Centrifuge-Dewatered Mature Fine Tailings: Geotechnical Observations from a Field Test



Rick Lahaie Syncrude Canada Limited, Fort McMurray, Alberta, Canada Jack T.C. Seto BGC Engineering Inc., Edmonton, Alberta, Canada

ABSTRACT

Syncrude Canada Ltd. has been examining several alternative tailings technologies aimed at reducing the accumulation of mature fine tailings (MFT) and creating trafficable surfaces for reclamation. One such method is to dewater the MFT using centrifuges. During a six-week period in 2008, centrifuge cake was produced and deposited in five partly-contained cells as well as two large culverts. Centrifuging increased the solids content of MFT from 30 percent to over 50 percent. The deposits were instrumented, sampled, and tested over a one-year period. Natural desiccation densified and strengthened the exposed cell deposits, resulting in solids content exceeding 70 percent and undrained shear strengths exceeding 15 kPa less than one year after deposition. Cake in the two large culverts were slower to consolidate and strengthen.

RÉSUMÉ

Syncrude Canada Ltd examine plusieurs technologies de résidus de remplacement visant à réduire l'accumulation de résidus fins mûrs (MFT) et la création de surfaces praticable pour la remise en état. Un tel procédé consiste à assécher le MFT en utilisant des centrifugeuses. Au cours d'une période de six semaines en 2008, le matériau a été produit et déposé en cinq cellules partiellement contenu ainsi que deux grands ponceaux. La centrifugation a augmenté la teneur en solides de MFT de 30 pour cent à plus de 50 pour cent. Les dépôts ont été instrumentés, échantillonnés et testés sur une période d'un an. La dessiccation naturelle a densifié et renforcé les dépôts de cellules exposées, ce qui entraîne une teneur en solides de plus de 70 pour cent et des résistances au cisaillement non drainé plus de 15 kPa moins d'un an après le dépôt. Les matériaux dans les deux grands ponceaux ont été plus lents à consolider et à renforcer.

1 INTRODUCTION

Syncrude is currently examining several technologies for managing Mature Fine Tailings (MFT) volumes at Syncrude's Mildred Lake operations in Fort McMurray, Alberta. One such technology is centrifuge-dewatering, in which MFT is diluted and dosed with flocculent, then processed through a centrifuge plant, and the highdensity underflow (also known as "cake") is transported to a tailings deposit and the low density overflow centrate is recycled back to the operation.

Centrifuge-dewatering of tailings is not a new technology. For instance, this method has been used in a few instances in Australia to dewater tailings before disposal, typically at mines where land for a tailings storage facility is not available or where transportation options preclude pumping (Australia Dept. Of Industry, Tourism and Resources, 2007). Historically, tailings dewatering by centrifuges has been the most costly method for removing water from tailings prior to disposal. Improvements in the design and operation of centrifuges, and most especially in flocculants needed to prepare the tailings, have improved the efficiencies of the equipment and reduced the costs of dewatering.

In the oil sands industry, centrifuges are used extensively in oil sand froth treatment. However, they

have not been used to dewater fine fluid tailings on a commercial scale.

Syncrude began laboratory bench trials of this technique in 2005. In 2007, a pilot study was carried out over a 2-week period using relatively large oilfield centrifuges.

2 CELL LAYOUT AND INSTRUMENTATION

Between August and October, 2008, a six-week trial was carried out on better understand the process and operation of MFT centrifuging and to evaluate how centrifuge-dewatered MFT could be reclaimed. The test was carried out on the tailings beach of the Mildred Lake Settling Basin (MLSB). A large excavated pit located just north of the test cells served as an interim storage pit for MFT that was dredged over from the MLSB tailings pond and ultimately fed through the centrifuge plant.

The centrifuge cake was deposited in five partlycontained cells (cell deposits) ranging in size from approximately 10 m by 25 m to 25 m by 35 m in area.

It was intended to fill the cells up to initial thicknesses of between 1 m and 3 m, but none of the cells were ever filled more than 2 m thick. It was also intended to deposit the cake in a variety of methods, including from a conveyor, with a front-end loader, and with a positive displacement pump system. The cell deposits were left exposed to ambient climatic conditions



Figure 1. Layout of centrifuge test (prior to deposition)

Two excavation pits lined with large, upright culverts (culvert deposits) (3 m diameter and 5 m deep) were also constructed. One of the upright culverts was lined with a geomembrane liner and filled with process water prior to filling with centrifuge-dewatered MFT and was intended to simulate subaqueous deposition of cake. The second upright culvert was left unlined prior to filling and was intended to simulate subaerial depositon of cake. Cake was deposited into each culvert via a conveyor. These deposits acted as large-scale column tests to study one-dimensional consolidation behaviour. Each culvert was eventually housed in a structure that was heated during the winter to prevent it from freezing.

