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A CONTRIBUTION TO UNDERSTANDING
THE HARDENING PROCESS OF CEMENTED PASTEFILL

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ABSTRACT: Mine backfill has become a common practice in many modern mining operations around the world. Pastefill is an innovative tailings management method that returns much of this waste material to the underground mine. At the same time, it can be used as a structural element participating in the ground support. This allows the mine operator to extract a greater amount of the underground ore. In addition to the mill tailings, pastefill contains enough water to obtain the desired consistency and various quantities of binders that give this composite the needed cohesion. The purpose of this paper is to bring some new evidence to better understand of the hardening processes that occur in this complex material. It has been demonstrated that the strength development of pastefill depends on the physical, chemical and mineralogical properties of the tailings, the water chemistry and the amount of water and finally, the binder type and proportion. The hardening is caused not only by direct hydration of binder reagents but also by precipitation of hydrated phases from the pore water of paste backfill. The sulphates have a significant influence on the mechanical performance of the pastefill in different ways depending on their concentration in the pore water: inhibition or participation of the hardening phenomenon or, after the material has hardened; sulphates can also cause strength losses due to the precipitation of expansive species.

KEY-WORDS: Mine tailings, Sulphide ore, Acid Rock Drainage, Environmental, Wasteprocessing.

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I- Introduction

The use of cemented pastefill as an underground mine backfill material has become a widely used technology in most modern mines around the world (Landriault, 1995; Hassani & Archibald, 1998, Belem & Benzaazoua, 2003). Cemented pastefill is a mix of fine process tailings with a water content (obtained by slurries filtration at solid percentage between 75 and 85 %), a hydraulic binder composed by one ore more cement reagents with a proportion between 3 to 7 by dry total weight percentage, and finally, mixing water to set the paste solid percentage between 70 and 80 % depending on the desired consistency (Landriault 1995, Benzaazoua et al. 2002). Each component of cemented pastefill (tailings, water and binder) plays a critical role on the transport, emplacement and strength acquisition for both short and long-term duration (Lamos & Clark, 1989; Stone, 1993; Hassani & Archibald, 1998; Benzaazoua et al. 2002). The main advantages to the use of pastefill technology are that it allows (i) to decrease the amount of sulphide tailings (potentially acid mine drainage generating) to manage on the mine-site surface, reducing the potential pollution problems and their impact on the environment and, (ii) to increase the available ore reserves by acting as secondary ground support pillars favouring the mine stability. This use for ground support explains the mechanical constraints required for the pastefill to satisfy the design for underground mine support. The main economic factor that the mine operators have to deal with it is the binder costs (approximately 1 US $ per % per ton of pastefill). Thus, any cost optimization of backfill technology would involve reducing the binder proportion without affecting the strength of the material.

The tailings incorporated in the pastefill are the waste fraction of the original ore. This ore is finely ground to reach the liberation size corresponding to the valuable mineral. At the end circuit, a significant tonnage of tailings is generated in the form of slurries. In the modern mines, between 40 to 100 % of the total tailings slurries are deposited on the mine-site surface (tailings pond). The remainder goes underground as backfill (Hassani & Archibald, 1998). A relatively new practice of tailings management is to store the slurries on the surface as either thickened cemented or un-cemented paste (Grabinsky et al. 2002). Mine tailings from polymetallic or gold ores often contain significant amounts of sulphides ranging from a few percent to more than 40 %, depending on the mine. Hydraulic binders are used in the pastefill preparation to generate cohesiveness to satisfy ground support design requirements (Belem & Benzaazoua, 2003). Except for manufactured cements (such as Portland cements), there is a limited variety of alternative reagent binders on the market. Mainly these reagents are some type of recycled waste from other industries such as blast furnace slag or fly ash (Benzaazoua et al., 2001; Bernier et al., 1999). Additional water is mixed into the pastefill mixture to reach the desired consistency. Depending on the availability, this water can either be recycled process water from the mine or fresh water.

Moreover, the chemical interactions that occur between the added water, the tailings pore-water and the used binder reagent in cemented pastefill are very complex (Benzaazoua et al. 2002). Previous work has clearly demonstrated the effects chemistry has on the strength acquisition within pastefill materials (e.g. Benzaazoua et al., 1999; Bernier et al., 1999; Benzaazoua et al., 2000; Belem et al., 2001; Benzaazoua et al., 2002). The binders used in the preparation of cemented pastefill mixtures can be defined as hydraulic reagents; these are anhydrous phases that are able to react with water (hydration) to form hydrated phases. The latter gives the pastefill cohesion, i.e. strength that generally increases with time (curing period). Although the hydration processes for mortars and concretes are generally understood (Taylor, 1990), this is not true for the reactions within cemented pastefill). This situation is mainly due to the high water-cement ratios (w/c; often higher than 5) compared to the typical w/c
values of about 0.4 for mortars and concretes. The hydrates that can form within cemented pastefill seem to be quite different from those found in mortar and concrete materials (Benzaazoua et al., 2002). This is due to the excess water, the pH of the mix generally lower than 12 and the chemical charge (e.g. sulphates) within the mixing water (Ouellet et al., 1998; Benzaazoua et al., 2002).

