A laboratory study of the behaviour of surface paste disposal

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Abstract:

It was recently proposed to use the pastefill technology as a surface tailings management method. Surface paste is an economic and safe storage method that respects current environmental regulations. In this paper, a laboratory small scale model was developed to simulate and study the physical, geochemical and fluid flow behaviours of surface pastefill disposal. A paste mix made up of a Canadian gold mine sulphidic tailings and a small amount of cement (2 wt% of slag-based binder) was prepared and then deposited sequentially to study the evolution of different parameters (volumetric water content, matric suction, desiccation crack, binder leaching, etc.) in the course of time. The preliminary results showed that the sulphide reactivity is inhibited while the material remains very impermeable even if cracking was unavoidable.

1 Introduction

In the province of Quebec in Canada, the mine wastes are submitted to a strict regulation mainly governed by the «019» rule, which imposes tolerable standards with regard to pH and the heavy metal concentrations in cut-off waters resulting from mining industrial wastes. Thus, the mining operators must pay attention during the surface tailings management operations.

It is well known the sulphide minerals such as pyrite and pyrrhotite can oxidize in the presence of water and oxygen and generate sulphuric acid as one of the by-products. The leachate pH decreasing leads to an increase of the solubility and concentration of various elements, including metals derived from the waste rocks. The combined effect of acidity and solubilized elements increases the toxicity of the effluent, which can adversely affect nearby ecosystems. Sulphide oxidation mechanisms have been studied by many authors (e.g. Lowson, 1982; Nicholson et al., 1988, 1989, 1995; Elberling et al., 1993; Stromberg, 1997; Elberling et Damgaard, 2001; Aubertin et al., 2002; Rimstidt et Vaughan, 2003) and the phenomenon is well known as acid mine drainage (AMD). Mining industries have developed different strategies to make certain the AMD does not significantly affect the environment. The main methods are chemical or biological treatment of water, construction of impermeable or low diffusion covers, and underwater tailings disposal (Aubertin et al., 2002). Even if these strategies are efficient to control the AMD production, they make site reclamation more difficult upon mine closure. This is why alternative approaches are being developed to improve tailings management during the mine operation, and to facilitate rehabilitation of the site afterward (Ouellet et al., 2003).
Cemented paste backfill (CPB) is one of these alternative approaches (Benzaazoua et al., 2002, 2004 a,b; Ouellet et al. 2003). This method can be used to place tailings underground to stabilize open stopes (e.g. Hassani and Archibald, 1998; Belem, 2000, 2001; Benzaazoua et al., 1999, 2002, 2004a; Belem et al., 2000). When used as underground backfill material, paste backfill is a composite material made up of a mixture of mine tailings (at a solid concentration ranging from 75 to 85%), binder agents (such as ordinary Portland cement, fly ash, blast furnace slag or their combination) and added water. The main benefits of underground paste backfill are higher backfill strength and lower operating costs (in most cases) compared to hydraulic fills (Hassani and Archibald, 1998). Moreover, the use of paste backfill reduces the amount of tailings that have to be sent to surface disposal facilities (up to 50 %). This reduction decreases both the environmental impact and capital expenditures for the tailings facility.

Paste backfill has also been proposed as a new method for surface tailings disposal (e.g. Cincilla et al., 1997; Landriault, 2000; Crowder et al., 2000, 2002; Grabinsky et al., 2002; Verburg, 2002; Theriault et al. 2003). The main advantages of this approach come from the small amount of free water at the surface, which reduces the size of water-retaining structures, less particles segregation (more homogeneous materials), and improved tailings hydro-geotechnical properties which are then more stable. Moreover, the addition of hydraulic binder in the surface paste backfill increases its strength, durability, and acid neutralisation potential. Cementation can also stabilise contaminants in the paste backfill matrix (Benzaazoua, 1996; Benzaazoua et al. 2002, 2004b; Ouellet et al., 2003, Cadden et al., 2003). But despite these advantages, there are still considerable uncertainties on the environmental behaviour of paste backfill.

