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Physical modelling of tailings consolidation near a waste rock inclusion

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ABSTRACT
A laboratory physical modelling study was conducted to assess the effect of waste rock inclusion on the consolidation of tailings from hard rock mines. The evolution of pore water pressures during consolidation of tailings with and without a drainage inclusion has been monitored and analyzed. This investigation focuses on the evolution of tailings geotechnical characteristics (void ratio and volumetric water content), water transfer from the tailings to the waste rock, and movement of fine particles at the interface between the two materials. The experimental results demonstrate quantitatively how a waste rock inclusion affects tailings consolidation by reducing the pore water pressures with an accelerated water drainage.

RÉSUMÉ
Une modélisation physique en laboratoire a été menée pour évaluer l'effet des roches stériles sur la consolidation des résidus de mines en roches dures. L'évolution des pressions interstitielles lors de la consolidation des résidus avec et sans inclusion drainante a été mesurée et analysée. L'investigation porte principalement sur l'évolution des caractéristiques géotechniques des résidus (i.e. indice des vides et teneur en eau volumique), le transfert de l'eau des résidus vers les roches stériles et le mouvement des particules fines à l'interface entre les deux matériaux. Les résultats expérimentaux démontrent de manière quantitative comment une inclusion de roches stériles affecte la consolidation des résidus en réduisant les pressions interstitielles par un drainage accéléré de l'eau.

1 INTRODUCTION

The conventional method of slurry tailings deposition (often with upstream dikes) is widely used in the mining industry. This technique is relatively easy to apply and often considered less costly than other methods. However, several major dike failures have occurred in recent years, so serious concerns have been expressed about this method (e.g. Aubertin et al. 2002, 2011, Davies 2002; Roche et al. 2017).

The use of waste rock inclusions (WRI) in tailings impoundment was proposed over 15 years ago to help improve tailings management (Aubertin et al. 2002). Such inclusions strategically placed in an impoundment can significantly shorten the time required for tailings consolidation and alleviate the accumulation of excess pore water pressures, hence increasing their strength and stiffness. WRI can also serve to reinforce the tailings impoundment and increase static and dynamic stability, while reducing the size of waste rock piles (Aubertin et al. 2002, 2011; James and Aubertin, 2009; James et al. 2013, 2017). Waste rock is often available in the vicinity of the impoundment so its use to construct inclusions is relatively easy to implement. Despite these and other advantages, this approach is not yet commonly used, and it raises a few technical issues that must be addressed to optimize the design of WRI.

Preliminary numerical studies have been conducted to assess some of these issues. The simulations have mainly focused on the impact of WRI on the dissipation of pore water pressures and consolidation rate of tailings (Jaouhar et al. 2013, L-Bolduc and Aubertin 2014). The results from these conceptual calculations are encouraging, but several aspects still require further investigation with more realistic situations.

Experimental and numerical tools are used here to better assess the mechanisms involved and evaluate the conditions leading to an optimum application of WRI in tailings impoundment. Part of this ongoing work involved the development of an instrumented laboratory model to assess in a controlled manner the effectiveness of waste rock to accelerate consolidation of tailings (and related aspects). Different scenarios have been studied to gain a better understanding of the governing processes. The experimental protocol for this investigation is described. Representative results are also presented and discussed.

2 THE USE OF WASTE ROCK INCLUSIONS

Waste rock inclusions (WRI) are built by placing continuous rows of waste rock along selected paths in the impoundment to improve the overall behavior and create compartments (James and Aubertin, 2009; James et al. 2013, 2017). As illustrated schematically in Figure 1 (in 2D view)., such WRI are raised from the foundation over time as tailings are deposited hydraulically. A waste rock layer can also be placed at the base of the impoundment and on the sides of the external dikes to favor downward and lateral drainage in the tailings (Aubertin et al. 2002; Saleh-Mbemba et al. 2019).

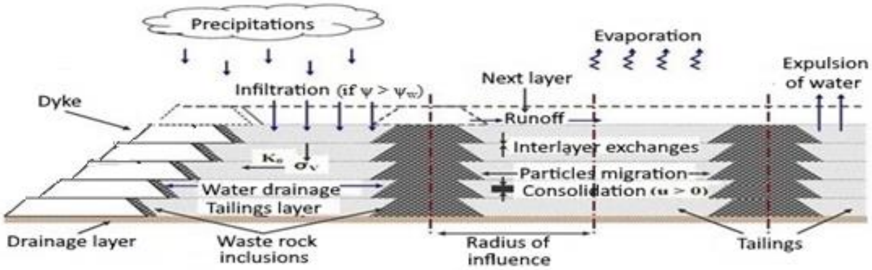

Figure 1 Schematic view of a tailings impoundment with waste rock inclusions (adapted from James et al. 2013).