Figure 1 shows the test layout.

Based on previous studies, it was anticipated that the produced cake would be initially at a solids content of approximately 55 percent and in a fluid-like state (less than 2 kPa undrained shear strength). Given time, it was expected that the cake would settle and densify due to self-weight consolidation. Natural desiccation from evaporative drying and freeze-thaw dewatering was expected to enhance densifications of the exposed cell deposits. The deposits were to be monitored over a one-year period.

In many of the cells, graduated posts were installed for visual monitoring of the deposit surface elevation. Vibrating wire (VW) piezometers were attached to some of the posts at various heights, as shown in Figure 2. The instrumented posts were installed prior to filling the cells.



Figure 2. Typical instrumented post.

Because the cell deposits were initially too soft to support foot traffic, conventional survey methods were impractical. Therefore, for this test, a ground-based laser scanning technique was is gaining. The technique is gaining acceptance in geotechnical applications such as landslide monitoring and consists of sending and collecting laser pulses from surface objects to build a point file of three-dimensional coordinates. The sensor is somewhat larger than a conventional SLR camera and is mounted on a tripod. The time of travel for a single pulse return from a surface is measured along a known trajectory such that the distance from the laser - and consequently the exact location - can be computed. In addition, visual data on points located within and outside of the laser range can be obtained through the use of a charge-coupled device (CCD) colour sensor. Scans are typically taken from a number of locations surrounding thetarget zone (in this study, each individual cell). The point files from the collected scans are then transformed into three-dimensional surfaces. Point measurement accuracy depends on a number of factors, including the number of scans, their coverage, the shape of the deposit, and the number and distribution of control points. The laser scanners cannot see behind objects or below water.

The laser scans were carried out on October 10, 2008, less than a week following filling of the last cell deposit, and again eight months later, on June 5, 2009.

3 CAKE PROCESSING

During cake production, samples were regularly collected from the centrifuge feed, centrate and cake for solids content measurements. The results indicated that early during the centrifuge pilot, when process controls were being adjusted and optimized, the solids content of the centrate was relatively high (up to 13 percent) and solids capture (amount of solids retained in the cake) during the processing was quite variable, generally ranging from 40 to 100 percent. During the other days, solids capture was better-controlled, typically exceeding 80 percent.

Apart from the solids content tests, there were only a few tests conducted for particle size analyses and Atterberg Limits.

Based on the dates and times from which samples were collected and knowing approximately when the deposits were filled, the initial conditions of each deposit were inferred.

The average initial solids content of the various deposits are estimated to range from 49 percent to 68 percent. The fines content (percentage of solids less than 44 microns) of the cake ranged from approximately 70 to 90 percent. Atterberg limit testing indicated that the cells that were filled earlier during the pilot test contained cake that was lower-plastic (liquid limits ranging from 33 to 49 percent and plastic limits ranging from 22 to 26 percent) than those that were filled later (liquid limit of 56 percent). Figure 3 shows how the cake typically looked like "fresh".

4 CLIMATE DURING PILOT TEST

The nearest weather station is located approximately 1 km west of the test site. Mean daily air temperatures were generally sub-freezing from early-November 2008 to late-March 2009. Relative humidity was generally low (averaging approximately 50 percent) from mid-April to mid-June 2009 and higher (averaging 76 percent) for the remainder of the pilot test. Wind was steady year-round, averaging 2.8 m/s.



Figure 3. Typical produced cake.

Weather data from Environment Canada's meteorological station at Fort McMurray Airport meteorological station were reviewed and compared against the long-term normals (average for period of 1971-2000) to assess if abnormal weather may have impacted the natural desiccation processes. Precipitation totals were observed to be lower than normal between December 2008 and June 2009 (combined 85 mm versus 128 mm). The drier spring of 2009 may have enhanced evaporative drying.

5 GEOTECHNICAL OBSERVATIONS

The test deposits were regularly sampled and tested in situ to assess changes in density and shear strength of the deposits over time. The first sampling/testing program was carried out in early-November 2008, approximately one to two months following cake deposition, and the last sampling/testing program was carried out in mid-September 2009, approximately one year following cake deposition.

