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Key issues related to behaviour of binders in cemented paste backfilling

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Abstract

Backfilling practices become widely used by modern hard rock mines helping ore extraction as well as allowing a more integrated solid waste management. Among backfill types, cemented paste backfill is taking an increasing interest since its easy placement in the underground stopes and its capacity to use reactive sulfidic tailings. Various binder agents, including conventional manufactured cements and alternative additives, can be used in order to set the needed mechanical properties of the backfill during mining sequences. Due to the high price of binders and their sensitivity towards chemical properties of the backfill material, backfill recipe optimisation becomes capital. The key note will focus on the various sources and compositions of the most common binders in paste backfilling. The paper will also contribute in the understanding of the binder hardening processes in cemented paste; focusing particularly on i) cement hydration, ii) water demand and water chemical interactions, iii) solid mineralogy, iv) sulfate and sulfide behaviours, v) temperature role, etc. The main short- and long-terms behaviour types of cemented paste backfill will be discussed (effects of drainage-consolidation, sulfate attacks, etc.).

1 Introduction

Mine backfill refers to waste materials, such as waste development rock, deslimed and whole mill tailings, quarried and crushed aggregate, and sands, that could be placed into underground mined voids for the purposes of either disposal and/or to perform some engineering function. Consequently, the disposal of mine tailings underground reduces the environmental impact and also provides a material which can be used to improve both ground conditions and the economics of mining. The waste materials are often mixed with common manufactured cements as well as other pozzolanic binders to improve their strength properties. Among the three existing backfill types (hydraulic-fill, rock-fill, paste backfill), the use of cemented paste backfill (CPB) is becoming an increasingly important component of underground mining operations worldwide, and especially in Canada for hard rocks polymetallic mines. Paste backfill consists of total mill tailings (full size fraction of the tailings) thickened and/or filtered to around 80 wt.% (by weight) to which binder and water are then added to achieve the desired rheological and strength characteristics. Figure 1 present a Schematic diagram illustrating the different components of paste backfill as well as the main factors involved in: the binder and tailings chemical composition, grain size distribution, density and solids percentage of the tailings and finally the mixing water chemistry. Each component plays an important role during the backfill transportation, its delivery and its strength acquisition at short, mid and long term curing time. The binder related parameters are very sensitive because of the cost corresponding to this component (representing more than 80% of the overall paste backfilling operation) and the role that it plays in reaching the mining requirements for underground support.

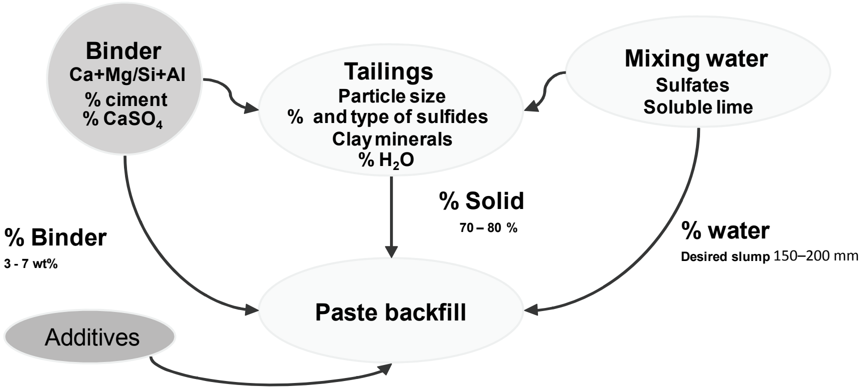

Figure 1 **Schematic diagram illustrating the different components of paste backfill (Benzaazoua et al., 2002)**

This paper will present key aspects related to the behaviour of binders within cemented backfills, focusing on paste backfill materials. The paper will thus summarise works done by the author's team as well as data obtained from the available literature. Common cements widely used in backfill operations will be first present before addressing the mechanisms of their hydration and the roles of the main related factors. A section will be dedicated to alternative binders, their limitation of use as well as the economical and environmental perspectives that they provide. The short and long-term behaviour of cemented paste backfill will be addressed before the concluding remarks.

2 Composition of commonly used cements

In this section the focus will be on manufactured cements that are the most used by the mine industry in backfill operations. Its regroup the following cements: Portland cement (ordinary and sulfate resistant cements called type 10 or GU and 50 or HS respectively), the granulated blast furnace slag (GBFS) and the C-type fly-ash.

2.1 Origin and manufacture of cements

Ordinary Portland cement (often referred to as OPC) is the most common type of cement in general use around the world, since it is a basic ingredient of various civil engineering building materials. OPC is a fine powder produced by grinding Portland cement clinker (more than 90%), a limited amount of calcium sulfate which controls the set time, and up to 5% minor constituents (as allowed by various standards). There are three fundamental stages in the production of Portland cement:

1. preparation of the raw mixture
2. production of the clinker
3. preparation of the cement.

Portland cement clinker is made by heating, in a kiln, a homogeneous mixture of raw materials to a sintering temperature, which is about 1,450°C for modern cements. The major raw material for the clinker-making is usually limestone ($CaCO_3$) mixed with a second material containing clay as source of alumino-silicate. Normally, an impure limestone which contains clay or SiO_2 is used. The $CaCO_3$ content of these limestones can be as low as 80%. Second raw materials (materials in the raw-mix other than limestone) depend on the purity of the limestone. Some of the second raw materials used are: clay, shale, sand, iron ore, bauxite, fly ash and slag.

2.2 Chemical and mineralogical composition of the most popular cement in the mine industry

Chemical composition of manufactured cements is based mainly on five chemical compounds: CaO, SiO_2, Al_2O_3, Fe_2O_3 and SO_3. There are five types of Portland cements with variations of their chemistry according to ASTM C150, they are optimised for various conditions of use. The chemistry of the most popular cement used by the mine industry is summarised in Table 1.

Table 1 Chemical composition of the most popular cement used by the mine industry

Binder	SiO_2	CaO	Al_2O_3+Fe_2O_3
PC 10 (GU)	18.05	62.82	7.23
PC 50 (HS)	19.98	63.66	7.55
Type F Fly Ash	51.40	6.29	22.53
Type C Fly Ash	36.60	20.80	23.82
GBFS	37.00	36.80	10.08

The crystal-chemistry of cement is very complex, so cement chemist notation was invented to simplify the formula of common oxides found in cement. This reflects the fact that most of the elements are present in their highest oxidation state, and chemical analyses of cement are expressed as mass percent of these notional oxides. The nomenclature used is as follow:

silica (SiO_2)	**S**	sulfur trioxide (SO_3)	**Š**
lime (CaO)	**C**	magnesie (MgO)	**M**
alumina (Al_2O_3)	**A**	potassium oxide (K_2O)	**K**
ferrite (Fe_2O_3)	**F**	sodium oxide (Na_2O)	**N**
water (H_2O)	**H**	carbon dioxide	**Č**

Type I Portland cement is known as common or general purpose cement. It is generally assumed unless another type is specified. The typical compound compositions of this type are: 55% (C3S), 19% (C_2S), 10% (C_3A), 7% (C_4AF), 2.8% MgO, 2.9% (SO_3), 1.0% Ignition loss, and 1.0% free CaO. A limitation on the composition is that the (C3A) shall not exceed fifteen percent. Type I Portland cement is widely used by the mine industry alone or blended with other cement additives.

