DENSIFICATION OF OIL SANDS TAILINGS BY BIOLOGICAL ACTIVITY

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ABSTRACT
Since operation began in 1978, the Mildred Lake Settling Basin (MLSB) has been Syncrude Canada's largest settling basin for fine tailings (FT), an aqueous suspension of silts and clays and un-recovered bitumen, that results from oilsands extraction processes. This suspension was originally expected to densify to a mature fine tails (MFT) slowly, with full consolidation taking many decades. However, since the mid 1990's, MFT densification in the MLSB has significantly accelerated over the rates seen up to that time, and this phenomenon occurred concurrently with increased microbial activity and biogas (CH_4, CO_2) accumulation and efflux from the MFT. A field and laboratory research program was initiated to study the mechanism leading to this more rapid densification. As part of the research program, small-scale column tests were carried out to observe the gas evolution and to measure the changes of some geotechnical parameters under different microbial activities. These tests have provided valuable insights into the role of microbial activity on this accelerated densification. The test procedures and results generated from these small-scale column tests are described. Through these column tests, a better understanding of the relationship between the rate of gas generation, its migration pathways in the MFT and the densification and development of strength within the MFT has been observed.

RÉSUMÉ
Depuis que l'opération a commencé en 1978, le bassin d'arrangement de lac Mildred (MLSB) a été le plus grand bassin d'arrangement de Syncrude Canada pour des produits de queue fins, une suspension des vases et des argiles et unrecovered le bitume, ce des résultats des processus d'extraction d'oilsands. Cette suspension a ét à l'origine prévue densify aux queues fines mûres (MFT) lentement avec la pleine consolidation prenant beaucoup de décennies. Cependant, depuis les mi années 90, le densification de MFT dans le MLSB a sensiblement accéléré au-dessus des taux vus jusqu'à ce temps. Ce phénomène s'est produit en même temps que l'accumulation microbienne accrue d'activité et de gaz. Un programme de recherche de champ et de laboratoire a été lancé pour étudier le mécanisme menant à ce densification plus rapide. En tant qu'élément du programme de recherche, des essais de petite taille de colonne ont été effectués pour observer l'évolution de gaz et pour mesurer les changements de quelques paramètres géotechniques sous différentes activités microbiennes. Les méthodes et les résultats d'essai produits de ces essais de petite taille de colonne sont décrits.

1. INTRODUCTION

The Mildred Lake Settling Basin (MLSB) contains mature fine tailings (MFT) that have been accumulating since Syncrude started production in 1978 (Figure 1). Currently, the MLSB has a surface area of about 11 km^2, and contains about 200 Mm^3 of MFT and 30 Mm^3 of released water. The MFT zone can exceed 40 m in depth. Until 1991, all extraction tails were discharged into the MLSB. By 1999, only a small fraction of whole tailings were input to the MLSB. As well, starting in 1995, MFT has been transferred to another pond, the West Inpit (WIP). Because of the low permeability of the fines fraction, considerable depth and chemical properties of the MFT, its densification is slow and the void ratio of the fines has been around 6 near the surface to 4 at depth (MacKinnon 1989). Analyses have indicated that self-weight consolidation would take many decades. Since 1995, the expected densification rate of the MFT at the pond has accelerated. Field investigations have provided convincing evidence for the rapid densification phenomenon (Guo et al. 2002). Methane producing microorganisms, known as methanogens, have become very active in the part of the pond that is experiencing rapid densification (Holowenko et al. 2000). Bubbles of the released methane emanating from the MFT have become very noticeable during this period, as illustrated in Figure 2. Figure 3 shows the depth profiles of the solids and fines contents (expressed as fines/(fines+water) where fines are solids <22um) during the period from 1986 to 2003. Rapid increases in solids and fines contents can be seen since 1996 from the profiles.

Acoustic geophysical methods that had been used to determine bottom topography of the MLSB became inefficient by 1994, and this was due to the presence of large amounts of gas bubbles in the MFT. By 1996, gas bubbles were evident at certain areas of the MLSB (Figure 2). Flux chambers identified this escaping gas to be mainly CH_4 (Clearstone Engineering Ltd.1998).

