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Chemical factors that influence the performance of mine sulphidic paste backfill

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Abstract

Sulphide-rich tailings from four Canadian mines were sampled (Mines A1, A2, B and C) to prepare several different paste backfill mixtures. The sulphur grade within these tailings samples range from 5 to 32 wt.%. The binders used were Portland-cement-based binders, fly-ash-based binders and slag-based binders with proportions ranging from 3 to 6 wt.%. The study was carried out in two stages. Stage I allowed us to understand the effects of binder type, binder proportion and tailings properties on compressive strength development of paste backfill during the course of curing time. It was pointed out that for high sulphide tailings, neither the slag-based binders nor the fly-ash-based binders were effective, whereas the sulphate-resistant-based binder (mix of Type I [TI] and Type V [TV] Portland cements) gave good long-term strength. However, the slag-based binders gave the best strength for low and medium sulphide-bearing tailings for which the Portland- and the fly-ash-based mixtures have a relatively low strength. Stage II allowed us to study the early stage strength acquisition of the various mixtures. It was found that the chemical composition of the mixing water plays a role on the mechanical behavior of certain cemented backfills. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Paste backfill; Hydration products; Compressive strength; Sulfate; Waste management

1. Introduction

Mine backfill refers to waste materials, such as waste development rock, deslimed and whole mill tailings, quarried and crushed aggregate, and alluvial or an eolian sand, which is placed into underground mined voids for the purposes of either disposal and/or to perform some engineering function. The disposal of mine tailings underground reduces the environmental impact [1,2] and provides a material that can be used to improve both ground conditions and the economics of mining. The waste materials are often mixed with very lean cement or other pozzolanic binders to improve their strength properties. Among the three existing backfill types (hydraulic fill, rock fill, paste backfill), the use of paste backfill is becoming an increasingly important component of underground mining operations worldwide, and especially in Canada [3–9]. Paste backfill consists of total mill tailings (full size fraction of the tailings) thickened and/or filtered to around 80 wt.% to which binder and water are then added to achieve the desired rheological and strength characteristics (Fig. 1). By far the most common hydraulic binder added to backfill is ordinary Portland cement (TI). There has been continuous research around the world into alternative binders and the most common solution has been to use pozzolanic products such as fly ash (FA) and blast furnace slags (BFS). Typical binder proportion additions are 3% to 7% by weight into paste fill.

The mechanical and rheological properties of cemented paste backfill depend on physical, chemical and mineralogical properties of the mine tailings, binder types and their proportions [10–14,16,19–24]. It is also common knowledge that sulphide mine tailings generate acid in the presence of water and oxygen, which may lead to possible chemical weathering [25] and others. The presence of sulphide minerals within cemented composites as well as the soluble sulphates has a deleterious effect on the strength of paste backfill due to sulphate attack [26–29]. Other recent works [3,15,17,18,30,31] 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 sulphates and production of acid).

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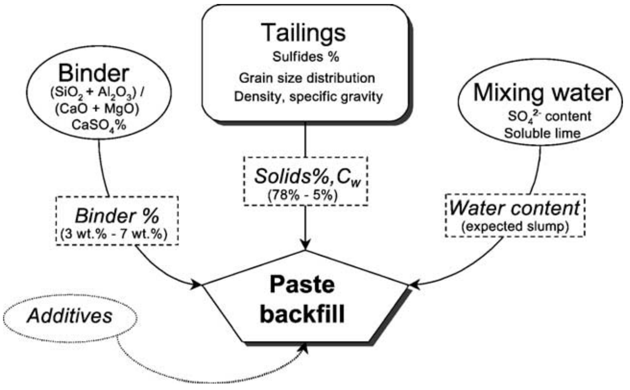

Fig. 1. Schematic diagram illustrating the different components of paste backfill.

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 possible harmful chemical reactions (such as hydration inhibition and sulphate attack) that can occur within a sulphide- and/or sulphate-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 stabilize underground stopes without being affected by the potential of long-term strength loss due to chemical weathering.

Fig. 1 shows the main components that can affect the quality of the paste backfill: the chemical composition of the binder and tailings, grain size distribution, density and percentage solids 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. Generally, mining operators neglect tailings and water chemistries when designing backfill process.

The purpose of this paper is to highlight the influence of some chemical factors of mill tailings, binders and mixing waters on the paste backfill strength acquisition. To reach this goal, mine tailings from four Canadian hard-rock mines were sampled (tailings samples A1, A2, B and C) for the preparation of different paste backfill mixtures using different binder types and binder proportions. The study was carried out in two phases: (i) Phase I investigated the effect of binder and tailings chemistry on the unconfined compressive strength (UCS) of paste backfill after curing periods of 14, 28, 56 and 91 days using tailings samples A1, B and C. (ii) Phase II of the study was about the effect of mixing-water chemistry on the paste backfill strength evolution after curing periods of 3, 7, 14 and 28 days using tailings sample A2 and 5 wt.% binder content.

2. Materials and methods

In order to better understand the effect of the chemical composition of mine tailings and mixing water on the mechanical strength of paste backfill, four Canadian hard-rock mine sulphide tailings (Mines A1, A2, B and C) were sampled along with typical mixing waters derived from mine process water of the different mines that differ by their sulphate content and their pH.

2.1. Mine tailings characteristics

The main chemical elements of the three tailings are listed in Table 1. Tailings A1 contain approximately 60% sulphides (essentially pyrite and a small amount of sphalerite); the remainder is a gangue composed of silicates and aluminosilicates. Tailings A2 come from the same mine but contain fewer sulphides. Tailings B contain about 30% sulphides (essentially pyrite and a small amount of pyrrhotite) and the gangue from these tailings is also composed of silicate and aluminosilicate. Finally, the tailings from mine site C contain lower sulphide grades (less than 10% pyrite) and the gangue is essentially silicates and barite ($BaSO_4$) minerals.

The grain size distributions of tailings A1, A2 and B (finer tailings) are closely similar and typical of tailings from hard-rock mines (Fig. 2). They differ from the tailings from mine site C where the grain size distribution is coarser (see Table 2). It is clear from Table 2 that there is a correlation between the proportion of sulphides in the tailings and their density, which is due to the specific gravity (G_s) of the pyrite, which is near 5, compared to the G_s of the gangue minerals, which has an average value of 2.7.

2.2. Mixing-water characteristics

The main chemical characteristics of the mixing waters that are derived from the different mine process waters are listed in Table 3. Mixing-water sample A1, which is from the Mine A1 process water is particularly sulphate and iron rich (24, 440 and 90 mg/l, respectively); water samples B and C have moderate sulphate content. On the basis of the German standard methods DIN 4030 [32] on the strength aggressiveness of sulphate on cement composites, the mixing-water samples B, C and A2 used in this study can be classified as strongly aggressive and as very strongly aggressive for water sample A1. Due to the addition of lime during ore mineral processing, all waters contained high levels of calcium ranging from 380 to 970 mg/l. Water sample A1, which is more acidic, has a pH of 5.8 while the water samples B and C have a near-neutral pH.

