Main results from an extensive geotechnical characterization of hard rock tailings from an open pit gold mine

Abtin Jahanbakhshzadeh and Michel Aubertin
Department of Civil, Geological and Mining Engineering,
Research Institute on Mines and Environment (RIME)
Polytechnique de Montréal,
P.O. Box 6079, Station Centre-ville, Montréal, QC H3C 3A7, Canada

ABSTRACT
Various tests have been conducted over the last decade to perform a comprehensive characterization of the hard rock tailings produced by a large open pit gold mine in western Québec. The experimental investigation comprised various types of laboratory and in-situ tests and measurements. The results and related geotechnical parameters have been used to conduct different types of analysis, including numerical simulations to evaluate the response and performance of the tailings impoundment. This article presents a detailed summary of the main experimental geotechnical properties of these tailings, which are fairly typical of low plasticity tailings from hard rock mines.
RÉSUMÉ
Divers essais ont été effectués au cours de la dernière décennie afin d'obtenir une caractérisation relativement complète des résidus de roche dure produits par une mine d'or à ciel ouvert de l'ouest du Québec. L'investigation expérimentale comprenait divers types d'essais et de mesures en laboratoire et in situ. Ces résultats et les paramètres géotechniques associés ont été utilisés pour effectuer différents types d'analyse, y compris des simulations numériques pour évaluer la réponse et la performance du parc à résidus. Cet article présente une synthèse détaillée des principales propriétés géotechniques de ces résidus, qui ont des caractéristiques similaires à celles d'autres résidus de faible plasticité de mines en roche dure.

1 INTRODUCTION

Experimental research projects have been conducted on the tailings disposal site at the Canadian Malartic (CM) mine, in collaboration with industrial partners of RIME. This mining operation, located in Abitibi-Témiscamingue, Quebec, is the largest open pit gold mine in Canada (Doucet et al. 2015).

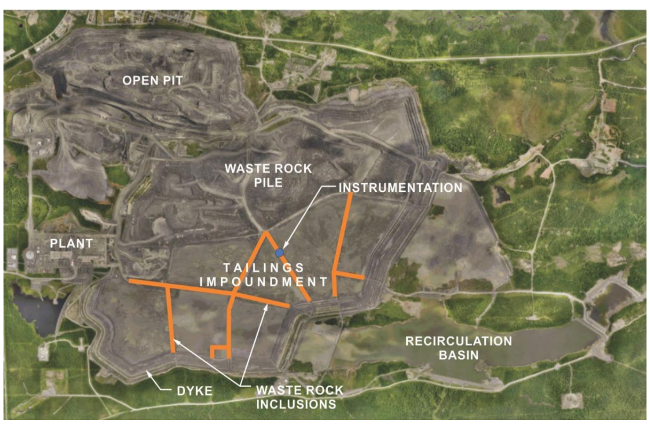

Figure 1. Plan view of the Canadian Malartic mine, showing the tailings impoundment with waste rock inclusions (in orange; photo provided by the Canadian Malartic Mine, 2015).

The extensive studies on the mine site included a NSERC Cooperative Research Project that ended in 2020 (with some analyses still ongoing). The research work comprised field instrumentation and monitoring, conventional and specialized laboratory testing, physical modelling, and various types of numerical simulations (James et al. 2017; Aubertin et al. 2021). The main objective of this CRD project was to evaluate the interactions between waste rock inclusions (WRI), constructed in the impoundment (see Figure 1), and the adjacent tailings, with a focus on the drainage capacity of inclusions, tailings consolidation, and geotechnical behavior of the impoundment under static and dynamic (earthquake) loadings. The detailed testing results obtained as part of this project, and of previous investigations, have been reported in a number of Theses and in a few related publications. This article gives a fairly detailed summary of the main results from this comprehensive experimental characterization campaign.