Type V is used where sulfate resistance is important. The typical compound composition is: 38% (C_3S), 43% (C_2S), 4% (C_3A), 9% (C_4AF), 1.9% MgO, 1.8% (SO_3), 0.9% Ignition loss, and 0.8% free CaO. This cement has a low (C_3A) composition which accounts for its high sulfate resistance. The maximum content of (C3A) allowed is 5% for Type V Portland cement. Another limitation is that the (C_4AF) + 2(C_3A) composition cannot exceed 20%. This type is used in concrete that is to be exposed to alkali soil and ground water sulfates which react with (C3A) causing disruptive expansion. It is unavailable in many places although its use is common in the western United States and Canada. Type V Portland cement has mainly been supplanted by the use of ordinary cement with added ground granulated blast furnace slag or tertiary blended cements containing slag and fly ash. Type V Portland cement is widely used by the mine industry for the preparation of paste when tailings are very reactive (occurrence of pyrrhotite for example).

Constituents that are permitted in Portland-composite cements are blastfurnace slag, silica fume, natural and industrial pozzolans, silicious and calcareous fly ash, burnt shale and limestone. Blast furnace slags are constituted by mainly amorphous anhydrous phases that are conditioned by their quenching (rapid water quenching). However for fly ashes the proportion of amorphous fraction is variable (between 20 and 90 % depending on the authors and origin) and the main crystallised phases widely described are quartz, mullite, periclase, gehlenite, hematite, magnetite, anhydrite). EN 197-1 norm defines 5 classes of common cement that comprise Portland cement as a main constituent.

1. Portland cement comprising Portland cement and up to 5% of minor additional constituents.
2. Portland-composite cement OPC and up to 35% of other single constituent.
3. Blastfurnace cement OPC and higher percentages of blastfurnace slag.
4. Pozzolanic cement OPC and up to 55% of pozzolanic constituents.
5. Composite cement OPC, blastfurnace slag and pozzolana or fly ash.

2.3 Fineness of the manufactured cements

The physical characteristics of the most common binder used by the mine industry are summarised in Table 2. The clinkers as well as the additives are grinded to a normalised particle size distribution to render the product more homogenised and reactive towards hydration. Binder fineness is of utmost importance so the norms limit the amount of coarse particle larger than 200 µm to 0–5 % and particles between 70 and 90 µm to 9–22 %. This parameter is usually estimated using a method called Blaine that measures the total surface area by powder weight (cm^2/g) which is between 3.000 and 3.500 cm^2/g. The values presented in Table 2 are determined by nitrogen gas adsorption using the BET method.

Table 2 Physical characteristics of the most popular cement used by the mine industry

Binder	Specific Gravity	Surface Area BET (m^2/g)	D_{10} (µm)	D_{50} (µm)
PC 10	3.14	1.10	0.60	14.11
GBFS	2.90	2.75	0.54	7.25
Type F FA	2.34	0.93	1.31	24.66
Type C FA	2.65	2.24	0.40	8.88

3 Strength acquisition within cemented paste backfills

3.1 Hydration of manufactured cements in normal conditions (civil engineering applications)

During OPC hydration, the main anhydrous clinker constituents in the contact with water are submitted to intense chemical reactions. As result, a release of numerous ions as Ca^{2+}, silicates $SiO_4H_2^{2-}$, $SiO_4H_3^-$, $SIO_7H_4^{2-}$; aluminates $Al(OH)_4^-$, AlO_2^-; sulfates SO_4^{2-}, as well as alkali like K^+ et Na^+ and hydroxides OH^-. These phenomena initiate many chemical reactions well described in the literature called «hydration» and that allow the formation of many hydrated products in hardened cement pastes which are summarised in Table 3 (Taylor, 1990).

Table 3 Main cementitious phases that form during hydration of the most popular cement used by the mine industry

Phase	Detailed Formula	Name
C-S-H	$2(CaO) \bullet SiO_2 \bullet 0.9\text{-}1.25(H_2O)$, and/or $CaO \bullet SiO_2 \bullet 1.1(H_2O)$, and/or $0.8\text{-}1.5(CaO) \bullet SiO_2 \bullet 1.0\text{-}2.5(H_2O)$, etc.	calcium silicate hydrate
C-A-H	This is even more complex than C-S-H	calcium aluminate hydrate
AFt	$C_3AS_3H_{30\text{-}32}$	aluminate ferrite trisulfate
AFm	C_2ASH_{12}	aluminate ferrite monosulfate
C3AH6	$3CaO \bullet Al_2O_3 \bullet 6\ H_2O$	hydrogarnet

Many of these products have nearly the same formula and some are solid-solutions with overlapping formula, as it’s the case of CSH the most abundant cementitious phase. All hydration reactions are exothermic and liberate heat especially during the first steps of the setting process. The sulfate of the cement controls the setting since it react with the C3A forming ettringite that inhibit for a certain time interval (sleeping period) the hydration processes allowing workability of the cement based prepared material. Calcium hydroxide (Portlandite) is a major phase in the cementitious materials but is the most instable to any pH decrease (buffering the pH at 12.5) whereas CSH gels that confer most of the material cohesion are more stable even at pHs near 9.

3.2 Role of binding agents within cemented backfills

It must be known that the hardening processes within CPB are very different to those encountered in mortar and concrete preparation. Table 4 below synthesises these differences. So no extrapolation can be made between these two kinds of material in order to understand their behaviour (Benzaazoua et al., 2004a). The water to cement ratio (w/c) represents the main difference.

Table 4 Main differences between mortar/concrete composites and cemented paste backfills (adapted from Benzaazoua et al., 2004a)

Parameter	Mortar/Concrete	Paste Backfill
Binder content	>12%	<7%
W/C (weight ratio)	<0.5	>5
Aggregate grain size	mm-cm	µm-mm
Degree of saturation	not saturated	saturated (>95%)
Hydration of solid cement particles	main phenomenon	important phenomenon
Precipitation in hardening process	negligible	important phenomenon
Strength	>5 MPA	< 2 MPA
Hardening	few hours	more than 1 month
Sulfide	accidentally present	frequently present
Internal sulphate attack	rare	frequent

Binding agents are used within backfill to get the required strength which in turn is dictated by the underground support constraints that are defined for the mine engineering staff. By far the most employed hydraulic binder added to backfill is ordinary Portland cement also called general use cement (Type 10 or GU). There has been continuous research around the world into alternative binders and the most common substitute has been to use pozzolanic products such as blast furnace slags (BFS) and fly ash (FA).

Figure 2 shows a ternary plot representing the main types of binders mostly used by the mine industry for backfill production.

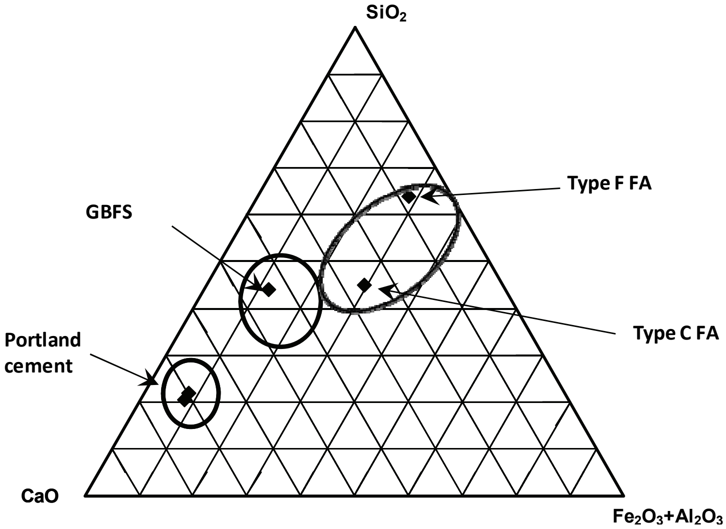

Figure 2 Ternary plot of Type I and Type V Portland cements and some pozzolanic constituents (slag and fly ash type C and F)

Among Portland cements, Type 10 (GU or OPC) and Type 50 (sulfate resistant also called HS) are the main used binders. Any binder substitute must fit with a given chemistry illustrated by the circles dram in the Figure 2. Typical binder proportion used within CPBs are 3% to 7% by weight; 7% being used mainly in the first meters of backfilling acting as plug for the subsequent stope filling. In some cases (secondary pillars) the cement content can drop down to 2% even if no hardening can be expected at this binder dosage.