Some authors have investigated the environmental impact of backfill material when used in underground mines. Thomson et al. (1986) concluded that the metal ions released from backfill were negligible. Levens and co-workers (Levens & Bodth, 1992, 1994; Levens et al. 1996) mentioned the following advantages of the use of CPB in underground stopes: i) the neutralization potential is higher, ii) there is a reduction of oxidation by decreasing the exposed surface area of sulphide minerals and the limitation of air diffusion prior to flooding, and iii) the low hydraulic conductivity of CPB allows it to retain metal ions.

The aim of this paper is to develop a laboratory small scale physical model allowing to study the behaviour of pastefill deposition in the purpose of surface disposal of paste backfill. The model must also allow the simulation of real in situ surface deposition conditions. The paper will first present the complete characterization of the tailings used for the pastefill preparation followed by the model presentation and its capabilities. Finally, some typical results, obtained from a pastefill mix with sulphidic tailings and a small amount of cement (2 wt% of slag-based binder) are presented. The main advantages of surface disposal of paste backfill are also discussed.

2 Material and methods

2.1 Physical model: experimental set-up

The physical model allows simulating of surface disposal of paste backfill. In order to reproduce the field deposition conditions of pastefill, the model must take into account a number of factors that can affect the paste deposition. The main factors which can be accounted for by the model are (i) the desiccation, (ii) the volumetric water content ($\theta$) and matric suction ($\psi$), (iii) the drainage and percolation, (iv) the deposition angle and finally, (v) the weather conditions including temperature variation: rain-drying and freeze-thaw cycles.
Figure 1: Schematic diagram of the small scale physical model of surface disposal of pastefill

Figure 1 shows the model box which is made up of Lexan transparent plastic and has the following dimensions: 200 cm length, 50 cm width and 100 cm height. To account for the effect of deposition angle, the box is mounted upon a resistant metallic structure equipped with pivoting and hydraulic jack systems as illustrated on Figure 1. After the pastefill casting, the drained water will be collected with the aid of the bottom plate equipped with drainage pattern (Figure 2a). A geotextile layer is placed upon the bottom plate to avoid the solid suspensions losses (Figure 2b). The box lateral side-walls are reinforced to avoid any deformation due to the pastefill pressure. The rain-drying cycles are simulated in the model by moistening-drying cycles using a straight pipe equipped with several sprinklers and a mobile fan mounted on the box top (Figure 2c&d). A flow cone equipped with a vane system was used for the pastefill discharge and deposition in the box (See Figure 3b).

At the end of all the performed tests the set-up side-walls can be dismounted to provide the pastefill sampling for different analyses.

Figure 2: Schematic diagram showing the detail of the set-up: a) bottom plate equipped with the pastefill water drainage pattern, b) the geotextile to avoid the suspension loss, c) the box equipped with the artificial rain system (moistening), d) sprinklers to produce homogeneous gush.
2.2 Tailings sampling

For this study the tailings is sampled at the Doyon gold mine (Cambior inc.) which is located in the Abitibi area in Quebec (Canada). In this mine, the gold (and silver) is extracted from the original ore using a combination of cyanidation and carbon in pulping processing. Before the pastefill preparation the tailings slurry produced in the mill is first dewatered to a filter cake consistency using disk filters (solids content of about 80% by mass) before its cyanide destruction.

Table 1 summarizes the tailings sample main physical and chemical properties. The particle size distribution parameters such as D_{10}, D_{50} and D_{90} show that this tailings grading is very finer (which is typical in gold ore processing) and this property will highly affect its mechanical and fluid flow behaviours. The tailings specific surface area, S_s, is relatively high (2460 m²/kg) due to its high content of sericite. While its specific gravity, G_s (2.82) reflects its low sulphide content. The pore water is very ioncharged as suggested by the high value of the electrical conductivity (5390 µmho). This tailings is also relatively oxidant and alkaline due to the initial lime addition.

