Dilatancy and strength characteristics of compacted mine waste fill used in oil sands dam construction

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ABSTRACT
Dilatancy and strength characteristics of mine waste fill are key considerations when designing tailings dams. Available laboratory testing data from the Oil Sands literature on reconstituted samples compacted in the laboratory indicate potential contractive behaviour for mine waste material sourced from McMurray Formation. However, published data on undisturbed core samples compacted in the field indicated that compacted mine waste is dilative. This difference in behaviour between the reconstituted and undisturbed core samples is a result of higher compaction effort by the mine heavy equipment. Published data on Oil Sands mine waste undisturbed core samples are limited to confining pressures up to 1000 kPa, whereas in-pit dams could be subject to higher confining stresses, up to 2000 kPa. This led to the potential uncertainty that mine waste used for constructing larger dams may become contractive under higher confining stress. To investigate this uncertainty, a fill characterization program was undertaken to assess the behaviour of mine waste materials used in dam construction at the Kearl Oil Sands site. The results indicated that McMurray mine waste remains dilative under high confining stress up to 2000 kPa. This paper also describes a reliable, cost-effective methodology for collecting undisturbed block samples of fine-grained dam fill materials placed and compacted in the field.

RÉSUMÉ
Les caractéristiques de dilatance et de résistance des stériles miniers sont des considérations importantes pour la conception de digues de résidus. Les résultats d'essais de laboratoire effectués sur des échantillons reconstitués (en laboratoire) de sables bitumineux de la formation McMurray indiquent que les stériles miniers compactés sont contractants. Cependant, les résultats d’essais effectués sur des échantillons intacts (prélevés par carottage) indiquent que les stériles miniers compactés sont dilatants. Cette différence de comportement entre les échantillons reconstitués et intacts prélevés par carottage est le résultat de l’effort de compactage plus intense offert par les engins lourds miniers. Les données publiées pour les échantillons intacts prélevés par carottage de stériles miniers de sables bitumineux sont pour des pressions de confinement de 1 000 kPa ou moins, alors que les dykes dans la fosse peuvent être soumises à des contraintes de confinement plus élevées, jusqu'à 2000 kPa. Compte tenu des incertitudes associées aux comportement des stériles compactés, i.e., contractants ou dilatants, un programme de caractérisation a été entrepris pour évaluer le comportement des matériaux utilisés pour la construction de digues sur le site de Kearl Oil Sands. Les résultats ont indiqué que les stériles miniers issus de la formation McMurray demeurent dilatants sous des contraintes de confinement élevées. Cet article présente également une méthodologie fiable et rentable pour la collecte de blocs intacts pour fins d’essais en laboratoire.

1 INTRODUCTION

The Kearl Oil Sands Mine (Kearl) is an open pit mine and processing facility owned and operated by Imperial Oil Resources Ltd. (Imperial). Kearl is located northeast of Fort McMurray, Alberta in the Athabasca Oil Sands region. As mining progresses at Kearl, in-pit tailings dams are constructed within mined out portions of the pit for tailings storage. In-pit tailings dams typically consist of an initial compacted mine waste starter dam that is subsequently raised by hydraulically placed Coarse Sand Tailings (CST) or mechanically placed mine waste. At Kearl and many of the Oil Sands sites, mine waste fill used in dam construction consists of Middle McMurray (MKm) and Lower McMurray (LKm) material. Construction lifts are typically one (1) meter in thickness and are compacted using a loaded 797 heavy hauler with a gross operating weight of approximately 620 tonnes.