One of the main advantages of using WRI in a tailings impoundment is to create cells (or compartments) that are adding flexibility for hydraulic deposition and improved water management. WRI also increase the geotechnical stability against static and dynamic loadings and they may also contribute to site reclamation when approaching mine closure by creating cells (compartments) with lanes for traffic in the impoundment, while increasing the bearing capacity of the consolidated tailings.

The analysis and design of WRI nonetheless raise a few challenges for an efficient application in the field. For instance, the lateral water flow near the waste rock needs to be properly considered as the accelerated drainage can produce desiccation at the tailings surface, which may be problematic when reactive minerals (like pyrite) are present. Desaturation may also influence the vertical and lateral flow rates in a manner that is not easily predicted. The possible migration of fine particles also needs to be evaluated as there may be a risk for pore clogging in the waste rock. The presence of WRI also affects the stress-strain behavior of the tailings close to the interface. Thus, methods must be developed to evaluate these and related aspects, including specifically the characteristics of the horizontal flow within the tailings-WRI system near the interface between two very distinct materials.

3 EXPERIMENTAL MODEL TESTING

Analytical solutions and numerical models are commonly used to assess how complex, large scale structures may behave. In general, these tools should be validated (at least in part) and calibrated (in some cases) using experimental data before they can be applied to the real, and often more complex cases. Experimental tests on physical models are well suited for such early stage in the analysis and design process. The modelling test results can also provide a better understanding of complex phenomena that sometimes involve several factors. These were some of the main objectives of the experimental program conducted here and described in the following sections.

3.1 Basic material properties

This testing program involved the use of fine-grained tailings and waste rock sampled at the Canadian Malartic gold mine, located in Abitibi, QC, Canada.

Laboratory tests have been conducted to determine their main geotechnical characteristics, including particle size distribution (sieving and sedimentation), relative density of the solid grains, and saturated hydraulic conductivity for different void ratios. The details of this characterization program are presented in Saleh-Mbemba (2016), who also provides all the results.

The grain size distribution curves indicate that the average effective diameter D_{10} of the tailings and waste rock (with a maximum grain size of 10 cm) is 0.0043 mm and 1.2 mm respectively. The corresponding coefficient of uniformity C_U (= D_{60}/D_{10}) is 8.2 and 18.3 (see Table 1).

The tailings include about 90% of particles smaller than 75 µm, with 6% having a size less than 2 µm. The waste rock contains mainly sand and gravel, with about 4% of fine particles. The relative density D_r of the tailings is 2.75 and that of waste rock is 2.70 (Table 1).

The saturated hydraulic conductivity k_{sat} measured on four tailings specimens varied from 2.6 to 8.9 x 10^{-5} cm/s for a void ratio e between 0.66 and 0.91. The k_{sat} value for the waste rock (measured by L-Bolduc 2012) is around 1.5 x 10^{-1} cm/s for a void ratio e near 0.5 (Table 1).

The characteristics of these materials are in the typical range for tailings (e.g., Vick, 1990; Aubertin et al. 2002, 2011; Bussière 2007) and waste rock (e.g. Barbour et al. 2001; McLemore et al. 2009; Peregoedova, 2012; Aubertin et al. 2013) from hard rock mines.

Table 1. Main characteristics of the tailings and waste rock used for the physical modelling tests

Characteristics	Tailings	Waste rock (maximum grain size of 10 cm)
D_{10} (mm)	0.0043	1.2
C_U (-)	8.2	18.3
Relative density, D_r (-)	2.75	2.70
k_{sat} (cm/s)	2.6 to 8.9x10^{-5}	1.3 to 1.8x10^{-1}
Void ratio e_0 (-) for k_{sat}	0.66 to 0.91	0.44 to 0.63

3.2 Equipment and sensors

Different types of test have been performed as part of this experimental program. The physical model tests presented here have been conducted in a rigid box having a section of 1.05 m x 1.05 m at the base and a height of 0.75 m (see

Figure 2; see also details in Pépin et al. 2012 for more details on the rigid container). One side of the box is made of a transparent Plexiglas© plate for visual observations. Gradation tapes placed along this side are used for measuring the water level in the waste rock (initially dry in most tests; see Table 2). Another side of the aluminum box includes holes with quick connects at different elevations, linked to pore-water pressure (PWP) sensors (10, 15, 25, 35, 45 and 50 cm from the base of the box; see Figure 2). The measurements have been recorded at 5 minutes intervals using the LabVIEW software, version 7.1, installed on a computer.