2 Basic properties of the tailings

2.1 Grain size distribution and water content

The grain size distribution curves of tailings specimens collected over a period of a few years were determined using conventional sieving and sedimentation techniques (ASTM D422-63). The curves shown in Figure 2 represent the different grain size distributions for tailings sampled at different times (data from Poncelet, 2012; L. Bolduc, 2012; Contreras, 2013; Essayad 2015; Saleh Mbemba 2016). A broad range typical of tailings (James 2009) is also shown with the 2 limiting curves in the figure. For the CM mine tailings, the average values of D_{10} (diameter corresponds to 10% of the passing), D_{30} and D_{60} are 0.0025 mm, 0,0075 mm and 0.02 mm, respectively.

The maximum particle size of most samples collected at the CM mine tailings is just above 0.08 mm, which corresponds approximately to the limit between silt and sand particles. The maximum size reported by Essayad (2015), Saleh Mbemba (2016), Archambault-Alwin (2017), and Grimard (2018) was slightly larger than those reported earlier by Poncelet (2012), L. Bolduc (2012) and Contreras (2013) on the CM mine tailings (Fig. 2), indicating that the tailings produced at the mill became coarser over time.

These grain size distribution curves and corresponding values of D_{10} and D_{60} are comparable to typical results obtained for hard rock tailings reported by Aubertin et al. (2002a), and Bussière (2007), i.e. D_{10} between 0.001 and 0.004 mm and D_{60} between 0.01 and 0.05 mm.

These hard rock tailings are non-plastic, as indicated by the difficulty in obtaining meaningful values for the Atterberg limits. The CM mine tailings can be classified as non-plastic silt (ML) per the USCS (Unified Soil Classification System; e.g. McCarthy, 2007; Holtz et al. 2011)). This is also typical of most tailings from hard rock mines in the Abitibi region (Aubertin et al. 1996, 2002a, b; Bussière 2007).

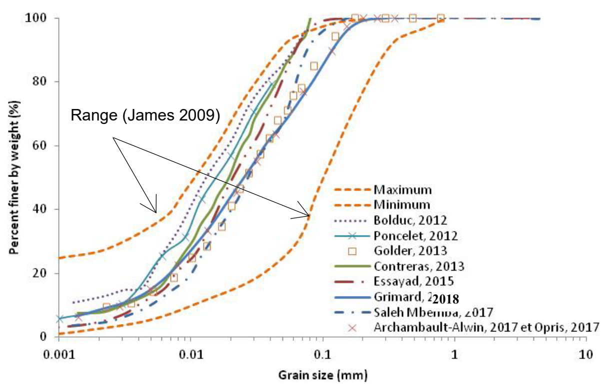

Figure 2. Grain size curves for the tailings collected at different times at the Canadian Malartic mine.

During the first few years of operations, the CM mine increased the density of the tailings (and reduced their water content) at the mill to reach a pulp density (solid content) of about 63% (Aubertin et al. 2021). This is sufficient to prevent significant particles segregation in the field, so the grain size appears fairly uniform in the impoundment, at least for tailings deposited over the last decade or so.

2.2 Relative density and mineralogy

The average value of the relative density D_r of the solid grains (or specific gravity G_s; ASTM D854-02) is 2.75 (L. Bolduc 2012; Contreras 2013; Essayad 2015; Saleh Mbemba 2016). Again, this value is fairly typical (or slightly higher) for gold mine tailings in Canada (Aubertin et al. 1996, 2002a; Bussière 2007). The CM mine tailings contain about 85% of silicate minerals (quartz, albite, muscovite, microcline); sulfide minerals (mainly pyrite) generally constitute less than 1.5% of the total.

2.3 Mass-volume characteristics

The compaction test results give a maximum dry density ρ_{max} of 1720 to 1770 kg/m^3, a minimum void ratio e_{min} close to 0.6 and an optimal water content (Modified Proctor test) w_{opt} near 16% (L Bolduc 2012; Contreras 2013; Saleh Mbemba 2016). Golder (2014) reported a maximum dry density (standard Proctor) of 17.22 kN/m^3 and an optimum water content of about 15%.

Poncelet (2012) measured a minimum density of 1057 kg/m^3 and a maximum void ratio of 1.60 (n = 0.61) in a dry state. Contreras (2013) measured similar values i.e. from 1049 kg/m³ to 1088 kg/m³. The maximum void ratio is lower, i.e. between 1.1 and1.3, for saturated (slurry) tailings at the end of the sedimentation phase (Essayad 2015; Saleh Mbemba 2016).