Table 1
Chemical composition of the four tailings by total dry weight (wt.%)

Tailings sample	S	Ca	Si	Al	Mg	Fe	Cu (ppm)	Zn (ppm)	Pyrite
A1	32.2	1.07	10.12	2.630	0.21	26.8	1870	45600	60.6
A2	24.4	0.99	15.7	4.870	0.35	20.6	0.24	2.1	42.4
B	15.9	1.44	15.3	4.065	2.695	20.7	1108	1795	29.8
C	5.2	1.17	26.29	5.640	0.57	5.13	30	149	9.75

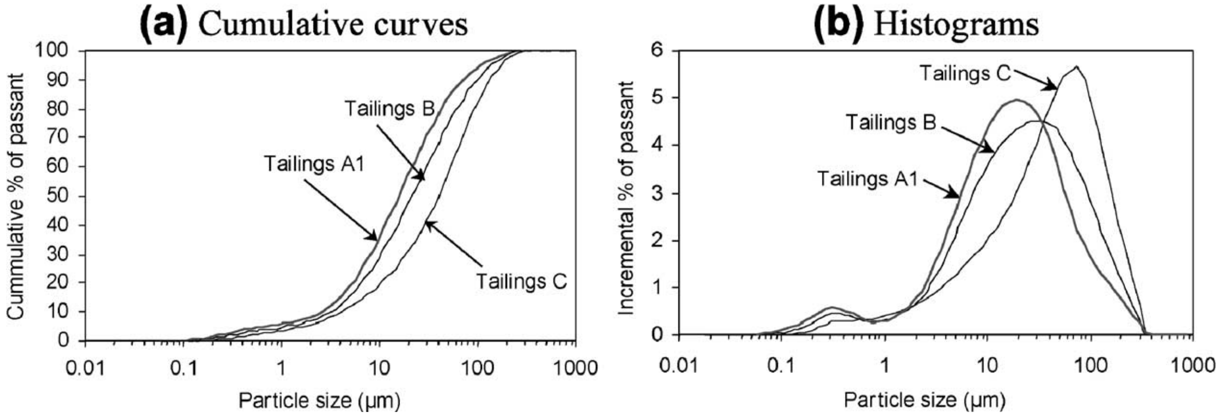

Fig. 2. Particle size distribution of the tailings studied. (a) Cumulative curves, (b) histograms.

2.3. Binder reagents

Ordinary or Type I (TI) and/or sulphate-resistant or Type V (TV) Portland cements are often used alone or with the addition of natural or artificial additives having specific hydraulic properties in cemented paste backfill. The additives are used to increase the durability and the strength of the mixture, and appreciably reduce the binder costs. In this study, TI and TV Portland cements, FA and BFS were chosen for the different binder types. Ordinary TI Portland cement was selected as the basic component of the different binder types. In Phase I of the study, the binder types used were the Portland-cement-based binder (binder type PC), the fly-ash-based binder (binder type FP), the slag-based binder (binder type SP) and slag-only binder (binder type Sg). In Phase II of the study, other slag-based binders (binder types SP-IIa and SP-IIb) and the binder types PC and FP were used (see Table 4). Fig. 3 is the ternary plot of the different cements and pozzolanic additives used in this study. It is well known that the more the binder trends toward the SiO_2 pole, the higher the durability of the cement-based composite. This is the case for the slag- and fly-ash-based binders (FP, SP, SP-IIa, SP-IIb, Sg). The Portland cements that have lower SiO_2/CaO ratios are more susceptible to aggressive aqueous media (e.g., binder type PC).

2.4. Paste backfill mixture preparation

During Phase I of the study, proportions of 3, 4.5 and 6 wt.% of the binder types PC, FP, SP and Sg (Table 4) were chosen for tailings samples A1, B and C to make the various mixtures of paste backfill using the corresponding mine process waters A1, B, C, respectively. Water was added to set the resulting paste backfill solids percentage to 78% for tailings samples A1 and C and 74% for tailings sample C. The final slump, which corresponds to the height between the top of an initial state of the paste (molded into a conic cylinder) and its final state (after removing the cone), was measured using the standardized ASTM C 143-90 test [33]. The slump value was similar for the three paste backfill mixture types and was approximately 7 in.

For Phase II of the study, a proportion of 5 wt.% binder was used to produce various mixtures using three different mixing-water samples (Mine A2 process water, lake water and municipal water) and tailings sample A2 with a fixed slump of 6.25 in. (see Table 4).

Table 2
Physical properties of the four tailings

	Tailings samples			
Parameter	A1	A2	B	C
D_{10} (μm)	2.6	3.0	3.22	4.1
D_{50} (μm)	17.0	16.0	21.6	40.2
D_{90} (μm)	100.4	71.3	98.8	133.9
Specific gravity, G_s	3.8	3.5	3.3	2.9

2.5. Test samples preparation

For the two phases of the study, the paste backfill mixtures were poured into plastic cylinders with a diameter of 10 cm and a height of 20 cm. After pouring the different mixtures into the cylinders, they were sealed and cured in a humidity chamber maintained at approximately 70% humidity (this is similar to underground mine conditions) for periods of 14, 28, 56 and 91 days (Phase I) and 3, 7, 14 and 28 days (Phase II). The resulting paste backfill specimens were then tested by uniaxial compression tests to evaluate their compressive strength.

2.6. Uniaxial compression tests

A total of 396 backfill samples (Phase I) and 192 backfill samples (Phase II) were subjected to uniaxial compression tests using a computer-controlled mechanical press (MTS 10/GL) having 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 rectified to get plane surfaces before running the tests. The uniaxial compressive strength (UCS)

Table 3
Chemical characteristics of the mixing waters

	Phase I of the study			Phase II of the study		
	Mine A1, process water	Mine B, process water	Mine C, process water	Mine A2, process water (PW)	Lake water (LW)	Municipal water (MW)
pH	5.8	6.65	7.37	6.08	7.16	7.22
Eh (ENH)	86.7	349	459.5	400.4	547.5	544.7
Conductivity	8550	2000	3180	8730	1590	2200
SO_4, mg/l	24444	1303	1944	1650.6	3.0	53.9
Ca, mg/l	842	387	518	969	21.7	35.9
Cu, mg/l	nd	nd	nd	0.281	0	0.462
Fe, mg/l	89.8	0.16	2.96	2.24	0.177	0
Zn, mg/l	nd	nd	nd	59.2	0.988	0.362
Al, mg/l	0.09	0.17	1.85	0.23	0.371	0.137
Na, mg/l	764	40.2	191	1080	4.54	4.95
Si, mg/l	4.57	1.25	9.26	12.7	4.38	0.876
Mg, mg/l	21.3	12.1	15.5	62.8	4.15	2.72

nd: not determined.

