EVOLUTION OF CEMENTED PASTE BACKFILL SATURATED HYDRAULIC CONDUCTIVITY AT EARLY CURING TIME

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ABSTRACT

One interesting management approach to reduce environmental impacts related to sulphide mine tailings storage consists in using them as a component of cemented paste backfill (CPB). CPB consists of a mixture of tailings, binder agent, and water. Binder hydration in CPB leads to an evolution of the porous matrix and entails a change in hydrogeotechnical properties of the backfill. Key property to investigate for an efficient management of tailings is the saturated hydraulic conductivity ($k_{sat}$). In this study, results of permeability tests performed on cemented paste backfill samples at different curing times are presented. Results show that the addition of 4.5 % wt of binder can reduce $k_{sat}$ by a factor of more than ten after 28 days of curing. The kinetic is also different depending on the binder used. Typically, a binder made of Portland cement and slag has a greater impact on the reduction of $k_{sat}$ than a binder made of Portland cement and fly ash. Finally, a simple equation to predict $k_{sat}$ of the studied CPB is proposed. Results show a relatively good correlation between predicted and measured values.

1 INTRODUCTION

The management of sulphide tailings represents one of the greatest environmental challenges for the mining industry. Sulphide tailings stored at the surface are usually in contact with air and water, favouring the generation of acidic effluents containing metals and sulphates (called acid mine drainage) (e.g. Aubertin et al., 2002). An interesting alternative to conventional surface disposal methods consists in thickening the tailings (to a pulp density which usually varies between 75 % and 85 %), and to mix them with binders. When used underground, the mixture is called cemented paste backfill (CPB), while the term paste tailings, with or without cement, is used when a surface storage is involved.

CPBs are transported in underground mine stopes during the mine operation (e.g.; Hassani and Archibal, 1998; Belem and Benzaazoua 2004). This technology allows the optimization of ore recovery by playing a ground support role, also reduce the problematic tailings volume at the surface and the consequent environmental impacts.

Paste tailings can also be stored at the surface in specific impoundments, with or without binder (Cincilla et al., 1997; Robinski , 1999; Crowder et al., 2002; Grabinski et al., 2002; Thériault et al., 2003; Verburg, 2002; Landriault et al., 2005; Martin et al., 2006). The presence of binder in paste tailings could confer favourable properties to the material by improving mechanical properties and reducing sulphides reactivity and contaminant mobility (Benzaazoua et al., 2004, 2005a). Surface disposal of paste tailings also reduces the need to construct large dams which can, if there is failure, generate harmful effects on the surrounding ecosystems.
Binder hydration in cemented paste backfill or paste tailings leads to geochemical reactions and to the formation of primary and secondary minerals (depending on initial inputs chemistry) which modify the internal structure of the porous matrix. The evolution of this matrix induces a change in the hydrogeotechnical properties of the paste (Belem et al., 2001; Godbout et al., 2004; Godbout 2005; Bussière, 2007). One important hydrogeotechnical property to determine for an efficient management of tailings is the saturated hydraulic conductivity (k_{sat}). Indeed, k_{sat} can influence the physical (mechanical strength, consolidation, and liquefaction potential) and chemical behaviour (sulphide reactivity and contaminant migration) of the paste.

In this study, results of permeability tests performed on CPB samples at different curing times (1, 3, 7, 14 and 28 days) are presented. The saturated hydraulic conductivity evolution is compared for two binder types and three proportions. A simple equation to predict k_{sat} evolution is compared for two binder types and three days) are presented. The saturated hydraulic conductivity of the paste (Belem et al., 2001; Godbout et al., 2004; Godbout 2005; Bussière, 2007). One important hydrogeotechnical property to determine for an efficient management of tailings is the saturated hydraulic conductivity (k_{sat}). Indeed, k_{sat} can influence the physical (mechanical strength, consolidation, and liquefaction potential) and chemical behaviour (sulphide reactivity and contaminant migration) of the paste.

In this study, results of permeability tests performed on CPB samples at different curing times (1, 3, 7, 14 and 28 days) are presented. The saturated hydraulic conductivity evolution is compared for two binder types and three proportions. A simple equation to predict k_{sat} of the studied CPBs is also proposed, and compared to results from the literature. Finally, a discussion on the main factors that could explain the k_{sat} evolution in CPBs is presented.