3 Geotechnical parameters

The geotechnical characterization program included laboratory tests and field measurements based on cone penetration tests (CPT) and seismic CPT (SCPT). The laboratory tests on tailings included self-weight consolidation and large strain consolidation (see below), and also triaxial compression, direct shear and cyclic simple shear tests. Tests were also conducted on unsaturated tailings to obtain the water retention curve, shrinkage curves and tensile strength from bending tests.

3.1 Internal friction angle

The effective internal friction angle ϕ' was estimated from the results of CPT tests (Golder, 2016, 2019). The ϕ' values were evaluated according to the relationships proposed by Robertson and Cabal (2015).

These field results lead to ϕ' values that vary widely, between 20° and 38°; the average (30°) is on the low side for tailings.

The results obtained from conventional triaxial compression (CTC) tests conducted by Poncelet (2012), under Consolidated – Undrained (CU) conditions showed that the effective internal friction angle ϕ' of the CM mine tailings is 35-36°, for relatively loose specimens with a void ration between 0.65 to 0.70; the corresponding value of ϕ (total stress) measured in these CU tests is close to 30°. Grimard (2018) measured an effective internal friction angle closer to 38°, for tailings with a larger proportion of sand (see also Grimard et al. 2017).

Direct shear tests (ASTM D-3080) have given a value of ϕ' of about 39° (Golder, 2014; 2019).

All these experimental values of ϕ' are in the typical range for hard rock tailings, which can go from 33° to 42° (Vick, 1990; Aubertin et al., 2002a; Bussière, 2007).

3.2 Effective and apparent cohesion

The value of the effective cohesion (c') of these (saturated) tailings is very close to zero (Poncelet 2012; Narvaez, 2013), as is commonly the case for fine tailings from hard rock mines.

Narvaez (2013) studied the unsaturated tensile strength, elastic modulus and apparent cohesion of the CM mine tailings using bending tests (see also Narvaez et al. 2015). Figure 3 shows the apparent cohesion values obtained from these tests as a function of degree saturation S_r. The experimental results indicate that the maximum value of the apparent cohesion c_{app} may exceed the Air Entry Value (AEV) of the tailings obtained on the water retention curve (see below). The apparent cohesion tends to drop rapidly when S_r exceeds about 80%, and converges toward 0 (= c') for saturated tailings.

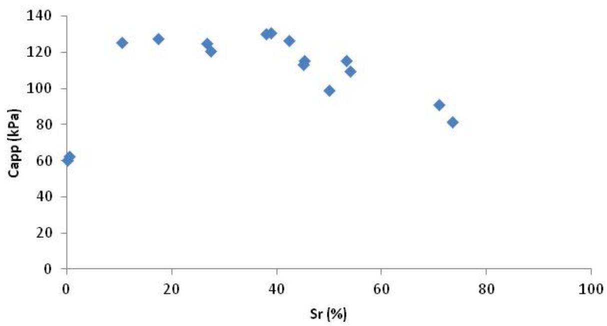

Figure 3: Variation of the apparent cohesion c_{app} as a function of degree of saturation S_r (Narvaez 2013).

The undrained shear strength S_u is also sometimes measured on tailings, despite the fact that their relatively high hydraulic conductivity (compared to clayey soils) raises questions about the actual drainage conditions during loading, particularly for field measurements like the vane shear test (Vick 1990). In general, it can be considered that the undrained shear strength S_u is close to 0.22 σ_v' (the effective vertical stress) for normally consolidated tailings. The value of S_u/σ_v' can however increase for over-consolidated tailings (with OCR > 1; Vick, 1990). The S_u/σ_v' ratio is typically reduced to about 0.10-0.12 for liquefied tailings (e.g. James et al. 2011; Contreras, 2022).

3.3 $N_{1(60)}$ value

The standardized value of $N_{1(60)}$ obtained from SPT is widely used to estimate geotechnical properties of granular soils, but this parameter (and the standard penetration test itself) is not always appropriate for very loose and soft materials such as recently deposited tailings.