Mechanical properties of pastefill materials are influenced by several parameters that can be classified into two main types:
- Macroscopic parameters that include all phenomena occurring at the scale of a stope filled with pastefill and its interaction with the adjacent rock. For examples, the effect of the interface of the pastefill – rock wall, the effect of the consolidation due to the pressure change, the effect of the drainage and the cracks in the rock which may have an effect on the amount of water within the pastefill.
- Intrinsic parameters that include all the parameters related to the 3 main pastefill components (tailings, water and binder) and their change during the curing process.

This paper will focus on the intrinsic parameters. However, both macroscopic and intrinsic factors are very much interrelated on each other, it will be demonstrated. The tailings will be studied in terms of their chemistry (sulphur content) and particle size distribution, the binders will be studied in terms of cement type and amount and the water will be studied in terms of its chemistry (sulphate content) and amount.

Thus, this paper is intended to bring some new information that will contribute to a better understanding of the hardening processes that occur in this complex composite material. We will present and discuss some cement dissolution tests to understand the behaviour of the binder during the course of curing. In addition, several pastefill mixes were produced that varied depending upon the given properties of the tailings (sulphide proportion and particle size), water (proportion and chemistry) and binder (proportion and chemistry). We will demonstrate that the strength development within paste backfill depends upon the physical, chemical and mineralogical characteristics of the tailings, on the chemistry and the amount of water and finally, on the binder type and proportion.

II- Material and methods

Mine tailings and process waters: In order to understand the effect of the chemical composition of the mine tailings, binder and mixing water on the acquisition of the mechanical strength of paste backfill, sulphide tailings from different Canadian hard rock mines (Mine A, B, C, D and E) were sampled along with typical pore water contents derived from the mine process water of the different mine that varied by sulphate content and pH. Some of the tailings were further processed to look at the individual effects of certain specific parameters. There was the case of tailings A that were desulphurized to obtain different sulphur proportions (see section III-2) and tailings B to produce different particle size distributions (see section III-3). Table 1 summarizes the main chemical and physical characteristics of the individual tailings.

Binder reagents: Ordinary or Type I (T10) or sulphate-resistant or Type V (T50) Portland cements are often used alone or with mineral additives that have specific hydraulic properties in cemented paste backfill. These additives are used to increase the durability and the strength of the mixture and sometimes to reduce the binder costs. Hence, in this study, CAN3-A5-M77 Type 10 and Type 50
Portland cements, high silica fume Portland cement (HSF), fly ash (FA) and blast furnace slag (Slag) were chosen as the different binder reagents. Portland cement Type 10 was used as the basic component for the different binder combinations. All of the binders were supplied by Lafarge Canada. More details on the characteristics of these cement reagents can be found in Benzaazoua et al. (2002).

Table 1: Main physical properties of the used tailings materials

<table>
<thead>
<tr>
<th></th>
<th>% sulphur</th>
<th>% Pyrite</th>
<th>D10 (µm)</th>
<th>D50 (µm)</th>
<th>D90 (µm)</th>
<th>Gs (g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tailings A</td>
<td>13.8</td>
<td>25.9</td>
<td>2.3</td>
<td>17.1</td>
<td>72</td>
<td>3.4</td>
</tr>
<tr>
<td>Tailings B</td>
<td>1.3</td>
<td>2.4</td>
<td>1.95</td>
<td>19.3</td>
<td>120.7</td>
<td>2.84</td>
</tr>
<tr>
<td>Tailings C</td>
<td>22.3</td>
<td>41.8</td>
<td>1.16</td>
<td>16.9</td>
<td>86.1</td>
<td>3.76</td>
</tr>
<tr>
<td>Tailings D</td>
<td>23.3</td>
<td>43.7</td>
<td>2.3</td>
<td>13.85</td>
<td>49.2</td>
<td>3.55</td>
</tr>
<tr>
<td>Tailings E</td>
<td>16.6</td>
<td>31.1</td>
<td>2.4</td>
<td>15.4</td>
<td>77.6</td>
<td>3.54</td>
</tr>
</tbody>
</table>

II-1. Cement dissolution experiments

In order to study the cement behaviour during making of the pastefill, fixed amounts of anhydrous binder were dissolved in 500 ml of deionised water. The slurries were free of tailings in order to see more easily the behaviour of the cement during time. This choice can be justified by the fact that the tailings are relatively inert after pastefill mix as it will be shown in the section III-2. The test conditions in terms of w/c ratio corresponded to pastefill mixtures with 78 wt % solids. Theses experiments did not take into account the sulphate effects. Five different binder types were chosen including ordinary Portland cement (T10), Portland cement type V (T50), Fly ash (FA) and blast furnace slag (Slag), and high silica fume Portland cement (HSF). The mixtures corresponded to different two water/cement (w/c) ratios, namely 6.3 and 4.7. Two proportions of cement (4.5 wt % and 6.0 wt %) were added to the water followed by agitation to mix the binder and water. After different mixing times of 2 min., 5 min., 10 min., 15 min., 30 min., 60 min., and 24h, 20 ml pulp samples were taken and then filtered. The filtrate was chemically analysed for the amount of dissolved or precipitated cement. The quantity of the insoluble fraction (residual mass) of binder was then weighed.