Table 4
Paste backfill mixtures characteristics

Binder type	Binder mix	Binder (%)	TI (%)	TV (%)	FA (%)	Slag (% BFS)	W/c	Part of the study	Tailings sample
PC	TI:TV	3	1.5	1.5	0	0	12	Phase I	A1, B, C
PC	TI:TV	4.5	2.25	2.25	0	0	8	Phase I	A1, B, C
PC	TI:TV	5	2.5	2.5	0	0	7	Phase II	A2
PC	TI:TV	6	3	3	0	0	6	Phase I	A1, B, C
FP	TI:FA	3	1.5	0	1.5	0	12	Phase I	A1, B, C
FP	TI:FA	4.5	2.25	0	2.25	0	8	Phase I	A1, B, C
FP	TI:FA	5	2.5	0	2.5	0	7	Phase II	A2
FP	TI:FA	6	3	0	3	0	6	Phase I	A1, B, C
SP	TI:BFS	3	0.6	0	0	2.4	12	Phase I	A1, B, C
SP	TI:BFS	4.5	0.9	0	0	3.6	8	Phase I	A1, B, C
SP	TI:BFS	6	1.2	0	0	4.8	6	Phase I	A1, B, C
SP-IIa	TI:BFS	5	1.5	0	0	3.5	7	Phase II	A2
SP-IIb	TV:BFS	5	0	1.5	0	3.5	7	Phase II	A2
Sg	BFS	3	0	0	0	3	12	Phase I	B, C
Sg	BFS	4.5	0	0	0	4.5	8	Phase I	B, C
Sg	BFS	6	0	0	0	6	6	Phase I	B, C

corresponds to the maximum stress value observed during the compression test.

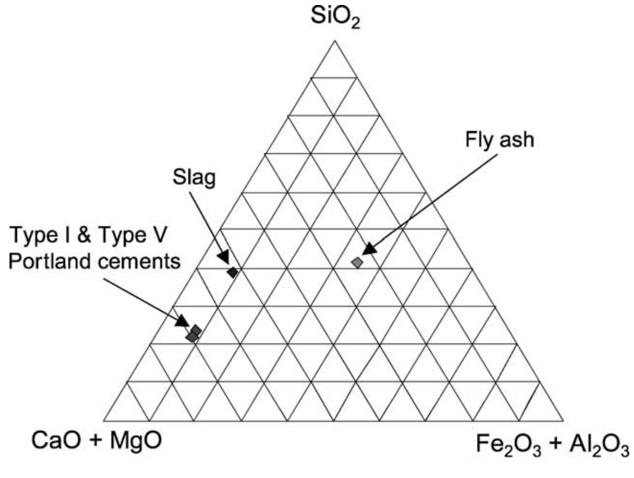

Fig. 3. Ternary plot of TI and TV Portland cements and pozzolans (slag and FA).

2.7. Scanning electron microscope investigations and chemical analyses

A Hitachi® 3500-N scanning electron microscope (SEM) was used to characterize the microstructure and texture of the various backfill samples. The backscattered electron (BSE) imaging mode was used because it produces images with the chemical contrast superimposed upon the relief contrast. All chemical analyses were done using an ICP ES spectrometer for all elements except for total sulphur and sulphates, which were determined with a Leco oven. The solid samples were digested entirely using aqua regia and hydrofluoric acids.

3. Results

3.1. Results of Phase I of the study

Figs. 4 and 5 show the effect of the sulphur grade of the tailings on the compressive strength of the different backfill