The cohesive strength, density and solid percentage are the determining factors in the use of paste backfill. The backfill cohesion is directly dependent on the binder quality and its potential to resist to possible harmful chemical reactions (such as hydration inhibition and sulfate attack, see sections below) which can occur within a sulfide and/or sulfates rich-backfill. So, to ensure the maximum safety of the underground mine workers, the challenge is to use a cemented backfill that is able to stabilise underground stopes without being affected by the potential of long-term strength loss due to chemical weathering.

3.3 Hardening of cemented paste backfill

Recent work results showed that the hardening process within paste backfill material is not only due to the binder hydration but also to the precipitation of hydrated phases from the pore water of the paste (Benzaazoua et al., 2004a). Figure 3 illustrates that paste backfill hardening occurs in two main stages: the first stage (dissolution-hydration), which is dominated by the dissolution process and the second stage (hydration-precipitation), which is characterised by the precipitation process and the direct hydration of binding agents, this later phenomena can happen during an important period of curing.

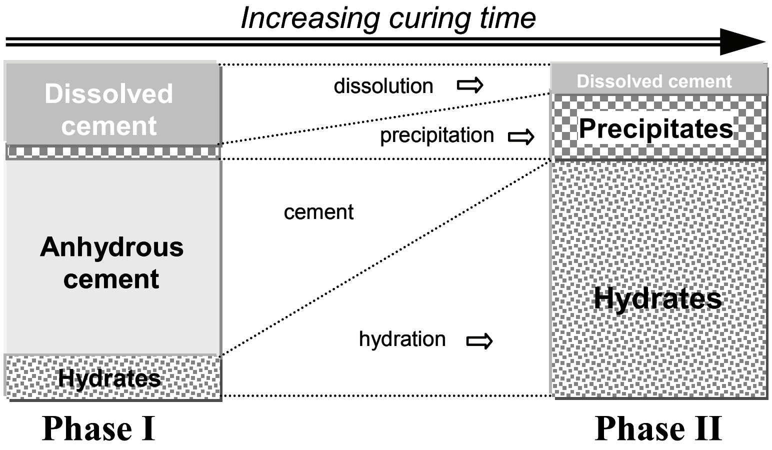

Figure 3 Schematic illustration of the time-depending importance of the reactions of dissolution and precipitation of the binder in the hardening process of the paste backfill (after Benzaazoua et al., 2004a)

3.4 Role of the water and interaction with the tailings mineralogy

Water is necessary to ensure that proper hydration of the binding agents occurs. If proper hydration of the binder does not occur, the CPB will not meet its required strength and stiffness. Also, additional water is usually required to pump paste backfill underground (to set the paste consistency) so that the volumetric water content of paste backfill is always far in excess of what is required for hydration of OPC (and blends of OPC with other cement additives). This factor is the main explanation of the slowness of the CPB hardening. The other concern then is the water chemistry: pH, concentration of sulfates salts and lime (frequently added in the upstream ore treatment processes). Thus, pore water of the filtered tailings is often loaded by soluble sulfates especially when the original ore contain sulfides and/or when SO_2-Air is used to destroy the cyanide content within gold treatment tailings. This justifies the need of doing the mixing of additional fresh water to allow pore water dilution. In addition, calcium sulphate in the form of gypsum ($CaSO_4.2H_2O$) or anhydrite ($CaSO_4$) that is added within the clinker to prevent flash-set, also can interferes and plays a role during the hydration processes. However the effect of sulphates in the CPB hardening is not so easy.

Figure 4 show the evolution of UCS values (mean from triplicate samples) versus the curing time for backfills made of various sulfate mixing water concentrations (0 to 1 gL^{-1}) and two binder types: PC type 10/50 50:50 and PC type 10/slag 20:80 blend. One can clearly observe that the effect is different depending on the binder type: no effect whatever the sulfate concentration in the case of Portland cement based CPBs and a clear beneficial effect for slag based CPBs for sulfate concentration higher that 5,000 mgL^{-1} even after 120 days curing time. The sulfate strength participating is mainly explained by the contribution of the precipitated hydrated sulfates during binder hardening.

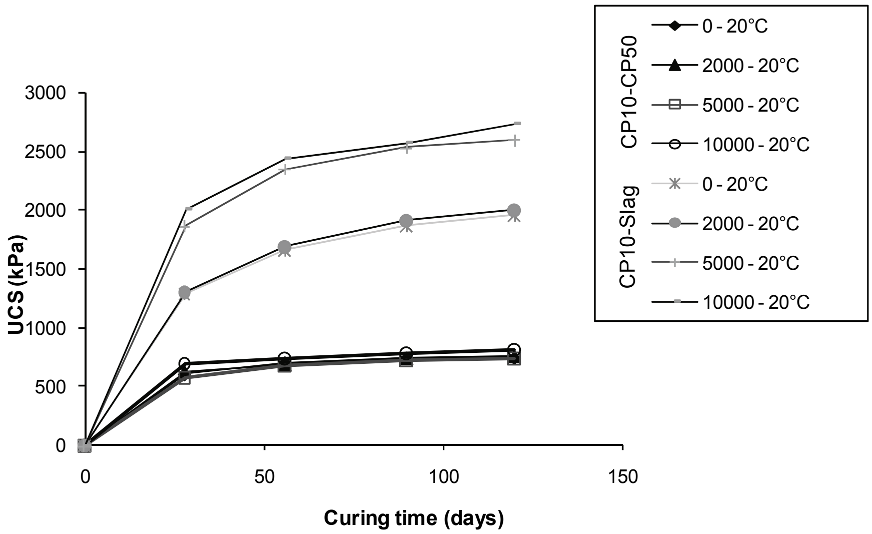

Figure 4 Mean UCS values versus the curing time for backfill samples made of various sulfate mixing water concentrations and two binder types: PC type 10/50 50:50 and PC type 10/slag 20:80 blend

3.5 Role of the drainage/consolidation phenomena

A work using consolidation setup called CUAPS was used to simulate the curing conditions of the CPB materials under self–weight consolidation settlement of laboratory–prepared CPB materials (Yilmaz et al., 2009). The CUAPS apparatus was used to evaluate the performance of CPB samples prepared from sulphide–rich mine tailings using two types of binding agent: slag blend binder (PCI–Slag) and ordinary Portland cement (PCI) alone at binder contents varying between 3 wt% and 10 wt%. The same batches were also casted in moulds using the standard laboratory testing. The effects of applied pressure (loading stress) on the strength development of the CPB material are presented in Figure 5, showing the mean UCS values (triplicates) according to binder content for backfill samples made of two binder types: OPC and OPC-slag blend.

Based on the geotechnical index properties, mineralogical composition, and strength properties of the CPB materials cured under different consolidation and drainage conditions, the following conclusions as respect to binder type and content have been drawn:

1. Drainage water measurement revealed that the amount of water escaped from CPB samples was higher (by 31%) for the slag blend binder than for the ordinary Portland cement. The CPB samples produced from the latter appeared to retain more water.
2. Geotechnical index parameters showed that porosity, degree of saturation, and specific surface area of the CUAPS–consolidated CPB samples were respectively 11.9, 4.9, 7.1% lower, and 19.3% higher than those of the unconsolidated CPB samples for a given binder type and content.
3. The CUAPS–consolidated CPB samples containing slag blend binder gave a 51 and 7% higher UCS than unconsolidated CPB samples at 3 and 10 wt% binder contents respectively. UCS changes for the CPB material having ordinary Portland cement varied between 37 and 14% at 3 and 10 wt% binder contents respectively.