Based on the monitoring data of MFT at the MLSB, MacKinnon et al. (1993) proposed an empirical relationship of solids content changes with time. This equation matched densification rates observed in fine tails up until about 1995. After 1996, the measured solids contents in profiles from southern part of the MLSB were greater than predicted by the earlier empirical equation (Mikula et al 1996):

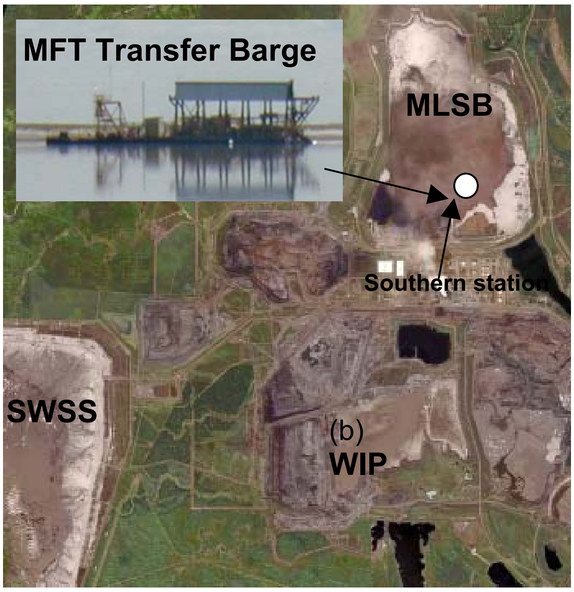

Figure 1 Syncrude's storage and settling basins

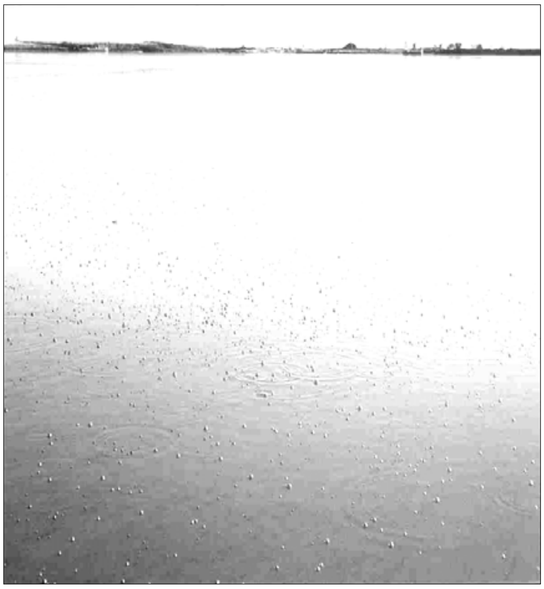

Figure 2 Gas bubbles on the surface of the pond

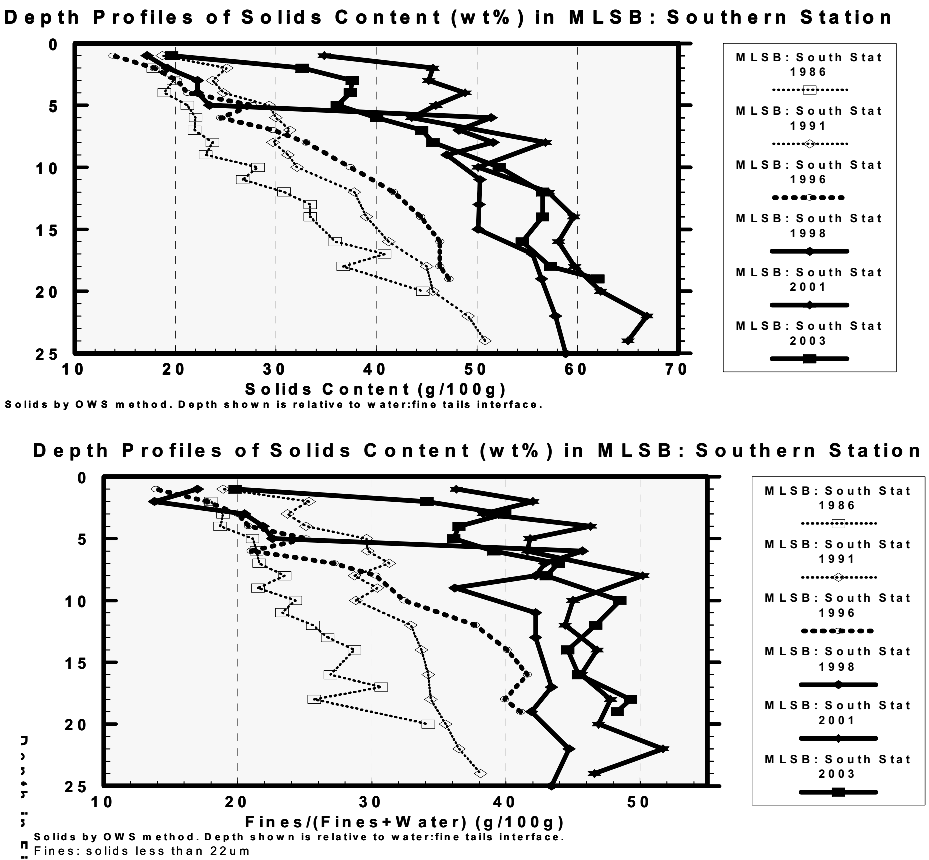

Figure 3 Changes in (a) solids and (b) fines (<22um) contents by depth for various years in vicinity of MFT transfer barge.

$F=18.6+6.3\ln(Y)$

where F = % fines {f/(f+water); f=solids<22um}
Y = years since deposition

The potential positive effects of the rapid densification of the MFT are considerable. An acceleration in fines densification by 10% over that predicted in the above equation would produce a fines content of about 43% after 10 years compared to the predicted 33%. For each 100 Mm^3 of MFT expected by the empirical relationship, the higher density would equate to an inventory reduction in MFT of 30 Mm^3. In the southern parts of the MLSB, such an increase in the density of the MFT has been observed (Figure 3). This has impact on water and tailings management, as well as an effect on reclamation options. With densification, a strengthening of the MFT occurs, and this may have implications on the transfer of fine tailings from one settling basin to another (currently there is MFT transfer from the MLSB to the WIP). This denser MFT could lead to challenges to alternative tailings treatment options such as composite tailings (Matthews et al. 2001). Increased biogenic gas production could lead to increased methane release, with ensuing greenhouse gas issues. In order to study the mechanism leading to the accelerated densification and to utilize the mechanism to accelerate reclamation of the MFT, a field and laboratory research program was initiated. The research program consisted of field investigations, small-scale column tests and laboratory gassy MFT densification tests with enhanced biological activity. In this paper, some results of the field investigations and small-scale column tests are presented.