The few field tests conducted on the CM tailings indicate that the average value of $N_{1(60)}$ is close to 4 (Opris, 2017). This value corresponds well to those estimated from the cone penetration tests conducted in the impoundment, based on the empirical relationships proposed by Jefferies and Davies (1993). In-situ CPT also helped identified stiffer layers (N up to 7) in the impoundment, near the dikes.

These $N_{1(60)}$ values are low in all cases, and would be considered below the required strength to resist liquefaction (Youd et al. 2001; Opris, 2017).

3.4 Consolidation characteristics

Consolidation behavior of hard rock tailings has been investigated extensively over the years. Consolidation tests conducted on relatively dense tailings have indicated that values of the compression index C_c typically vary from 0.046 to 0.15, the recompression index C_r from 0.004 to 0.01, and from 5×10^{-3} cm^2/s to 2.8 cm^2/s for the coefficient of consolidation, c_v (Aubertin et al. 1996; 2002). Qiu and Sego (2001) have reported C_c values between 0.056 and 0.319, and c_v values between 9.83×10^{-5} cm^2/s and 0.033 cm^2/s. Bussière (2007) summarized reported compressibility parameter values for hard rock mine tailings, with C_c varying between 0.05 and 0.3 and that of C_r from 0.003 to 0.03.

Essayad (2015) conducted compression tests in instrumented columns on loose (slurry) tailings (see also Essayad, 2021; Essayad and Aubertin 2021). The experimental value for the compressibility coefficient a_v, for $\sigma'_{vr} \leq 25$ kPa, varied between 1.37×10^{-3} kPa^{-1} and 1.8×10^{-1} kPa^{-1}. These values are slightly higher than those obtained by L. Bolduc (2012) for the same stress level (i.e. between 8.1×10^{-4} kPa^{-1} and 2.2×10^{-2} kPa^{-1}). The corresponding compression index C_c determined by Essayad (2015) varied between 0.0210 to 0.562, while L. Bolduc (2012) obtained a range between 0.035 and 0.34. For $\sigma'_{vr} > 25$ kPa, Essayad (2015) measured an a_v value varying from 9.17×10^{-5} kPa^{-1} to 1.6×10^{-3} kPa^{-1}; these values are in the range measured by L. Bolduc (2012) (i.e. a_v between 8.9×10^{-5} kPa^{-1} and 1.1×10^{-3} kPa^{-1}, for the same stress level). The compression index C_c varied from 0.035 to 0.18 in these tests.

3.5 G_{max} value

Variation of the maximum shear modulus, G_{max} with depth obtained from in-situ shear wave velocity V_s measurements, is shown in Figure. 4 (Opris 2017; Contreras 2022). The G_{max} values shown here are based on V_s measurements performed during cone penetration testing and converted using the following equation (Andrus et Stokoe 2000; Troncoso et Garcés 2000).

$$G_{max} = \rho V_s^2 \quad (1)$$

where ρ is the total in-situ density (kg/m³) and V_s is the shear wave velocity (m/s).

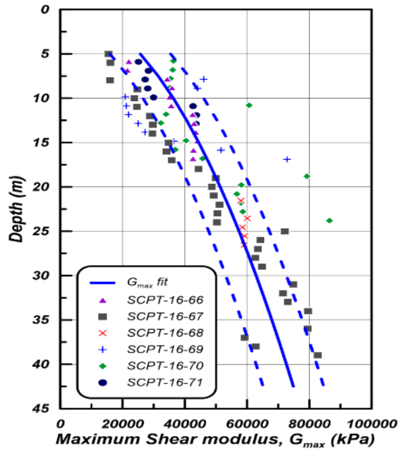

Figure 4. Maximum shear modulus, G_{max}, profile (average and range of one standard deviation) in the tailings impoundments computed from in-situ measurements of the shear wave velocity, V_s (Opris, 2017; Contreras, 2022).

3.6 Hydrogeological properties

3.6.1 Saturated hydraulic conductivity

The saturated hydraulic conductivity k_{sat} was measured in the laboratory, using oedometer and isotropic consolidation tests and triaxial tests. More than 140 k_{sat} measurements have been performed on the CM mine tailings (L. Bolduc, 2012; Golder, 2014; Essayad, 2015; Doucet et al., 2015; Saleh Mbemba, 2016; Boudrias, 2017).