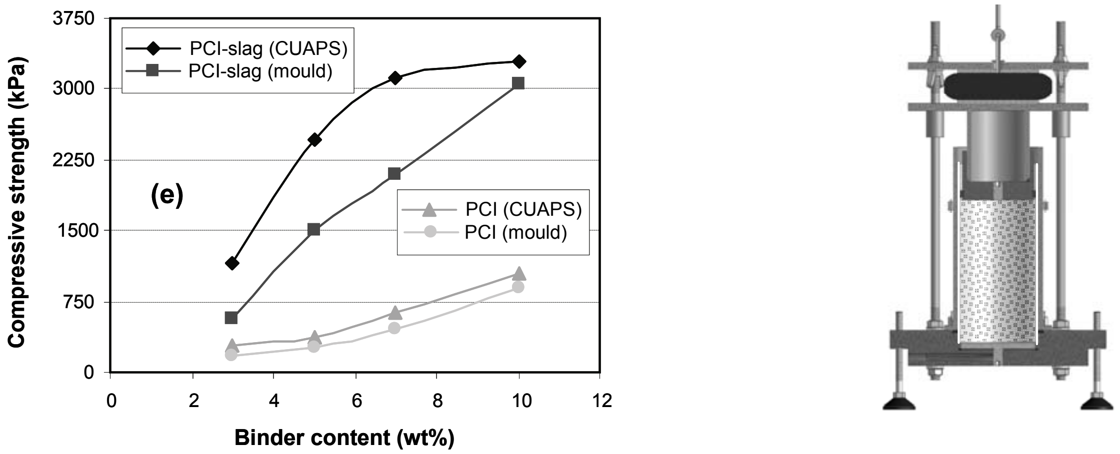

Figure 5 Mean UCS values with binder content for all backfill samples for the two binder types: CPB samples with ordinary Portland cement and with slag blend binder (in Yilmaz et al., 2009)

3.6 Role of sulfide content and sulfide reactivity within CPB

The presence of sulfide minerals within cemented composites as well as the soluble sulfates has a deleterious effect on the strength of paste backfill due to sulfate attack. Many works highlighted the possibility of backfill strength loss during the curing time due to a chemical weathering caused by the presence of an aggressive medium (presence of sulfates and production of acid).

It must be mentioned here that he origin of the sulfates in CPB mixes is triple:

- sulfide oxidation following the general equation
  $Sulfures + O_2 + H_2O \rightarrow Sulfates + ions_{métalliques} + H^+$
- cyanide destruction using Inco SO_2-Air process that provide sulfates
- initial binder sulfate content that can dissolve during the first steps of hydration.

Many works (Ouellet et al., 2006) demonstrated that sulfides are very slightly reactive since paste backfill are material that normally remains saturated in water due to their fineness. So, the sulfates that interfere in the hardening processes of freshly prepared CPBs are mostly produced during the upstream ore treatment process as well as during the paste filtering and mixing step.

3.7 Role of presence of clayey minerals: case of talc

The effect of the presence of some clayey minerals within paste backfill is not well known. Some tailings when containing phyllosilicates like talc, chlorite or séricite etc., show a water demand higher for a given consistency. This need of additional water in the mix impacts negatively the strength acquisition of the paste material. Figure 6 show the evolution of UCS values versus the curing time for simulated backfill samples made of various talc contents (0, 5, 10, 15 and 25%) and two binder types: PC type 10/50 50:50 and PC type 10/slag 20:80 blend. On can observe that the effect of presence of talc depend on the type of binder and the highest is the talc proportion the lowest is the strength gain.

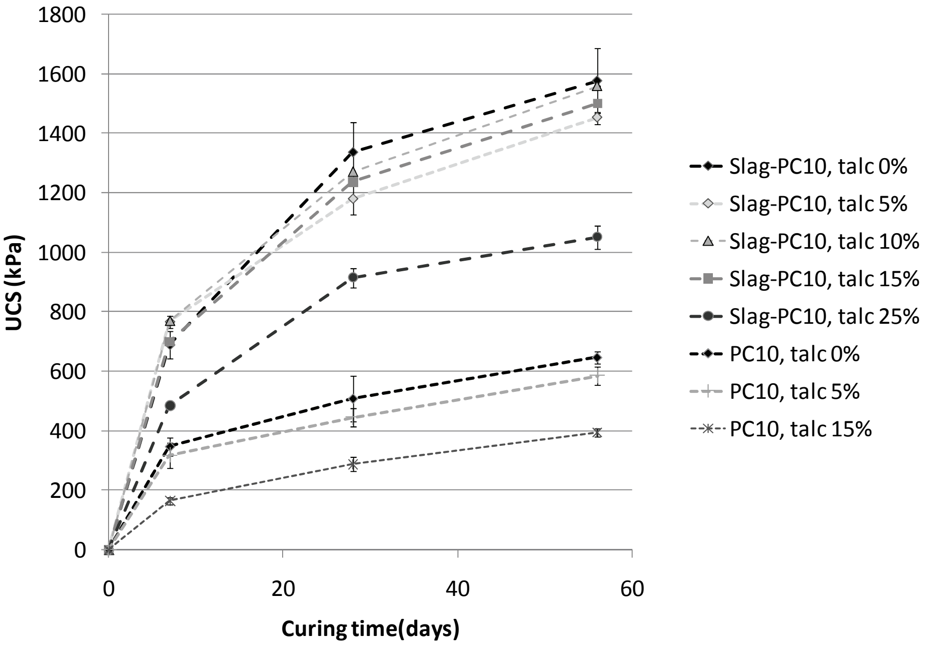

Figure 6 **Mean UCS values versus the curing time for simulated backfill samples made of various talc contents (0, 5, 10, 15 and 25%) and two binder types: PC type 10/50 50:50 and PC type 10/slag 20:80 blend**

3.8 Role of the temperature

Increase of temperature within CPB materials can have various origins. In addition to the geothermal effect (especially in the case of deep mines), heat generation can be due to the exothermic effect of some chemical reaction that happen within paste backfill during its curing. Binder hydration represents one of these reactions and sulfide oxidation is the second one. Finally the abrasion of the paste within the pipelines during its transportation can also lead to temperature increase. Figure 7 shows the evolution of the strength (UCS) in the course of curing time for backfill samples cured at two different temperatures (20 and 50°C) and made of two binder types at a proportion of 5%: PC type 10/50 50:50 (GU-HS) and PC type 10/slag 20:80 blend (GU-Slag). It can be observed here also that the slag based binder provide more strength for the CPB sample than the Portland cement based binder. Also, the temperature clearly influences positively the strength acquisition. An increase of temperature from 20 to 50°C lead to a gap of strength, this later is more pronounced in the case of Portland cement based CPBs than slag based CPB. The main explanation is the effect of temperature on the saturation indices of the cementitious phase which precipitate in the course of time and are responsible of CPB hardening.

In some extreme and still unknown conditions, the accumulation of the heat described above within CPBs lead to a self-combustion happening. These phenomena are often accompanied by some gases release (SO_2) and local fires. The cases where self-combustion have been reported, all are characterised by a high tailing reactivity. Oxygen which diffuses weakly within water saturated paste backfill can reach sulfides by the help of communication with the surrounding oxygen saturated medium.