II-2. Paste backfill mixture preparation and conditioning

Various proportions of the different binders were used with the different tailings to make various mixtures of paste backfill using different mixing waters. The additional mixing water was added to set the resulting paste backfill solids percentage to the desired consistency. The consistency was evaluated using the slump test (ASTM C 143-90 test [33]), which consists of measuring the difference in height between the top of the paste in its initial state (filled into a conic cylinder) and its final state (after removing the cone). The slump values were similar for the all of the paste backfill mixtures and were approximately 7 inches except for the tests used to evaluate the effect of water content.

The paste backfill mixtures were then poured into plastic cylinders 10 cm in diameter and 20 cm height. The samples that were to be drained were moulded into cylinders with holes in the bottom having the same configuration. After pouring the different mixtures into the cylinders, they were sealed and cured at room temperature in a humidity chamber maintained at approximately 70% humidity (similar to underground mine conditions) for various periods (between 14 and 180 days). The resulting paste backfill specimens were then tested by uniaxial compression tests to evaluate their compressive strength.
II-3. Uniaxial compression tests

The backfill samples were evaluated for their mechanical properties. The uniaxial compressive strength test (UCS) was used because of its simplicity and reliability. UCS was done with a computer-controlled mechanical press (MTS 10/GL) with a normal loading capacity of 50 kN and a displacement rate of 0.001 mm/min. The specimen’s height-to-diameter ratio was 2. The two ends of the samples were first planed to get their surfaces normal to the plates of the mechanical press prior to the tests. The uniaxial compressive strength (UCS) corresponds to the maximum stress value observed during the compression test.

III- Results and discussions

III-1. Cement behaviour in pastefill conditions

The main results of the cement dissolution tests are summarized in Table 2. It can be seen that the residual amounts of non-dissolved cement remain relatively constant for a given test and that between 15% and 25% of the initial binder amount had been dissolved by the end of the test. This dissolution rate did not account for the increase of the solid weight due to direct binder hydration or secondary precipitate formation. Immediately after the addition of cement to the water, the maximum cement dissolution rate was reached. Thus, we can distinguish two main stages:

- The first stage (stage I), very fast i.e. for a mixing time of less than 2 min, the prevalent reactions are those of binder dissolution; the cement passes from an anhydrous state to a liquid phase. The maximum dissolution rate is fixed by the initial amount of water and the saturation indexes of the binder minerals. Also, it can be noted that there are small variations in the dissolution rates for each of the tested binders which is due to their different chemical and mineralogical composition.

- The second stage (stage II), i.e. for a mixing time of more than 2 min, corresponds to a stage where there are two main phenomena:
  - The first is direct hydration of the residual cement. The hydration reactions lead to the formation of hydrated phases.
  - The second is the precipitation of hydrated secondary phases from the super-saturated solution. The super-saturation is maintained by the water consumption during direct hydration.

<table>
<thead>
<tr>
<th>binder type</th>
<th>Ratio W/C</th>
<th>% binder</th>
<th>Initial mass (g)**</th>
<th>Residual weight (g) at different mixing time (in 20 ml mixing water)</th>
<th>% dissolved binder</th>
</tr>
</thead>
<tbody>
<tr>
<td>T 10</td>
<td>6.3</td>
<td>4.5</td>
<td>79.8</td>
<td>2.04  2.11  2.08  2.34  2.37  2.05  2.58</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>4.7</td>
<td>6.0</td>
<td>106.4</td>
<td>2.70  2.92  2.60  2.52  2.54  2.61  3.12</td>
<td>16</td>
</tr>
<tr>
<td>T 50</td>
<td>6.3</td>
<td>4.5</td>
<td>79.8</td>
<td>2.18  2.34  2.09  2.27  2.08  2.11  2.67</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>4.7</td>
<td>6.0</td>
<td>106.4</td>
<td>2.70  2.73  2.72  2.74  2.73  2.77  3.31</td>
<td>16</td>
</tr>
<tr>
<td>Slag</td>
<td>6.3</td>
<td>4.5</td>
<td>79.8</td>
<td>2.22  2.27  2.30  2.25  2.23  2.24  2.34</td>
<td>23</td>
</tr>
<tr>
<td></td>
<td>4.7</td>
<td>6.0</td>
<td>106.4</td>
<td>2.89  2.97  2.90  2.96  2.74  3.01  2.77</td>
<td>18</td>
</tr>
<tr>
<td>FA</td>
<td>6.3</td>
<td>4.5</td>
<td>79.8</td>
<td>2.20  2.30  2.00  2.10  1.95  1.93  2.31</td>
<td>23</td>
</tr>
<tr>
<td></td>
<td>4.7</td>
<td>6.0</td>
<td>106.4</td>
<td>2.50  2.88  2.91  2.84  2.30  2.74  2.80</td>
<td>18</td>
</tr>
<tr>
<td>HSF</td>
<td>6.3</td>
<td>4.5</td>
<td>79.8</td>
<td>2.05  2.25  2.12  2.13  2.00  2.01  2.68</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>4.7</td>
<td>6.0</td>
<td>106.4</td>
<td>2.83  3.00  2.77  2.76  2.49  2.69  3.37</td>
<td>16</td>
</tr>
</tbody>
</table>