Figure 5 presents the results obtained on specimens with slightly varying grain size, for a void ratio ranging from 0.55 to 0.9. The saturated hydraulic conductivity values on this graph are widely scattered (as is often the case with this parameter), and extend from 2×10^{-6} cm/s to 3×10^{-5} cm/s. The average value is close to 2×10^{-5} cm/s, for the range of void ratio.

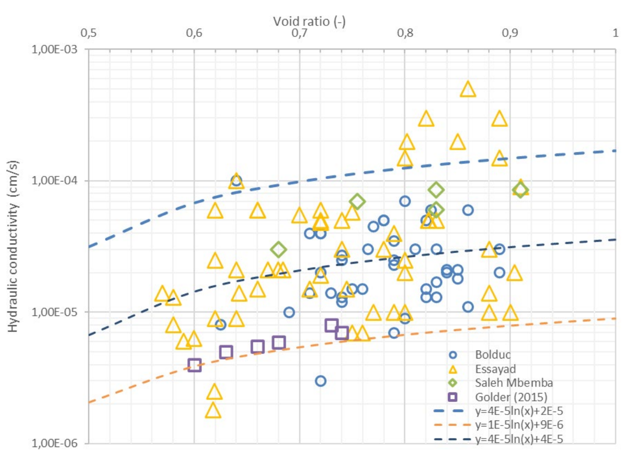

Figure 5. Saturated hydraulic conductivity measured in the laboratory as a function of the void ratio. The dashed lines correspond to the average and one standard deviation range.

Many of these values of the saturated hydraulic conductivity were obtained from compression or oedometric tests, interpreted using the commonly used consolidation theory (e.g. Holtz and Kovacs, 1981), However, the variability of the k_{sat} value obtained from these tests is typically higher than for direct k_{sat} measurements (from rigid or flexible wall permeability tests). Figure 6 presents the saturated hydraulic conductivity values measured within a triaxial cell. Most of these results (Essayad, 2015; Saleh Mbemba 2016; Boudrias 2017) were obtained on similar CM mine tailings, while those reported by L. Bolduc (2012) were obtained on somewhat finer tailings (sampled earlier) that led to a smaller saturated hydraulic conductivity.

Previous investigations showed that the saturated hydraulic conductivity of tailings can be estimated with specific predictive equations based on grain size and porosity. Good results are generally obtained with the Kozeny-Carman (KC) equation (Eq. 2), and a corrected version for tailings (Eq. 3), presented by Chapuis and Aubertin (2003) The modified KC, or KCM (Aubertin et al. 1996; Mbomba et al. 2002) (Eq. 4) has also been used, and it typically leads to even better results, when predictions are compared with measured k_{sat} values. These equations show that the value of k_{sat} is related non-linearly to the void ratio, as illustrated also by the dashed lines shown in Figures 5 and 6.

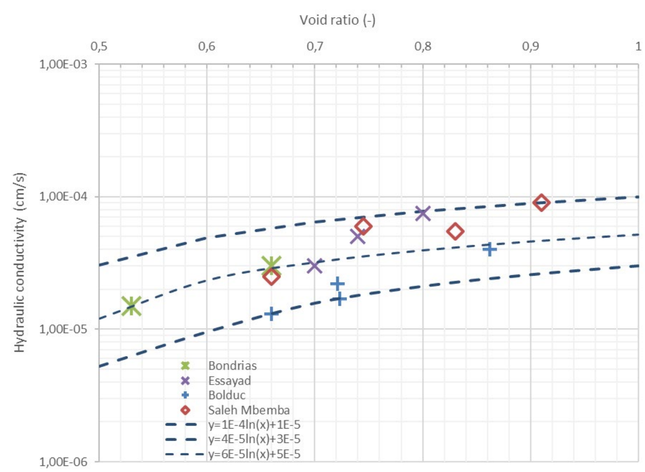

Figure 6. Saturated hydraulic conductivity measured in laboratory vs. void ratio.