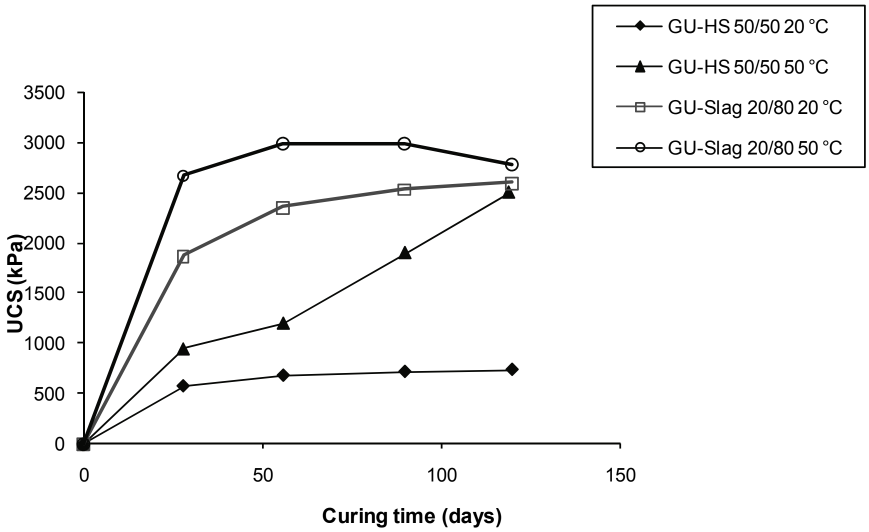

Figure 7 **Mean UCS values versus the curing time for backfill samples cured at two different temperatures (20 and 50°C) and made of two binder types: PC type 10/50 50:50 and PC type 10/slag 20:80 blend**

3.9 Economical impacts of using various binding agents within backfills

Since the binder represent the most important cost in any paste backfilling operation (up to 80%, Gauthier, 2004) and knowing its capital role in reaching the mine design requirements in terms of ground support, any CBP economical optimisation have to target an adequate use of the binder. It consists of choosing the best binder that fit with the mine design requirements at the lowest price. The best binder implies reaching the desired properties in terms of mechanical properties without forgetting its transportability and placement requirements. Table 5 shows the prices (not actualised) of the most used binder by the mine industry (indicative of Abitibian mines). However, in addition to the market laws, cement prices have a very large freight component; therefore, depending on how close the customer (mine localisation) is to the cement plant (and/or the cement additive source) this will dictate a large part of the cost. So prices are variable. Also, cement pricing is not just about the product but includes technical, logistical and other services which can be included in the price (O'Hearn, 2009, written comm.). The energy cost has also a great effect on the cement prices because involved during cement manufacture (high energy consuming) and transport.

Table 5 **Indicative prices of the most popular cement used by the mine industry**

Binder Types	**$ CAD (2003)***
Portland cement Type 10, OPC or GU	155 $
Portland cement Type 50 HS	163 $
Fly ashes Type C	105 $
Fly ashes Type F	95 $
Blast furnace slag	150 $

* Indicative of Abitibian mines

Mine paste backfill plants are doted in general with two silos for binder storage. This provides some time certain flexibility in sourcing as well as by the possibility of changing the binder recipe as function as the type of chamber to be backfilled.

3.10 Dosage methods (for mixing conception issues): precautions

Typical binder content $B_{M\%}$ (= 100 × $M_{binder}/M_{dry\_tailings}$) varies from 3 to 7 wt% (by dry mass of tailings). From the known solids concentration by mass of paste backfill ($C_{M\%}$), the corresponding anhydrous binder concentration ($C_{\%binder}$) and tailings grains concentration ($C_{\%tailings}$) can be calculated using the following formulas (Belem and Benzaazoua, 2007):

$$C_{\%binder} = C_{M\%}\left(\frac{B_{M\%}}{100 + B_{M\%}}\right) \tag{1}$$

and

$$C_{\%tailings} = \left(\frac{C_{M\%}}{100 + B_{M\%}}\right) \times 100 = C_{M\%} - C_{\%binder} \tag{2}$$

where $C_{M\%}$ = solids concentration by mass of PB (%); $B_{M\%}$ = binder content by dry mass of tailings (wt%).

Since the binder proportion in the mix $B_{M\%}$ is calculated according to the tailings dry mass, any small variation in the tailings grain density $\rho_{s\text{-}t}$ will involve an excess or lack of profit of the binder proportioning. This variation of $\rho_{s\text{-}t}$ can be due to the mineralogical changes of the ore body during the stope extraction. In polymetallic hard-rock mines, the sulfide content is responsible of the main specific gravity variation. Thus, for a given constant binder type and content, an increase in $\rho_{s\text{-}t}$ will involve an increase in the volumetric binder content $B_{V\%}$, and a reduction in $\rho_{s\text{-}t}$ will involve a reduction in $B_{V\%}$ which can have economical (lost of binder) or under dosage (lack of strength) impacts. More details on this topic can be found in Belem and Benzaazoua (2007).

In addition to the effect of the specific gravity variation, other factors can play important role. The first is related to the precision of the weighting system that must be calibrated frequently and the second concerns the binder dispersion and homogeneity during addition which is related to the kneading quality.

4 Alternative binder and cement additive

The use of industrial by-products that are characterised by some hydraulic properties (cementitious potential) is very promising for mine backfill operations. In addition to economic interests, recycling of such industrial wastes leads to important environmental benefits. The main advantage is a contribution to the reduction of carbon dioxide gas emissions related to the production of Portland cements. These by-products includes in addition to those already used (blast furnace slag form steel industries and fly ashes from coal combustion plants) slag from base metal smelters, post consuming glass, cogeneration ashes, etc. This perspective appears as very promising for cement and mine industries.

4.1 Variety of the industrial by-products having hydraulic potential

There is a wide variety of industrial by products that can be used as cement substitute within paste backfill. Table 6 summarises the most important by-products presenting pozzolanic properties with some reference to example and citations. Certain pozzolanic by-products like red mud can be used in association with other materials (particularly blast furnace slags, coal fly ashes) to produce binder without Portland cement addition (Pan et al., 2009; Liu et al., 2009).

Table 6 List of some industrial pozzolanic by-products

By-Product	Origin	Examples Of Local Production	Use In Mine Backfill
Slags from metallurgy	Ore concentrate smelting	Horne smelter (Xstrata Copper)	Benzaazoua, 2004a; Lun, 1986; Grice, 1998
Post-consuming glass	Unrecyclable used glass	Sanitri Inc.	Archibald et al., 1998
Fly ashes from biomass	Combustion agricol and forestry biomass	Senneterre (Boralex) Kirkland Lake (Northland power/Wood ash Inc)	Benzaazoua et al. (unpublished report)
CAlSiFrit	Treatment (NovaFrit) of Al spent potlining	Ciment St Laurent, 50,000 t/an.	Benzaazoua et al. (unpublished report)
Calcinated paper sludges	Calcination of paper sludges (deinking)	Paper paste and paper plants Amos	_
Ashes from waste incinerators	Incineration of domestic wastes	Only 3 incinerators in Quebec	Benzaazoua et al. (unpublished report)
Red muds	Al production (Bayer process)	Estimated at 2.5 Mt/year in Canada	Benzaazoua et al., 2006

The chemistry of these by-products is reported in Figure 8. This later shows also the composition of the common manufactured binders and some additives that can be used for the activation of some the pozzolanic products.