Table 1: The tailings sample main physical and chemical properties

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific gravity, G_s</td>
<td>2.82</td>
</tr>
<tr>
<td>Solids content</td>
<td>79 % by mass</td>
</tr>
<tr>
<td>pH of the pore water</td>
<td>8.23</td>
</tr>
<tr>
<td>Eh (SHE)</td>
<td>376 mV</td>
</tr>
<tr>
<td>Conductivity</td>
<td>5390 µmho</td>
</tr>
<tr>
<td>Specific surface area, S_s</td>
<td>2460 m²/kg</td>
</tr>
<tr>
<td>D_{10}</td>
<td>4.07 µm</td>
</tr>
<tr>
<td>D_{50}</td>
<td>23.45 µm</td>
</tr>
<tr>
<td>D_{90}</td>
<td>96.99 µm</td>
</tr>
</tbody>
</table>

The chemical analysis of the Doyon tailings slurries was done using an ICP-AES spectrometer and the results are listed in Table 2. The final tailings mainly contain silicon-gangue minerals and a low amount of barren sulphides (less than 5% of pyrite). The solution analysis shows that the Canadian environmental standards are met as regards to the main metals except the iron. Sulphur analysis of the particle size fraction under 25 µm suggests that the sulphides are most concentrated within the ultra-fine fraction. The acid generating potential (AGP) results of the Doyon tailings is presented in Table 3. These results show
that even if the tailings is low sulphide content, it is acid generating due to the absence of neutralizing potential.

Table 2: Chemical analysis of the Doyon tailings slurries (Solid and solution)

<table>
<thead>
<tr>
<th>Elements</th>
<th>Solid composition</th>
<th>Liquid composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>5.91 %</td>
<td>0.07 mg/L</td>
</tr>
<tr>
<td>K</td>
<td>2.36 %</td>
<td>127 mg/L</td>
</tr>
<tr>
<td>Na</td>
<td>0.676 %</td>
<td>317 mg/L</td>
</tr>
<tr>
<td>Si</td>
<td>N.A.*</td>
<td>2.88 mg/L</td>
</tr>
<tr>
<td>Ca</td>
<td>1.47 %</td>
<td>1210 mg/L</td>
</tr>
<tr>
<td>Mg</td>
<td>0.873 %</td>
<td>5.52 mg/L</td>
</tr>
<tr>
<td>Mn</td>
<td>0.047 %</td>
<td>0.002 mg/L</td>
</tr>
<tr>
<td>Fe</td>
<td>4.8 %</td>
<td>3.82 mg/L</td>
</tr>
<tr>
<td>S</td>
<td>3.14 %</td>
<td>1310 mg/L</td>
</tr>
<tr>
<td>S$_{sulfates}$</td>
<td>0.3576 %</td>
<td>-</td>
</tr>
<tr>
<td>SO$_4^{2-}$</td>
<td>-</td>
<td>3924 mg/L</td>
</tr>
<tr>
<td>As</td>
<td>0 %</td>
<td>&lt; 0.03 mg/L</td>
</tr>
<tr>
<td>Co</td>
<td>0.001 %</td>
<td>0.21 mg/L</td>
</tr>
<tr>
<td>Ni</td>
<td>0.012 %</td>
<td>0.019 mg/L</td>
</tr>
<tr>
<td>Cu</td>
<td>0.072 %</td>
<td>0.052 mg/L</td>
</tr>
<tr>
<td>Pb</td>
<td>0.004 %</td>
<td>&lt; 0.07 mg/L</td>
</tr>
<tr>
<td>Zn</td>
<td>0.094 %</td>
<td>&lt; 0.02 mg/L</td>
</tr>
</tbody>
</table>

*N.A.: not analyzed

Table 3: Acidity and neutralizing potentials of the Doyon tailings

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>% sulphur = %S - %S$_{Sulfates}$</td>
<td>2.78</td>
</tr>
<tr>
<td>AP (kg CaCO$_3$/t) = % sulphur * 31.25</td>
<td>87.0</td>
</tr>
<tr>
<td>NP (kg CaCO$_3$/t)</td>
<td>21.8</td>
</tr>
<tr>
<td>NNP = NP – AP</td>
<td>- 65.2</td>
</tr>
<tr>
<td>NNP = NP/AP</td>
<td>0.25</td>
</tr>
</tbody>
</table>

Note: Determined using the modified ABA method (Lawrence, 1997)

2.3 Binder and water

For the mix preparation, we used

- The same binder as the one used at the Doyon mine: a binder composed by 70 % of slag and 30 % of Portland cement type 10. The chemical composition of these binders is shown in Table 4. A proportion of 2% binder by dry solids mass of the total tailings was tested. This value seems to be realistic knowing the high costs related to binder in the backfilling operation.

