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Comparative experimental study of consolidation properties of hard rock mine tailings

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ABSTRACT

Tailings consolidation properties are critical parameters to estimate storage capacity of tailings storage facilities (TSF) and plan mine waste integrated management. In this study, consolidation parameters of tailings were experimentally evaluated using various consolidation tests, including column tests, constant rate of strain (CRS) tests and conventional oedometer tests. Column tests with an internal diameter of 10 cm and a height of 45 cm were used to determine the compressibility of initial loose and saturated tailings under incremental loadings, including compression index, C_c, coefficient of consolidation, C_v, coefficient of compressibility, a_v, and coefficient of volumetric compressibility m_v. Pore water pressure at three different elevations along the column and the displacement of the sample were continuously measured during the tests. CRS tests and conventional oedometer tests were also conducted to determine the compression behavior of the tailings. Results obtained from these different approaches were compared and their reproducibility and precision were evaluated. Experimental procedures and representative results are compared, analysed and discussed in this paper. Recommendations are proposed regarding the choice of experimental approach depending on the application and field conditions.

RÉSUMÉ

Les propriétés de consolidation des résidus sont des paramètres essentiels pour estimer la capacité de stockage des aires de stockage des résidus et planifier la gestion intégrée des rejets miniers. Dans cette étude, les paramètres de consolidation de résidus ont été évalués expérimentalement au moyen de divers essais de consolidation, notamment des essais en colonne, des essais à taux de déformation constant (CRS) et des essais œdométriques conventionnels. Des colonnes d'un diamètre interne de 10 cm et d'une hauteur de 45 cm ont été utilisées afin de déterminer la compressibilité des résidus saturés et estimer l'indice de compression, C_c, le coefficient de consolidation, C_v, le coefficient de compressibilité a_v et le coefficient de compressibilité volumétrique m_v. La pression interstitielle à trois élévations différentes le long de la colonne et les déplacements de l'échantillon ont été mesurés en continu pendant les essais. Plusieurs essais CRS et œdométriques conventionnels ont également été réalisés afin de déterminer le comportement en compression des résidus. Les résultats obtenus à partir de ces différentes approches ont été comparés, et leur reproductibilité et précision ont été évaluées. Les procédures expérimentales et certains résultats représentatifs sont comparés, analysés et discutés dans cet article. Des recommandations sont également proposées quant au choix de l'approche expérimentale en fonction de l'application et des conditions de terrain.

1 INTRODUCTION

Mining operations generate large quantities of tailings which are typically transported and stored hydraulically in tailings storage facilities (TSF) surrounded by dykes. Slurry tailings are deposited in a loose state at a high water content and subsequently consolidate with time (Saleh-Mbemba & Aubertin, 2018; Zhou H et al., 2019). Tailings consolidation can take a very long time because of their low hydraulic conductivity, which directly affects the construction and maintenance of tailings impoundments (Vick, 1990; Zhou H et al., 2019; Qi & Simms, 2019). Slurry tailings deposited in TSF can also induce other geotechnical instabilities, including failure of tailings dams and liquefaction(Bussière, 2007). A proper assessment of the evaluation of the tailings consolidation properties is therefore critical in terms of long term management of TSF (L.Bolduc & Aubertin, 2014; Bussière, 2007).

Several tests have been developed to specifically evaluate the consolidation properties of materials.