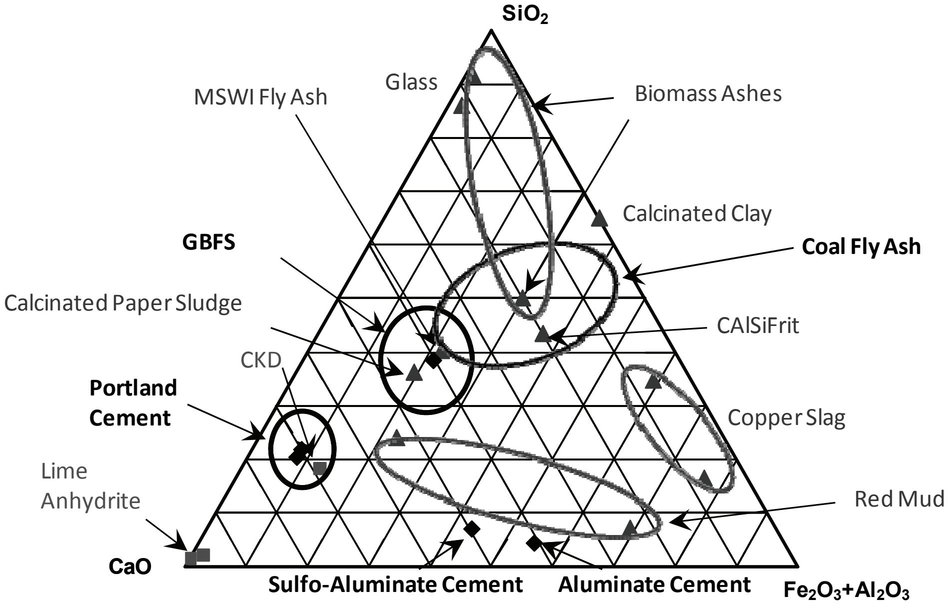

Figure 8 Plots of the composition of many by-products as well as conventional cements in the ternary diagram CaO-SiO2-Al2O3+Fe2O3

It can be seen that many of the industrial by products have potential for use as substitute of the manufactured cements based on their chemistry. However, the chemistry is not the only parameter that conditions the cementitious potential of such products, in fact the mineralogy and especially the crystallisation conditions (during the cool-down) are of utmost importance. More formed phases are amorphous (fast quenching using water for example) more they should have cementitious potential.

4.2 Mechanical strength acquisition in alternative binder based CPBs

Optimisation laboratory tests show that performing alternative binders can be obtained by substituting up to 50 wt% of GBFS and GU by pozzolanic and activating by-products. The curves shown in Figure 9 represent the evolution of the strength (UCS) in the course of time for paste backfill samples made of various alternative binders at 4.5% dosage and a sulfide rich tailings.

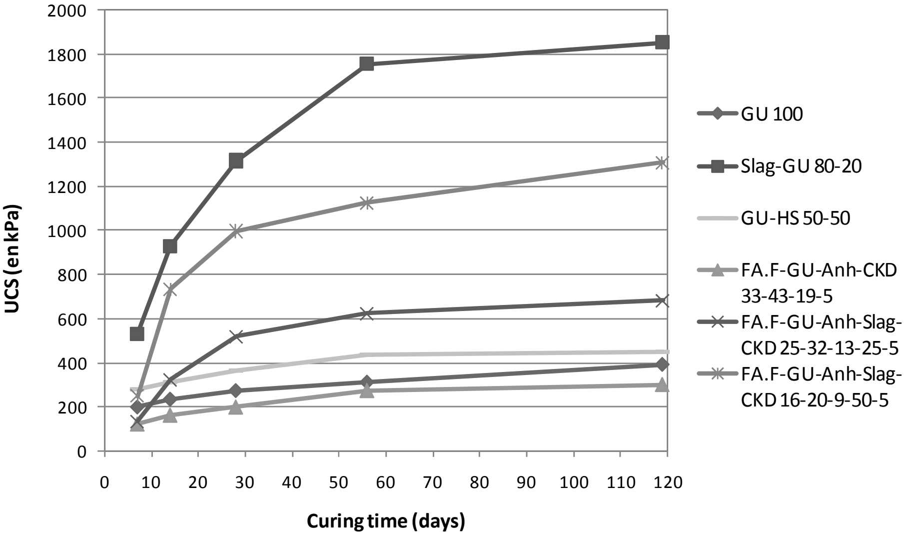

Figure 9 Evolution of the strength (UCS) in the course of time for paste backfill samples made of various alternative binders

If it is clear that the blast furnace slag confer the best mechanical behaviour, other recipes containing up to 30% cement substitute show also acceptable strengths and many of them well perform in comparison of only Portland cement based binder.

When very high strength (UCS28 d > 800 kPa) are required, the GBFS amount have to be increased, so the possible substitution rate is limited to 25 to 30 wt%. Anhydrite and CKD, alone, are unable to activate pozzolanic by-products hydration. Nevertheless, in blend with Portland cement, they permit to accelerate the strength development. The maximal CKD amount allowed is around 5 wt% of the binder and GU-Anh 70–30 amount gives the best results. The anhydrite content could, probably be adjusted depending on the sulfates content of mixing and tailings interstitial waters.

4.3 Perspectives of the use of alternative binders or cement additives within CPBs

In some cases, it's too difficult for mine operators in some localities to source their adequate binder due to the geographic sourcing of cement manufactures. Thus, many industrial by-products can be used as supplementary cementitious materials in mine cemented paste backfill for their pozzolanic properties or as hydration activators. A total of eight pozzolanic by-products, including post-consumer glass, copper slag, wood ashes, CAlSiFrit and coal fly ashes, and two activating by-products (CKD and fluorgypsum) have been demonstrated sufficiently reactive to develop interesting strength. Therefore, the binder recipe used by a given mine can be optimised according to the locally available by-products: metallurgical slag when closed to a smelter, wood ash if near a power plant.

All studies realised up to date show the high performances of GBFS due to their chemical and mineralogical compositions. Further works are required to investigate the possibility of creating alternative binders with other industrial by-products. For ashes and metallurgical slag, their water quenching would confer them a more amorphous structure. The chemical composition could also be adjusted by mixing various by-products: WG as SiO2 source, waste lime as CaO source, red mud could be used as aluminium source, etc. Finally, additional treatment or even addition of these industrial by-products during the cement manufacture can favour their use as cement substitutes.

5 Short and long-term behaviours of CPB

5.1 Normal behaviour of CPB

In normal conditions, cemented paste backfill show a more or less increase in terms of their mechanical properties. This behaviour is characterised generally by a fast strength gain during the first month of curing then reach a plateau which is characterised by little increase of the mechanical properties. This behaviour is influenced by many factors related to the three components (tailings, water and binder) as well as the conditions of CPB placement (drainage, consolidation, temperature, etc.). In some case, one can observe a certain hardening inhibition during the first days of curing which represent a problem for the mine operators (high pressure on the barricades, delay of the mining sequences, etc.)

Benzaazoua et al. (2002) investigated six binder types and six mixing water chemistries with four different sulphide tailings from three Canadian hard rock mines to produce various paste backfill mixtures. The resulting paste backfill curing time-dependent compressive strengths were investigated with uniaxial compression testing. The results of this study clearly demonstrate the inefficiency of choosing paste backfill mixtures without testing first the tailings and mixing water characteristics. The binder chemistry combined with the mixing water chemistry affects the formation of primary and secondary hydrates during paste backfill strengthening. The cohesion of the paste backfill matrix is directly dependent on the nature of the precipitated hydrates. This study particularity highlighted the complexity of paste backfill materials for which the compressive strength acquision depends on three main components (tailings, binder and mixing water characteristics). There is no typical recipe for all paste backfill mixtures. Each type of tailings and each type of mixing water require laboratory optimisation for choice of binder.