Omega PX243-05BG and PX243-15BG pressure sensors (precision of 0.25%) have been used to monitor water pressures in the experimental set-up.

Additional measurements have been conducted with ECH_2O moisture sensors (type EC-5, Decagon; precision of ± 2%). These were installed at elevations of 10, 30 and 40 cm, along a fixed rod in the box, as shown in Figure 2b (at a horizontal distance of 45 cm from the wall). These sensors measure the volumetric water content, which can be converted into pore water pressure, void ratio and other characteristics following a special calibration procedure based on the consolidation theory developed for that purpose (Saleh-Mbemba and Aubertin 2018). An Em50 data logger (with the ECH_2O Utility software) was used to record the moisture sensors measurements at 60 seconds intervals.

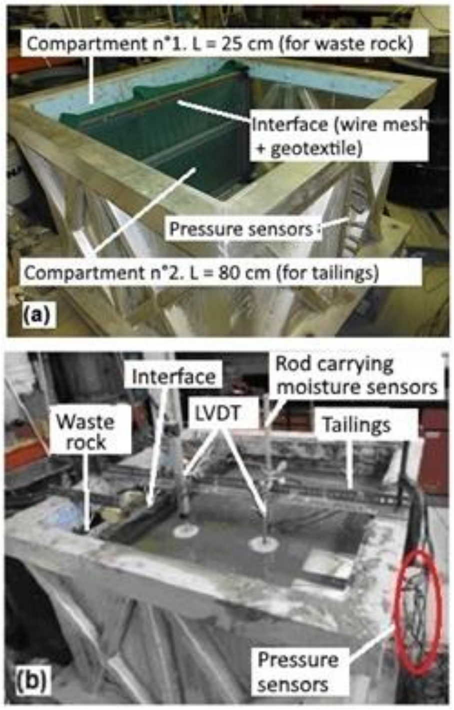

Figure 2 (a) Photo of the rigid box used for the physical modelling tests, showing the waste rock compartment (b) Experimental set-up with the measuring equipment installed in the tailings and waste rock.

The settlement at the tailings surface was measured using displacement transducers (LVDT, series "S", precision of 0.2%), shown in Figure 2b (see also Table 2).

3.3 Experimental procedures and testing conditions

The first test in the physical model set-up (rigid box) was performed with tailings only (no waste rock). The results from this test are used to complete the material characterization and for comparison purposes (i.e. with results from other tests conducted with waste rock). The tailings were initially prepared and homogenized at the desired water content in larger containers. A 60 cm thick layer of tailings was then discharged from flexible pipes into the box using two pumps (in about 5 minutes).

The three other tests described here have been conducted on the same tailings with a waste rock compartment (Tests 2, 3 and 4). The testing conditions and scenarios are described in Table 2. For each test, the box is first compartmented in two vertical sections using wire mesh and (for Tests 3 and 4) a geotextile. The 25 cm wide compartment on one side is first filled with the waste rock and the rest (80 cm) receives the tailings slurry (see Figure 2a). Test 2 was performed without the geotextile fabric at the interface to assess its influence.

Waste rock was initially placed into its compartment up to the desired elevation (height of about 60 cm, Table 2). The homogenized tailings were then discharged into the other compartment up to the desired height; the measuring equipment previously placed was then activated.

For Test 2, without the geotextile at the interface, in this article a special attention was paid to the tailings (fine particles) that migrated towards the waste rock. The other testing conditions (height of the layer, initial water content, types of measurements) were identical to Test 1.

For Test 3, a tube connected to a pump was placed at the surface of the tailings to withdraw continuously the water expelled upward during consolidation. The other end of the pipe was placed at the surface of the waste rock (other compartment) where the pumped water was poured, generating a rapid rise of the water level within the initially dry waste rock. The goal here was to investigate the effect of quick saturation of the WRI (by infiltrating and run-off waters) on horizontal drainage and drying of the tailings.

During Test 4, water was also pumped from the surface, but the pipe was discharged outside the system (in a tank). The level of water rising within the (initially dry) waste rock was measured over time, until equilibrium was reached (when the water rise ended).