2. FIELD INVESTIGATIONS OF THE RAPID DENSIFICATION OF THE MFT

Since 2000 systematic field surveys in the MLSB have focused on the distribution and properties of the densified MFT in the MLSB (Guo et al. 2002). Methods such as, piston and freeze sampling were used to collect undisturbed samples from these densified layers. In situ testing with shear vane, cone penetration tests (CPT), piezometer and earth pressure measurements, and steel plate penetration tests (SPP) were developed and applied. In this paper, some results of the field mapping of gas bubble distribution and steel plate penetration (SPP) tests are presented.

Due to microbial activity in the MFT, biogenic gas is produced. According to Fedorak et al. (2000), the main component of the biologically produced gas in the strict anaerobic environment of the MFT is methane, which is generated by methanogenic bacteria. When the gas volume in the MFT reaches a critical state, some of it will escape from the MFT zone and can be observed as bubbles at the water surface of the pond (Figure 2). The distribution of gas bubbles at the water surface reflects microbial activity within the MFT in that area.

Field observations were used to map the gas bubble distribution. The presence and level of gas bubble release were mapped using GPS. In 2002, two zones were outlined as shown in Figure 4. Zone B represents the intensified gas bubbling zone with a large number of gas bubbles on the water surface and active ongoing gas bubble release. Zone A showed low or absent gas release activity, with fewer gas bubbles visible on the surface. The photos of the water surfaces at zone A and zone B are shown in Figure 5 and Figure 6.

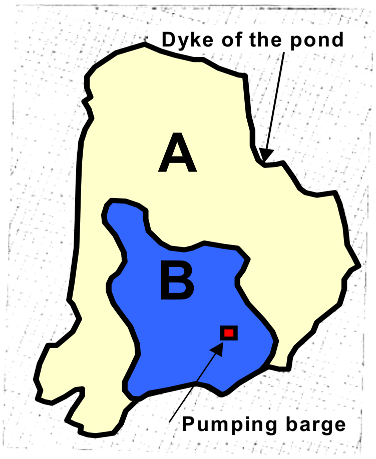

Figure 4 Mapping of gas bubble distribution at the MLSB in 2002

Figure 5: A photo of the water surface at zone A

Figure 6: A photo of the water surface at zone B

The steel plate penetration (SPP) test was found to be a simple and effective method to measure relative bearing strengths and locations and areal extent of the densified layer of the MFT. Guo et al (2002) described its operation and application on MFT investigation. This test is rapid and cost effective. The range of the densified MFT could be determined both vertically and areally with this method.