2 EXPERIMENTAL PROGRAM

2.1 Material

Different CPB mixtures were made to evaluate the influence of curing time and of the proportion and type of binder.

2.1.1 Tailings

The studied tailings come from a volcanogenic massive sulphides mine, mineralized in copper, zinc, gold and silver. The physical tailings parameters have been determined with a Malvern laser Mastersizer® (for the grain-size distribution), with a Micromeritics helium pycnometer Accupyc 1330 (for the relative density D_r), and a with surface area analyzer Micromeritics Gimini III 2375 (for the specific surface area S_{s}). The mineralogical composition of the tailings was evaluated by X-rays diffractometer (Bruker A.X.S. model D8 Advance). Minerals quantification was performed using the Rietveld method (Taylor et Hinczak, 2001) through the Bruker’s TOPAS software.

The main physical and mineralogical properties of the tailings are presented in Table 1.

<table>
<thead>
<tr>
<th>Physical properties</th>
<th>Tailings</th>
<th>Mineral</th>
<th>DRX (wt %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D_r</td>
<td>3.55</td>
<td>Pyrite</td>
<td>47</td>
</tr>
<tr>
<td>% &lt; 2 µm</td>
<td>5 %</td>
<td>Quartz</td>
<td>24</td>
</tr>
<tr>
<td>D_{10} (µm)</td>
<td>3.20</td>
<td>Magnesite</td>
<td>10</td>
</tr>
<tr>
<td>D_{50} (µm)</td>
<td>17.19</td>
<td>Dolomite</td>
<td>4</td>
</tr>
<tr>
<td>D_{90} (µm)</td>
<td>23.40</td>
<td>Muscovite</td>
<td>2</td>
</tr>
<tr>
<td>% &lt; 80 µm</td>
<td>95%</td>
<td>Other</td>
<td>13</td>
</tr>
<tr>
<td>C_U = D_{10}/D_{10}</td>
<td>7.32</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C_r = (D_{90})/D_{10}</td>
<td>3.82</td>
<td></td>
<td></td>
</tr>
<tr>
<td>S_{s} (m^{2}/kg)</td>
<td>1910</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 1 illustrates the grain size distribution of the tailings. The tailings are characterized by a coefficient of uniformity (C_U) of 7.3, a percentage passing 2 µm and 80 µm of 5 and 95 % respectively, and by a grain diameter corresponding to 10 % passing (D_{10}) of 3.2 µm. The solid grains have a relative density (D_r) of 3.55 and a specific surface (S_{s}) of 1910 m²/kg. The main minerals in the tailings are pyrite (47 %) and quartz (24 %). These tailings are fairly typical of Abitibi base metal tailings (e.g. Bowles, 1984; Aubertin et al., 1996, 2002; Bussière, 2007) and can be classified as low plasticity silt (ML) according to the unified system classification of soils (USCS).

2.1.2 Binder and mixing water

Two mixtures were used to evaluate the effect of the binder type on k_{sat} evolution. The first mixture (CPSG) is made of ordinary Portland cement mixed with slag at a ratio of 20:80 respectively. The second mixture of binders (CPFA) is made of ordinary Portland cement and fly ash at a ratio of 70:30. Different proportions of binders were used to evaluate the effect of this parameter on the k_{sat} evolution: 1%, 2% (only for the CPSG binder) and 4.5 % binder by dry weight of tailings.

The choice of binders was based on the most common recipes used by the mining industry to manufacture CPB (Benzaazoua et al. 2005b). Fly ash and slag are both by-products of industrial processes. The replacement of a fraction of the Portland cement by these mineral additives in the CPB mixture is often seen as an environmental value-added. Moreover, due to the lower cost of fly ash, its use can significantly reduce overall operational costs of a paste backfill plant (Ouellet et al., 2004; Benzaazoua et al., 2005b).

Table 2 presents the main chemical and physical characteristics of the different types of binders used in this study.