Notes: *1440 min = 24 h; **in 50 cm³ volume of water
Figure 1 shows the evolution of soluble calcium and silicon concentrations in the mixing water. It can be noted that the kinetic of dissolution and precipitation of these two chemical elements (Ca and Si) depends on the binder. Ca is the predominant dissolved phase for the Portland cements (T50, T10 and HSF) and Si dissolves for the slag based cements. Fly ash based cement shows a significant calcium decrease due to calcium precipitation after stage I. This can be explained by carbonation (precipitation of Ca carbonates) that can happen at high CO₂ pressure (P\text{CO}_2) levels and it is recognized that the fly ash reagents are carbon-rich. The proportion of the binder also influences the kinetics of calcium dissolution rates, but this effect is less obvious for Si.

![Graphs showing the evolution of calcium and silicon concentrations in mixing water for 6% and 4.5% cement](image)

The results of the dissolution tests explain the hardening of the cemented paste backfill. Contrary to concrete or mortar, the hardening processes within paste fill are not only due to the cement hydration but also to the precipitation of hydrated phases from the pore water of the paste. The paste backfill hardening occurs in two main stages as illustrated in Figure 2:

- First stage (Stage I); dominated by the dissolution reactions, but binder hydration begins (dissolution-hydration stage). As shown in Figure 1, in this stage the dissolution (15 to 25 % of the total cement amount in weight) of the cement compounds is very rapid (1 to 2 min of mixing). The dissolution of tricalcium silicate C₃S (Ca₃SiO₅), which is the major anhydrous phase of cement, leads to Ca²⁺, H₂SiO₄²⁻ and OH⁻ ions release as shown by equation 1 and
Figure 2. The Ca concentration increases very rapidly during the first curing steps until it reaches super-saturation.

\[ 2\text{Ca}_3\text{SiO}_5 + 6\text{H}_2\text{O} \rightarrow 6\text{Ca}^{2+} + 8\text{OH}^- + 2\text{H}_2\text{SiO}_4^{2-} \]  

Second stage (Stage II, once cement super-saturation reached); this stage is characterized by the precipitation reactions and direct hydration of the binder (precipitation and hydration stage). The dissolution reactions show a significant decrease in this stage (Figures 1 and 2). The possible precipitation of hydrated phases such as, C-S-H (equation 2) contributes to the hardening of the pastefill. Portlandite (Ca(OH)\(_2\)) can also precipitate under test conditions but not in pastefill conditions where the pH is lower than 12. In addition, if sulphates are present (sulphate content of the cement or sulphates produced by sulphide oxidation or also by the addition of sulphates in the previous process to destroy cyanide remnants), gypsum or sulfo-aluminate phases can precipitate participating to the pastefill hardening (see section III-6). In stage II, the unused water remains super-saturated as regards the cement minerals. Hydrates formation occurs slowly at this stage.

\[ 3\text{Ca}^{2+} + 2\text{H}_2\text{SiO}_4^{2-} + 2\text{OH}^- + 2\text{H}_2\text{O} \rightarrow \text{Ca}_3\text{H}_2\text{Si}_2\text{O}_7\text{(OH)}_2.3\text{H}_2\text{O} \]  

Figure 2. Schematic illustration of the time-depending importance of the reactions of dissolution and precipitation of the binder in the hardening process of the pastefill

**III-2. Effect of tailings chemistry**

Mineralogy of the mine tailing determines their chemistry. The most important aspect of the mineralogy is the percentage of sulphides. The amount of sulphides has a direct impact on the density of the tailings and consequently, on the quantity of binder necessary to add per volume unit (proportions of added binder are always calculated using the dry total mass of tailings). There is also an indirect effect; it corresponds to the amount of sulphates available in the initial mixture that is proportional to the amount of sulphides in the process tailings. Thus, to isolate this parameter, a series of tests consisting of depleting and enriching sulphides in the mine tailings (mine A) was done. This operation was done by using desulphurization tanks for the non-selective flotation of the sulphide minerals (Benzaazoua et al. 2000; Benzaazoua & Kongolo 2002). In sum, tailings with four different composition were made: S1, S2, S3 and S4 having four different sulphur contents, approximately 2, 6, 12, and 18 of sulphur respectively. The particle size distributions for to the four obtained tailings are...
very similar as shown in Figure 3. Two type of binder were tested with the same proportion (4.5 wt %). The first is based on 50% Portland cement T10 and 50 % Portland cement T50. The second binder contains 80 % blast furnace slag and 20 % ordinary Portland cement T10.