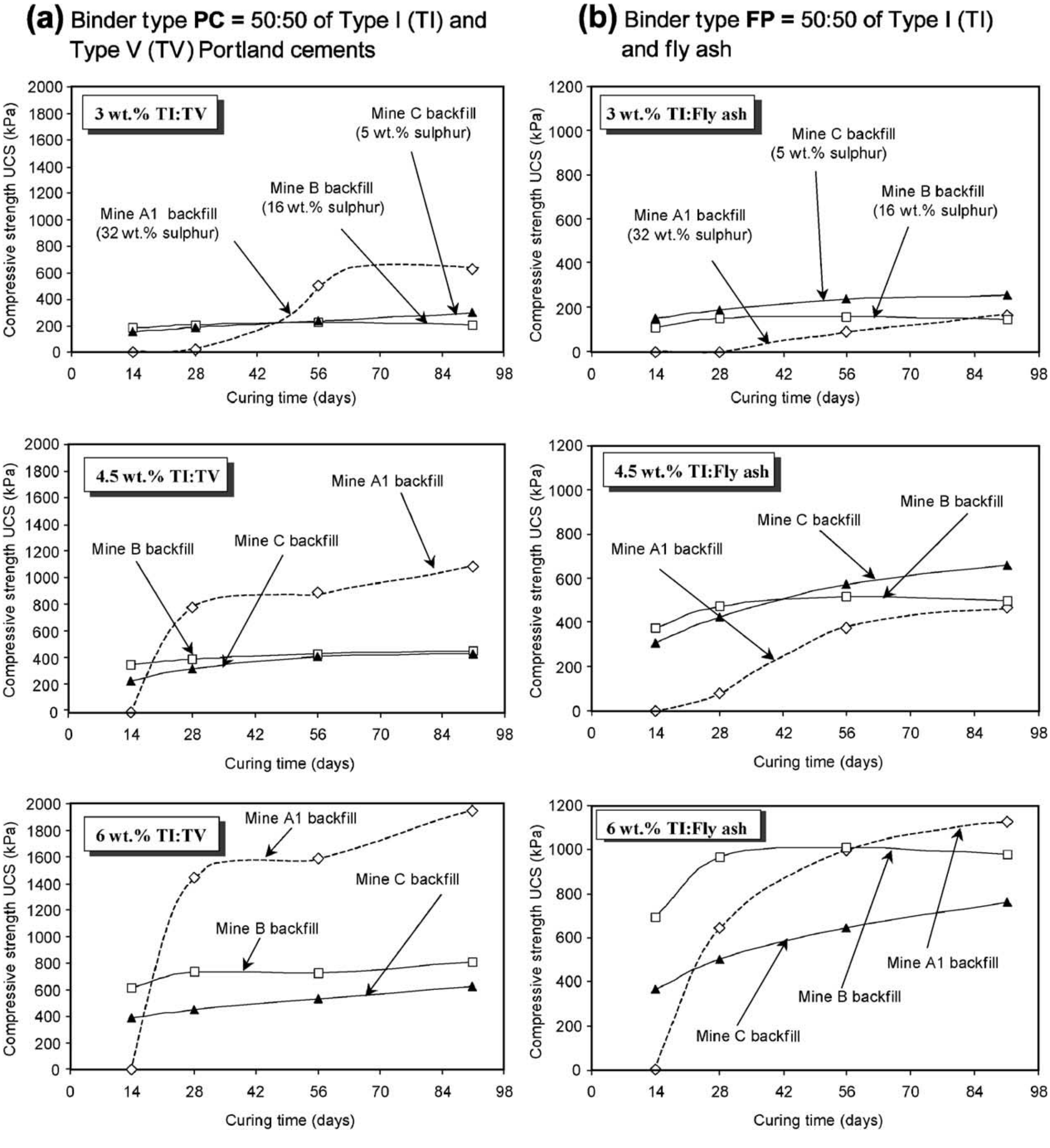

Fig. 4. Compressive strength of the paste backfill prepared with binder types (a) PC and (b) FP.

samples. These figures also show the evolution of the UCS as a function of curing time for the mines A1, B and C paste backfill samples. Each UCS value represents an average value obtained from three uniaxial compressive tests; the standard deviation of these three tests was usually between 10 and 50 kPa. The UCS evolution is shown in Fig. 4 for the binder types PC and FP and in Fig. 5 for the binder types SP and slag only (Sg). These figures clearly show the difference in the mode of strength acquisition of the paste backfill mixtures (binders hydration mode). This means that the four binder types used (PC, FP, SP, Sg) do not solidify the tailings samples A1, B and C in the same manner. For a given binder type, these differences concern both the magnitude of UCS and the effect of binder proportion.

Fig. 4a shows that when using the binder type PC (mix of TI and TV Portland cements), the strength acquisition of the paste backfill sample A1 is better than that of the backfill samples B and C after 28 days of curing. This is true regardless of the binder proportion. However, the maximum value of UCS obtained with the three tailings samples is always proportional to the binder proportion. The binder type PC solidifies the backfill samples B and C in the same

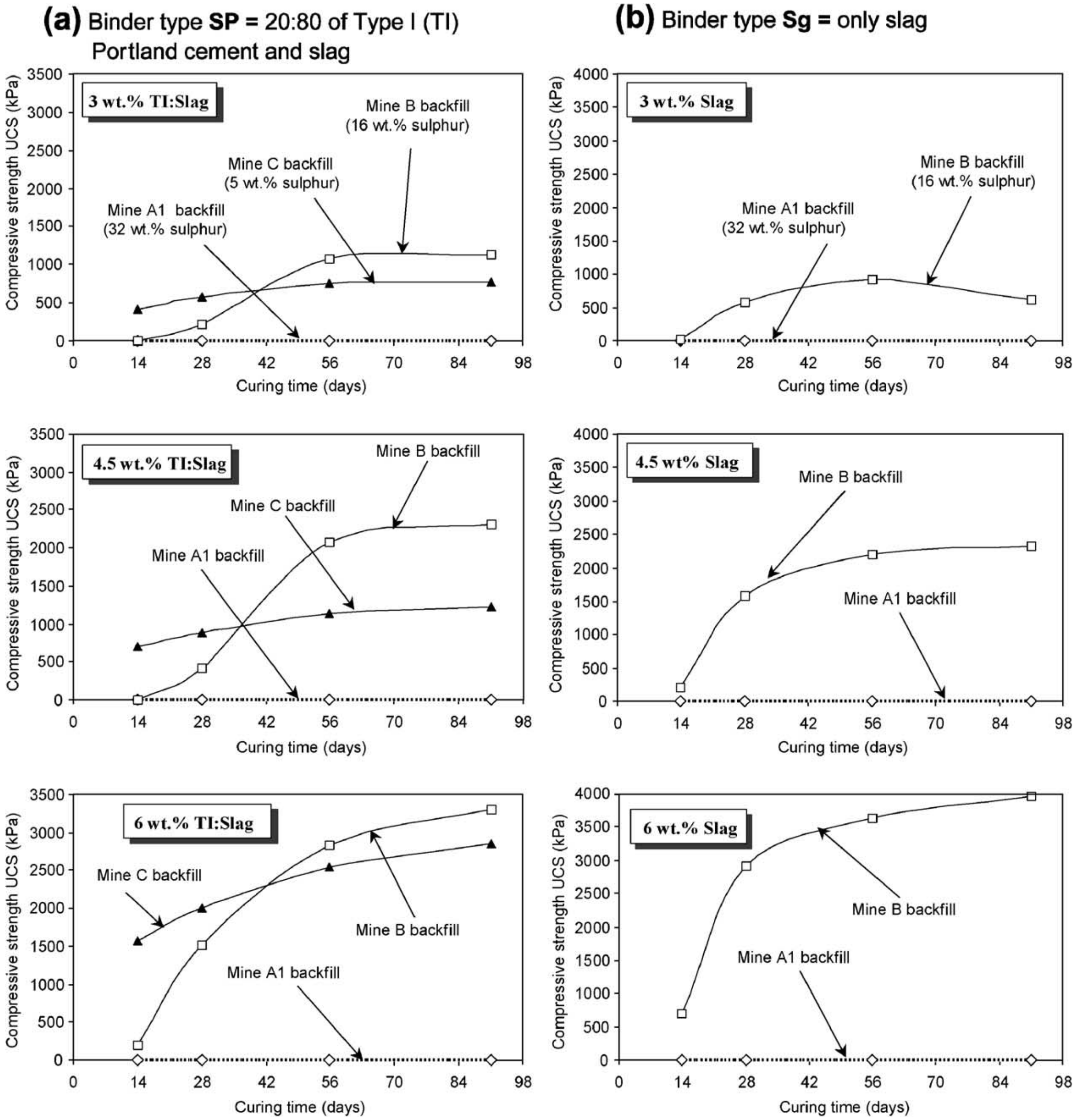

Fig. 5. Compressive strength of the paste backfill prepared with binder types (a) SP and (b) Sg.

manner and gives relatively low strength that increases slightly with curing time unlike backfill sample A1.

Fig. 4b shows that when using the binder type FP (mix of TI Portland cement and FA) within the same tailings samples A1, B and C, the strength acquisition of the backfill samples differs from that of the binder type PC (cf. Fig. 4a). With 3 and 4.5 wt.% binder proportion the backfill sample A1 exhibits the lowest strength when compared to the backfill samples B and C. With 6 wt.% binder, the strength of the backfill sample B is always higher than that of the backfill sample B, but backfill sample A1 seems to have the highest strength after 91 days of curing time (long term strength).