- The additional water was a domestic one. In fact, the domestic water is used to dilute the pore water charged in term of sulphate, which is very deleterious for the paste strength development. The water addition depend on the solid percentage (consistency) desired.

Table 4: Chemical composition of the slag and Portland T10

<table>
<thead>
<tr>
<th>Binder</th>
<th>S (%)</th>
<th>Ca (%)</th>
<th>Si (%)</th>
<th>Al (%)</th>
<th>Mg (%)</th>
<th>Fe (%)</th>
<th>Cu ppm</th>
<th>Na (%)</th>
<th>Si / Ca</th>
</tr>
</thead>
<tbody>
<tr>
<td>Portland T10</td>
<td>1.53</td>
<td>44.9</td>
<td>8.43</td>
<td>2.41</td>
<td>1.6</td>
<td>1.89</td>
<td>53</td>
<td>nd</td>
<td>0.18</td>
</tr>
<tr>
<td>Slag</td>
<td>1.21</td>
<td>26.6</td>
<td>16.89</td>
<td>3.88</td>
<td>6.87</td>
<td>0.482</td>
<td>14</td>
<td>nd</td>
<td>0.63</td>
</tr>
</tbody>
</table>
3 Experimental programs

3.1 Paste backfill preparation and deposition

The paste backfill was made of Doyon tailings, a binder (a ratio of 70:30 of Slag:Portland T10 at 2% by dry mass of tailings) and domestic water to produce a paste of the desired consistency for surface disposal conditions which typically has a slump of 250 mm (Theriault et al. 2003). Figure 4 shows the mixer used (Figure 4a) and the prepared pastefill (Figure 4b).

![Figure 4 : Photographs of : a) the mixer used, b) the prepared pastefill](image)

The slump of 250 mm (Figure 5b) corresponds to solids content of about 66% (by mass) which seems to be very low due to the tailings characteristics (its fineness and its mineral morphology). The water-to-cement ratio (w/c) is of 26.3 and the moisture content is of 51.5%. To simulate the filed surface disposal condition like the case of the Bulyanhulu mine in Tanzania (Theriault et al. 2003), the pastefill is deposited in thin layers (4 cm) in the model box and the deposition is cycled regularly until the total number of 7 layers (28 cm). Each layer corresponds to a paste batch preparation. The deposition cycling was separated by duration of 2 to 3 days.

![Figure 5 : Photographs of the slump tests: a) slump of 184 mm (7¼ in), b) the desired slump of 250 mm (10 in), c) flow cone used for pastefill discharge](image)

3.2 Volumetric water content ($\theta$) and matric suction ($\psi$) measurements

Seven TDR (Time Domain Reflectometry) sensors were installed on one side wall of the box at approximately the mid-height of each layer and spaced at 4 cm intervals in order to get a measure of volumetric water content in each layer during time (Figure 6). For the pastefill matric suction measurement, seven tensiometers equipped with ceramic sparks were mounted on the other side-wall in the same

![Figure 6 : TDR sensors installed on the side wall of the box](image)
manner than for the TDR sensors (Figure 6). The equipments are provided by Soilmoisture Equipment Corp.

![Figure 6: Schematic diagram illustrating the instrumentation of the 7 layers with TDR sensors and tensiometers.](image)

3.3 Leachate analysis

The chemical analysis was done using an ICP-AES spectrometry. The tailings initial pore water was analysed as well as the percolated solution (seepage) collected after the first layer deposition. Once the 7 layers deposited into the model box, the moistening test began in order to saturate the paste and the resultant percolated solution was then analysed.