Conventional oedometer test (Holtz & Kovacs, 1981) has been most widely used to test the compressible properties of soil using the small strain Terzaghi's theory. However, this test is not originally standardized for the slurry materials and exhibits certain limitations when it is used to estimate the consolidation properties of slurry materials, (e.g., tailings and dredged soils) because of initially low density and high water content of the materials (Berilgen et al., 2006; Estepho, 2014; Ahmed & Siddiqua, 2014; Tian et al., 2019). Tailings slurry experiences the settlement and self-weight process (Imai, 1981; Bonin et al., 2014), yet it is not the case in the oedometer test since loading is applied immediately after the sample is place on the ring. The compressibility of tailings slurry at very low pressure (i.e., ranging from values lower than 1kPa to a few kPa) is critical and usually nonlinear (Berilgen et al., 2006; Tian et al., 2019). However, the initial loading pressure in the oedometer test is usually 5kPa. Thus, low loading pressures cannot be covered in conventional oedometer test, missing a significant behavior range of tailings. Finally, the constitutive relations between void ratio and effective stress and void ratio and hydraulic conductivity are essential for the estimation and simulation of consolidation of tailings (Ahmed & Siddiqua, 2014; Lévesque, 2019; Bonin et al., 2014; Ngo et al., 2020). The relation between hydraulic conductivity and void ratio cannot be achieved from oedometer test, and the values of hydraulic conductivity is usually estimated by using equations from small strain theory, which is supposed not to be suitable for slurry materials (Tian et al., 2019). Imai (1979) developed a seepage induced consolidation test (which is also called hydraulic consolidation test) to overcome the shortcoming of conventional oedometer test. The principal of this test is to use an induced seepage at a constant flow rate to generate the change in the effective stress through a slurry (Tian et al., 2019). This test can be performed at low applied pressure and the hydraulic conductivity is directly measured from the test by the application of Darcy's law (Abu-Hejleh et al., 1996; Tian et al., 2019). However, this test requires a sophisticated instrumentation to perform, there is a risk of formation of preferential flow along the interface of the wall and the material as well (Li, L. et al., 2013). Another method for determination of compressibility of soil is constant rate of strain test (CRS). This test takes significantly less time to perform compared to the oedometer test (i.e., each test takes from 2 to 3 days to perform) (Mesri & Feng, 2018). However, it still inherits the limitations from conventional oedometer test when it is used for slurry soils. A testing procedure for slurry tailings was developed at Polytechnique Montreal using instrumented columns to investigate consolidation parameters of tailings under incremental loadings with the continuous monitoring of excess pore water pressure (Boudrias, 2018; Essayad & Aubertin, 2020). The setup also allows to measure the saturated hydraulic conductivities at each loading step (Lévesque, 2019). The compression index C_c, recompression index C_r, coefficient of compressibility a_v, coefficient of volumetric compressibility m_v and coefficient of consolidation C_v can be estimated during the test.

The paper aims to evaluate the consolidation properties of the slurry tailings from various consolidation tests. Several column tests, CRS and conventional oedometer tests were carried out to determine the compression behavior of the tailings sampled at a partner mine. Experimental methods are briefly described, and representative results are compared and discussed in the following. The influence of the wall friction on the results of column tests are also discussed in this paper.

2 TAILINGS HYDROGEOTECHNICAL PROPERTIES

Fine-grained tailings were sampled from the concentrator at Malartic mine (Quebec) during summer 2019 and transported saturated to RIME laboratory at Polytechnique Montreal.

Tailings particles size distribution (PSD) was determined using ASTM D7928-17 for particles finer than 75 μm and ASTM D6913M-17 (2017) for coarser particles (Figure 1). The values of D_{10} - the diameter corresponding to 10% finer in the particle-size distribution, D_{60} - the diameter corresponding to 60% finer in the particle-size distribution, and the coefficient of uniformity C_u ($C_u = D_{60} / D_{10}$) were determined. The test was carried out in triplicate, and the difference between each measurement was smaller than 2%. The average values of D_{10}, D_{60} and C_u were 0.003mm, 0.04mm and 13.3 respectively.

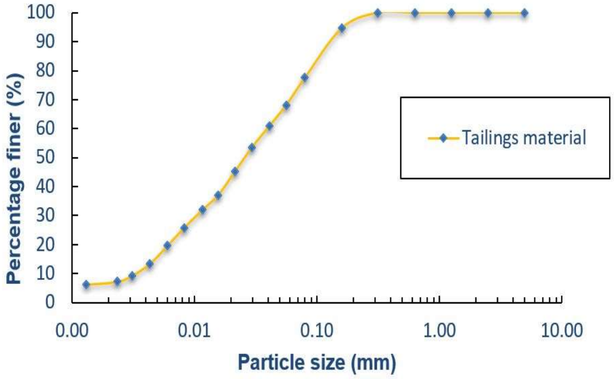


Figure 1. PSD curve of Malartic tailings sample.

