et al. 2019) and two layers of 0.2 µm glass microfiber filters (Whatman) were fixed to the caps for the outflow of pore fluid only. The consolidation displacement was tracked using a LVDT position transducer (GeoTac-Trautwein) and the constant load was applied by a load cell (GeoTac-

Trautwein). The diameter of the samples was 5 cm. And the initial height of the Control, CC and BC groups were 10.15 cm, 10.5 cm and 11 cm, respectively.



(a) Schematic



(b) Photo

Figure 1. Large strain consolidometer setup

The friction between the O-Ring and acrylic wall was tested and recorded before the consolidation. Stresses of 5, 10, 20, 40 and 80 kPa were applied to the samples with the allowance of double drainage. When the excess pore water was less than 0.689 kPa, the stress was manually changed to next load increment. The initial water content and sample height of the three groups were recorded.

By using the Eqs (4) - (6) to estimate the parameters, the value of excess pore water was required. The P3 was no longer applicable when the sample height was lower than 6 cm. Therefore, the parameters were calculated based on the values from P2 and P1. To calculate the C_F , the real time k , σ' and e were used and the average values of the C_F between each load interval were reported. To estimate the relationships of void ratio-effective stress and hydraulic conductivity-void ratio, the average values of e , σ' and k were reported in this paper.

The permeability of the samples was estimated by Eq (7) from the experimental results (Been and Sills 1981), where v_s was the average solids velocity which was calculated by the rate of change in height of soils. And i was average hydraulic gradient which was determined from pore water pressure transducers P1 and P2.

$$k = -v_s / i \quad (7)$$

RESULTS AND DISCUSSION

Stress-strain Relationship: The consolidation of the Control group is a long-term and large strain process. The high compressibility response of the Control can be found in Figure 2. The 5 kPa is the seating load for the Control and the settlement under 5 kPa is almost zero. When the

effective stress went to 10 kPa, it took 10 days for the specimen to reach a settlement of 5.15 cm (Fig. 2), corresponding strain to 50.7% (Figure 3). The settlement of the Control drops suddenly when the stress increases to the next level. When the stress of the Control sample reaches to 80 kPa, the final height and strain of the specimen is 1.8 cm and 81.6%, respectively.