![Figure 3. Grain size distribution corresponding to the four obtained tailings S1, S2, S3 and S4](image)

The results from the evolution of the uniaxial compressive strength (UCS) and its relationship to the sulphide content are shown in Figure 4. In addition to the effect of the binder type, which will be extensively demonstrated later in this paper, one can note that the amount of sulphides influences the strength (UCS) of the pastefill. However, the influence of the amount of sulphides depends on the binder type. Samples containing Portland cement (T10-T50) generally have less mechanical resistance. However, its positive effect is more marked in the case of the binder containing slag (T10-Slag) which seems to generate a better resistance after 28 days curing. It can be noted that, independently of the binder type, the proportion of sulphides in the tailings adversely affects the pastefill strength up to sulphide contents of less than 12 %. At higher sulphide contents, there is a beneficial effect, which could be related to one or the two following effects:
- Higher sulphide content implies higher density. Consequently this lead to larger proportion (in volume) of binder
- Higher sulphide content implies higher sulphate available. Consequently this leads to precipitation of the sulphates, which aids cohesion development (as will be shown more clearly later).

Moreover, to understand the sulphate production behaviour within pastefill systems and to demonstrate the low reactivity of sulphides within the cemented pastefill, oxygen consumption tests (Eberling et al., 1994) were done on the pastefill samples for both binders. In addition, free binder samples (only wet tailings) were also studied in terms of their sulphide reactivity and for later comparison to the paste pastefill reactivity. The results of this study are presented in detail in Benzaazoua et al. (2003) and Ouellet et al. (2003). It has been demonstrated that the sulphide reactivity is limited in pastefill. This is largely due to the water saturation within the backfill, which is always at high levels (near 100%). This confirms the assumption that the sulphates affecting mechanical strength are mainly those that were in the initial mix (pre-oxidized products).
III-3 Effect of the tailings particle size distribution

To evaluate the effect of particle size distribution of the tailings on the pastefill mechanical strength development, a study on process tailings having five different particle size distributions was done. These tailings were created using process tailings (mine B), by desliming (elimination of fine particles using hydrocyclones) and sieving (elimination of coarse particles). The five obtained tailings (G1, G2, G3, G4 and G5, shown in Figure 5) represent a wide range of possible particle size distribution as we can also see by plotting the mean value from 11 different tailings from different Canadian mines.

Figure 5 Particle size distributions of the five tailings studied and a typical size distribution

Tailings G1 to G5 were used to produce various pastefill mixtures with two different types of binders. The first one was a mix 50:50 of Portland cement T10 and T50 and the second a mix 20:80 of Portland cement T10 and blast furnace slag. The amount of cement added was 4.5wt% and the curing periods were 14, 28, 56 and 90 days. The effect of water drainage on the mechanical resistance was also studied on three tailings (G1, G3 and G5) using the same types and proportion of cement (T10-T50, T10-Slag).
T10-Slag at 4.5 wt %) and punched cylinders. The drainage phenomenon allows for the evacuation of the excess water, which contributes to better hardening of the pastefill (see section III-1). The drainage rate is also by the paste settling in the cylinder during the first step of curing. Drainage is directly affected by the particle size distribution as shown by the results of Table 3. In fact, the coarser the tailings particle size distribution (case of G5), the higher the amount of lost water (w = 26 % for non drained samples and 23 % for drained samples). As well known, the particle size influences the hydraulic conductivity (k).

Table 3. Water proportion (%wt) evaluated for the different cylinders

<table>
<thead>
<tr>
<th>Curing time (days)</th>
<th>Water proportion (%wt) (Binder T10-T50 at 4.5%)</th>
<th>Water content w (%) (Binder T10-Slag at 4.5%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>14 days</td>
<td>28 days</td>
</tr>
<tr>
<td>Tailings G1</td>
<td>48.6</td>
<td>48.0</td>
</tr>
<tr>
<td>Tailings G2</td>
<td>38.5</td>
<td>38.2</td>
</tr>
<tr>
<td>Tailings G3</td>
<td>34.8</td>
<td>34.5</td>
</tr>
<tr>
<td>Tailings G4</td>
<td>27.3</td>
<td>27.6</td>
</tr>
<tr>
<td>Tailings G5</td>
<td>26.4</td>
<td>26.0</td>
</tr>
</tbody>
</table>

Figure 6. Effect of particle size distribution and drainage on the mechanical strength (UCS) for pastefill samples containing two types of binder (T10-T50 and T10-Slag) at 4.5% after 28 days curing.