All cell deposits were initially too wet and soft to support foot traffic. In November 2008, 1.22 m by 2.44 m (4 ft by 8 ft) plywood sheets were laid onto the deposit surface to reduce bearing pressures so that field personnel could safely walk over the deposits for sampling and testjing. During the other sample and testing periods (from April 2009 onward, or approximately six months after the cells were filled), the deposit surface was firm enough to support foot traffic.

Samples were generally collected using a piston tube sampler, which provides 38 mm diameter continuous cores. Frozen cake from the cell deposits was sampled on April 1, 2009, using a CRREL core barrel attached to a portable 2-person auger. This method provided 76 mm diameter cores. Laboratory testing included oven-dried solids content, in addition to the washed sieve (passing the No. 325 or 45 microns), Atterberg Limits, and the Dean Stark test for determination of bitumen content.

In situ strengths were determined using predominantly a field vane but also a portable cone penetration probe and a ball penetrometer probe. The ball penetrometers is similar to a cone penetrometers except that the conical tip is replaced by a spherical attachment. It is an investigation tool that is generally used to measure the undrained shear strength of very soft cohesive soils. The ball tip used in this investigation had a projected area of 100 cm² and was pushed by hand at a rate of approximately 2 cm/sec.

For the sake of brevity, only the results from the planned 3 m Cell (referred to here as Cell A) and from the Lined Culvert deposits are described in this paper. The other cell deposits showed more densification and strength gain after one year than did Cell A. The geotechnical response of the Unlined Culvert was very similar to that of the Lined Culvert.

5.1 Cell A Observations

Based on laboratory tests conducted on samples collected during the time that the cell was being filled, cake deposited in Cell 3 A had the following initial index properties:

- Oven-dried solids content = 52 %wt
- Fines content (< 44 microns) = 87 %wt
- Plastic limit = 24%
- Liquid limit = 56 %

Figure 4 shows a view of Cell A one week after the cell was filled (October 10, 2008). By this time, desiccation cracks started to develop around the perimeter.



Figure 4. View of Cell A (October 10, 2008).

The exposed cake began to freeze by November 2008 and it is believed that all cell deposits completely froze through (up to approximately 1.5 m thickness) by the end of the winter. Reticulate ice lenses were visible in all frozen cores sampled on April 1, 2009. All snow cover melted from the deposit surface by mid-April 2009 and by then, surface cracking became more widespread, as shown in Figure 5.



Figure 5. View of Cell A (April 22, 2009)

By early-June 2009, extensive surface cracking of Cell A was evident and cracks approximately 25 cm deep were observed near the cell perimeter. Water was not encountered during sampling, but water was observed in the open sample holes near the centre of the deposit at depths ranging from 4 cm to 12 cm two days after sampling. Frost was observed in some of the cores. The surface was firm enough to support foot traffic but the deposit had a spongy feel, particularly near the cell perimeter.

Figures 6 and 7 shows views of Cell A in June and September 2009, respectively. The cell deposit continued to dry through the summer, although little visual differences were observed after July 2009.



Figure 6 View of Cell A (June 5, 2009)

Table 1 presents the observed surface heights at the reference posts.

Table 1. Height of Deposit Surface (in metres) at Reference Posts

Date	Upslope Post	Downslope Post
November 2008 (1 month)	1.38	1.18
April 2009 (6 months)	1.31	1.17
June 2009 (8 months)	1.08	0.93
July 2009 (9 months)	0.97	0.86
September 2009 (11+ months)	0.95	0.83

As shown in Table 1, Cell A settled vertically approximately 30 percent between November 2008 and July 2009. The greatest incremental change occurred between April and June 2009 when ice lenses that formed in the cake over the winter thawed and drained away.

As previously mentioned, ground-based laser scanning was carried out in October 2008 and June 2009 to remotely map the surface topography of the cell deposits. Sub-centimetre accuracy was both desired and expected, but when the results from the June 2009 survey were compared against spot elevations taken using conventional survey methods, the error in surface elevations was found to be up to 30 cm. The technique is still considered useful for this type of application, and should be tried again, possibly with more scans to improve the accuracy.



Figure 7 View of Cell A (September 11, 2009)

Cell A did not have any piezometers installed during the test, so the consolidation behaviour of the cake deposit could not be directly back-calculated.

In July 2009, over fifty nuclear densometer tests were conducted at four locations in Cell A and test pits were excavated to measure field densities at multiple depths. The average measured wet and dry densities were 1627 kg/m 3 and 1093 kg/m 3 , respectively. The average measured geotechnical fluid content was 36.3 %wt.