The dilatancy behaviour of the mine waste material typically guides the selection of the appropriate material parameters for dam design. Drained strength parameters are considered appropriate for dilative material, whereas undrained strength parameters are appropriate for contractive material (Ladd 1986). Triaxial test results from Kearl and the Oil Sands literature on reconstituted samples of mine waste fill compacted in the laboratory to 95% SPMDD (hereafter referred to as reconstituted samples) indicate that positive excess pore water pressure was generated during undrained shearing at confining pressures as low as 300 kPa, indicating potential contractive behaviour. However, published triaxial testing results from the Muskeg River Mine on undisturbed core samples indicated that compacted mine waste is dilative for much higher confining stresses (Biggar et al. 2016). This difference in behaviour between the reconstituted and undisturbed samples was explained to be a result of the higher compaction effort by the mine heavy equipment used in the Oil Sands dam construction, which is better represented by the undisturbed samples. The triaxial testing reported by Bigger (2016), however, was limited to confining pressures up to 1000 kPa, whereas in-pit dams could be subject to higher confining stresses, potentially up to 2000 kPa. This led to the potential uncertainty that mine waste materials used for constructing larger dams may become contractive under higher confining stress. To further investigate this potential uncertainty, a fill characterization program was undertaken in 2020 to assess dilatancy and strength characteristics of mine waste fill materials used in dam construction at Kearl. The fill characterization program consisted of a field and laboratory testing program to assess the mine waste material behaviour under confining stress levels up to 2000 kPa.

Undisturbed samples are often obtained by collecting undisturbed core using a drill rig. Different types of drill rigs and soil samplers can be used successfully to collect undisturbed samples. However, common limitations for these rigs/samplers include: (a) core diameter is often small which increases the likelihood of causing sample disturbance at the time of sampling; (b) core diameter may not be large enough to capture a representative sample structure; (c) drill rigs and support equipment rates are expensive; (d) it is often difficult to extrude a soil specimen in the lab without causing significant disturbance due to small sample size, especially if the soil sample contains blocky or granular material as it is usually the case for MKm. For collecting samples at shallow depth (up to 3 m), a large size block sample can be carved in the field to overcome most of the limitations associated with drilling. However, carving block samples in the field is typically time consuming and can be difficult to undertake without disturbing the sample, especially when using the large size Oil Sands mining equipment, which is a limitation that was addressed by the sampling methodology described in this paper.

This paper summarizes the findings of the fill characterization program that was undertaken to assess the behaviour of mine waste materials used in dam construction at Kearl. The paper also describes a simple, cost-effective, and reliable methodology for collecting field compacted block fill samples (hereafter referred to as block samples).

2 FIELD PROGRAM

2.1 Test Strip Construction

At Kearl, dam construction is typically performed using the “drive-over and dump” method which involves a loaded 797 haul truck trafficking over a loose lift and dumping fill material at the end of the lift, providing compaction effort during construction. Each completed lift then receives an additional four (4) dedicated passes of a loaded 797 haul truck. Each pass consists of a haul truck driving over the running surface of the lift and staggering its wheels until the entire surface has been trafficked once.

As part of the fill characterization program described in this paper, four (4) Test Strips (TS) were constructed, including three (3) comprised of MKm mine waste and one (1) comprised of LKm mine waste. The TSs were constructed using the “back-in and dump” method. This method requires haul trucks to “back-in” to the end of the TS and “dump” the fill material at specified locations where the material is then spread and broken down by a D11 dozer, as shown on Figure 1. The back-in method was chosen for this program as it represents the absolute minimum compaction effort since the drive-over method used for dam construction would likely result in higher compaction due to heavy equipment traffic, in addition to the four (4) dedicated passes in the dam construction specification.

The TSs were approximately 40 m wide by 200 m long and 1.5 m thick (loose). Each TS then received four (4) passes by a loaded 797 haul truck, as shown in Figure 2.

Upon completion of the TS compaction, three Test Pit (TP) locations within each TS were identified for field testing and sample collection. The TPs were excavated in three stages: 0 to 300 mm, 300 to 600 mm and 600 to 900 mm, to allow for field density measurements and sampling with depth.

Figure 1. Test Strip Construction using the “Back-in and Dump” Method.

Figure 2. Test Strip Compaction Using a Loaded 797 Haul Truck.

2.2 Field Testing

A total of 36 in-situ density tests were completed as part of the field program using a Troxler 3430 nuclear densometer in accordance with ASTM D6938. The nuclear density tests (hereafter was referred to as Troxler) were completed at depths of 300 mm, 600 mm and 900 mm. For each test, Troxler readings were recorded in four positions (0°, 90°, 180° and 270°), and the final density was taken as the average of the four readings.

A total of 20 Sand Cone tests, completed in accordance with ADTM D1556-15, in combination with an additional 20 Troxler tests were completed in existing starter dam mine waste fill, to assess the reliability of the nuclear density tests.