Fig. 5 shows that of the slag-based binder types SP, SP-IIa, SP-IIb (mix of TI Portland cement and slag) and Sg, only binder type Sg gave a similar performance to that of backfill samples A1 and B. Hence, the backfill sample A1 does not exhibit any strength until 91 days of curing time, while the backfill sample B exhibits a good strength from 14 to 91 days curing age regardless of the binder proportion (see Fig. 5a and b). The strength of the backfill sample C obtained with the binder type SP is between those of the backfill samples A1 and B. With 6 wt.% binder the strength of the backfill sample B is slightly higher using the binder type Sg than that using the binder type SP.

3.2. Results of Phase II of the study

Fig. 6 shows the variation of compressive strength, UCS, with curing time for the mine A2 backfill samples using only 5 wt.% of the binder types PC, FP, SP-IIa and SP-IIb. The curves were obtained for the three types of mixing water used, namely lake water (LW), municipal water (MW) and mine A2 process water (PW). The overall trend of the curves shows the difference in the mode of hydration of the different binder types used. Fig. 6a shows that when using the binder type SP-IIa (mix of TI and slag) within the same tailings sample, A2, mixed with different water types, the strength acquisition is slow until after 14 days of curing time. Beyond this curing date and at 28 days of curing time the compressive strength (UCS) reaches a value of about 1.6 MPa with the sulphate-free waters (water types MW and LW) and only 1 MPa with the sulphate-rich water (water type PW). Fig. 6b clearly shows that when TI cement is replaced by TV cement to make the binder type SP-IIb, the compressive strength acquisition is also slow from 3 to 21 days of curing time. But in contrast to the binder type SP-IIa, the magnitude of UCS is much lower than that obtained by using the binder type SP-IIa: approximately 100 kPa with the sulphate-rich water (PW) and about 400 kPa with the water types MW and LW.

When using the binder type PC, Fig. 6c shows that the overall trends of the strength acquisition curves are quite different from those obtained with binder types SP-IIa and SP-IIb. Indeed, the compressive strength increases rapidly after only 3 days of curing time and seems to reach a plateau at approximately 1.6 MPa regardless of the chemistry of the mixing water (LW, MW, PW). Fig. 6d shows that when using the binder type FP, a similar mode of compressive strength acquisition takes place similar to that obtained with the binder type PC (Fig. 6c). However, the maximum compressive strength did not exceed 700 kPa. The Portland-cement-based binder and the fly-ash-based binder seem to be independent of the mixing-water chemistry.

4. Discussions

4.1. Effects of tailings and binder chemistry on the UCS of the Phase I paste backfill samples

The results of Figs. 4 and 5 suggest that the binder hydration seems to be directly related to the physical properties, and specifically to the tailings sulphur content (32 wt.% for the tailings sample A1, 16 wt.% for the tailings sample B and 5 wt.% for the tailings sample C). From Figs. 4 and 5, its can be noticed that:

- Binder type PC (a mix of TI and TV Portland cements) gives less strength with low sulphur grade tailings (e.g.,

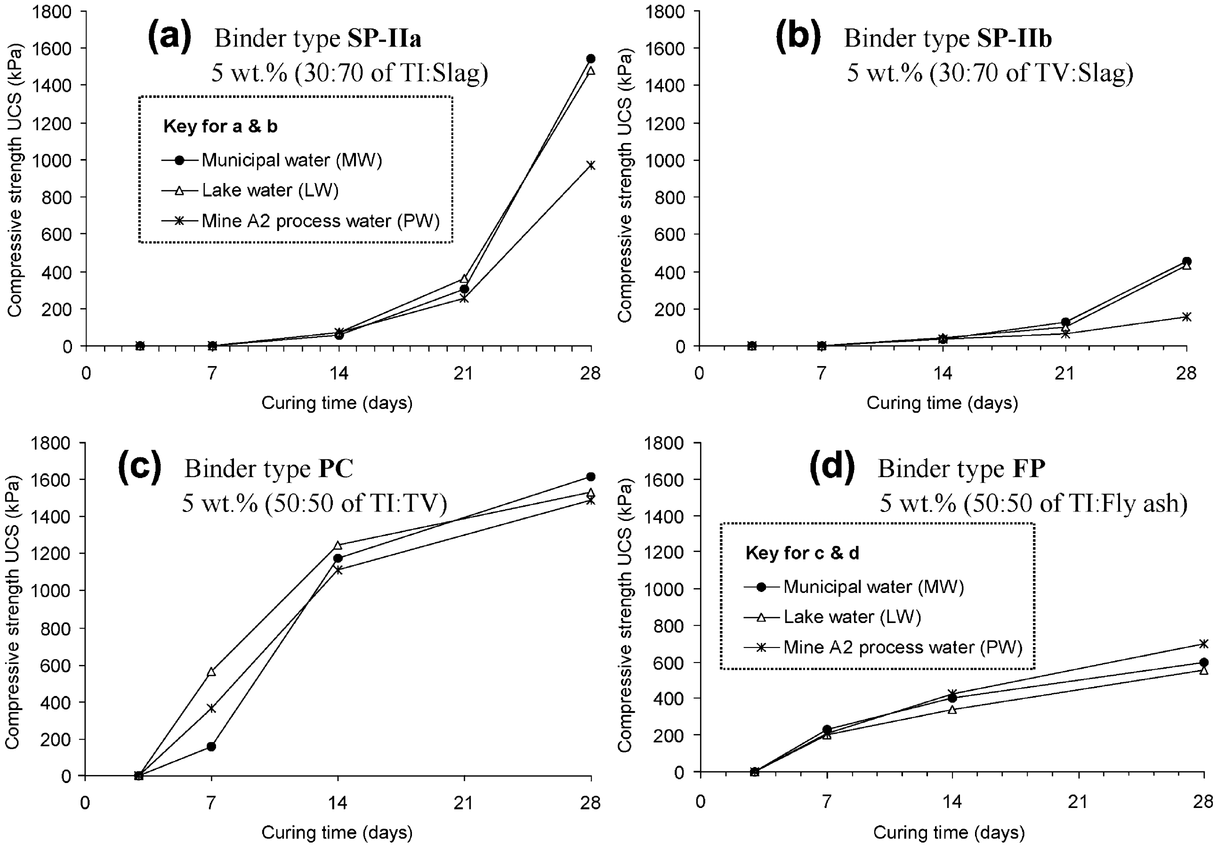

Fig. 6. Effect of mixing water on the strength acquisition of paste backfill sample A2.

tailings sample C), or medium sulphur grade tailings (e.g., Mine B). However, the binder type PC gives good strength with sulphur-rich tailings (e.g., tailings sample A1).