3.4 Crack density quantifying

Mi (1995) and Miller et al., (1998) introduced the crack intensity factor (CIF) to describe the surface cracking. The CIF is defined as the ratio of the crack area and the total area of the studied surface. This ratio can be easily determined by images processing on the photographs of the surface of pastefill deposited in the course of time. The image processing (as illustrated by Figure 7) was performed using the «ImageJ» version 1.29 software. When a cracked surface is photographed, the cracks appear darker than the intact zones; this difference in contrast makes possible a good analysis. Several photographs were taken at regular time intervals in order to be processed.
5 Main results

5.1 Collected drained water

Figure 8 presents the variation of the cumulative drained water during the elapsed time since the end of the first layer deposition. It can be seen that drainage occurs rapidly just after the layer deposition and reaches its maximum cumulative value after about 80 minutes (end of drainage). In addition, no water was collected after the casting of the 6 following layers deposited upon the layer 1. This meaning that all the water within the pastefill was not flowed throughout the first layer.

![Figure 8: Variation of collected water in the course of time from the first layer](image)

5.2 Geochemistry of the collected water

The elemental analysis of the collected water from the layer 1 at its early stage was done and compared to the tailings initial pore water (Tables 5 and 6). From these two tables, one can observe that the calcium (Ca), silicon (Si) and pH are relatively high in the paste collected water compared to their initial values in
the pore water. The increase of the Ca and Si species can be explained by a partial leaching of the binder and leading to a low loses of the initial non hydrated binder. But one has to remind that only the first layer was drained water.

Tables 5 and 6 also contain data obtained from the collected water after the moistening test performed on the total deposit after curing. The results show a decrease of the Ca and Si species compared to the collected water after the layer 1 deposition. One can also observe that the pH value after the moistening is the same that of the initial pore water of the tailings. This tends to suggest that after the deposition of the seven pastefill layers, water percolation do not cause binder lost and that the hydrate species are stabilized within the paste material.

**Table 5 : Elemental analysis of the collected water (in ppm)**

<table>
<thead>
<tr>
<th>Element</th>
<th>Al</th>
<th>As</th>
<th>Bi</th>
<th>Ca</th>
<th>Cu</th>
<th>Fe</th>
<th>Mg</th>
<th>Mn</th>
<th>Na</th>
<th>Pb</th>
<th>SO₄²⁻</th>
<th>Si</th>
<th>Zn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detect. limit</td>
<td>0.007</td>
<td>0.03</td>
<td>0.02</td>
<td>0.01</td>
<td>0.005</td>
<td>0.005</td>
<td>0.002</td>
<td>0.2</td>
<td>0.07</td>
<td>0.09</td>
<td>0.04</td>
<td>0.02</td>
<td></td>
</tr>
<tr>
<td>Tailings pore water</td>
<td>0.137</td>
<td>&lt; dl*</td>
<td>&lt; dl</td>
<td>578</td>
<td>0.076</td>
<td>0.767</td>
<td>1.63</td>
<td>0.014</td>
<td>644</td>
<td>&lt; dl</td>
<td>3565</td>
<td>2.83</td>
<td>0.052</td>
</tr>
<tr>
<td>Collected water from the layer 1</td>
<td>0.117</td>
<td>&lt; dl</td>
<td>&lt; dl</td>
<td>744</td>
<td>&lt; dl</td>
<td>1.14</td>
<td>0.110</td>
<td>0.004</td>
<td>433</td>
<td>&lt; dl</td>
<td>3475</td>
<td>24.3</td>
<td>0.055</td>
</tr>
<tr>
<td>Collected water after the moistening test</td>
<td>0.204</td>
<td>&lt; dl</td>
<td>&lt; dl</td>
<td>409</td>
<td>0.042</td>
<td>0.197</td>
<td>20.3</td>
<td>0.048</td>
<td>228</td>
<td>&lt; dl</td>
<td>2061</td>
<td>9.35</td>
<td>0.039</td>
</tr>
</tbody>
</table>