2.3 Sampling

Bulk samples of mine waste fill were collected from the cuttings of the TPs at each depth stage (i.e., 0 mm to 300 mm, 300 mm to 600 mm, and 600 mm to 900 mm). A total of 36 bulk samples were collected as part of the field program.

A total of 15 block samples were collected as part of the field program, including twelve samples from the TSs (three (3) block samples from each TS). Three (3) block samples were collected from the starter dam to assess the potential effect of the back-in fill placement method used for the TSs compared to the drive-over method used for the actual starter dam construction.

3 BLOCK SAMPLING METHODOLOGY

Conventionally, undisturbed samples are collected using small diameter Shelby tubes or large sized hand carved block samples (i.e., approximately 300 mm by 300 mm by 300 mm). These methods are relatively expensive, time consuming and subject to a high degree of disturbance given the granular and blocky nature of the Oil Sands mine waste. An alternative sampling method was developed which consisted of a custom-made large diameter steel tube. Each steel tube was manufactured to the dimensions shown on Figure 3.

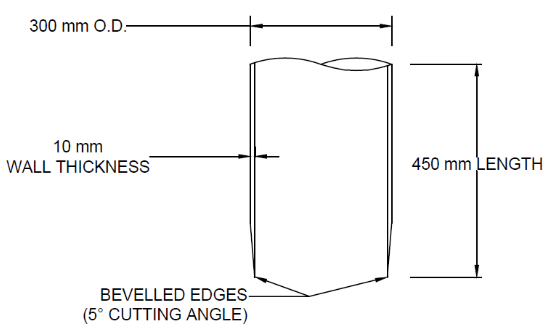

Figure 3. Dimensions of Custom-Made Large Diameter Steel Tube.

For sample collection, the steel tubes were placed on a flat area of compacted mine waste fill and two (2) 4"x4" posts measuring 600 mm in length were placed on top of the steel tube to act as a push block. An excavator was then used to push the tube into the compacted mine waste fill at approximate rate of sixty (60) mm/sec, using the flat side of the bucket, as shown in Figure 4. The steel tube was advanced until the top of the steel tube was flush with the compacted mine waste fill surface, as shown in Figure 5. The material around the block sample was removed using hand tools. To separate the sample at the base, the underlying material was partially excavated, leaving a conical shape of fill in-place. The base was then cut to provide a flat or level surface for transport. The block sample was sealed with paraffin wax and cheesecloth, and placed in a Styrofoam insulated plywood box for shipping, in accordance with ASTM D7015-13, to limit moisture loss and disturbance during transportation. Figure 6 presents an excavated block sample and Figure 7 shows a sample that has been sealed with paraffin wax and cheesecloth.

Figure 4. Pushing of Large Diameter Steel Tube using Excavator Bucket.

Figure 5. Large Diameter Steel Tube Advanced Into Mine Waste at the Base of a Test Pit.

Figure 6. Excavated Block Sample.

Figure 7. Block Sample Sealed with Paraffin Wax in Box for Transportation.

4 LABORATORY TESTING

4.1 Index Testing

The laboratory testing program included a suite of index testing, including particle size distribution (PSD), moisture content, Atterberg, and Dean Stark tests. A total of 20 PSD and 20 Atterberg limit tests were completed as part of the laboratory testing program, including 15 on MKm samples and five (5) on LKm samples. Additionally, 11 moisture content tests were conducted to supplement the moisture content data collected as part of the in-situ density testing. A total of 19 Dean Stark tests were completed on select samples of bulk and block samples. The index testing results are summarized in Table 1 and Table 2 for MKm and LKm, respectively.