![Figure 1: Grain-size distribution of the tailings](image)
The Portland cement Type 10 (CP) has a typical Bogue’s composition of 64.4% for CaS, 6.6% for CaS, 8.7% for CaA and 7.4% for CaAF. The slag (SG) follows the recommendations of Malhotra (2001) to prevent sulphate attack with a percentage of Al₂O₃ lower than 11%. According to ASTM C618-00 standard, the fly ash (FA) is classified as a class C with a cumulative value for SiO₂, Al₂O₃, and Fe₂O₃ of less than 70%, and a SO₃ content of less than 5%. SG and FA show high BET specific surface with values of 2 140 and 2 163 m²/kg. The BET specific surfaces of the CP binder is lower at 1 318 m²/kg.

The process water used to prepare the CPB specimens was recovered directly at a CPB plant (same mine as where the tailings were sampled). This process water has a pH close to the neutrality (7.67) and a sulphate content of 4 730 ppm (see Godbout 2005 for more details).

2.2 Samples preparation and permeability tests

CPB mixtures were prepared in small batches in a 20-litre bucket and mixed for at least 10 minutes with a ½ inch electric drill using a paint mixer bit. A total of 54 CPB cylinders 20 cm long and 10 cm in diameter were cured at room temperature and at a relative humidity greater than 90%. Water to cement ratio (w/c) was 7.3 for CPB mixtures containing 4.5% binder, 16.1 for CPB mixtures containing 1% binder and 31.9 for CPB mixtures containing 2% binder.

The k_sat value of CPB was determined with rigid wall permeameter (ASTM Standard 5856-95) and with flexible wall permeameter (ASTM Standard D 5084-90), both according to the falling head method (e.g. Bowles, 1984). The rigid wall permeameter was generally used when k_sat was larger than 10⁻⁵ cm/s, while the flexible wall permeameter was used when k_sat was lower than 10⁻⁵ cm/s. Hence, the rigid wall permeameter was used for the mixtures having a binder content of 1% and 2% for all curing times, as well as for the mixtures having a binder proportion of 4.5% for the first seven days of curing (1, 3 and 7 days). The assessment of k_sat for samples having a binder content of 4.5% and for curing times of 14 and 28 days was achieved with a flexible wall permeameter. The permeability tests are performed on a relatively short period of time (< 1 hour) and suppose that the length of the test doesn’t affect the results. Two permeametry tests were performed for each mixture and each curing time. Repeatability of the permeametry tests was usually good; the results being always inside the precision limits of the test, i.e. half an order of magnitude.

3  PERMEABILITY TEST RESULTS

3.1 Effect of binder proportion on k_sat evolution

Figure 2 presents the evolution of the k_sat value according to curing time and binder proportion for the mixtures made of Portland cement type 10 and slag (CPSG). The black line represents k_sat for the control samples (without binder).

The results indicate a nearly constant value for the control samples, as expected. In all cases there is a reduction of k_sat for samples with binders. With a binder proportion of 4.5%, k_sat decreases quickly during the first 14 days of curing, from 4.5 x 10⁻⁵ cm/s to approximately 2.5 x 10⁻⁶ cm/s. The value of k_sat decreases at a slower rate during the next 14 days to a value of approximately 1.0 x 10⁻⁶ cm/s. The addition of 4.5% binder then reduces k_sat by a factor of approximately 1 ½ order of magnitude in a period of 28 days of curing.

The curve illustrating the evolution of k_sat for the mixture made with 2% CPSG shows a similar evolution as the one for the mixture made of 4.5% CPSG, but with a lower amplitude. k_sat values decrease from 7.0 x 10⁻⁵ cm/s to 3.0 x 10⁻⁶ cm/s in 28 days of curing.

A proportion of 1% CPSG added to the tailings decreases k_sat during the first 14 days of curing from 6.0 x 10⁻⁵ cm/s to approximately 1.0 x 10⁻⁶ cm/s. After this period, the k_sat value seems to stabilize. The addition of 1% CPSG reduces k_sat by a factor of approximately half and order of magnitude (for a curing period of 28 days).