- Binder FP (a mix of TI Portland cement and FA) is more suitable with lower sulphur grade tailings such as tailings samples B and C than binder type PC. With the same binder proportions, the compressive strength gained with the binder type FP is always higher than the one obtained with binder type PC, except for tailings sample A1.
- Binder type SP (a mix of TI Portland cement and slag) is not suitable for sulphide-rich tailings such as tailings sample A1, but can be highly recommended for low to medium sulphur grade tailings such as tailings samples B and C. Also, this binder gives more strength to the backfill samples B and C than the binder types PC and FP.
- Finally, binder type Sg (slag only) is not recommended for sulphide-rich tailings such as tailings sample A1. However, it could be used for low and medium sulphur grade tailings such as tailings samples B and C. Moreover, the binder type Sg confers the highest compressive strength to the backfill sample B regardless of the binder proportion.

4.2. SEM micrography of the Phase I paste backfill samples

SEM micrography was performed on the 56-day curing age samples after the uniaxial compression tests to better understand some of the relationships between the compressive strength acquisition process and the texture of each paste backfill samples studied. SEM micrography showed that paste backfill grains are evenly dispersed within their matrix. The voids between the coarse particles of the initial tailings are filled with ultrafine particles and cement hydrates depending on the cement proportion and its hydration rate [17]. Figs. 7, 8 and 9 show two series of SEM backscattered micrographs of two samples, respectively, of the paste backfill A1, B and C at × 100 and × 1000 magnifications. All the samples are 56 days old. Fig. 7a and b micrographs illustrate a backfill sample A1, which developed a compressive strength, UCS, of 1.6 MPa using 6 wt.% of the binder type PC (mix of TI and TV Portland cements). Fig. 7c and d micrographs illustrate a backfill sample A1, which developed compressive strength less than 50 kPa using 6 wt.% of the binder type SP (mix of TI Portland cement and slag). The images of Fig. 8a and b illustrate a backfill sample B, which developed a 650-kPa

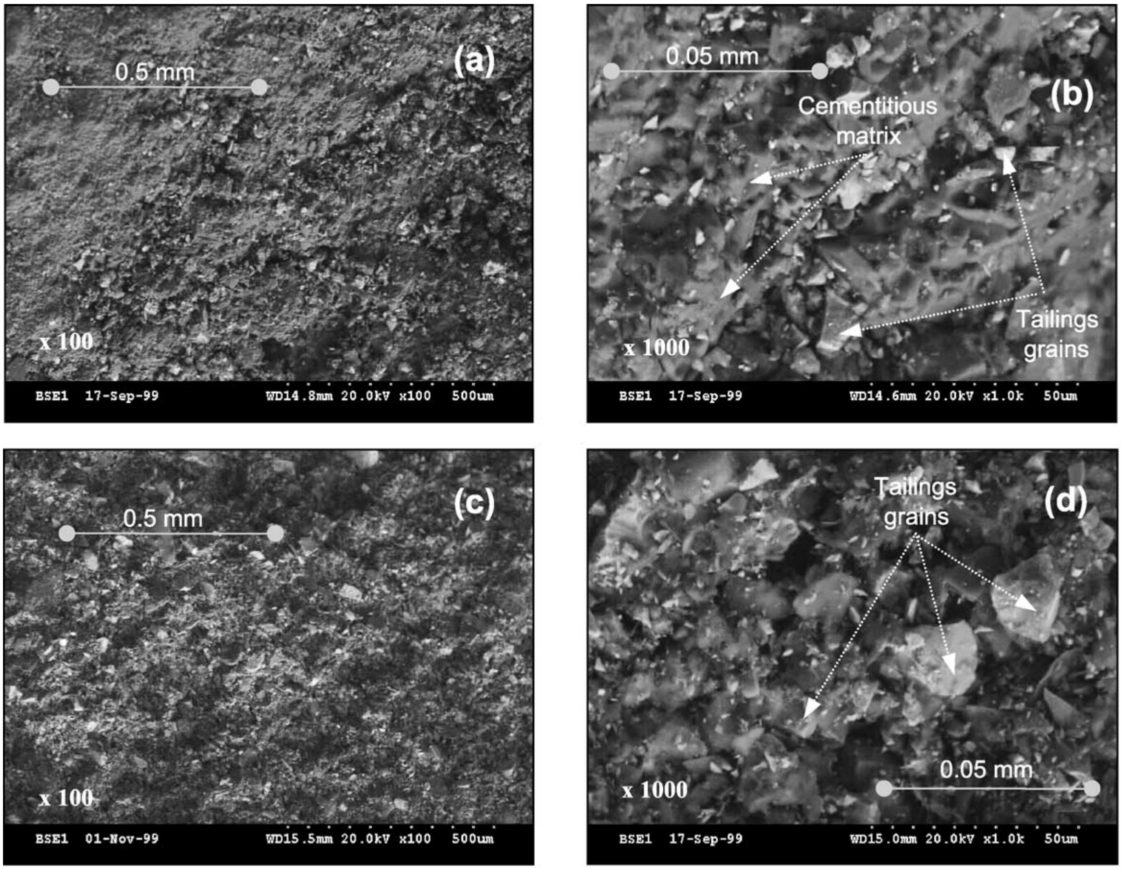

Fig. 7. SEM micrographs showing paste backfill A1 two sample textures. (a and b) Sample with 6 wt.% of binder type PC; (c and d) sample with 6 wt.% of binder type SP.