Table 1. Summary of Index Testing Results for MKm Material

Index Testing Property	Range	Average	No. Tests
Sand (%)	14 – 69	40	15
Silt (%)	26 – 62	46	15
Clay (%)	4 – 27	14	15
Liquid Limit	27 – 37	30	15
Plastic Limit	15 – 24	20	15
Plasticity Index	4 – 15	11	15
Water Content (%)	6 – 12	8	8
Bitumen Content (%)	1 – 8	4	14

Table 2. Summary of Index Testing Results for LKm Material

Index Testing Property	Range	Average	No. Tests
Sand (%)	15 - 61	34	5
Silt (%)	36 - 55	49	5
Clay (%)	3 – 30	18	5
Liquid Limit	27 - 36	30	5
Plastic Limit	15 - 22	19	5
Plasticity Index	5 – 16	11	5
Water Content (%)	6 - 10	8	3
Bitumen Content (%)	1 - 3	2	5

4.2 Density Testing

A total of 12 standard and 12 modified proctor tests were completed using the bulk samples collected during the field program according to ASTM D698 (Method A) and ASTM D1557 (Method A), respectively. For each TP, a homogenous sample was produced by combining the bulk samples collected from each depth interval.

The density testing results are summarized in Table 3 and Table 4 for MKm and LKm, respectively. In general, these results indicate that the level of compaction applied as part of the TSs construction exceeds 95% SPMDD.

Table 3. Summary of Density Test Results for MKm Material

	Range	Average	No. Tests
Troxler Dry Density (kg/m³)	1707 – 1961	1843	27
Standard Proctor Maximum Dry Density (kg/m³)	1770 – 1875	1817	9
% SPMDD	95 – 109	101	-
Modified Proctor Maximum Dry Density (kg/m³)	1900 – 2005	1954	9
% MPMDD	88 – 101	94	-

Table 4. Summary of Density Test Results for LKm Material

	Range	Average	No. Tests
Troxler Dry Density (kg/m³)	1837 – 1973	1912	9
Standard Proctor Maximum Dry Density (kg/m³)	1830 – 1875	1850	3
% SPMDD	100 – 105	103	-
Modified Proctor Maximum Dry Density (kg/m³)	1980 – 2020	2003	3
% MPMDD	93 – 98	95	-

Figure 8 presents the dry densities of block and reconstituted samples of MKm and LKm. Corresponding maximum dry densities (SPMDD and MPMDD) of bulk samples obtained from laboratory testing are also presented on Figure 8. The results show that the block samples are denser than the reconstituted samples, which were prepared to 95% SPMDD. The block samples, compacted by loaded 797 heavy haulers, generally exceed 100% SPMDD and are more closely aligned with 95% MPMDD. These results suggest that the compaction energy imposed by a Modified Proctor test is more representative of the compaction energy applied by four (4) passes of a loaded 797 haul truck on a 1 m lift.

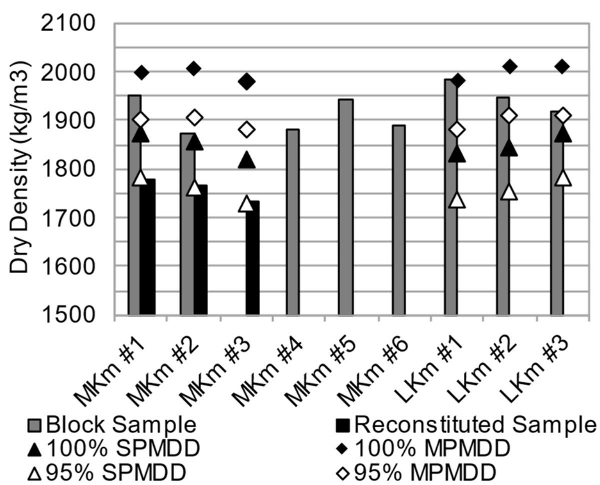

Figure 8. Density Comparison of Block Samples and Reconstituted Samples Prepared to 95% SPMDD.

In general, undisturbed sampling techniques have the potential to cause “loosening” or “densification” of the sample material. Figure 9 presents the dry densities of block and reconstituted samples of MKm and LKm, as well as the corresponding average dry density measurements obtained by the Troxler in the field. As shown on Figure 9, the dry density measurements of the block samples are slightly higher than the average dry density measurements obtained by the Troxler. These results suggest that densification may have occurred during the block sampling process, or the Troxler tests may have underestimated the in-situ density.