4 MAIN RESULTS

4.1 PWP measurements

Figure 3 shows the PWP measurements given by the pressure sensors (Omega) and PWP values deduced from the moisture sensors (ECH_2O) at different elevations during Test 1 on tailings (without waste rock). The results indicate that there is as good agreement between the two types of experimental data. This figure also shows that the plateau corresponding to the hydrostatic pressure equilibrium was reached after about 14 hours.

Table 2 Characteristics of the tests performed in the physical model set-up shown in Figure 2

N°	Type of test	Description	Measurements
1	Tailings without WRI.	- Self-weight (1D) consolidation. - H_0 = 60 cm, w_0 = 43.0 ± 0.5%. Total time = 73 h.	- For both four tests: pore water pressure u using Omega pressure sensors at elevations of 10 cm, 15 cm, 25 cm, 35 cm, 45 cm (and at 50 cm for Tests1, 2 and 4); - Additional measurements for Tests 1 and 2 only: volumetric water content θ using moisture sensors at elevations of 10 cm, 30 cm and 40 cm; - For Tests 1 and 2 only: the settlement S_t has been measured at the tailings surface using LVDT.
2	Tailings + WRI initially dry, without a geotextile at the interface.	- H_0 = 60 cm, w_0 = 43.0 ± 0.5%. Total time = 69.5 h.	
3	Tailings + WRI initially dry + geotextile fabric at the interface.	- The water expelled at the tailings surface during vertical consolidation is transferred towards the WRI. - H_0 = 50 cm, w_0 = 43.0 ± 0.5%. Total time = 101 h.	
4	Tailings + WRI initially dry + geotextile at the interface.	- The water expelled at the tailings surface is evacuated from the box (in a tank to quantify the amount). - Measurements of the progressive water level rise in the initially dry WRI. - H_0 = 60 cm, w_0 = 43.0 ± 0.5%. Total time = 122 h.	

The theoretical hydrostatic equilibrium, computed as $u_w = \gamma_w h_w$, corresponds well to experimental data, with larger pressures at the base of the tailings (compared to the top part).

Figure 4 presents the PWP measured by the pressure sensors (Omega) and those obtained from the moisture sensors (ECH_2O) at different elevations during Test 2. The results from the pressure sensors located at 80 cm from the waste rock indicate that the time required to reach the plateau is again about 14 h (Figures 2a and 2b). The pressures inferred from the moisture sensors located at 45 cm from the inclusion give a time of about 9 hours. These results suggest that the time required to complete the dissipation of excess PWP was shorter for the sensors located closer to the drainage inclusion. Measurements from the pore water sensor at an elevation of 50 cm in Test 2 doesn't however follow this trend that clearly because of the readings fluctuation (near the tailings surface).

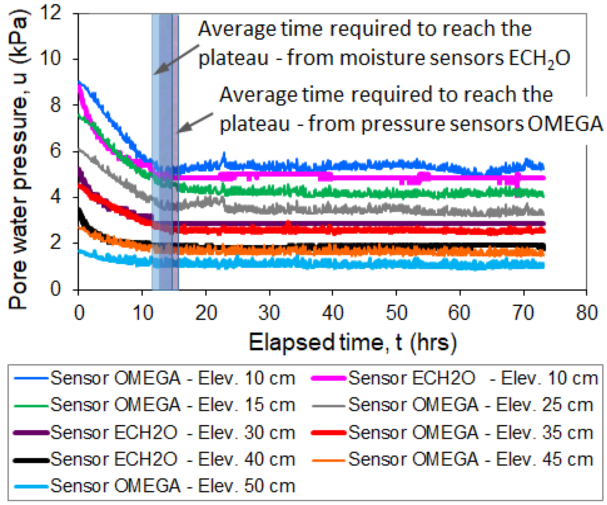

Figure 3 PWP obtained from the pressure and moisture sensors at different elevations during Test 1.