Figure 6 illustrates the variation of mechanical strength (UCS) as a function of the particle size distribution after 28 days curing time. The same trend has been observed for other samples for longer curing times. The results underlines that slag based binder (T10-Slag) generate UCS values 220 % to 340 % higher than Portland cement (T10-T50) after 28 days curing. The increases are 260 % to 425 % higher after 56 days curing. The percentage increases for the drained cylinders due to slag addition are 280 % to 530 % after 28 days of curing and 300 % to 430 % after 56 days of curing.

These results clearly show the strong effect of particle size distribution on the mechanical behaviour of pastefill material. Moreover, this effect is also strongly dependant on the type of binder used (as will be detailed in section III-4) and the curing time. Figure 7 shows the evolution of the mechanical strength (UCS) as function of the uniformity coefficient Cu (D60/D10) for the two types of binders. It can be noted that for a given binder type (T10-T50 or T10-Slag) at 4.5%, in the range of studied curing time
(14, 28, 56 days), the pastefill samples reach higher mechanical strengths for an uniformity coefficient value of approximately 12, in drained configuration. Otherwise, one can observe that pastefill material containing unsorted tailings (spread distribution) are more resistant mechanically than those pastefill materials having uniform distribution. In the case of drained cylinders made of the T10-T50 binder, the results show that the pastefill samples containing the tailings G1 and G3 are quite similar, contrary to the undrained samples. However, pastefill made of tailings G5 shows a large difference (200 kPa), which seems to be associated to the amount of lost water from the samples. But, with pastefill samples containing binder based on T10-Slag, one can observe that pastefill made of tailings G1, G3 and G5 show more significant differences compared to the pastefill sample in the undrained configuration (between 48 kPa for G1 and 370 kPa for G5. In this case also, the differences were certainly due to water evacuation from the samples.

One of the findings of this part of the study is that the amount of water necessary to reach a desired consistency, measured with the slump test, generally at 7 inches (17.8 cm) is strongly dependant on the particle size distribution of the tailings. The finer is the tailings, the more water is necessary to reach the target consistency. Thus, all of the physical parameters (water proportion, humid and dry volumetric mass, weight solid percentage, volume of the solid, volume of voids, void index, degree of saturation, theoretical porosity, and volumetric water content) are directly influenced by the particle size distribution of the tailings. In conclusion, an increase of the particle size of a given tailings generally leads to an increase in solid weight percentage increase and this causes a decrease in porosity and an increase of the degree of saturation.

**III-4. Effect of the type of binder**

The type of binder has a significant effect on the mechanical behaviour of pastefill materials (for both short mid and long-term) and even its resistance to deterioration. To better illustrate this, another series of tests was done with sulphide rich tailings (mine C) to allow finding the best type of binder. The binder proportion chosen for all of the prepared mixtures was 5%. Figure 8 illustrates the effect of different binder types on the mechanical strength with time. The main observations from this part of the study are presented in Figure 7.

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**Figure 7. Evolution of the mechanical strength (UCS) as function of the uniformity coefficient Cu (D60/D10) for two types of binders (4.5 wt % T10-50 and T10-Slag) during time curing of 14 days**

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One of the findings of this part of the study is that the amount of water necessary to reach a desired consistency, measured with the slump test, generally at 7 inches (17.8 cm) is strongly dependant on the particle size distribution of the tailings. The finer is the tailings, the more water is necessary to reach the target consistency. Thus, all of the physical parameters (water proportion, humid and dry volumetric mass, weight solid percentage, volume of the solid, volume of voids, void index, degree of saturation, theoretical porosity, and volumetric water content) are directly influenced by the particle size distribution of the tailings. In conclusion, an increase of the particle size of a given tailings generally leads to an increase in solid weight percentage increase and this causes a decrease in porosity and an increase of the degree of saturation.
study are that the binders containing fly-ashes (FA) does not confer good mechanical performances, the binders containing Portland cement (ordinary T10, sulphate resistant T50 or enriched in silica fume, HSF) give good UCS values and that the best strength is reached with the mixture with slag cement (T10-Slag). One can also observe a small decrease in terms of UCS for all of the tested binders, after an initial peak that occurred from 14 to 28 days of curing time. Other studies (Benzaazoua et al., 1999, 2002; Bernier et al., 1999) clearly demonstrated that there is no ideal, universal recipe for all mines to get good performance for their pastefill operations. A binder can be effective in one case and completely ineffective in other cases. Thus, it is necessary for the mines to do thorough preliminary mix optimization to find the most optimal recipe that accounts for technical constraints (for support ground), environmental (tailing management methods) and costs (operation cost aspect) before each backfill operation.