To evaluate this potential uncertainty, 20 Sand Cone density tests were conducted in the existing starter dam adjacent to 20 Troxler tests. In general, the sand-replacement (which is considered a more reliable, direct density measurements) dry density results were higher than the corresponding dry density measured by the Troxler by ~2% (i.e. Troxler may have underestimated the in-situ density by ~2%). Troxler average dry densities were corrected by 2% to account for this observed difference in density measurements. As shown on Figure 9, the corrected Troxler average dry density results are similar to the dry densities of the block samples. The difference between the corrected Troxler dry densities and the block sample dry densities is likely attributed to minor differences in moisture content and gradation. Therefore, block samples were not considered to have been densified due to the sampling process.

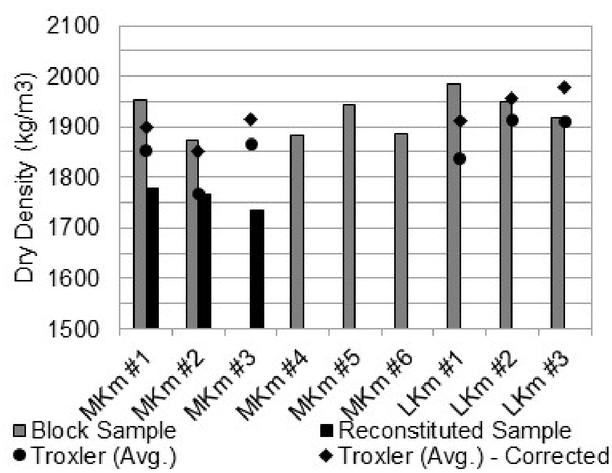

Figure 9. Corrected Field Compacted Density Results.

4.3 Consolidated Isotropic Undrained Triaxial Tests

A total of 22 Consolidated Isotropic Undrained (CIU) triaxial testing were undertaken as follows:

- 10 tests on block samples from TSs,
- six (6) tests on bulk samples from TSs, reconstituted to 95% SPMDD, and
- six (6) tests on block samples collected from the starter dam.

Testing was conducted after the samples were allowed to consolidate under effective cell pressures of 1000 kPa and 2000 kPa. A back pressure between 400 kPa and 600 kPa was used to saturate the test specimens.

Figure 10 shows the stress paths for MKm CIU tests on block and reconstituted samples carried out as part of the 2020 fill characterization program, as well as historical test results on reconstituted samples. Based on the 2020 program results, the peak effective friction angles for block MKm samples ranged from 25° to 37° with an average of 32°. Whereas peak effective friction angles for reconstituted MKm samples ranged from 25° to 36° with an average of 30°.

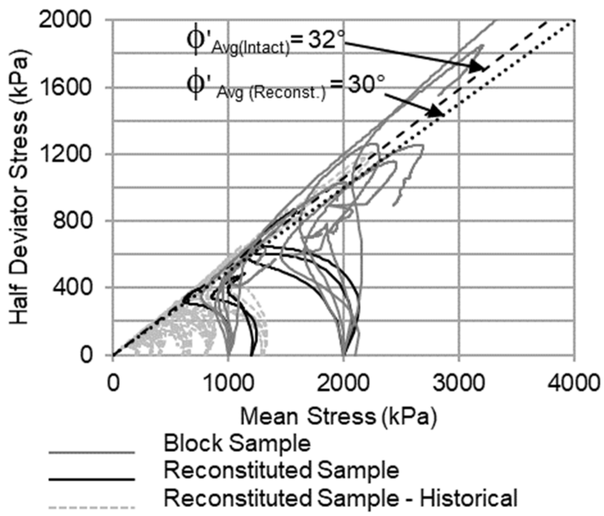

Figure 10. CIU Triaxial Test Results on Block and Reconstituted MKm Samples.

Figure 11 presents a distribution of the calculated peak effective friction angles for block and reconstituted MKm samples. In general, the results for block and reconstituted samples collected from TS are similar to the historical test results obtained from Kearl. The results also indicate that the block samples collected from TS show slightly higher peak effective friction angles than the reconstituted samples collected from TS. This observed difference in strength is expected because the block samples are denser compared to the reconstituted samples.