$$\log(K\_KC/[1\text{m/s}]) = 0.5 + \log(e^3 / [D_r^2 \times S^2 \times (1+e)]) \quad (2)$$

$$\log(K\_KC\_tailings[1\text{m/s}]) = 1.5 \times \log(K\_KC/[1\text{m/s}]) + 2 \quad (3)$$

$$K\_KCM = 0.1 \times (\gamma_w/\mu_w) \cdot C_U^{1/3} \times D_{10}^2 \times e^5/(1+e) \quad (4)$$

In these equations, e is the void ratio, D_r is the solid grain density (specific weight), S (m^2/kg) specific surface; γ_w (= 9.81 kN/m^3) is the water unit weight; μ_w (10^{-3} Pa.s^{-1}) is the water viscosity, D_{10} is the diameter corresponding to 10 % passing on the grain size curve, and $C_U=D_{60}/D_{10}$ is the coefficient of uniformity.

3.6.2 In-situ saturated hydraulic conductivity

Measurements were also conducted in the field to evaluate the tailings hydraulic conductivity using tests in wells with ascending and/or descending conditions, as well as a dissipation phase during CPT measurements (based on Robertson 2010).

The hydraulic conductivity estimated from CPT performed in 2013 ranged from 1×10^{-3} to 1×10^{-7} cm/s while those conducted in 2016 ranged from 2×10^{-5} to 1×10^{-6} cm/s (Opris, 2017). Values estimated from dissipation tests ranged from 3×10^{-5} to 1×10^{-6} cm/s, with a mean value around 1×10^{-5} cm/s, which is close to the results obtained in the laboratory on homogenized tailings specimens.

3.6.3 Water retention curve and shrinkage

The water retention curve (WRC) of various tailings, including the CM mine tailings, was characterized in the laboratory for different initial water content using pressure plate and Tempe cell tests (Essayad 2015; Saleh Mbemba 2016; Boudrias 2017). Doucet et al. (2015) also reported results from pressure cell and pressure plate tests to establish the water retention curve at relatively low suction, and saturated salt solution tests for higher negative pressures.

Figure 7 presents different WRC based on volumetric water content as a function of suction (kPa).

The various laboratory testing results have been fitted to two well-known descriptive equations proposed by van Genuchten (1980) and Fredlund and Xing (1994). The corresponding WRC parameters are presented in Tables 1 and 2 respectively. The measured WRC are also compared with curves obtained with the MK predictive model, based on grain size and porosity (Aubertin et al. 2003).

These results indicate that the AEV of relatively dense CM tailings (porosity n near 0.4) is usually between 20 and 50 kPa, which is typical for tailings from hard rock mines; the AEV is lower for looser, more compressible, tailings. The effect of the initial porosity (or void ratio) on the WRC has been investigated by Saleh-Mbemba and Aubertin (2016).

Table 1. Average parameters of the WRC expressed with the Van Genuchten (1980) equation, for the CM mine tailings

θ_s (m³/m³)	θ_r (m³/m³)	α (kPa⁻¹)	n (-)	$m=1-1/n$ (-)
0.5 0.4	0.005	0.01	2.1	0.52