![Figure](image.png)

**Figure 8.** Effect of different types of binders on the mechanical strength (UCS) of pastefill mixtures made of sulphidic tailings (from mine C) during time curing

**III-5. Effect of the proportion of binder**

These results (Figure 9) are those from a study that consisted of testing several types of binder by using proportions of 3 %, 4.5 % and 6 % (representing the range usually used in the mining industry) mixed with a given tailings (mine A). Figure 9 shows clearly a sub-linear and proportional relationship between increasing proportions of binder and the obtained mechanical resistance. Other studies (Benzaazoua et al., 2002), which were done on other mine residues (with both high and low sulphide contents), confirm this tendency, namely, the quasi-linearity of the relationship between the binder percentage and developed mechanical resistance. The proportion of binder and its effect on quality of the cemented pastefill materials is simple to understand, since an increase in the amount of binder in a mixture results in a corresponding increase in the pastefill strength.
III-6. Effect of the soluble sulphate concentration

The pore water of the filtered tailings is often rich in soluble sulphates especially when the original ore contain sulphides or when SO₂-Air is used to destroy the cyanide content within tailings. Thus, the additional fresh water quantity (added to set the paste consistency) allows dilution of the pore water that is usually charged with various chemical species (sulphates, calcium and other metals). In addition, calcium sulphate in the form of gypsum (CaSO₄·2H₂O) or anhydrite (CaSO₄) that is added within the clinker to prevent flash-set, also can interfere and plays a role during the hydration processes.

In order to highlight the effect of sulphates on cemented pastefill hardening, a series of mixtures was made with the same type of a sulphidic tailings (mine D) and the same type of binder (4.5 wt % of a binder based on Portland cement T10-T50 in proportion of 50:50). Figure 10 presents the resistance variation (UCS) according to the total soluble sulphate concentration in the tailings pore water after 28 days of curing time. This concentration is the recomputed total water concentration, i.e. the water used during mixing (tailings pore water + added water). Up to 8000 ppm of sulphate, the increasing presence of soluble sulphates leads to an increased slowing of hardening process due to inhibition of cement hydration in presence of sulphates. This is possibly due to the well-known phenomenon of hardening
delay due to the presence of gypsum in Portland cement reagents. However, there is beneficial side effect observed beyond 8000 ppm and which could be explained by the contribution of the precipitated hydrated sulphates during binder hardening. This phenomenon was also observed after 56 and 90 days of curing time.

### III-7. Effect of the amount of water

As shown in section III-1, the water-binder ratio is very important because it controls all of the hydration and precipitation reactions, which in turn, control all of the hardening processes within pastefill materials. It can be remembered that the additional water in the mixture, plus to residual water left after filtration, is primarily used to reach the desired paste consistency to be conveyed underground (Belem & Benzaazoua, 2003). This parameter is controlled by the pumping and distribution system in the mine. As mentioned before, it is now well established that, for pastefill material, an increase in the water content and the degree of saturation has a negative influence on the mechanical strength. Figure 11 presents the results obtained from a series of mixtures produced with the same type of a sulphide tailings (mine E) and the same type of binder (4 and 5 wt % of a binder based on Portland cement T10). It can be clearly observed that a decrease in strength (UCS) occurred with an increase in the water content (or slump value). This effect is clear at short-term (7 days of cure) as well as medium term curing times (28 and 56 days of cure), however it is less clear at the long-term curing time (120 days of cure) possibly due to a certain internal weathering of the samples as seen for samples made of tailings C (Figure 12). This Figure illustrates the combined effects of slump value (water content w) and the proportion of added cement (Portland cement T10 at 4% wt) on the mechanical strength (UCS) according to curing time. The tailings from Mine E were used. One can clearly observe the strength losses after 56 days, due to weakness of the cement matrix (see section III-8).

![Figure 11. Effect of the water content (w) on the mechanical strength (UCS) of pastefill mixtures made of sulphidic tailings (from mine E) and Portland cement (T10) during time.](image)

Indeed, mechanical strength acquisition within the pastefill is conditioned by the appearance of hydrated phases that form the binding matrix for the fine grains from the tailings. The hardening
processes are governed by the hydration reactions and the chemical solubility rates. The precipitation phenomena led to solid phases that formed when they reached their saturation index (sufficient concentration). Thus, increased water content from high saturation is difficult to reach due to the dilution of the soluble species. Precipitation is favoured by several factors leading to a water loss through the combined effects of consolidation, drainage and evaporation processes. Among these factors one can note the particle size distribution (see section III-2), the water-tightness of the wall surrounding the backfill material, the dimension of the backfilled stopes, and finally the mode of installation (sequence of backfilling).