Figure 7 shows the areal extent of the densified MFT in the pond based on the penetration of the steel plate with an effective base stress of 10.3 kPa. At the northern regions of the MLSB, little resistance was noted and this steel plate penetrated to the bottom, while at most locations in the southern part of the pond, its descent was stopped at depths ranging from 4 m to 11 m below the water-MFT interface. This indicated that in those areas where rapid densification has progressed as in most of the southern region of the pond, a corresponding increase in bearing strength occurred. The shaded zone in Figure 7 represents the approximate areal extent, about 3 km^2, of the rapidly densified MFT. By comparing Figure 4 and Figure 7, a clear connection between the intense microbial activity and the rapid densification of the MFT can be observed.

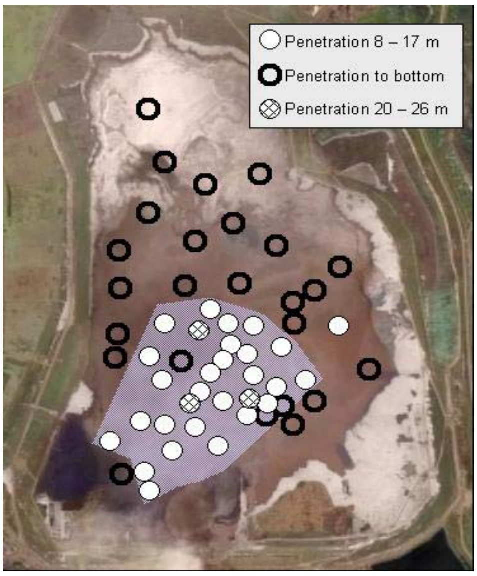

Figure 7 Steel plate penetration tests in the MLSB

3. SMALL-SCALE COLUMN TESTS

3.1 Test device and procedures

The objective of the small-scale column tests was to model the microbial activity occurring in the MLSB, to observe gas bubble migration and to provide preliminary data on the influence of microbial activity on the densification of the MFT.

Figure 8 is a sketch of the small-scale column test for gassy mature fine tailings. The test device consists of a glass column with an inner diameter of 60 mm for the test materials and a graduated cylinder (overflow water collection cylinder for gas volume measurement)) of a small inner diameter. The height of the glass column is 50 cm. A glass tube connects the glass column to the water collection cylinder. A rubber stopper completely seals the top of the glass column. Silicon sealant is used to prevent water or gas leakage

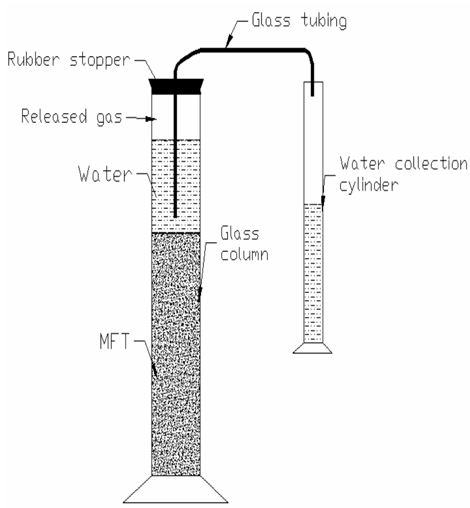

Figure 8 Schematic of small-scale column test

Before filling with MFT, the column was flushed with nitrogen gas to replace air in the column. This helped to maintain an anaerobic environment for methanogenesis. Above the sample, recycle water from the MLSB was poured into the column until it was full. A ruler is fastened vertically on the outside wall of the column to measure height changes.

The test assembly was then placed in a constant temperature room. During microbial activity, the water-MFT interface movements, released gas volumes and water volumes in the water collection cylinder were all measured with time. Microbial activity and gas bubble migration were observed and photographed

3.2 Test condition and initial parameters

The MFT were originally retrieved from about 2.5 m below the water-MFT interface in the southern part of the MLSB. The samples were totally remoulded prior to testing. Fused crystals of sodium acetate (CH3COOHNa) were uniformly mixed with the sample before pouring into the column. After the samples were remoulded and mixed, some initial parameters were measured, as shown in Table 1.