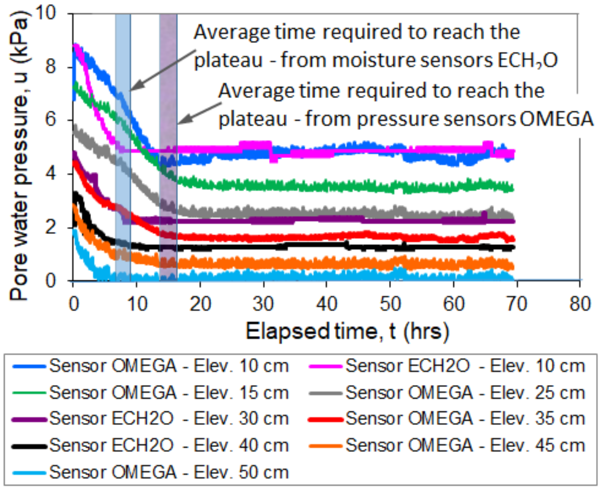

Figure 4 PWP obtained from the pressure and moisture sensors at different elevations during Test 2.

Figure 5 shows the PWP at different elevations during Test 3, given by the pressure sensors located at 80 cm (horizontal distance) from the waste rock. The results indicate that the time required to reach equilibrium was again close to 14 hours.

The dotted line for u_w (= $\gamma_w h_w$) at an elevation of 10 cm has been drawn in this figure to mark the final pressure level (hydrostatic equilibrium) for tailings alone (see Figure 3). The comparison indicates that the WRI in the tailings tends to produce a larger reduction of the PWP at the same elevation, compared with tailings alone. This aspect is discussed below.

The results indicate also that a stable condition was reached after dissipation of the excess PWP. Later during Test 3, at a time of about 55 hours, the PWP started decreasing again. The phreatic (water table) level, initially at the tailings surface (at elevation of 50 cm for this test; see Table 2), then gradually moved downward, as indicated also by the appearance of negative PWP (suction) in the top part of the tailings. The pore water pressures could have decreased even further if the test had been continued.

Figure 6 presents the PWP at different elevations during Test 4. The pressure drop was more pronounced in this case, and it continued for about 56 hours. The pressures then remained stable up to t ≈ 92 hours when an additional decrease was observed. The latter reduction of PWP can be related to evaporation at the tailings surface exposed to atmospheric conditions and to the corresponding decrease of the water table level.

The dotted line in Figure 6 corresponds to the equilibrium pressure u_w (= $\gamma_w h_w$) at an elevation of 10 cm This theoretical pore water pressure exceeds the readings of the pressure sensors at the same elevation. This indicates that there was a more pronounced drop of PWP for tailings consolidating near the WRI (compared with tailings alone). Here also, the trend shows that the pressures could have decreased further if the test had been continued.

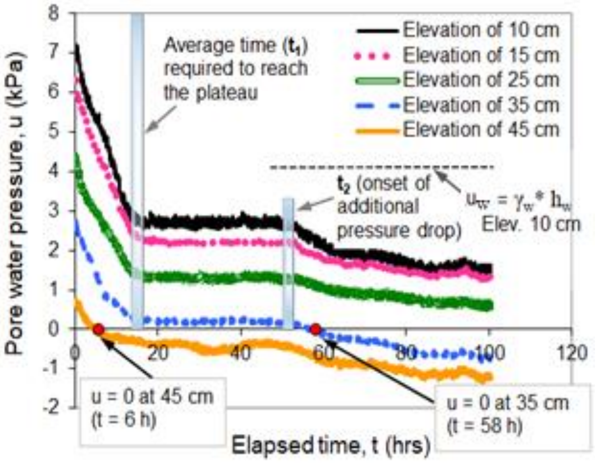

Figure 5 PWP obtained from the pressure sensors at different elevations during Test 3.

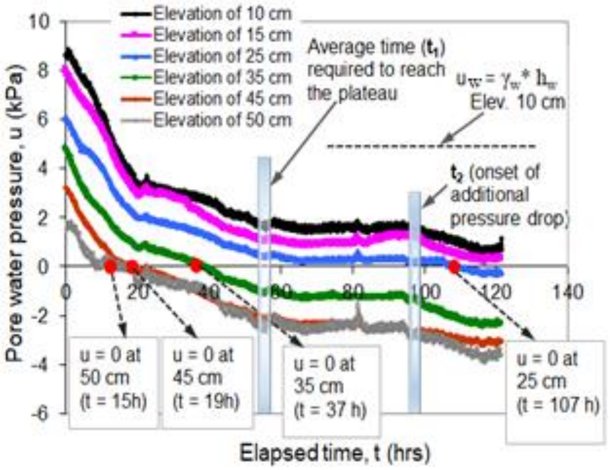

Figure 6 PWP obtained from the pressure sensors at different elevations during Test 4.

4.2 Evolution of tailings characteristics

Some geotechnical characteristics of the tailings evolved during consolidation, with and without the WRI.