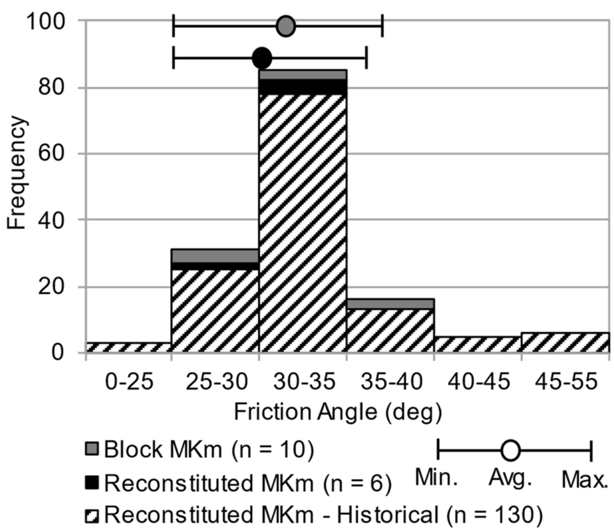

Figure 11. Distribution of Peak Effective Friction Angles Based on CIU Test Results.

Figures 12 and 13 present the CIU triaxial test results for the block MKm and LKm samples, respectively. As shown, MKm and LKm block samples exhibited excess pore water pressure generation during initial undrained shearing up to an axial strain of approximately 3% to 4% followed by reduction in pore pressure during continued shearing, indicating dilative behaviour under confining stress levels up to 2000 kPa.

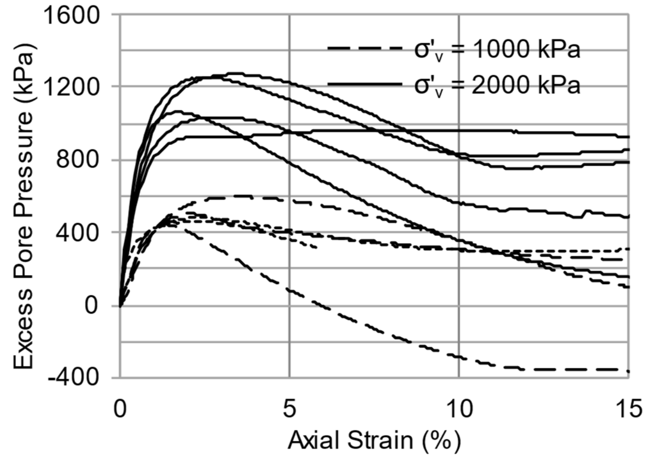

Figure 12. CIU Triaxial Test Results on Block MKm Samples.

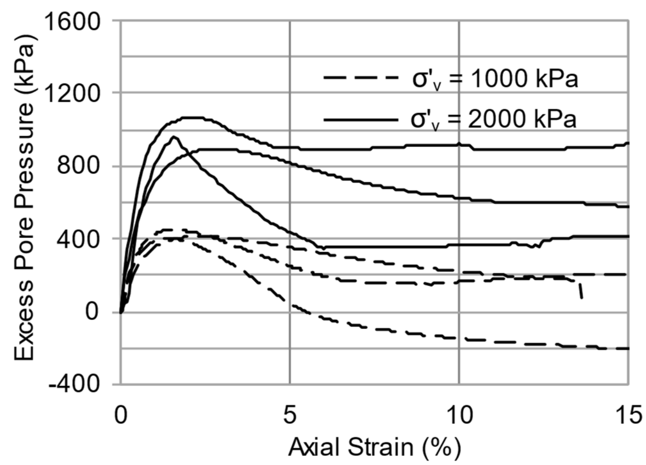

Figure 13. CIU Triaxial Test Results on Block LKm Samples.

Figures 14 and 15 present the CIU triaxial test results for MKm and LKm samples reconstituted to 95% SPMDD, respectively. As shown, reconstituted samples of MKm and LKm mine waste fill show excess pore water pressure generation that remain positive to the end of the test at axial strain levels greater than 15%, indicating contractive behaviour. These results are consistent with historical MKm and LKm triaxial data obtained from Kearl, which are also shown on Figures 14 and 15.