The microbial activity could be controlled by adjusting the dosages of sodium acetate and by incubating the system under different temperatures, as shown in Table 2. Samples 1, 3 and 5 were incubated at 25^o C with sodium acetate levels of, 0, 0.52 and 1.52 g/L of MFT. For columns 2 and 4, two levels of acetate were added and incubation occurred at 4° C. The purpose of these two tests was to determine the influence of the acetate itself on densification of the MFT at a lower temperature where microbial activity should be slower.

Table 1 Some initial parameters of the remoulded MFT sample

Density	Solids	Bitumen	Void ratio	Particle size distribution (%)		
g/cm^3	content (%)	Content (%)	(e)	<2μm	<22μm	<44μm
1.262	36	4.82	4.43	51	89.9	93.1

Table 2 Test conditions of the small-scale columns

Column No	Initial sample height (cm)	Acetate addition (g./L MFT)	Incubation Temperature (Deg. C)
1	25.9	0	25
2	24.6	0.52	4
3	23.4	0.52	25
4	24.8	1.52	4
5	24.4	1.52	25

3.3 Test results

The interface and volume measurements were used to estimate the gas and water volumes within the MFT at different times during microbial activity. The solids volume in a column was assumed to be constant during the test. In these columns, the pressures for both the trapped and released gas were close to atmospheric pressure.

Figure 9 shows the ratio of the total gas production volume to the initial MFT volume. Some details about the gas generation are summarized in Table 3. The more acetate that was added to the MFT, the more gas was produced, provided the temperature was sufficient to support microbial activity. In columns 2 and 4, large amounts of acetate were added, but there was no visible gas generation under low temperatures (4° C).

Figure 10 shows the gas contents (a ratio of the trapped gas volume within the MFT to the total sample volume in %) in samples 1-3 at different times. All the gas produced in samples 1 and 3 remained trapped in the MFT structure. For sample 5, gas started to release from the sample after the gas content reached 14.6%. For sample 3, the maximum gas content reached was 12.5%, which is less than the peak gas content for sample 5. These results suggest there may exist a threshold gas content at which gas starts to escape from the MFT. After dramatic microbial activity (gas generation and release) had ceased in samples 3 and 5, the gas contents in these two samples continued to increase at slow rates. Measurements of water volumes in the water collector, released gas volumes at the top of the column and the water-MFT interface movements, allowed the water volume drained from the samples to be estimated at

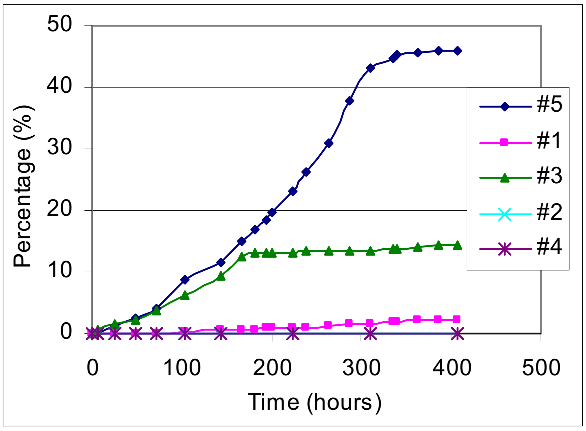

Figure 9 Ratio of total gas production volume to initial MFT volume in %

Table 3 Some details of gas generation in the columns

Column No	Ratio of total gas vol. to initial MFT vol. In %	Notes
1	2.3	Continue to slowly generate gas at the end of the test
2	0	No visible gas generation
3	14.2	Significant gas activity lasted 8 days
4	0	No visible gas generation
5	46	Dramatic gas activity lasted 15 days

different times. Figure 11 shows the drained water volumes with time for samples 1, 3 and 5. At the end of the tests, the drained water volumes in columns 5, 3 and 1 were approximately 48.8 ml, 30.9 ml, and 7.1 ml, respectively.