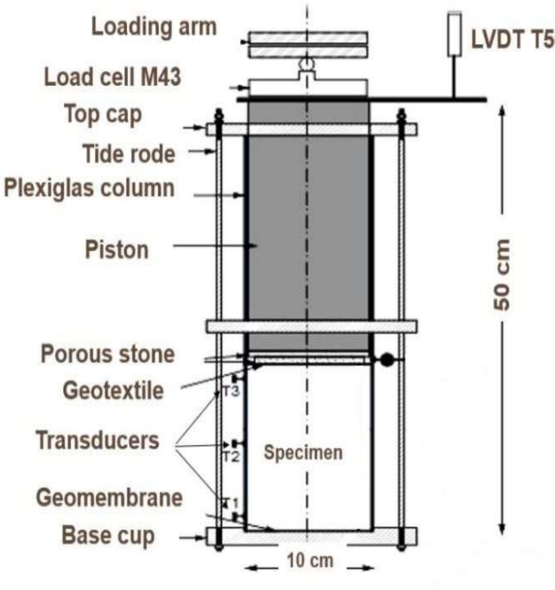
The specific gravity G_s of tailings was determined according to ASTM D854-14 (2016). The average value of G_s was 2.61, which is slightly smaller than that of typical tailings from gold mines (Boudrias, 2018; Essayad & Aubertin, 2020).

3 CONSOLIDATION TESTS

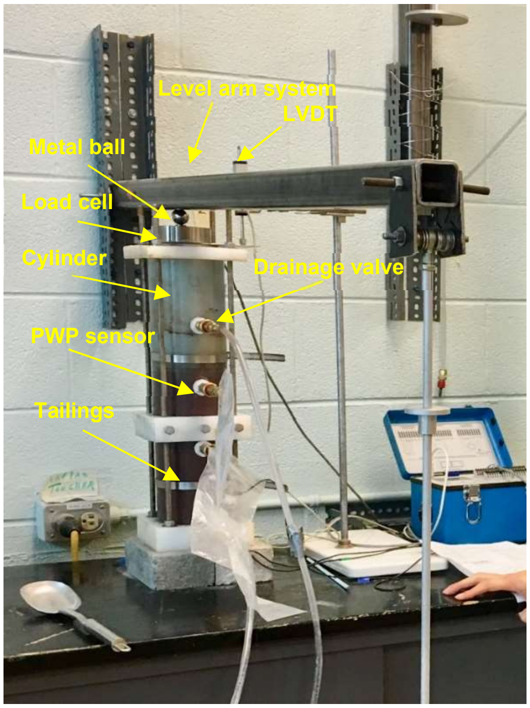
3.1. Column tests

Two consolidation tests (S1, and S2) were carried out in rigid columns (Figure 2). Columns have an internal diameter of 10 cm and a height of 50 cm. The tailings material was first mixed and homogenized at a water content of around 35% (i.e., a pulp density of around 74%). This value was slightly lower than those of the tailings in the mine site and can contribute to limit the segregation of the tailings during the test setup (Boudrias, 2018; Essayad & Aubertin, 2020). Tailings were then rapidly deposited in the column. Initial high of the specimens were recorded and the samples were left for 24 hours after deposition to allow for particle settlement. A PVC cylinder was then placed on the top of the sample to act as a piston. A load cell (Honeywell model 43) was installed on the top of the PVC cylinder to measure the vertical loading applied during the compression tests. A metal ball at the top of the load cell transmitted the applied vertical loading to the sample. A lever arm system was used to apply increasing compression loadings. A few centimeters of water were left on top of the specimen to keep the sample saturated during the tests.

Excess pore water pressure and settlement of tailings were measured continuously during the tests using three pressure sensors installed at the top (elevation z_1 = 23.5 cm), middle (z_2 = 13.5 cm) and bottom of the sample (z_3 = 3.5 cm) and a T50 LVDT (Novotechnic) placed at the top of the cylinder. The pore water pressure sensors and the LVDT were calibrated before starting the test. More details on the column test setup can be found in (Essayad, 2015; Boudrias, 2018; Lévesque, 2019; Essayad & Aubertin, 2020).