Table 2. Fredlund and Xing (1994) descriptive retention curve model parameters

θ_s (m³/m³)	Ψ_r (kPa)	a_f (kPa)	n_f (-)	m_f (-)
0.5 0.4	300	80	2.6	0.95

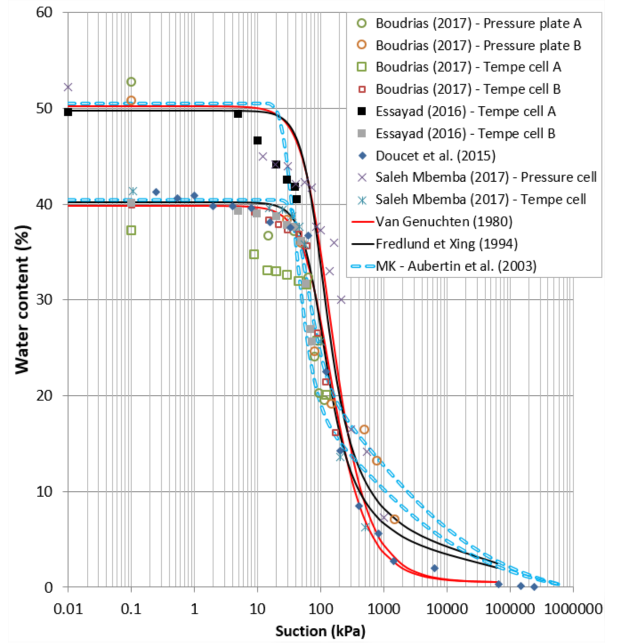

Figure 7. Experimental results obtained to define the water retention curve of the CM mine tailings.

The figure also shows that the two descriptive equations follow the data quite well, and that the predictive MK model lead to WRCs that are also close to experimental results.

Shrinkage and desiccation were also studied in details for the unsaturated CM tailings and other hard rock tailings (Saleh Mbemba and Aubertin, 2015). The experimental results showed that the shrinkage limit w_s is a function of the initial water content w_o of the tailings, with measured w_s values typically ranging between 20 and 35%. The corresponding void ratio is between 0.6 and 0.8. Cracking during desiccation occurs when suction becomes close to the tailings AEV.

3.6.4 Cyclic behavior

Tailings specimens were subject to uniform shear strains, γ_{cyc}, ranging from 0.275 to 1.57% in amplitude to establish cyclic shear strength curves, based on the strain amplitude as a function of the number of cycles, up to liquefaction, N_{LIQ}. These tests were conducted with a sinusoidal cyclic shear stress applied at a frequency of 1.0 Hz. (Archambault-Alwin 2017).

Typical results from a cyclic TxSS test (for a CSR =0.2) are presented in Figure 8, for an effective confining stress of 300 kPa and a uniform cyclic strain of 1.39% (Archambault-Alwin et al. 2017; Archambault-Alwin, 2017). As can be observed on this figure, the specimen was stronger early in the test, before the development of excess pore water pressure. As the cyclic loading progressed, additional excess pore water pressure was generated and the specimen progressively lost its stiffness and shear strength, until the pore water pressure ratio r_u reached about 0.9 corresponding to liquefaction; it occurred after about 7 cycles or for a shear strain (γ_{cyc}) of 1.39% approximately in figure 8.

The hysteresis curves shown on Figure 8c are typical of strain-controlled tests (Movahed et al. 2011). The cyclic Stress ratio decreased after each loading cycle, while the maximum shear strain amplitude remained constant at 1.39% during cyclic testing. This amplitude remains uniform for the frequency of 1 Hz used here; the number of cycles then corresponds to the time (in seconds) elapsed during cyclic loading.

Figure 8b shows the evolution of the cyclic stress ratio, CSR as a function of the number of cycles *N*. The first amplitude of CSR is about 0.2 and then decreases with each cycle. The CSR is about 0.05 when r_u reaches 0.9.

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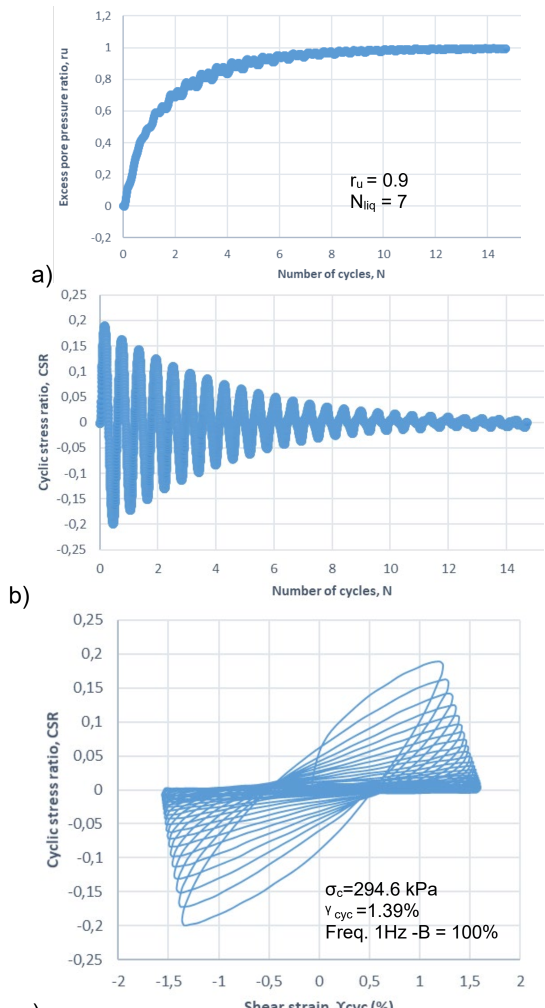