Three Standard Proctor density tests were carried out on samples recovered from Cell A. The results indicated an average Standard Proctor maximum dry density of 1500 kg/m³ and an average optimum fluid content of 24.8 %wt. The densities are lower than what would be expected for a mineral soil that is predominantly clay and silt sized.

For each densometer test, a sample of the tested cake was collected for laboratory index testing. Table 2 summarizes the average values for the property index.

Table 2. Average Index Properties of Samples Collected from Cell A, July 2009

Index Property	Value	
% Sand (> 75 microns)	12	
% Silt	46	
% Clay (< 2 microns)	42	
Gravimetric moisture content (%wt)	40	
Geotechnical bitumen content (%wt)	5.5	
Geotechnical fluid content (%wt)	49	
Liquid Limit, LL (%)	62	
Plastic Limit, PL (%)	30	
Plasticity Index, PI (%)	32	
Activity	0.76	
Liquidity Index	0.4	

The samples indicated that the cake in Cell A was fairly uniform with respect to particle size distribution but more variable with respect to plasticity (liquid limits ranging from 50 to 72 percent and plasticity indices ranging from 21 to 40). The cake is classified as a medium- to high-plastic clay according to the Unified Soil Classification system plasticity chart.

Samples were generally collected from four to eight locations over the cell and continuously sampled through to the foundation tailings sand at approximately 30 cm depth intervals. Field vane strength tests were carried out at approximately the mid-point of the sample depth interval. Table 3 summarizes the oven-dried solids content and peak vane strength changes over time.

Table 3. Summary of Average Solids Content and Shear Strength in Cell A over One-Year Period (Range Shown in Parentheses)

Date (Elapsed Time)	SolidsContent (%wt)	Peak Vane Strength (kPa)
October 2008 (initial)	52	-
November 2008 (1 month)	59 (56-64)	3 (2-3)
July 2009 (9 months)	71 (64-79)	14 (9-23)
September 2009 (11+ months)	73 (62-87)	17 (8-28)

Cone penetration tests were also carried out adjacent to the sample hole locations in July and September 2009. Undrained shear strengths were estimated from the cone penetration data using the N_{kt} method (Lunne et al., 1997). Using an N_{kt} value of 15 provided a fair correlation between the computed undrained shear strength and the peak vane strength.

The test observations indicated that the cake densified and gained strength over time, due in large part to natural desiccation processes such as freeze-thaw and evaporative drying.

5.2 Lined Culvert Observations

The Lined Culvert was lined with a geomembrane liner sock and fitted with a vertical post, onto which vibrating wire piezometers were installed at heights of 0.3 m, 1.3 m, 2.3 m, 3.3 m, and 4.3 m above the bottom. The culvert was initially filled with recycled process water and produced cake was deposited into the culvert via a conveyor. Figure 8 shows the Lined Culvert deposit on October 3, just after the culvert was filled.



Figure 8. Lined Culvert deposit (October 3, 2008).

Based on laboratory test data from samples of produced cake taken during the same day that the culvert was filled, the initial oven-dried solids content was approximately 55 percent and the fines content was approximately 85 percent.

Like the cell deposits, the culvert deposits were regularly sampled and tested from November 2008 to September 2009. Figure 9 shows the profiles of solids content over time. In November 2008, the average solids content was approximately 52 percent, lower than the average of 56 percent from samples of the cake collected during processing. This suggested that the cake dispersed itself somewhat when it was dumped into process water. The average solids content increased to 55 percent by April 2009 approximately and approximately 56 to 58 percent in September 2009. The change in densification profile was far less for the culvert deposits than it was for the exposed cell deposits.



Figure 9. Solids Content Profiles, Lined Culvert Deposit

The undrained shear strength of the cake was predominantly determined from vane strength tests, but cone penetration tests and ball penetration tests (BPTs) were also carried out. Figure 10 summarizes the shear strength measurements. Correlated against the vane test results, an N_{ball} value of 15 was used to estimate undrained shear strengths from the ball peneterometer data. A cone penetration test hole was probed in June 2009 and the undrained shear strength determined from the CPT data using N_{kt} = 30 compared well against the vane data but the results have not been presented for clarity.