Figures 7 shows the void ratio at elevations of 10 cm (close to the base of the tailings), 30 cm (near mid-height) and 40 cm (close to the tailings surface) during Tests 1 (no waste rock) and 2 (with waste rock). The data shown in this figure have been obtained from the measurements with the moisture sensors, which have been translated into PWP (using the approach described by Saleh-Mbemba and Aubertin, 2018).

The initial void ratio e_0 of the tailings was close to 1.19. Figure 7a indicates that this void ratio was reduced significantly at the base of the model during Test 1, down to a final void ratio $e_f \approx 0.97$. This variation at the base is larger than near the surface, where $e_f \approx 1.05$ (see Table 3).

For Test 2 (same e_0), Figure 7b indicates that the change of void ratio in the presence of the WRI lies between the two values obtained with Test 1, i.e. $e_f = 0.99$ and 1.02 at the base and near the surface respectively. The final tailings void ratio (with the WRI) appears to be relatively uniform with depth for this Test (at least in the region close to the inclusion).

Consolidation and water drainage also affect the dry density (ρ_d) and total unit weight (γ) of the tailings, and the corresponding volumetric and gravimetric water contents (θ and w). The initial and final values obtained from the moisture sensors readings for both Tests 1 and 2 are also presented in Table 3. The values obtained for Test 1 indicate that θ and w decreased much more near the base (elevation of 10 cm) than near the top part of the saturated tailings layer. The corresponding values of the dry density ρ_d and unit weight γ during Test 1 thus increased more significantly near the base than in the top part. The results of Test 2 with a waste rock inclusion show smaller changes along the vertical profile.

The settlement measured during Test 1 (without waste rock) is S_t = 5.20 cm (average total strain of 8.7%); this value is quite close to that given by the Terzaghi consolidation theory, when the corresponding parameters are used (S_t = 5.15 cm). During Test 2, the movement of tailings towards the waste rock (when there is no geotextile) appears to affect the settlement magnitude, with a total settlement S_t = 6.10 cm (i.e., average strain of 10.2%). These data are analysed and discussed below.

5 ANALYSIS AND DISCUSSION

5.1 Evolution of PWP and geotechnical characteristics

Figure 8 shows the change in pore water pressures at a depth of 25 cm from the tailings surface for Tests 1 to 4.

As mentioned above, the absence of a geotextile fabric at the interface for Test 2 has led to tailings particles moving towards the waste rock, which in turn produced larger settlement at the tailings surface. During this test, the water expelled at the surface during consolidation accumulated and this prevented drying of the tailings and prevented further reduction of PWP beyond the initial phase of dissipation.

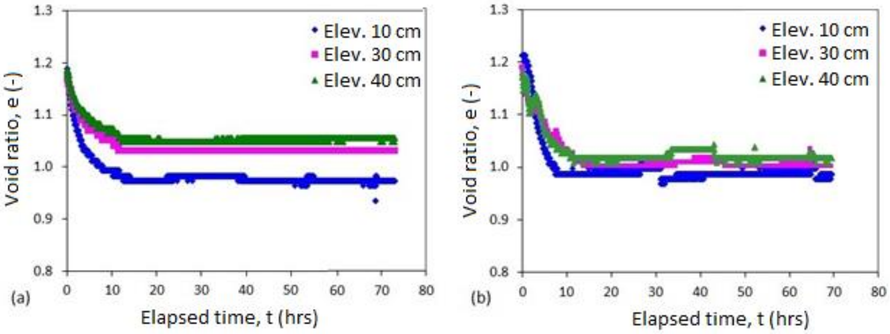

Figure 7 Void ratio at three elevations during (a) Test 1 (without WRI) (b) Test 2 (with WRI).

Table 3 Evolution of tailings characteristics during Tests1 and 2

Parameter			Vol. water content	Water content	Dry density	Unit weight	Void ratio
Symbol (unit)			θ (-)	*w* (%)	ρ_d (kg/m^3)	γ (kN/m^3)	*e* (-)
Initial (average) value along the vertical profile (for both tests)			0.54	43.0	1245	17.50	1.19
Finale value at elevation of	10 cm	Without waste rock (Test1)	0.50	36.1	1405	18.75	0.97
	30 cm		0.51	37.8	1365	18.45	1.02
	40 cm		0.52	38.5	1347	18.30	1.05
	10 cm	With waste rock (Test n°2)	0.51	36.5	1390	18.61	0.99
	30 cm		0.51	36.9	1380	18.53	1.00
	40 cm		0.51	37.4	1368	18.43	1.02