Figure 3 shows the impact of curing time on k_sat for the mixtures constituted of Portland cement type 10 and of fly ash (CPFA).
Results show that the addition of CPFA binder also reduces the \( k_{\text{sat}} \) value of the tailings. When 4.5% CPFA is added to the mixture, \( k_{\text{sat}} \) is reduced from 2.3x10^{-5} cm/s to 1.5x10^{-5} cm/s after 7 days of curing, and later stabilizes at a value of 7.8x10^{-6} cm/s. This corresponds to a \( k_{\text{sat}} \) reduction of nearly one order of magnitude. The addition of 1% CPFA also reduces the \( k_{\text{sat}} \) value of the material, but with a lower magnitude (< ½ order of size).

### 3.2 Effect of binder type on \( k_{\text{sat}} \) evolution

Figure 4 presents the evolution of \( k_{\text{sat}} \) according to the binder type for a proportion of 4.5% binder.

Figure 5 shows than at low proportion of binder (1%), the type of binder influences the \( k_{\text{sat}} \) value of the material. Even though the different mixtures have curves with similar shapes, the influence is more significant for the CPSG binder than for the CPFA binder. After 28 days of curing, \( k_{\text{sat}} \) is reduced from 5.5x10^{-5} cm/s to 4x10^{-5} cm/s for the mixture with CPSG, and to 4x10^{-5} cm/s for the mixture with CPFA. Contrary to the 4.5% binder recipes, the addition of 1% binder seems to influence the \( k_{\text{sat}} \) value only for the first 14 days.

### 3.3 A simple equation to predict \( k_{\text{sat}} \) of CPBs

A simple model based on the approach proposed by Belem et al. (2001) is proposed here to predict \( k_{\text{sat}} \) of the studied CPBs. The equation represents the evolution of \( k_{\text{sat}} \) as a function of curing time and the type and proportion of binder:

\[
    k_{\text{sat}(t)} = k_0 e^{-[\beta \ln(\text{wt} \% \text{ binder}) + \chi]}
\]

where \( k_{\text{sat}(t)} [\text{LT}^{-1}] \) is the saturated hydraulic conductivity of the CPB for a given curing time, and type and proportion of binder, \( k_0 [\text{LT}^{-1}] \) is the saturated hydraulic conductivity of the control sample (without binder), \( t \) is the curing time in days (1 < t < 28 days), \( \beta \) and \( \chi \) are adimensional fitting parameters that may vary depending on the binder type (\( \beta = 0.3366 \) for both binder types, and \( \chi = 0.7072 \) for CPSG binder and \( \chi = 0.4853 \) for CPFA binder).

Figure 6 shows a comparison between the predicted values with Equation 1 and the values measured in the laboratory for the different CPBs studied. Figure 6 also presents permeability test results obtained by Belem et al. (2001) and Jones et al. (2001) on other CPBs. Belem et al. (2001) performed their permeability tests on CPBs made of an uranium mine tailings and ordinary Portland cement (CP) at different proportions (2, 4, 6 and 8 %wt). In their study, a flexible
wall permeameter was used and the tests were performed according to the falling head method at 28 days of curing.

![Figure 6: Comparison between predicted values with equation 1 and values measured in laboratory (dashed lines represent + or – half an order of magnitude from the 1:1 line)](image)

For the CPBs studied here, Figure 6 (see the red triangles) shows that a good correlation exists between the predicted and the measured values (the values are generally inside the precision limits of the permeability test, estimated at half an order of magnitude). The figure also shows that Equation 1 provides good estimates of $k_{sat}$ of other CPB mixtures. The values of $k_{sat}$ measured by Belem et al. (2001) and Jones et al. (2001) are usually located inside or close to the half order of magnitude range. However, the tests performed by Belem et al. (2001) at 28 days (the three pink points on the y axis) gave $k_{sat}$ values much lower than the predicted values using Equation 1. One possible reason is the use of rigid wall permeameters to evaluate $k_{sat}$ of these mixtures, as these permeameters are not well adapted for materials having $k_{sat}$ values lower than about $10^{-5}$ cm/s (Bussière 1993).

4 DISCUSSION

According to some studies on cemented paste backfill (Belem et al., 2001; Mohamed et al., 2002), the progressive reduction of $k_{sat}$ could be explained by microstructure evolution (due to mineral precipitation and binder hydration) during curing, that changes the quantity and the structure of voids.