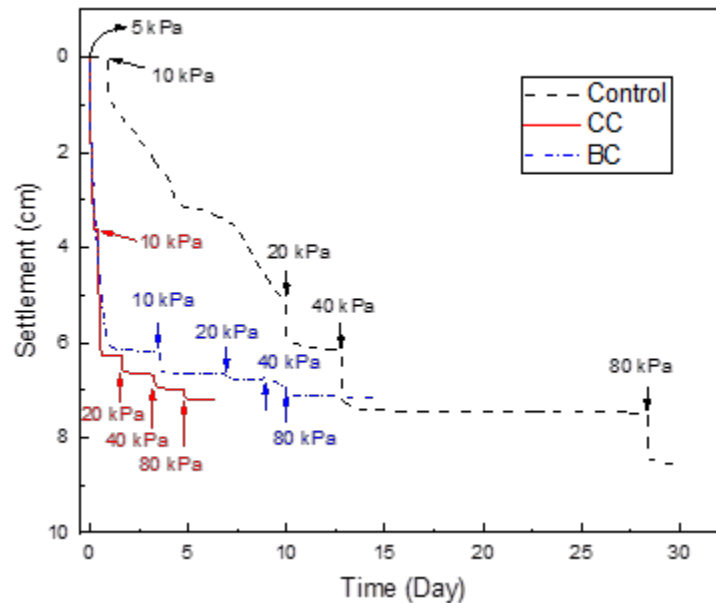


Figure 2. Vertical settlement measurement of test groups

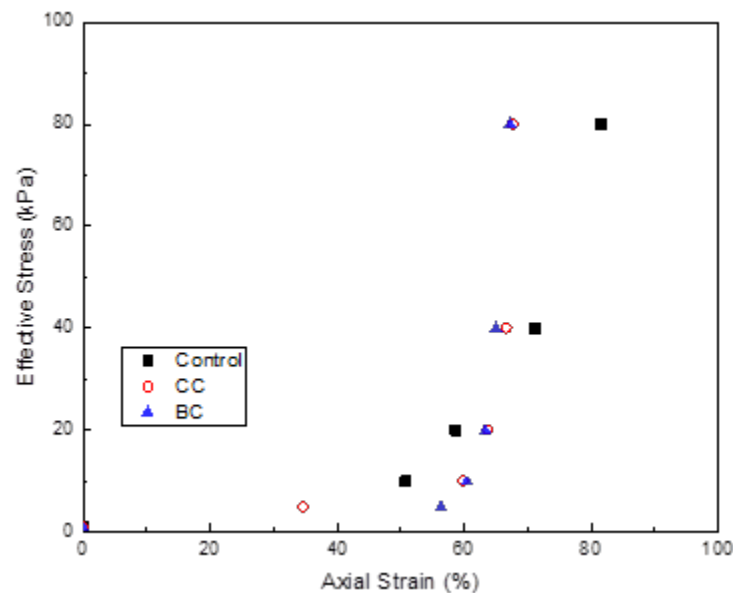


Figure 3. Effective stress versus axial strain behavior of each specimen

Comparing CC and BC with the Control, the settlement and strain of the treated samples are lower. Under 5 kPa, the settlement curves of the CC and BC are almost overlapped. The CC specimen reaches equilibrium faster than BC, so the next load increment is loaded onto the CC specimen earlier (Fig. 2). This is because the chemical reaction in the CC specimen is quicker than the biochemical reaction in the BC specimen. Bacteria need a retention time to help hydrolyze the urea. When the effective stresses of treated samples reach to 10 kPa, the strains of

the CC and BC are 59.8% and 60.4% (Fig. 3). After 10 kPa, the settlement curve of the BC group did not reduce as much with the incremental loads, which is different from the CC and Control specimens. This may be because of the development of the soil skeleton (Hawlder et al. 2008). A well-developed soil structure can resist the stress without sudden changes. The soil structure of the CC may be also developed, but with the extra stress the structure of the CC is not as good as the one of BC based on these results.

Coefficient of consolidation of large strain consolidation: Gibson et al. (1967) recommended using the C_F value (Eq (4)) as the coefficient of consolidation within Terzaghi's theory of consolidation. The average C_F values under each effective stress of the three groups are presented in Figure 4. The C_F values of the Control and treated samples have similar ranges. The C_F may represent the inherent properties of the MFT. Some studies also showed that the C_F values of other slurries were constant (Been and Sills 1981; Gibson et al. 1982).

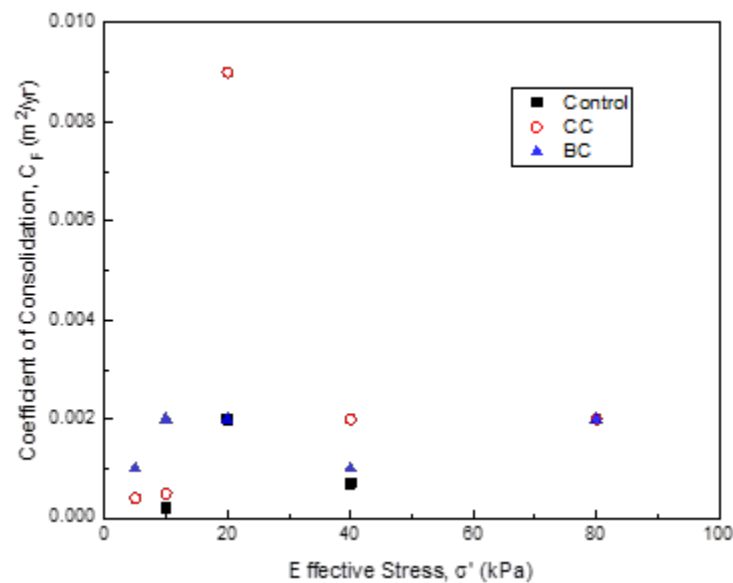


Figure 4. The relationship of coefficient of consolidation and effective stress of test samples