Figure 8. Results of Test S-30 on CM mine tailings (σ'_c =294.6 kPa and γ_{cyc} = 1.39%): a) Excess pore water pressure ratio as a function of number of cycles. B) Cyclic stress ratio, CSR as a function of number of cycles and c) Hysteresis loops (adapted from Archambault-Alwin, 2017).

The relationships between the shear strain amplitudes and the number of cycles at liquefaction are plotted on Figure 8, for different consolidated void ratios (values given next to the data points). It is seen that the number of cycles required to induce liquefaction increases with decreasing shear strain amplitude. The cyclic resistance, expressed in terms of shear strain amplitude, is also a function of the effective confining stress.

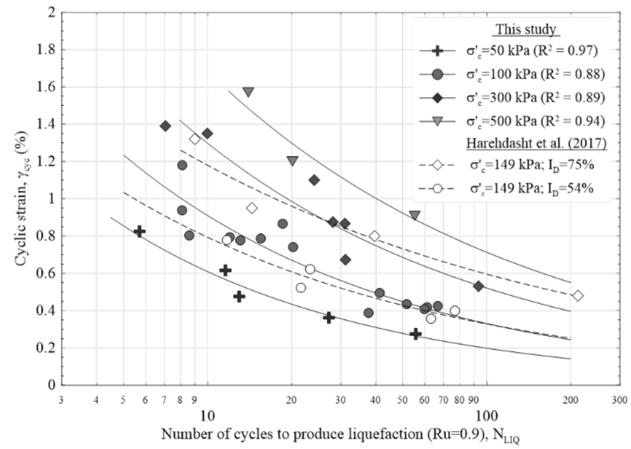

Figure 9. Cyclic shear strain resistance of the tailings compared to silty sand tested by Harehdasht et al. (2017).

The cyclic curves shown on Figure 9 also indicate that cyclic resistance tends to increase with increasing effective confining stress. The cyclic strain curves obtained from strain controlled cyclic TxSS tests conducted on a silty sand by Harehdasht et al. (2017) are also shown on Figure 9. These correspond to an effective consolidation stress of approximately 145 kPa and void ratios of 0.75 and 0.67, resulting in density index of 54% and 75% respectively. The comparison indicate that the CSR obtained on the silty sand with a density index of 54% is close to results obtained for the CM mine tailings consolidated at 100 kPa with a void ratio of 0.53.

These experimental results have been used to calibrate the parameters of a cyclic constitutive model applied to analyze the seismic response of the tailings impoundment (Zafarani et al. 2020; Contreras 2022)

4 Conclusion

The article presents a fairly detailed summary of the experimental results obtained from various tests conducted on the CM mine tailings over the last decade or so. This extensive experimental program has lead to a comprehensive characterization of the hard rock tailings produced at this large open pit gold mine located in Abitibi, Québec. The results presented here include basic characteristics, including grain size curves and relative density, and various geotechnical properties defining strength and compressibility. The geotechnical parameters presented here have been used to conduct different types of analysis, including numerical simulations to evaluate the response and performance of the tailings impoundment. These geotechnical properties of these tailings, which are fairly typical of low plasticity tailings from hard rock mines, should be of interest to those planning a similar experimental program.

5 Acknowledgement

The authors acknowledge the financial support from NSERC and from the industrial partners of the Research Institute on Mines and the Environment (RIME UQAT-Polytechnique; http://rime-irme.ca/en).
The first author also thanks Wood (employer) for their support.

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