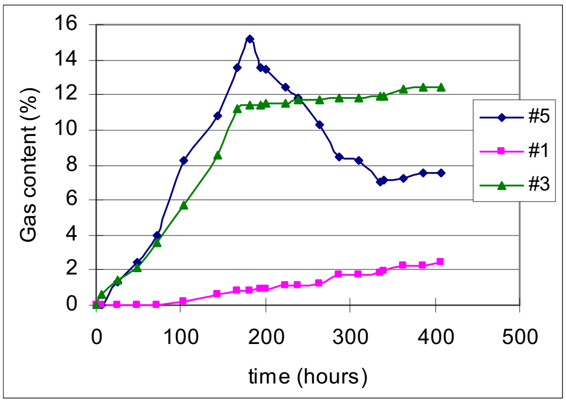

Figure 10 Trapped gas contents within the MFT

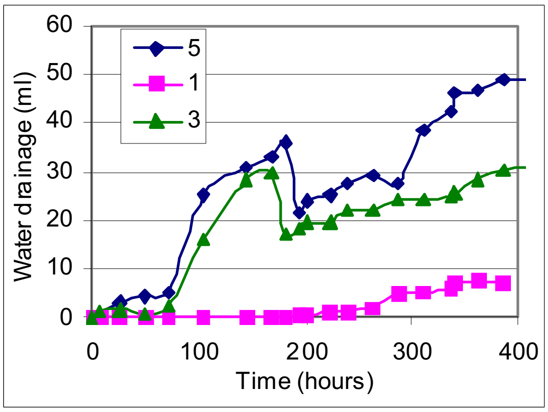

Figure 11 Drained water volumes from the MFT

Figure 12 shows the trapped gas volumes and the changes of total MFT volumes in column 3 during microbial activity. During the first 180 hours, the gas volume within the MFT increased rapidly, but the expansion of the global MFT structure lagged behind the increase of gas bubble volume. After 180 hours, the gas volume in the MFT increased slowly, but the total MFT volume decreased slightly. It is likely that the viscous structural resistance within the MFT restricted the expansion of the MFT matrix during the early period of gas bubble growth, and the MFT structure slightly collapsed during the later test period.

Table 4 gives a summary of some parameters measured after completion of the small-scale column tests. These parameters are the averages for each column. Since the column size is relatively small, each column was treated as a single sample even though there were small variations in the parameters at different levels within the column. The average values still remain useful in characterizing the overall influence of gas generation on densification of the MFT.

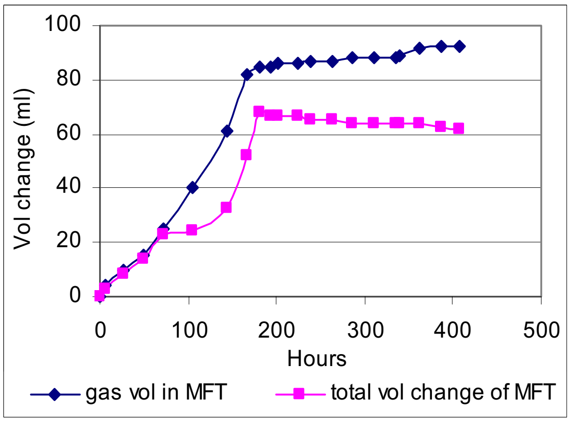

Figure 12 Trapped gas volumes and total MFT volume changes in column 3

At 25° C, increased sodium acetate concentrations lead to increased generation of gas and an increase in the final average solid contents. Although column 5 yielded the largest amount of gas, the final gas content was lower than that in sample 3 due to the release of large amounts of gas from sample 5.

In order to further compare the densification properties of the five columns under different microbial activities, the MFT in the columns was sampled at different elevations with a spoon sampler at the end of each test. The results are shown in Figure 13.

Table 4 Some parameters at the end of testing

Column No.	solids content (%)	Density (g/cm^3)	Void ratio (e)	Fluid void ratio	Gas void ratio	Degree of saturation (%)	Water content (%)	Gas content (%)
1	36.3	1.236	4.51	4.34	0.17	95.7	175.5	2.41
2	36.1	1.267	4.41	4.41	0	100	177	0
3	37.98	1.092	4.96	4.14	0.82	81.4	163.3	12.47
4	36.08	1.269	4.40	4.397	0	100	177.2	0
5	39.7	1.15	4.46	4.0	0.46	85.1	151.9	7.56