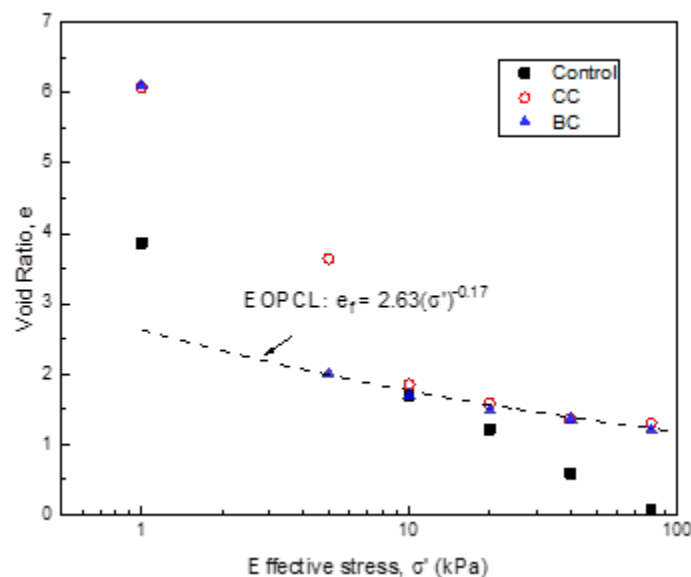


Figure 5. Void ratio versus effective stress relationships of test samples

Void ratio relationships: The compressibility of the Control was large. The void ratio of the Control specimen continues to drop with an increase in effective stress (Figure 5). However, the strains of the CC and BC specimens are changed within 10% after 10 kPa (Figure 3). The void ratios of the CC and BC specimens are almost the same after 10 kPa. By using Eq (5), the fitting for EOPCL of the CC and BC specimens is $e_f = 2.63(\sigma')^{-0.17}$ ($R^2 = 0.95$). The EOPCL represents the development of the soil skeleton and the end of primary consolidation (Hawladar et al. 2008). After 10 kPa, the soil skeleton of the CC and BC specimens can withstand the applied stress. It is noted that the void ratio of the BC reaches the EOPCL under 5 kPa. This is also consistent to previous discussion that the BC group develops the soil skeleton at lower stress.

For Control and CC groups, the void ratios keep decreasing with the decrease of the void ratio (Figure 6). The Eq (7) is used herein to model the relationship. However, the permeability of the BC group keeps the same level even with the decrease of the void ratio. From the chemical perspective, the CC and BC groups have the same chemical reactions (Eq. (2)). So, the different behavior of permeability is from the biological influence. Because of the surface negative charge, calcium ions deposit on the surface of the soils and microbial cells (DeJong et al. 2006). The calcite of the BC groups precipitates on the soil surface maintain a relatively constant permeability, while the precipitation of the CC group may be found in pores thus reducing the permeability.

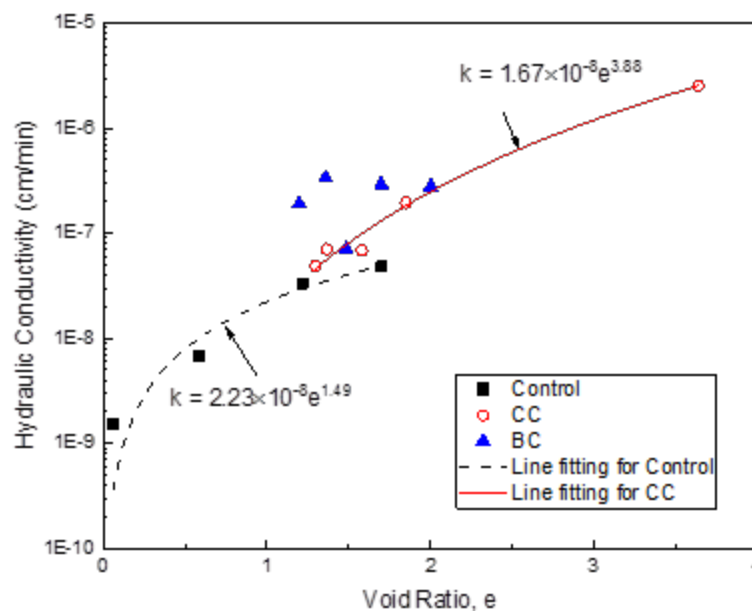


Figure 6. Hydraulic conductivity versus void ratio relationships of test samples

CONCLUSIONS

The consolidation behavior of the MFT treated by MICP method has been studied by a large-strain consolidation setup. The Control presents the large-strain and long-term consolidation behavior which result in decreasing permeability and void ratio with increasing effective stress. The sudden changes in shapes with extra stress shows that the soil skeleton of the Control has not develop during the test. While, the CC and BC can accelerate the settlement process of the MFT by developing the soil skeleton. After 10 kPa, the strain of two treated groups is smaller

than 10% and the soil skeletons have been established. The consolidation behavior of the CC and BC are similar due to similar chemical reactions. However, BC which represents the MICP treated group shows an earlier development of soil skeleton and less reduction in permeability. The difference of the MICP method from the chemical treatment may come from the preference of precipitation on the soil particles as the nucleation site.

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