(a)



(b)

Figure 2. a) Column test set up for saturated tailings, with the lever arm system and PVC cylinder to apply vertical compression loading. LVDT and PWP sensors (placed at different elevations) are connected to a data logging system (modified after Essayad, and Aubertin (2020); b) Photo of the set up.

The first loading stage started with the installation of the piston cylinder and the load cell on top of the sample. A lever arm was then applied to the top of the load cell at the beginning of the second loading stage. Subsequent loading steps were imposed by applying a dead weight on the lever arm. Each loading step was considered finished when the excess pore pressure in the sample was totally dissipated. A total of 10 loading steps for a total load of approximately 470 kPa were applied to the specimens (Table 1). After the loading procedure was finished, rebound during unloading was also monitored.

The variation of void ratio was plotted against applied loads, and the compression index C_c and recompression index C_r were then estimated. Coefficient of compressibility a_v, coefficient of volumetric compressibility m_v and coefficient of consolidation C_v were calculated using following equations (Holtz & Kovacs, 1981):

$$a_v = -\frac{\Delta e}{\Delta \sigma'} \qquad [1]$$

$$m_v = -\frac{a_v}{1+ e_0} \qquad [2]$$

$$c_v = \frac{0.848\ \ ^{2}}{t_{90}} \qquad [3]$$

Table 1. Loading steps and load applied on the samples (with σ': effective stress and μ: coefficient of friction).

Loading steps	Loads S1			Loads S2		
	σ' (kPa)	μ	σ'_{cor} (kPa)	σ' (kPa)	μ	σ'_{cor} (kPa)
01	3.2	0	1.3	3.2	0	1.5
02	26.4	0.1	24.5	26.5	0.18	22.6
03	64.0	0.22	52.3	63.6	0.23	51.1
04	101.4	0.33	77.4	100.6	0.46	71.2
05	138.6	0.58	92.9	139.2	0.58	87.4
06	174.6	0.44	113.6	174.2	0.57	102.3
07	248.5	0.69	136.1	248.8	0.68	126.1
08	322.5	0.74	154.9	321.9	0.71	147.4
09	397.2	0.72	176.4	397.2	0.78	163.9
10	472.4	0.74	195.4	471.7	0.77	180.7

3.2. Conventional consolidation tests and CRS test

Two conventional oedometer tests (ASTM D2435/D2435M-11) and one additional CRS test (ASTM D4186) were also carried out on the same materials. The samples for the oedometer and CRS tests were also prepared by mixing the tailings materials at a moisture content of 32% and 36% respectively to ensure that no air was trapped in the slurry tailings. The samples were then quickly poured into consolidation rings. The maximum load applied on the specimen was around 430 kPa for the oedometer tests, and around 2000 kPa for the oedometer tests. Evolutions of effective axial stress and axial deformation were measured during these tests.

4 RESULTS

4.1 Column tests

Effect of friction between tailings and the wall of columns

Ratio $\Delta u/\Delta\sigma$ (i.e., the ratio of the increase of the pore water pressure to the load increment for each step) was close to 1 for the first few loading steps, but the value then decreased as the loading increased. The minimum ratio measured was approximately 0.23 for the final loading steps. The loading increment seemed therefore only partially transferred to the tested specimens. This observation could be explained by friction between tailings and column walls, as suggested by others (Boudrias, 2018; Essayad & Aubertin, 2020).

Analytical solutions proposed by Aubertin et al. (2003) and Li, Li, and Aubertin (2009) were used here to assess the influence of the wall friction on the measured consolidation properties. These equations were first proposed to evaluate the effect of stress state in backfilled openings, taking into consideration rock wall friction. A detailed procedure for the correction of the wall friction effect during column test on the saturated tailings materials was also proposed by Essayad (2015). In general, the shearing force S [kN], which is generated by the wall friction, is related to the applied force $\Delta\mathrm{P}$ [kN] by the coefficient of friction μ [-] as follow (Mittchell & Soga, 2005):

$$\mathrm{S} = \mu \times \Delta\mathrm{P} \qquad [4]$$

The coefficient of friction μ is calculated as:

$$\mu = 1 - \frac{\Delta u}{\Delta\sigma} \qquad [5]$$

The corrected axial compression stress at the middle of the sample can then be calculated as:

$$\sigma_{\mathrm{cor}} = \frac{(\Delta\mathrm{P} - \mathrm{S} - \mathrm{W})}{\mathrm{A}} \qquad [6]$$

Where W [kN] is the weight of the material above the middle point of the column ($\mathrm{W} = \gamma \times (1/2)\mathrm{H}$, with H [L] is the height of the sample column; A is the area of the sample [L^2].