![Figure 12. Evolution of the mechanical strength (UCS) of the pastefill mixtures related to the slump values (water content).](image)

**III-8. Pastefill weathering**

The loss of mechanical resistance is a phenomenon often observed within pastefill materials (Benzaazoua, 1996; Ouellet et al., 1998; Benzaazoua et al., 1999, 2000, 2002, 2003; Bernier et al., 1999). It is a phenomenon that seems to be almost always related to the presence of reactive sulphide minerals. The question that can arise is: is this relationship direct or indirect? In other words; can the sulphides oxidize within a cement matrix? Part of the answer comes from Benzaazoua et al. (2000) who stipulated that the pastefill materials are very impermeable materials that remain saturated for a long time. Oxygen cannot diffuse through such matrix as proven by oxygen consumption measurement carried on sulphide rich pastefill (Benzaazoua et al., 2003; Ouellet et al., 2003). These observations are confirmed from a previous study (Belem et al., 2001) of permeability evolution within pastefill samples and which showed that the permeability values rapidly decrease (close to the one of clays materials after only 24 hour). Thus, sulphides would play a part in an indirect way by providing an initial (during mixing) amount of sulphates that can either make a positive or negative contribution (see section III-6).

The initial sulphide reactivity, which happen as well as the oxygen available in the mixture will provide more or less sulphates depending upon the initial sulphide content and also whether the ore processing uses sulphates (for example, cyanide destruction by the method SO$_2$-Air). Moreover, the sulphide reactivity has an appreciable effect on the pH by acidity production. The pH decrease will destabilize the hydrated phases. The most alkaline hydrates “leave” for phases more resistant to acidic media. To
date, nobody is familiar with all of the phenomena contributing to pastefill hardening. The only point on which the researchers working in the field agree on is that pastefill hardening is quite different from that of the mortars and concretes as mentioned above (see section III-1). Table 4 underlines the main differences between pastefill, mortars and concrete.

Table 4. Main differences between mortar/concrete composites and cemented pastefill materials.

<table>
<thead>
<tr>
<th></th>
<th>Mortar / Concrete</th>
<th>Paste backfill</th>
</tr>
</thead>
<tbody>
<tr>
<td>Binder content</td>
<td>&gt;12%</td>
<td>&lt;7%</td>
</tr>
<tr>
<td>W/C (weight ratio)</td>
<td>&lt;0.5</td>
<td>&gt;5</td>
</tr>
<tr>
<td>Aggregate grain size</td>
<td>mm-cm</td>
<td>µm-mm</td>
</tr>
<tr>
<td>State of saturation</td>
<td>not saturated</td>
<td>saturated (&gt;95%)</td>
</tr>
<tr>
<td>Hydration in solid state</td>
<td>majority</td>
<td>important</td>
</tr>
<tr>
<td>Precipitation in hardening process</td>
<td>negligible</td>
<td>important</td>
</tr>
<tr>
<td>Strength</td>
<td>&gt;5 MPA</td>
<td>&lt;2 MPA</td>
</tr>
<tr>
<td>Sulphide</td>
<td>accidentally present</td>
<td>frequently present</td>
</tr>
<tr>
<td>Internal sulphate attack</td>
<td>rare</td>
<td>frequent</td>
</tr>
</tbody>
</table>

In addition to the acidity production, formation of expansive phases such as hydrated sulphates can lead to a physical deterioration in the pastefill materials. Indeed, when the sulphates are formed in a cement matrix where voids still remain, the sulphates participate in the cementing processes. The voids are porosity (considered being more than 40% per geotechnical calculation and confirmed by mercury intrusion porosimetry (Benzaazoua et al., 2000). However, when the space is completely filled, the precipitation of the sulphates is accompanied by strong pressure dissipation (due to expansive sulphate crystallisation) that leads to the fracturing of the already hardened pastefill. This phenomenon was highlighted by Benzaazoua, 1996; Benzaazoua et al., 1999, 2002; Bernier et al., 1999).

IV- Main conclusions

The present work gives some new evidence that can contribute to the understanding of the hardening phenomena of paste backfill materials. Cement dissolution tests in the pastefill preparation clearly shows that a major part of the total added cement (up to 20%) dissolves very rapidly. At the same time, the hydration processes takes place, which leads to the formation of hydrates and the concentration of the residual solution. Consequently, precipitation of hydrated phases (including calcium sulphates) occurs which aids the hardening phenomena.

This paper also highlighted the effect of the main parameters governing the performance of pastefill materials. It clearly appears that the pastefill behaviour is determined, in addition to environment where they are placed, by the mixture itself. The mixture is composed by three main components whose contribution is critical. Tailings, which are the most abundant component, have an influence by their physical characteristics (such as particle size distribution) but also by the rate of their ability to deliver sulphates within the medium due to their initial reactivity. The available water has a strong effect due to its proportions which influences, through the dilution rate, the precipitation reactions of a part of the cementing phases. The other portion came from direct hydration of the added binder. Moreover, the water chemistry, especially as regards to soluble sulphates, is an important factor that influences the mechanical resistance at the short and long term curing times. The last component is the binder. The binder effect lies to its chemistry and its proportions in the mixture. It will support the more or less mechanical strength development. The different binders give different strength for a given tailings. The
binder is the major cost in a pastefill operation. This explains the necessity of optimizing its addition in order to have a profitable operation.

Finally, it is clear that too many differences exist between the behaviour of pastefill materials and mortars/concrete materials. Thus, knowledge transposition between the two types of composite is not evident.

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