5.2 Case of lost of strength within CPB

Several investigations showed that chemical weathering can seriously affect the long-term strength of backfill. This alteration is not limited to a surface oxidation effect but can act throughout the whole backfill mass. Benzaazoua et al. (1999) analysed core samples taken from a backfilled underground mine stope. They observe the presence of a fracture network accompanied by oxidation phenomena (Figure 10).

Chemical and mineralogical analysis showed that the presence of sulfides in the tailings caused dissolution (congruent or incongruent) of the silico-calcic phases of the cement hydrates and promoted the formation of swelling phases (gypsum mainly) which in turn induced a deterioration of the cemented backfill. Figure 11 illustrates this phenomenon. In a first time the precipitation of sulfated hydrates fill the CBP porosity and contribute consequently to its hardening. When these expansive phases (gypsum, ettringite and mono-sulfo-aluminates) cannot grow freely, they generate high pressure that causes in turn the mass cracking. This phenomenon, called sulfate attack, is well known in civil engineering material that contains pyrite as impurities.

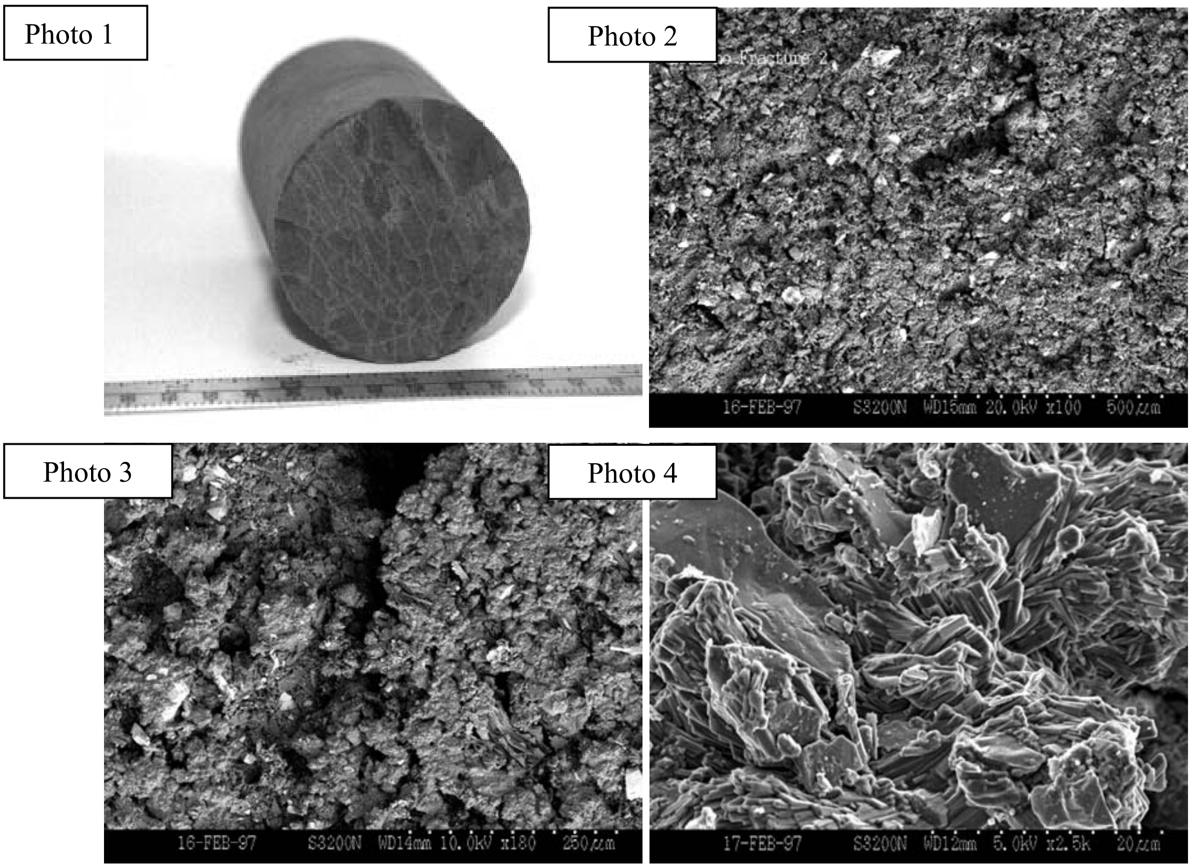

Figure 10 Photographs representing a macroscopic view (1) of an in situ backfill core sample, SEM backscattered electron images: General (2) and detailed (3) aspect and SEM secondary electron image: Bars of gypsum (4) encapsulating grains of the tailings (Benzaazoua et al., 1999)

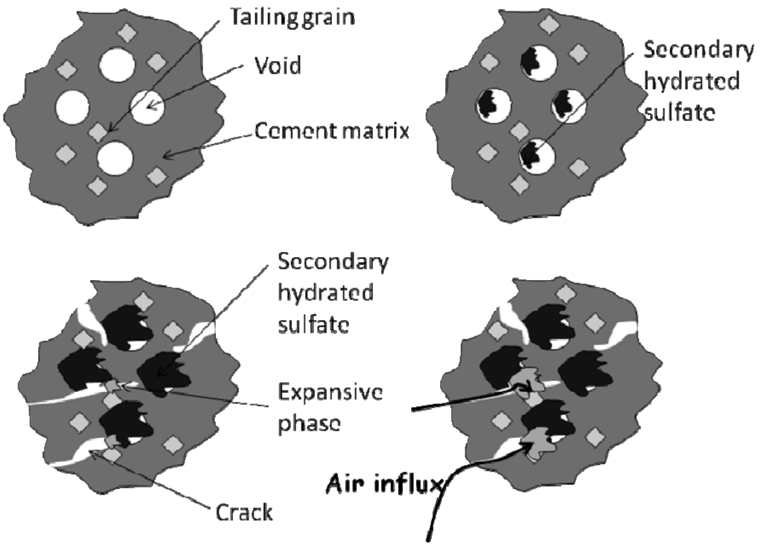

Figure 11 Schema illustrating the expansive phenomena due to sulfate attack within paste backfill

This phenomenon can be clearly observed in Figure 12 which show the evolution of the strength (Mean UCS values from triplicates) in the course of curing time for backfill samples made of a very reactive tailings (around 80% pyrite) and six different binder types at a proportion of 5%: PC type 50, PC type 10/50 50:50, PC type 10/ Fly ash 50:50, PC type 50/ Fly ash 50:50, PC type 10/ High silica fume 50:50 and PC type

10/slag 20:80 blend. High strength due probably to sulfate precipitation during the first month of curing is followed by a loss of strength whatever the binder used. Blast furnace slag showed the best behaviour at short and long-term curing.