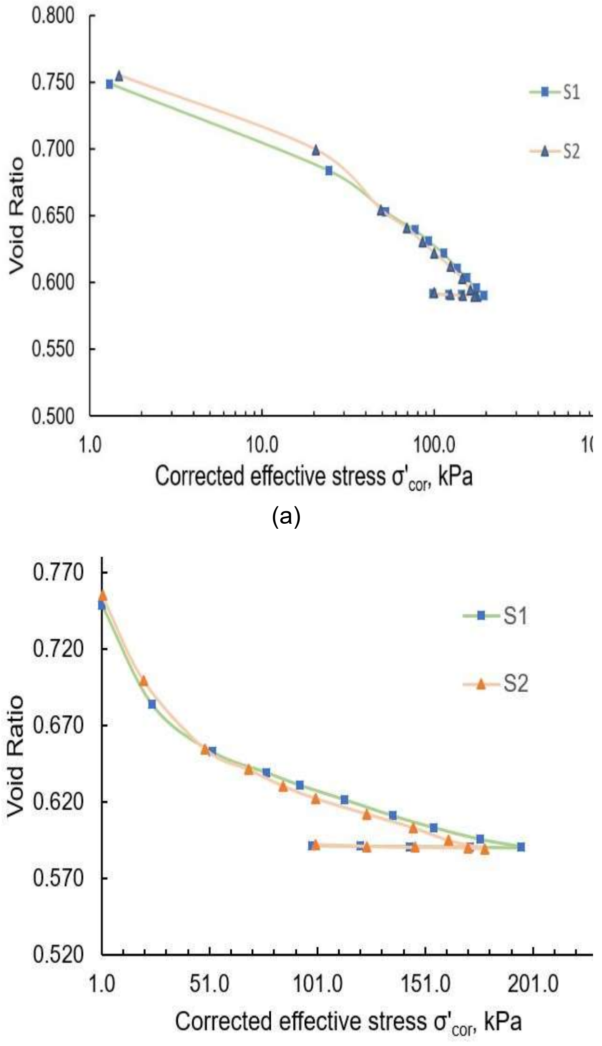
The void ratio of the samples decreased rapidly and significantly (around -X) after the first two loading steps ($\sigma'_{cor} \leq 25$ kPa) because the initial state of the slurry samples is quite loose (Figure 3). For $\sigma'_{cor} \geq 25$ kPa, the relation between void ration and σ'_{cor} was quasi-linear. The average final void ratio was around 0.58, i.e., a decrease of 0.17 throughout the test. The average compression index C_c and the re-compression index C_r of the two samples was estimated from the compression and re-compression slopes of void ratio - σ'_{cor} curves and were around 0.033 and 0.002, respectively. Those values are in the typical range of hard rock mine tailings (Bussière, 2007). The coefficient of compressibility a_v was comprised between 2.1×10^{-2} and 2.8×10^{-4} kPa^{-1} for sample 1 and between 1.1×10^{-2} and 3.3×10^{-4} kPa^{-1} for sample 2, and the coefficient of volumetric compressibility m_v was between 1.2×10^{-2} and 1.6×10^{-4} kPa^{-1} for sample 1 and between 5.9×10^{-3} and 1.8×10^{-4} kPa^{-1} for sample 2. These values are also representative of this type of tailings (Bussière, 2007).