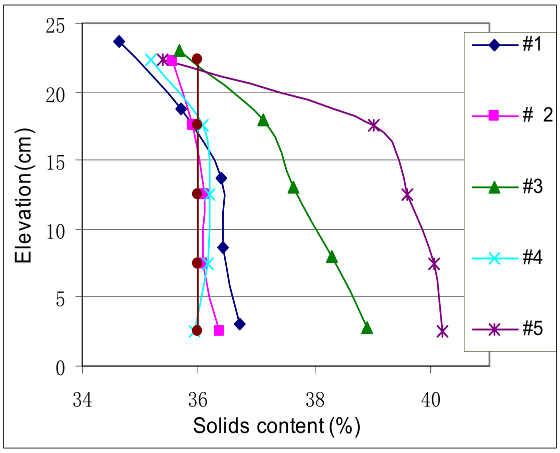

Figure 13 Profiles of final solids contents

The initial solids content of the MFT was 36% by weight. After gas generation the solids contents in the samples varied considerably. For columns 2 and 4, the final solids contents were close to the initial value, although there was a slight increase. While the amount of sodium acetate added to column 4 was much higher than that added to column 2, the final solids contents in the two columns were similar. This demonstrates that the sodium acetate alone has very little influence on densification of MFT and serves only to stimulate microbial activity and biogas generation. For columns 1, 3 and 5, having increasing amounts of sodium acetate, microbial activity was accelerated and the final solids contents were increased. Although no sodium acetate was added to column 1, the final solids content is still higher than those in columns 2 and 4 which had acetate added. This demonstrates that the microbial activity within the initial MFT can be accelerated by temperature increase, and that water drainage can also be improved even if gas generation occurs at a relatively slow rate. Even in MFT samples not amended with acetates, anaerobic bacteria activity will proceed. The added acetate augments this activity, but the absence of the added substrate does not imply that microbial activity would not occur.

The results of small-scale column tests can also help answer another important question: can water drainage and its release from the MFT be improved even if there is no gas release? Although all the gas produced in column 3 remained within the MFT, the drainage was still accelerated compared with columns 1, 2 and 4, so the answer to the question appears to be yes.

3.4 Observation of gas migration in column 5

All columns were set up on March 7, 2003 (Day 1). On Day 2, small fissures were observed in the upper part of the MFT in column 5. On Day 5 the level of the MFT interface was visibly higher, and cracks appeared on the top of the MFT. On Day 7 (Figure 14) these large cracks divided the top of the MFT into brick-shaped blocks. At a level about 6 cm below the interface a large crack (2.3 cm length and 0.3 cm width) was observed. Most of the large voids and cracks were above a height of about 10 cm from the bottom of the column. This was likely due to the upward migration of large gas bubbles. On Day 9 gas accumulation within the MFT reached a critical state. The gas bubbles burst out of the interface (Figure 15). The brick-shaped blocks were broken due to the sudden flooding of gas bubbles. The interface of the MFT then rapidly settled and the large gas cracks located at 6 cm below the water-MFT interface disappeared. Gas bubbles continued to form, migrate, accumulate and release until Day 18 (March 24). Some large cracks were observed to form and disappear during the test period. When gas bubbles were released from the MFT, obvious structural collapse within the MFT was observed, which caused a rapid downward movement of the water-MFT interface. At the end of the test (Day 24), mainly occluded gas voids remained, as shown in Figure 16.

Figure 14 Column 5 on Day 7

Figure 15 Column 5 on Day 9

Figure 16 Column 5 on Day 24

4. CONCLUSIONS

From field investigations and small-scale column tests, some preliminary conclusions are:

- microbial activity and biogas generation can accelerate water drainage from the MFT;
- microbial activity of the MFT can be controlled by changing the temperature or adding sodium acetate;
- sodium acetate alone has very little influence on the densification except for its role in stimulating microbial activity and gas generation;
- microbial activity and biogas generation can accelerate the drainage of the MFT even if all the generated gas remains within the MFT (no gas is released);
- when gas accumulation in the MFT reaches a critical state, part of the produced gas will escape from the MFT;
- gas bubble formation, migration and release can change the structure of the MFT. This change may help accelerate the water drainage from the MFT; and
- due to the resistance provided by the MFT matrix, the global expansion of the MFT lags behind the gas bubble growth during the early period of gas generation.

The phenomenon observed in the small-scale column tests provides a preliminary understanding of the rapid water drainage from the MFT during microbial activity and gas generation. Research is continuing on comprehensive consolidation tests of MFT under varying conditions.

5. ACKNOWLEDGEMENTS

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