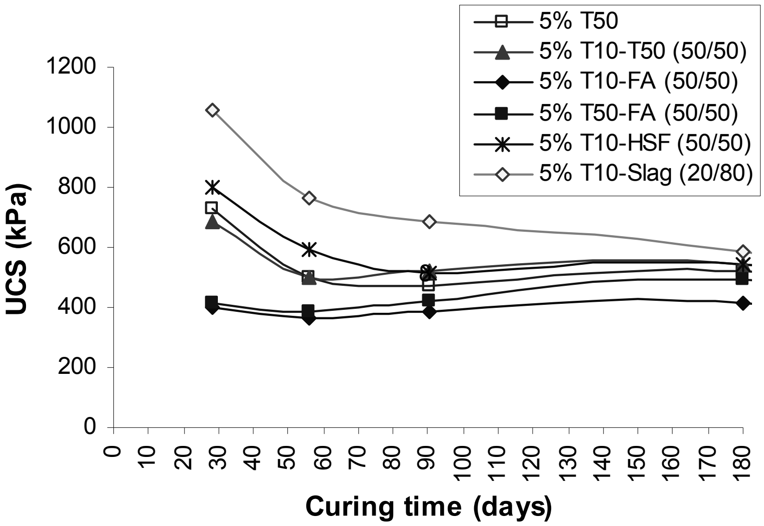

Figure 12 Mean UCS values versus the curing time for backfill samples made of a very recative tailings and six different binder types at a proportion of 5%: PC type 50, PC type 10/50 50:50, PC type 10/ Fly ash 50:50, PC type 50/ Fly ash 50:50, PC type 10/ High silica fume 50:50 and PC type 10/slag 20:80 blend (in Benzaazoua et al., 2004a)

5.3 Environmental behaviour of CPB

Despite that the backfill practices in the mining operations have grown spectacularly during the last decades around the world, there are possible environmental impacts (positive and negative) of this kind of material and such impacts remain not well known. When focusing on the interactions of placed mine backfills with their surrounding environment, many key factors must be considered:

- drainage of water
- sulfide reactivity, mainly their oxidation
- relationship between strength acquisition and its los (sulfate attack for example
- the mobility of certain contaminant : fixation and or stabilisation
- interaction of backfills and underground water: case of flooded mines.

Many parameters play important role as the hydro-geological properties, the binder type and proportion, the sulfide content and their reactivity, the upstream process and finally the mechanical properties. In the case of paste backfill, and based on the few exiting studies, one can notice that these materials are less permeable and remain consequently and for long time full saturated of water (Godbout et al., 2004; Ouellet et al., 2006). It is also common knowledge that sulfide mine tailings generate acid in the presence of water and oxygen that may lead to possible chemical weathering. Sulfide mineral are protected from any reactivity in these condition. The binder content brings in addition to the cohesion, a neutralising potential boost as well as fixation and stabilisation properties for possible mobile contaminants as zinc, nickel, arsenic (Benzaazoua et al., 2004b). A study conducted by Benzaazoua et al. (2006) demonstrated the feasibility of including treatment sludge within CPBs. So in this basis, CPB can be considered as a solidification/stabilisation method for mine wastes.

6 Conclusions

To conclude, it is important to underline some of the most sensitive aspects discussed along in this paper. Binder is required for the preparation of cemented paste backfill materials and its proportion within is linearly correlated with the strength acquisition rate. However, the mechanical behaviour of CPB is very dependant to the chemistry of the mixing water. Sulfates concentration is the most important parameter and it reacts in different ways depending on their concentration (inhibition effect, strength participating effect, sulfate attack) and the type of binders; Portland cement type 50 are more resistant than OPC and blast furnace slag based binders perform very well even at high sulfate concentration. Other soluble species may also affect the hardening processes within CPB, for example the Ca, Zn, and Fe contents. The tailings mineralogy also plays an important role and affects indirectly the strength acquisition. The following are some ways of tailings mineralogy and particle size effects:

- presence of sulfide with capacity to lower the pH and release sulfates (oxidation) that has a deleterious effect the mechanical performance of the CPB
- presence of clay mineral that induce more water for the mixing and slowness of the hardening processes by limiting the precipitation of cementitious phase
- fineness which condition the consolidation and drainage rates within placed CPB (more tailings is fine more water retention is high), and consequently affect the hardening processes, here also by influencing the cementitious precipitate saturation levels.

So each tailings mineralogy and each ore treatment process (dictating the quality of the process water and the particle size distribution) that generate this tailings, require binder recipe optimisation. This later allows through experimental testing in laboratory (even if usually underestimate the actual field behaviour of CPB) to appreciate the aspects discussed above. The characterisation and optimisation approaches should avoid bad binder formulation technical problems with the ground support requirements as well as lots of money.

The CPB preparation manner is also very important. A good filtration allows decreasing the chemical loading of the mixing water if fresh water is used thereafter. An optimal addition of water will help CBP in their strength acquisition. Finally, for environmental and economical point of views, the use of alternative binders seems to be very promising and must take more attention from the cement industry, the mine operators and research scientist.

References

Archibald, J.F., Chew, J.L. and Lausch, P. (1998) Use of ground waste glass and Portland cement mixtures for improving slurry and paste backfill support performance, available online at: http://mine.queensu.ca/people/faculty/Archibald/GlassfillCIM98.pdf

Belem, T. and Benzaazoua, M. (2007) Underground mine paste backfill technology: applications and design methods, Geotechnical and Geological Engineering, Vol. 26-2, pp. 147–174.

Benzaazoua, M., Fiset, J-F., Bussière, B., Villeneuve, M. and Plante, B. (2006) Sludge recycling within cemented paste backfill: Study of the mechanical and leachability properties, Minerals Engineering, Vol. 19-5, pp. 420–432.

Benzaazoua, M., Fall, M. and Belem, T. (2004a) A contribution to understanding the hardening process of cemented pastefill, Minerals Engineering, Vol. 17-2, pp. 141–152.

Benzaazoua, M., Marion, P., Picquet, I. and Bussière, B. (2004b) The use of pastefill as a solidification and stabilization process for the control of acid mine drainage, Minerals Engineering, Vol. 17-2, pp. 233–243.

Benzaazoua, M., Belem, T. and Bussière, B. (2002) Chemical factors that influence on the performance of mine sulphidic paste backfill, Cement and Concrete Research, Vol. 32-7, pp. 1133–1144.

Benzaazoua, M., Ouellet, J., Servant, S., Newman, P. and Verburg, R. (1999) Cementitious backfill with high sulfur content: physical, chemical and mineralogical characterization, Cement and Concrete Research, Vol. 29, pp. 719–725.

Gauthier, P. (2004) Valorisation des liants et des rejets industriels dans les remblais miniers, Mémoire de DESS, Université du Québec en Abitbi-Témiscamingue.

Godbout, J., Bussière, B., Belem, T. and Benzaazoua, M. (2004) Évolution des propriétés de rétention d'eau des remblais miniers cimentés en pâte durant le curage, The 57th Annual Canadian Geotechnical Conference and 5th joint IAH-CNC-CGS Conference "Geo-engineering for society and its environment", Québec, Canada, October 24–26, pp. 15–22.

Grice, T. (1998) Underground mining with backfill, In Proceedings 2nd annual summit on Mine Tailings Disposal Systems, Brisbane, 14 p.

Liu, W., Yang, J. and Xiao, B. (2009) Application of Bayer red mud for iron recovery and building material production from alumosilicate residues, Journal Hazard. Mater., Vol. 161(1), pp. 474–478.

Lun, P.T.W. (1986) Soil reinforcing technique in mine backfilling, Geotechnical and Geological Engineering, Vol. 4, No. 1, pp. 47–66.

Ouellet, S., Bussière, B., Mbonimpa, M., Benzaazoua, M. and Aubertin, M. (2006) In situ reactivity of an underground mine sulfidic cemented paste backfill Minerals Engineering, Vol. 19-5, pp. 407–419.

Pan, Z., Zhang, Y. and Xu, Z. (2009) Strength development and microstructure of hardened cement paste blended with red mud, Journal of Wuhan University of Technology, Mater. Sci. Ed., Vol. 24-1, pp. 161–165.

Taylor, H.F. (1990) Cement Chemistry, Academic Press, Harcourt Brace Jovanovich Publishers, London, 475 p.

Yilmaz, E., Benzaazoua, M., Belem, T. and Bussière, B. (2009) Effect of curing under pressure on compressive strength development of cemented paste backfill, Minerals Engineering, Vol. 22(9-10), pp. 772–785.