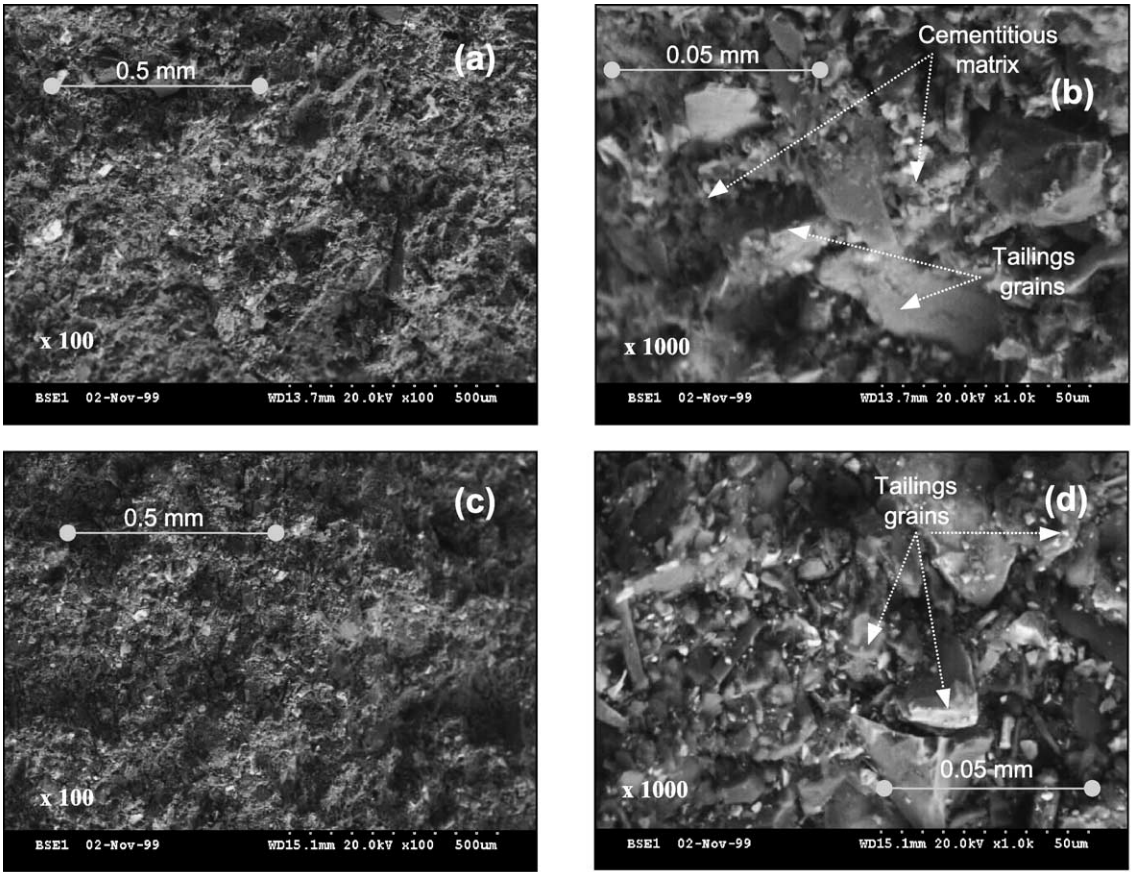

Fig. 8. SEM micrographs showing paste backfill B two sample textures. (a and b) Sample with 6 wt.% of binder type PC; (c and d) sample with 6 wt.% of binder type SP.

UCS using 6 wt.% of binder type PC. Fig. 8c and d micrographs illustrate a backfill sample B containing 6 wt.% of the binder type SP and which developed a very high compressive strength (around 3 Mpa). In the same manner, Fig. 9a and b micrographs illustrate the microstructure of a backfill sample C containing 6% of binder PC and having a UCS of 500 MPa. Fig. 9c and d images illustrate a backfill sample C using 6 wt.% of the binder type SP, which developed a UCS of 2.5 MPa. From these micrographs, one can notice that the paste backfill matrix texture is directly related to its strength development. This means that the more the backfill matrix is loose (with void spaces), the less the strength will be developed (see Figs. 7b, 8d and 9d), and the more the backfill matrix is dense, the more the strength will be developed (see Figs. 7d, 8b and 9b). The type of tailings seems to have an effect on the paste structure as we can see when comparing the images corresponding to backfill samples containing the same cement content.

SEM investigations also allowed us to observe the precipitation of some secondary minerals within the paste backfill samples B and C when using pozzolanic binders such as slag- and fly-ash-based binders (e.g., binder types SP, FP and Sg).These secondary minerals include all the hydrated phases appearing after paste backfill hardening. Secondary minerals sometimes contribute to the cohesion of the paste backfill matrix by filling the intergranular voids (see Fig. 10b). Fig. 10a and b shows the formation of secondary gypsum into an air bubble within paste backfill sample B. Hence, the mechanical strength of paste backfill mixtures depends on cementitious matrix quality that is the result of the tailings, mixing-water and binder chemistry. During the paste mixture the binder was almost dissolved within the mixing water, and the tailings reacted with the water by releasing sulphates and various metals, which decreased the pH of the resulting solution. The different binder types used had different chemistries, which resulted in different cementitious matrix compositions. The presence of sulphate seems to inhibit the precipitation of hydrates when using slag-based binders, in contrast to the Portland-cement-based binders where the formation of gypsum is easier and contributes to the paste backfill strength acquisition.

Common primary hydrates, like portlandite, were not observed while investigating the different cementitious matrixes using SEM coupled to microanalysis. This fact can be explained by the relatively low pH of the mix-tures since their preparation. C-S-H gels are the only identified hydrates.

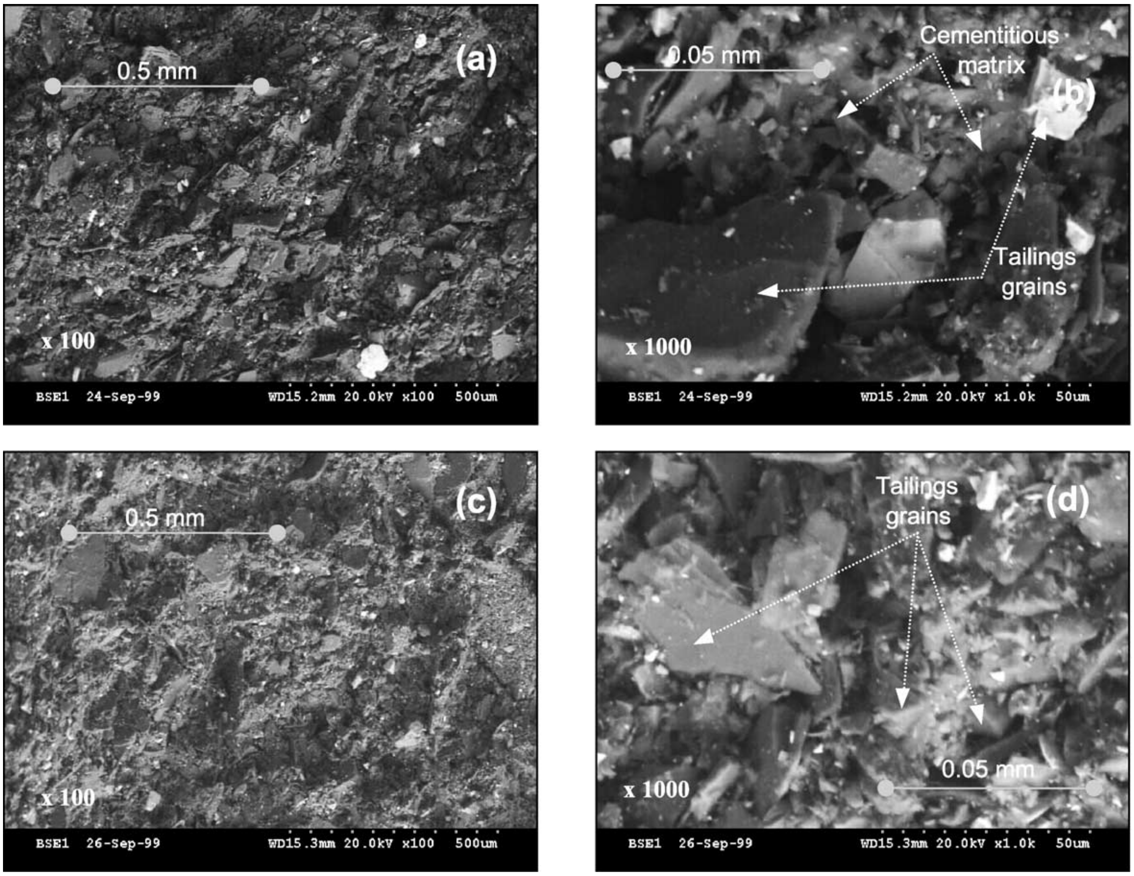

Fig. 9. SEM micrographs showing paste backfill C two sample textures. (a and b) Sample with 6 wt.% of binder type PC; (c and d) sample with 6 wt.% of binder type SP.