The results of Test 2 presented above in Figure 4 indicate that about 9 hours were required to reach PWP equilibrium in the central part of the model (where the moisture sensors were located, i.e. 45 cm from the waste rock inclusion). This corresponding time was somewhat longer, i.e. 14 hours, at the location of the PWP sensors (i.e. 80 cm from the inclusion). This suggests that the excess PWP dissipated more quickly closer to the inclusion The WRI seems to have had little influence at a distance of 80 cm, as the time required to reach equilibrium (14 h) was the same as for Test 1 (without WRI; see Figure 8). At this location, vertical drainage would thus appear to control the consolidation process. This is consistent with evaluations of the zone of influence of WRI on PWP dissipation (L. Bolduc and Aubertin, 2014; Boudrias, 2018; Saleh-Mbemba et al. 2019).

During Test 3, the water at the tailings surface (due to vertical drainage during consolidation) has been removed (pumped) and transferred towards the initially dry waste rock to simulate the run-off that may occur in the field. This water infiltrated the waste rock, where the level rose quickly within the inclusion (due also to the horizontal drainage from the tailings). The water levels soon became the same on both sides, leading to a reduction of the horizontal hydraulic gradient near the interface. The lower initial thickness of the tailings (H_0 = 50 cm) in Test 3 (compared to 60 cm for the other tests) also contributed to the more rapid dissipation of the excess PWP.

The absence of water at the surface during Test 3 favored drying (desiccation) of the tailings, and a more pronounced reduction of the PWP later during the test (after 55 hours).

During Test 4, the water at the tailings surface was entirely removed (pumped out) from the model (see Table 2). This induced a higher difference in the water levels between the tailings and waste rock compartments, with a larger hydraulic gradient and more pronounced horizontal drainage. This led to a more rapid drop of the PWP within the tailings. In addition, the upper part of the tailings was quickly subjected to a phase of evaporation and desaturation with an additional decrease in PWP (after ≈ 96 hours), leading to negative pressures (suction) near the surface.

The results presented in Figure 8 thus indicate that the presence of waste rock acting as a drainage inclusion promoted lateral drainage and faster consolidation. There was also drying from the tailings surface when there was no water accumulation.

The results also indicate that the decrease of PWP in the presence of a waste rock inclusion depends on several factors (or testing conditions), including the thickness of tailings, time, presence of water on the surface, exposure to atmospheric conditions (with possible desaturation), and the presence of a geotextile fabric (filter) at the interface between the two materials.

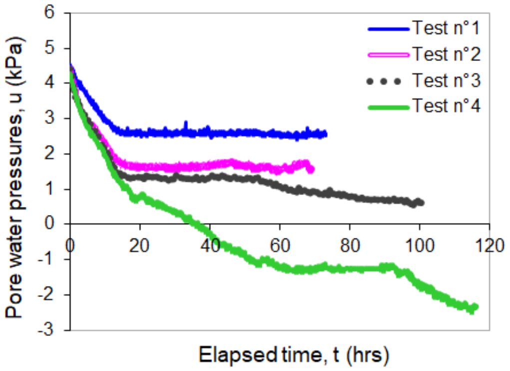

Figure 8 PWP measured at a depth of 25 cm from the tailings surface during the four tests conducted in the physical model (see details in Table 2).

Other experimental results, not presented here, have also shown that initially saturated waste rock tends to reduce the influence of the inclusion on tailings consolidation, because of the much smaller hydraulic gradient at the interface. Such situation is however deemed less representative of field conditions (where the water level in the WRI is expected to be much lower than in the adjacent tailings following hydraulic deposition).

The results in Figure 7 indicate that the changing tailings characteristics near the waste rock inclusion appear to be relatively uniform along the vertical profile, in terms of the void ratio, volumetric and gravimetric water contents, and unit weight. This uniformity of the tailings density at different elevations was also observed upon dismantling of the models and sampling of the tailings. This uniformity appears to be related to the mechanical interaction between the two materials, which limits the vertical stresses and displacements in the soft tailings.

5.2 Transfer of water to the WRI

One of the key features related to tailings consolidation near a WRI is the amount of water transferred from the former to the latter. This aspect has been specifically assessed during Test 4, by measuring the water level within the waste rock.

The horizontal water flow rate Q_h (m^3/s) and the horizontal water flux v_h (m/s) passing through (crossing) the interface between the tailings and waste rock can be calculated at different times using the water level within the waste rock.