Figure 10 shows that in November 2008, approximately one month after the culvert was filled, peak vane strengths were generally uniform at between 1.5 to 2.0 kPa.. With time, the shear strength profiles have shown a slight trend of increasing peak vane strength with depth, although after April 2009, the changes in the strength profiles have been negligible



Figure 10 Shear Strength Profiles, Lined Culvert Deposit

A few weeks after the culvert was filled, sediments began to settle out, leaving a relatively solids-free water cap over the cake. The water surface was 4.69 m above the bottom in November 3, 2008 and 4.08 m above the bottom from April 2009 onward. The surface of the solids ranged in height above bottom from 4.25 m in November 2008 to 3.80 m in April 2009 and 3.76 in June 2009. Figure 11 shows the changes in pore water pressure profiles with time. The piezometers were connected to а data logger for automated measurements, but because of equipment problems, no measurements were recorded between November 2008 and May 2009. Figure 11 shows that the pore water pressures changed very little during the summer of 2009, where they remained above hydrostatic.



Figure 11. Pore pressure profiles, Lined Culvert deposit

6 CONCLUSIONS

Syncrude has successfully piloted a field scale test using centrifuges to dewater the fine tails. Centrifuging tailings accelerates the release of water and can increase the solids content of MFT from 30 percent to greater than 50 percent practically instantaneously, to produce a cake-like deposit, resulting in a reduction in tailings storage area by 50 percent or more.

Cake in the large culvert deposits underwent only minor self-weight consolidation and did not densify or strengthen (remaining less than 5 kPa) appreciably even one year after deposition. Removing the water cover and exposing the deposit to allow freeze-thaw and evaporative drying could have improved densification, although it remains uncertain as to how much it would have gained in strength over the same one-year period.

On the other hand, cake in the cell deposits were exposed to the natural climate and completely froze over the winter of 2008/2009 before fully thawing by June 2009. The deposits did not densify much prior to the winter, but did densify and gain strength after the cake thawed, and gained more strength over the summer as the surface dried from evaporation. Cracking of the cell deposit surface enhanced surface drainage and allowed the deposits to shed rather than pool surface water. The relatively thin layers (less than 2 m) and the sloping surface, which shed surface water and prevented water from pooling, may have enhanced dewatering compared to a larger or deeper deposit.

In the context of Energy Resources Conservation Board's (ERCB's) Directive 074, which mandates oil sands operators to reduce fluid tailings accumulation and achieve a minimum undrained peak shear strength of 5 kPa for material deposited in the previous year, storing the centrifuge cake in large, deep storage pits using the process piloted this year is unlikely to produce material that meets the minimum 5 kPa strength requirements within the one-year time frame if relying solely on selfweight consolidation. Strength gain may be improved by a variety of methods, including: i) co-disposing of the cake with overburden or coarse tailings, ii) controlled layering of the cake with another material (e.g., coarse tailings), and iii) placing in thin lifts to enhance natural dewatering through freeze-thaw and evaporative drying.

Future Studies

The 2008/2009 centrifuge-dewatered MFT field test yielded invaluable information about operating a centrifuge, as well as the geotechnical response of exposed and sheltered field-scale deposits, from which Syncrude can draw from this experience for improving on a commercial scale.

Syncrude continues to aggressively pursue centrifuge-dewatering as a key dewatering strategy for the management of oil sands tailings within its leases, and in the summer of 2010, Syncrude is planning its next field trial, with the plan to produce approximately 60,000 m³ of cake. This stage of field test will focus on providing data and a better understanding of cells filled by truck-dumping, the geotechnical response of a cell filled by cake transported by a positive displacement pump system, more detailed instrumentation to measure the near-surface water and evaporative fluxes for water and surface energy balance computations.

ACKNOWLEDGEMENTS

The writers would like to thank Syncrude Canada Limited for granting permission to publish the findings from this study. The writers would also like to acknowledge the contributions of a number of many parties and individuals to this work, including Ms. Sophie Kessler of O'Kane Consultants Inc., Mr. Gerry Cyre of Geoforte Services, Mr. Henxing Lan of the University of Alberta, Ms. Alexis Maddalonni of ConeTec Investigations Inc., Dr. Randy Mikula of CanMET Energy, and Dr. Ed McRoberts of AMEC Earth and Environmental.

REFERENCES

Australia Department of Industry, Tourism and Resources, 2007. Tailings management : Leading Practice Sustainable Development Program for the mining industry. February 2007, 79 p. Lunne, T., Robertson, P.K., and Powell, J.J.M., 1997. Cone Penetration Testing in Geotechnical Practice. Blackie Academic/London, Routledge, New York. 312 p.