*dl = detection limit

**Table 6 : Geochemical analysis of the collected water**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>pH</th>
<th>Eh (mV)</th>
<th>Conductivity (µmho)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tailings pore water</td>
<td>8.23</td>
<td>376</td>
<td>5390</td>
</tr>
<tr>
<td>Collected water from the layer 1</td>
<td>12.05</td>
<td>169.5</td>
<td>6680</td>
</tr>
<tr>
<td>Collected water after the moistening test</td>
<td>8.13</td>
<td>303.8</td>
<td>2410</td>
</tr>
</tbody>
</table>

**5.3 Desiccation cracks propagation**

Figure 9 presents the variation in desiccation crack density (CIF) in the course of time for the layer 1 (Figure 9a) and the layers 2 to 5 (Figure 9b). For the layer 1 the time in abscise is in hours, while for the rest of the four layers (layers 2 to 5) the time is in minutes. The observed maximum desiccation crack density (CIF) was not exceeding 4%.
Figure 9: Variation of crack intensity (CIF) during time for: a) the layer 1 and b) the layer 5.

From this figure it can be observed that the pastefill surface cracking occurred very slowly for the layer 1 compared to the layers 1 to 5. As a matter of fact, the CIF value of 3% was reached after about 20 hours for the layer 1 (Figure 9a) and after only 25-37 minutes for the layers 1 to 5 (Figure 9b). This difference in desiccation crack initiation suggests the importance of the nature of the material upon which the paste is deposited. Indeed, layer 1 was deposited on geotextile while layers 2 to 5 are deposited upon already dry surface pastefill. So, immediately after the deposition of a fresh paste material upon a dry surface layer, the drainage of the upper layer is much accelerated due to the suction developed by the layer below. This matric suction produces a fast migration of water towards the bottom and this phenomenon seems to induce the desiccation cracks occurring.

Figure 9 also shows that the crack propagation slows down and stabilises (end-value) after 72 hours for the layer 1 and after only 150 minutes for the layers 2 to 5. The end-value of the CIF increases with the increase of the number of layers (except for layer 3). Consequently, the CIF values are high when the total thickness of the pastefill is high.

5.4 Volumetric water content and suction measurements

Volumetric water content ($\theta$) and matric suction ($\psi$) were recorded in the course of time during the pastefill deposition layer by layer in the model box.

5.4.1 Variation of the volumetric water content versus time

Figure 10 presents the variation in volumetric water content ($\theta$) with elapsed time since the deposition of the layer 1. The data was recorded at 10 min time interval. It can be clearly observed a progressive desaturation of the pastefill layer 1 in the course of elapsed time since its deposition. At the end of the layer 1 deposition the volumetric water content ($\theta_w$) is about 43% and after 80 hours this value decreases to 15% and seems to reach a plateau corresponding to its residual value ($\theta_r$).
Figure 10: Variation of the volumetric water content within the layer 1 versus time.

Figure 11: Variation of the volumetric water content versus time after the deposition of the layer 5.

Figure 11 presents the variation of \( \theta \) as a function of the elapsed time since the deposition of the layer 5. On this graph the initial values of the volumetric water content for the layers 1 to 4 corresponds to their values obtained after the total deposition duration of 8-days (\( \theta_i \)). The data was recorded at 2 min time interval for the first three hours and 10 min beyond this time. One can also notice that the elapsed time was reset to zero for only the layer 5 which deposition started at \( t = 18 \) minutes.

It can be observed that the desaturation of the layer 5 was very fast compared to the desaturation observed for the layer 1 (see Figure 10). Indeed, the volumetric water content of the layer 5 drops from \( \theta_w = 37\% \) to 21\% after only 3 hours and then decrease more slowly until reaching a value of about 18\%. 
corresponding to its residual value ($\theta_r$). Figure 11 also shows that during the desaturation of the layer 5, the layer 4 starts its saturation after about only 10 min followed by the saturation of the layer 3 after about 14 min (beginning of the desaturation of the layer 4). After about an elapsed time of 28 min the layer 3 reaches its maximum of re-saturation (increasing of 0 from 16 % to 25 %), while the layers 4 and 5 continue their desaturation. At the same time, the layers 1 and 2 begin their slight and slow re-saturation (it was observed an increase of about 3 % followed by a same order of decrease). This figure also suggests that the drained water (seepage) from the upper layers (layers 5 and 4) seems to progressively accumulate within the layer 3 which lets pass only very little water towards layers 2 and 1. One can thus suppose that the lower layers are not saturated during the deposition of the fresh pastefill layers and the total paste thickness concerned by the re-saturation is approximately 9 cm below the last layer deposited. This could be explained by the preferential flows and the binder hydration (low permeability) of the sub-layers.