Figure 9 shows the evolution of the horizontal flow rate Q_h and flow velocity v_h across the interface between the tailings and waste rock. The high initial values of Q_h and v_h (around 1.5×10^{-6} m^3/s and 2.5×10^{-6} m/s respectively, when the void ratio is $e = 1.19$) decreased gradually to reach about $Q_h = 1 \times 10^{-7}$ m^3/s and $v_h = 3 \times 10^{-7}$ m/s at the end of the test (for a void ratio $e \approx 0.98$).

The response of the system can also be evaluated analytically (also with numerical solutions; Saleh-Mbemba, 2016). In this regard, the two-dimensional analytical solution for drainage and consolidation of mine tailings near a waste rock inclusion, presented (in part) by Saleh-Mbemba and Aubertin (2019), may used to estimate the quantity of water (cumulative volume V m^3) transferred to the waste rock inclusion. This is an ongoing component of the experimental analysis.

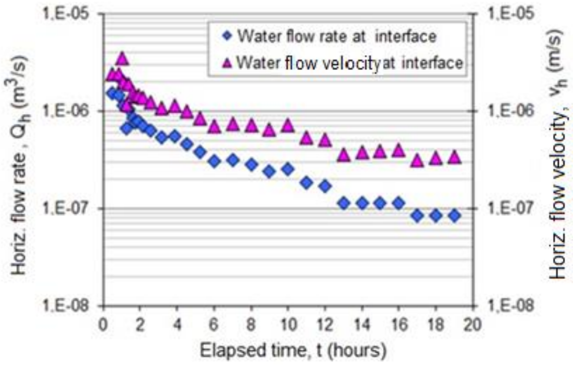

Figure 9 Water flow rate Q_h and velocity v_h across the interface between the tailings and waste rock, for Test 4.

5.3 Movement of fine particles at the interface

Test 2 has been performed without a geotextile fabric (which served as a filter at the interface in other tests). This was done to evaluate the possible migration of tailings particles towards the waste rock and the related impact on consolidation. As indicated above, the results of this test gave a total settlement S_t of 6.10 cm for an initial thickness H_0 of 60 cm, corresponding to an average strain of about 10.2%. This settlement is larger than the one measured during Test 1 without the waste rock (S_t = 5.20 cm, or average strain of 8.7%); the latter values are quite close to those given by the Terzaghi consolidation theory.

The difference between the tailings final settlement in Test 1 and Test 2 is therefore about 9 mm. This value can be used to estimate the quantity (volume) of tailings that moved into the waste rock across the interface area A (= 1.05 m * 0.80 m, see Figure 2). The corresponding volume of displaced tailings is about 0.0076 m^3, which represents nearly 1.5% of the initial tailings volume, and about 12.5% of the total porosity n (~0.39) of the waste rock. Such relatively small quantity of displaced tailings did not seem to affect the decrease in pore water pressures, which evolved in the same way as for the other tests with WRI, as shown in Figure 8. This figure also shows that the time required to complete the consolidation has not been affected significantly, as the time is about the same for Tests 2 and 3 ($t \approx 14$ h). Test 4 gave a somewhat different result with a more pronounced drop of PWP due to a combination of a high hydraulic gradient and desiccation.

Essayad et al. (2018) also recently evaluated the movement of tailings at the interface between waste rock and tailings, and its effect on drainage, using physical modeling in the laboratory. Field observations were also conducted at a mine site where IRS are constructed. This ongoing study suggests that the quantity of tailings that migrates into the waste rock is relatively small and doesn't affect significantly the drainage conditions near the interface of a WRI.

6 CONCLUSION

The results of the physical model testing program described above indicate that the tailings consolidation was accentuated by the horizontal transfer of water to the (initially dry) waste rock. This lateral drainage enhanced the desiccation of tailings surface, which in turn contributed to an additional drop of PWP beyond the phase of dissipation (when the surface was allowed to dry).

The drop of PWP depends on several factors, including the thickness of the tailings layer, the presence of a geotextile (filter) at the interface, and the time of exposure to atmospheric conditions (and the ensuing desaturation).

For the testing conditions used in this investigation, the tailings hydrogeotechnical characteristics near the interface remained relatively uniform along the vertical profile (height).

This investigation also showed that the quantity of tailings that moved towards the waste rock compartment was relatively small and did not affect the rate of pore water pressures dissipation.

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