The largest settlements occurred for the first few loading steps (i.e., step 01, 02 and 03) (Figure 4). The largest deformation was recorded in the first loading step and was around 1 cm. Displacements measured for the second and third loading steps were about 0.4 cm. Settlement was much smaller during the subsequent loading steps and the average settlement for the loading steps 7 to 10 was around 0.1 cm. The coefficient of consolidation c_v was between 0.07 cm^2/s and 0.43 cm^2/s for the sample S1, and between 0.09 cm^2/s and 0.25 cm^2/s for S2. These results were lower than values obtained by Boudrias (2018) and Essayad (2015) (between 0.02 cm^2/s and 6.6 cm^2/s) on tailings from the same mine site.

Consolidation parameters are summarized in Table 02.

Table 2. Consolidation parameters of tailings sample S1 and S2 measured using various consolidation tests.

Parameters	Sample S1	Sample S2	Oedometer test	CRS
C_c (-)	0.031	0.035	0.02	0.05
C_r (-)	0.002	0.002	0.008	N/A
a_v (kPa^{-1})	2.1×10^{-2} - 2.8×10^{-4}	1.1×10^{-2} - 3.3×10^{-4}	3.6×10^{-2} - 5.8×10^{-4}	N/A
m_v (kPa^{-1})	1.2×10^{-2} - 1.6×10^{-4}	5.9×10^{-3} - 1.8×10^{-4}	1.9×10^{-2} – 3.1×10^{-4}	N/A
C_v (cm^2/s)	0.07 - 0.43	0.09 - 0.25	0.09 - 0.36	N/A



(a)

(b)

Figure 3. Variation of void ratio with axial compression stress for samples S1 and S2, presented on (a) semi-logarithmic (e-log σ'$_{cor}$) and (b) arithmetic (e- σ'$_{cor}$) scale.

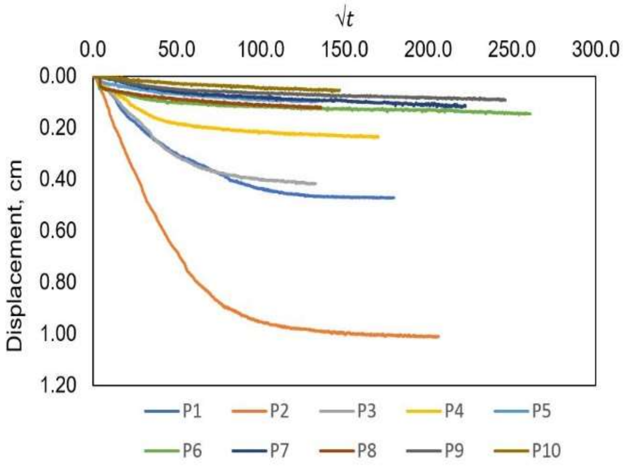


Figure 4. Settlement of sample 01 for different loadings.

4.2 Evolution of pore water pressures

The dissipation of PWP after applying loading on top of the tailings sample occurred quite rapidly and generally in less than 1 hour (Figure 5). More specifically, the excess PWP dissipated more rapidly on top than in the middle and bottom of the columns (because of a shorter drainage distance).

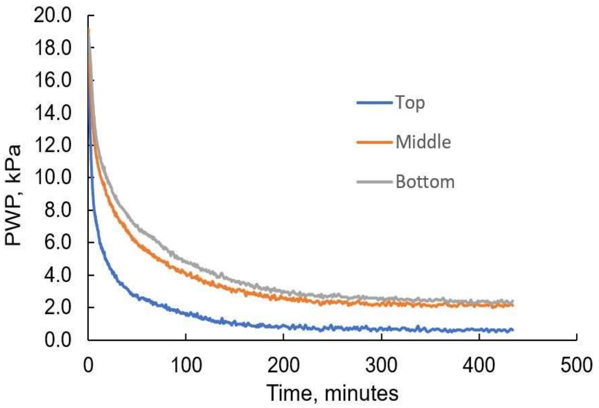


Figure 5. Evolution of PWP measured in sample 02 during loading step 02 (22.6 kPa).