In addition to the change in void space, it is also recognized that saturated hydraulic conductivity is influenced by other factors such as the fluid properties and solid grains surface characteristics. The influence of these three factors can be represented by the following general equation (Aubertin et al., 1996):

$$k_{sat} = f_f f_s$$

where $f_f$ [L$^1$T$^{-1}$] is the fluid function, $f_s$ [L$^2$L$^{-3}$] is the void space function, and $f_s$ [L$^2$] is the solid grains surface features function. Mbonimpa et al. (2002) and Chapuis and Aubertin (2003) proposed equations to predict $k_{sat}$ of granular soils, based on equation 2, taking into account the basic geotechnical properties of the material (grain size distributions parameters and porosity). According to these authors, $k_{sat}$ can be predicted by the following equation (Mbonimpa et al., 2002):

$$k_{sat} = c_0 \cdot \frac{\gamma_w}{\mu} D_m^2 \frac{C_U}{c} \cdot \frac{e^{3+m}}{1+e}$$

[3]

Where $c_0$ is an adimensional constant, $\gamma_w$ is the unit weight of water ($\gamma_w = 9.81 \text{ kN/m}^3$ at 20°C), $\mu$ is the dynamic viscosity of water ($\mu = 10^{-3} \text{ Pa.s}$ at 20°C), and $m$ is a parameter introduced to represent the influence of tortuosity (Aubertin et al., 1996).

To evaluate if the decrease of $k_{sat}$ of CPBs can be explained only by the modification of porosity (the $f_f$ function in equation 2), Equation 3 was used assuming constant values for $f_f$ and $f_s$. For example, for the studied cemented paste backfill with 4.5% CPSG after 28 days of curing, the total porosity ($n = e/1+e$) must decrease from a value of 0.45 to 0.28 to reach the measured $k_{sat}$. However, work of Ouellet (2006) on a similar CPB mixture (CPB with 4.5% CPSG) using Scanning Electron Microscope (SEM) observations and image analysis showed that the total porosity decreases to a minimal value of 0.37 after 92 days of curing. Ramlochan et al. (2004) also showed (using SEM images) a refinement of the porosity in cemented paste backfill with curing time but revealed that the total porosity only slightly decreases and remains highly connected. This signifies that the porosity reduction cannot fully explain the decrease of $k_{sat}$ of CPBs at early curing time, and that other factors (probably related to $f_f$ and $f_s$) participate to the phenomenon.

Investigations conducted by Mitchell and Smith (1979) and by Benzazoua et al. (2004) give some indications on other possible factors. According to these authors, the addition of a low proportion of Portland cement could lead to the formation of gels in the pores at early curing time. Because of their properties, the gels could reduce $k_{sat}$ of the material by creating obstacles to water movement in the pores. However, more work is needed to confirm this hypothesis.

5 CONCLUDING REMARKS

Results of permeability tests have shown that the addition of binder reduces the saturated hydraulic conductivity of the tailings by up to 1 ½ order of magnitude in a period of 28 days. The proportion of binder has a direct impact on the reduction of $k_{sat}$: a higher proportion of binder leads to a greater reduction of $k_{sat}$. Depending on the type of binder used, $k_{sat}$ evolution may be different. The binder made of CPSG has a greater impact on $k_{sat}$ than the CPFA binder, although at early curing age (less than 7 days) the reduction is relatively similar.
A simple predictive equation to estimate the $k_{sat}$ evolution of the studied CPBs was proposed. This equation could be used at the preliminary phase of a project when few or no data are available. Even if the comparison with results from the literature is promising, this prediction tool must be used with caution since it was developed mainly for one tailing type and only for few binder types and proportions. Additional works are presently underway to extend the proposed equation to other CPB recipes.

Finally, some hypotheses on the factors susceptible to affect the CPBs $k_{sat}$ evolution were proposed. The refinement of the porosity, due to binder hydration, could explain in part the decrease of $k_{sat}$ with curing time. Other factors such as gel formation and chemical interactions between the solid and the fluid could also explain the $k_{sat}$ evolution observed in this project.

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REFERENCES


Mitchell, R.J., Smith, J.D. 1979. Mine backfill design and testing. CIM bulletin, 72(8018), January 1979, pp. 82-89.