5.4.2 Variation of the suction versus time

Figure 12 presents the variation of the matric suction ($\psi$) as a function of elapsed time since the deposition of the layer 1 and 4 respectively. The data was recorded at 10 min time interval for the layer 1 and at 2 min time interval for the first three hours and 10 min beyond this time for the layer 4. It can be observed that the matric suction increase with the paste desaturation. The maximum suction increases of about 10 kPa for the layer 1 and of about 70 kPa for the layer 4. This increase was relatively slow for the layer 1 than for the layer 4 which is fast.

The difference between the suction values obtained for the layers 1 and 4 can be explained by the fact that the sub-layers will affect the suction strength of the upper layers by governing the movement of the water from the fresh deposited paste upon the sub-layer materials.

![Figure 12: Variation in matric suction with elapsed time: a) for the layer 1 and b) for the layer 4](image)

5.4.3 Relationship between CIF, volumetric water content and suction

Figure 13 presents the variation of CIF as a function of the matric suction for the layers 4 and 5. This figure shows that immediately after the 4th paste layer deposition the cracking begins at a suction value of about -10 kPa. At a suction value of -15 kPa the CIF increase rapidly and then reaches a plateau of about 3.75 % starting from -40 kPa. The major part of the cracks (80%) occurred at a suction value higher than -40 kPa and which the maximum observed suction was about -80 kPa. For the layer 5 the CIF increase starting from a suction value of -25 kPa and 80 % of the cracks occurred at a suction value of -55 kPa. The value at which the CIF value increases can be designated as a «critical value» and was -15 kPa ($\psi'$).
for the layer 4 and -25 kPa for the layer 5. Thus, the increase of the paste thickness leads to an increase of the critical suction which will affect the fresh deposited paste layer.

Figure 13: Relationship between the CIF and the suction

Figure 14 presents the variation of the CIF as a function of the volumetric water content ($\theta$) for the layers 4 and 5. One can notice that the relationship between the CIF and suction and volumetric water content is similar. For the layer 4 the first cracks occur at a volumetric water content of about 36%. The crack propagation increases progressively until a volumetric water content of about 30% before reaching rapidly a plateau at a CIF value closes to 4%. One can also note that 90% of the cracks occur at volumetric water content higher than 25% for the layer 4 and 28.5% for the layer 5. The minimum observed $\theta$ value is about 17% after complete drying (when the CIF no more varies). The equivalent «critical value» of the volumetric water content ($\theta'$) is about 31% for the layer 4 and 33% for the layer 5.

Figure 14: Relationship between the CIF and the volumetric water content

These relationships suggest that the successive paste layers deposition causes an increase of the critical water content. This can be due to the fact that the thickener the pastefill layer, the higher the suction
involves in the desaturation. Thus, the cracking occurs for higher water contents. The suction caused by the sub-layer materials is higher when the thickness of the upper paste layers is high.

### 5.4.4 Relationship between suction and water content

Figure 15 presents the relationship between the volumetric water content \( (\theta) \) and the matric suction \( (\psi) \) within the fourth layer. Except for the layer 1, this curve shape is the same for the six layers (layer 2 to 7). As it can be expected, the volumetric water content begins to decrease with the increase of the matric suction at a suction value corresponding to the «Air Entry Value» \( (\psi_a) \). After about 80 hours elapsed time since the deposition of the concerned layer this water content decreases until its residual value \( (\theta_r) \) which corresponds to a residual suction \( (\psi_r) \). This could be explained by the fact that when the water leaves the pores a number of voids take place within the material and increase the suction.