4.3 Oedometer tests and CRS tests

The average values of C_c and C_r measured during oedometer tests for the same tailing materials was 0.02 and 0.008 respectively. C_c for the CRS test was 0.05 (Figure 6). It is noted that the unloading phase for the CRS test was not performed because of experimental constraints, and PWP could not be measured during CRS test because high permeability of tailings promoted almost instant dissipation of excess PWP. Thus, only value of C_c was generated from CRS test.

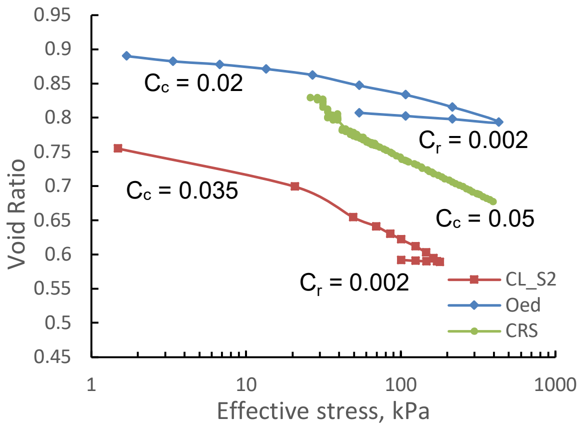


Figure 6. Void ratio as a function of axial compression stress for different compression tests.

5 RESULT ANALYSIS AND DICUSSION

Compression index C_c obtained from the column tests (0.03) was higher than result measured from oedometer tests (0.02) and smaller than one obtained from CRS test (0.05). Results were, however, relatively similar. The re-compression index C_r measured in the column tests (0.002) was lower than one achieved from the oedometer tests (0.008). The initial void ratios between the tests were also slightly different, with initial void ratio in the column test being lower than the values of oedometer and CRS tests, which was 0.75, 0.83 and 0.89 respectively. A possible explanation is that the tailings in the column tests were given 24 hours for particles to settle which better reflects in-situ conditions and limits the influence of particle settlement on the result (Essayad & Aubertin, 2020). On the other hand, the oedometer tests and CRS test were started immediately after tailings being poured into the sample rings. The average final void ratio from column test was around 0.59, while that for the oedometer tests and CRS test was 0.80 and 0.66 respectively.

The difference of measured compressibility between consolidation tests could also be explained by the differences of sample heights, i.e., the height of column test was around 30 cm while that for oedometer test and CRS test was around 2 cm. The influence of friction along the column wall and some other uncertainties could be attributed to this difference. Additional tests would be required to confirm these observations. Finally, the measurement of zero PWP in the CRS test (Table 02) also indicates that this type of test is only suitable for the fine tailings materials which have somewhat low hydraulic conductivity.

Small differences of compression indices (< 8.8% for C_c and < 1% for C_r) from the column tests tend to indicate a good reproductivity of the approach, as observed by Boudrias (2018) and Essayad, and Aubertin (2020). However, only two experiments were carried out in this study and additional tests and duplicates are required to confirm this observation for different tailings and initial water contents. The installation of PWP sensors at various elevations allowed the measurement of PWP during the test which was also beneficial. It can help to estimate the effective stress during the test, quantify the influence of the friction on the test and determine the termination of each loading step. Some numerical simulation works have been carried out using the result from column tests (L.Bolduc & Aubertin, 2014; Boudrias, 2018). The results have been validated by the comparison with the instrumentation data on the consolidation of tailings in practice.

Several limitations of the column tests could be indicated. It is necessary to use low pressure value for the first few loading steps of test becaues significant changes in the properties of tailings happen within this range of pressures. In this paper, the first loading was around 3.2 kPa and the second loading value was 26.4 kPa which can lead to the missing of nonlinear behavior of the tailings slurry. The influence of friction was also notable, some types of material could, thus, be used to reduce such friction, i.e., teflon sheet and/or lubricant could be employed.

6 CONCLUSIONS

Several types of consolidation tests were carried out in this study. Measured consolidation properties were similar and in the range of typical values for this type of tailings. The correction of the effect of friction between column wall and tailings was also considered in the correction of effective stress this paper. Column tests were considered suitable for testing slurry tailings, and the parameters from these tests could further be used for numerical simulations that could help to estimate consolidation of tailings and optimize the deposition of tailings during mining activities.

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