The observed difference in behaviour between block and reconstituted samples is due to the difference in compaction effort and resulting density of the test samples. The behaviour exhibited by the triaxial test results for block sample is more representative of the actual field conditions. These test results are consistent with published triaxial testing results from Muskeg River Mine on undisturbed core samples which indicated a similar dilative behaviour on field compacted lean oil sand under confining pressures up to 1000 kPa (Biggar et al. 2016). The results from the 2020 fill characterization program at Kearl further demonstrate that the behaviour of the MKm and LKm mine waste fill, when placed and compacted by loaded heavy haulers as previously described in Section 2, is expected to be dilative when sheared under confining stresses up to 2000 kPa.

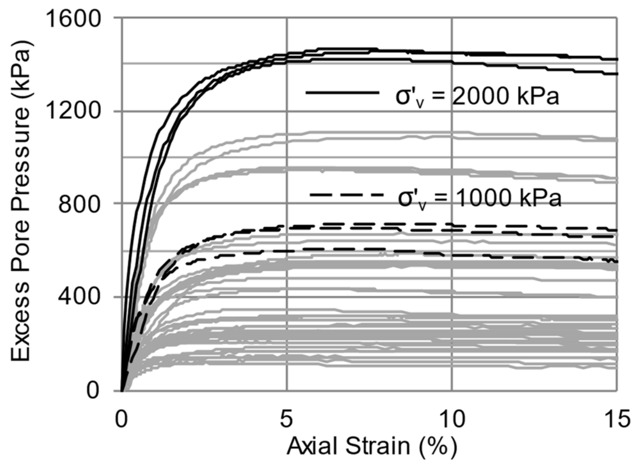

Figure 14. CIU Triaxial Test Results on Reconstituted MKm Samples – Historical Reconstituted MKm (σ'$_v$ range: 200 - 1300 kPa) shown in grey color.

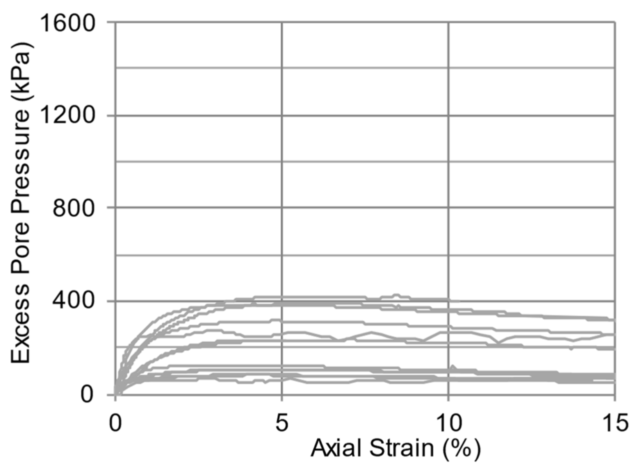

Figure 15. CIU Triaxial Test Results on Historical Reconstituted LKm (σ'$_v$ range: 200 - 1000 kPa).

5 CONCLUSIONS

A fill characterization program was undertaken to assess the dilatancy and strength characteristics of mine waste fill materials used in dam construction at Kearl. The fill characterization program consisted of a field and laboratory testing program to assess the mine waste material behaviour under confining stress levels up to 2000 kPa. As part of the program, bulk and block samples of mine waste fill were collected for index and advanced laboratory testing. The block samples of compacted mine waste fill were collected using custom-made large diameter sampling tubes that were advanced using mine equipment.

The key results of the fill characterization program are summarized as follows:

- Collection of “undisturbed” block samples using large diameter steel tubes is a simple, cost-effective, and reliable method for sample collection in McMurray mine waste fill at shallow depth.
- “Undisturbed” Block samples of the fill compacted by a loaded 797 heavy hauler were denser than laboratory reconstituted samples compacted to 100% SPMDD.
- The results suggest that the compaction energy imposed by a Modified Proctor test is more representative of the compaction energy applied by four (4) passes of a loaded 797 haul truck on a 1 m thick lift.
- Block samples showed higher peak effective friction angles than reconstituted samples compacted to 95% SPMDD.
- The results from the fill characterization program at Kearl further demonstrate that the behaviour of the MKm and LKm mine waste fill is expected to be dilative under confining stresses up to 2000 kPa.
- The dilative behaviour exhibited by the triaxial test results of block samples as well as the higher density and strength observations are representative of the actual field conditions and are likely due to the high compaction energy by the mine equipment.

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