![Figure 15](image)

**Figure 15 : Relationship between volumetric water content and matric suction**

### 5.5 Moistening and drying tests

After the deposition of the 7 pastefill layers we simulated one cycle of rain upon the pastefill by it moistening (see Figures 2c&d). The moistening was performed at a water flow rate of 80 L/hrs at a duration of about de 57 min. The results of the variation of the volumetric water content as a function of the elevation in the box (from the bottom) are presented on Figure 16. During this test the cracks which occurred during the 7th paste layer deposition were disappeared in a major part after the moistening. This figure shows that the water content (re-saturation) within the paste layers increase progressively. On the total of the 7 layers deposited the infiltration is much more important within the first 5 surface layers.
Figure 16: Volumetric water content profiles during the moistening process.

Figure 17 presents the results of natural drying test (see Figure 3a) obtained after the moistening test. It can be observed that the water content of the top paste layer (7th layer) decreases rapidly after the end of the moistening process.
the moistening until it reach a value closed to its initial value after about 45 hours. This figure also shows that the desaturation of the bottom layers (1st and 2nd layer) did not change at the same proportion that for the superficial layers (maximum water content of about 22 % and 30 % respectively). In addition, Figure 17 shows the presence of a saturated zone which concerns the layers 3 and 4 where the water content remain high even after 2 days of drying period. Many reasons could explain this phenomenon. The first one is that when the water did not evaporate will drain from the top layers down within this saturated zone. The second one concerns the bottom layers (layers 1 and 2) which can drain by the set-up bottom drainage outlet; this explain the water recovered after the end of moistening test, while an other part of the water can also migrate by capillarity from the bottom layers up to the saturated zone.

In addition, as mentioned in section 5.2 the chemical analysis of the leachate obtained after the moistening test show that the major part of the cement was not leached and remain within the material and that the oxidation was completely inhibited.

6 Summary and conclusions

The Doyon gold mine produces tailings with a certain acid generating potential even if their sulphide content is low. The tailings management method used presently is the underwater storage of the part remained after underground paste backfilling. In this work, the behaviour of surface pastefill disposal have been investigated through a laboratory scale physical model specifically developed. This technique which consists to deposit thickened tailings on surface rather than underground, is new even already used in some mine sites. For this reason, this study remains a preliminary experimental study in order to understand the behaviour of such material. Binder agents can be used in the mixing process if there is a need of chemical and mechanical stabilization of the produced paste.

To do so, the objectives of the work were:

- To build a laboratory scale physical model (experimental set-up) to study the behaviour of surface pastefill disposal.
- To evaluate the reliability and the workability of the physical model by running some preliminary tests.

Pastefill have been prepared and deposited in the model box layer by layer until a number of 7 layers of approximately 4 cm thick. The pastefill was made of Doyon gold mine tailings (Canadian mine), 2 wt% binder (Slag / Ordinary Portland cement at 70%/ 30%) at a solid concentration (by mass) of 66% which corresponds to 250 mm (10 inches) slump.

The built model size and instrumentation allowed to run a realistic study of the behaviour of a paste material deposited in surface conditions. Many factors were taking into account: desiccation cracking, drainage, evolution of the volumetric water content and matric suction. The main conclusions are:

- Desiccation crack intensity increase with the increase of the number of deposited layers. Cracking occurred slowly after the first layer deposition in comparison to the next layers. This seems to be due to the high relationship existing between the desiccation crack propagation and the developed suction and the evolution of the volumetric water content.
- The crack intensity factor (CIF) was correlated with the water content ($\theta$) and suction ($\psi$) and pointed out the existence of critical values. The critical water content ($\theta'$) as well as the critical suction ($\psi'$) increase with the layers accumulation (sub-layers total thickness). This phenomenon was explained by the suction developed after the pastefill desaturation increase with the layers thickness.
- The chemical analysis in term of calcium (Ca) and silicon (Si) of the tailings initial pore water, the collected drained water from the first layer and the one obtained after the moistening test show a negligible loss of the anhydride binder (by dissolution) only in the case of the first layer drainage.
- The chemical analyses in terms of sulphate ($SO_4^{2-}$) show that the sulphide did not react (no oxidation) due to the very low permeability and the cement stabilization.
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References