4.3. Effect of mixing-water chemistry on the UCS of the Phase II paste backfill samples

The results of the Phase II study show that the mixing water is an important parameter that affects the quality of the paste backfill for two reasons: (i) the water-to-binder ratio affects the backfill strength acquisition process and (ii) the water chemistry interferes with the cement chemistry and alters the hydration processes. Fig. 11 illustrates the complexity of the chemical interactions between mixing water and binder during the hydration processes. During cement manufacture, calcium sulphates are often added in

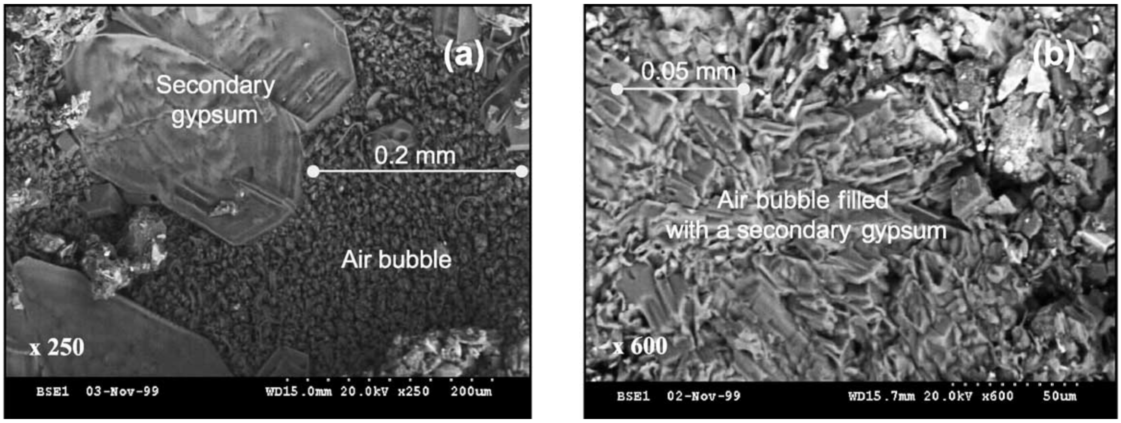

Fig. 10. SEM micrographs showing (a) a secondary gypsum, (b) air bubble filled with secondary gypsum within the paste backfill sample B.

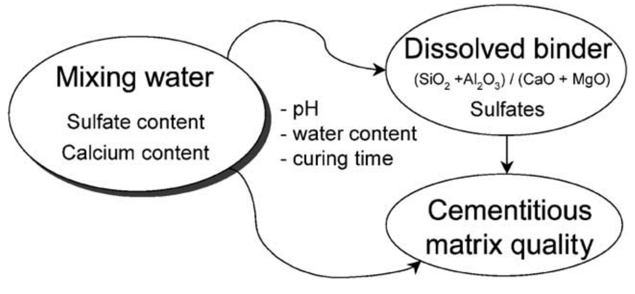

Fig. 11. Schematic diagram illustrating interactions between mixing water and binder during hydration processes.

the form of gypsum ($CaSO_4{\cdot}2H_2O$) or anhydrite ($CaSO_4$). The role of this additive is to set the cement hydration rate as a hydration regulator [34]. The calcium and silicon content of the cement greatly contribute to the formation of hydrate phases. The ratio ($SiO_2+Al_2O_3$)/($CaO+MgO$) is an important parameter that affects the durability of the backfill against sulphate attack [35]. After cement dissolution, calcium and silicon availability becomes so high that various hydrates can form rapidly. These are mainly portlandite ($Ca(OH)_2$) and calcium silicon hydrated gels (C-S-H). Other elements also contribute to the hydration processes but are of lesser importance.

The results of this Phase II study suggest that Portland cements- and fly-ash-based binders have fast hydration rates compared to slag-based binders. The harmful effects of the presence of sulphate in the mixing water on cement hydration was demonstrated for the slag-based binders backfill mixtures (cf. Fig. 6a and b). Indeed, the slag-based binders hydrate more slowly when the mine process water was used (sulphate-rich water) compared to sulphate-free waters (e.g., lake and municipal waters). The results also clearly show that the water chemistry plays an important role in the binder hydration within the backfill. One should remember that the total mixing water is made up of tailings residual water (water remaining after the filtration process) and the water added to set the desired slump (either process water or fresh water). The residual water is often soluble sulphate rich when the tailings are sulphide rich. Thus, depending on the sulphate content, the added water will simply dilute more or less than the residual water.

5. Conclusions

Six binder types and six mixing-water types were used to produce various paste backfill mixtures with four different sulphide tailings from three Canadian hard-rock mines (tailings samples A1, A2, B and C). The tailings samples A1 and A2 are sulphur rich (32% wt and 24% wt sulphur, respectively), tailings sample B is medium grade for sulphur (16% wt) and tailings sample C is low grade for sulphur (5% wt). The six binder types are Portland-cement-based binders (PC), fly-ash-based binder (FP) and slag-based binders (SP, SP-IIa, SP-IIb and Sg). The six mixing-water types are lake water (LW), municipal water (MW) and mine A2 sulphate-rich process water (PW). The resulting paste backfill curing-time-dependent compressive strengths were investigated with uniaxial compression testing. At early-stage curing times (i.e., from 0 to 14 days) the cement hydration is weak, indicating little or no compressive strength for all backfill samples studied. This is particularly true concerning backfill sample A1 (sulphide-rich backfill), which did not exhibit any strength until after 14 days of curing time regardless of the binder type. Only binder types PC and FP are suitable for this backfill, which developed good compressive strength after 28, 56 and 91 days of curing time. The pozzolanic binders such as the slag-based binders exhibit hydration inhibition until after 120 days of curing time. The slag-based binders are appropriate for low and medium sulphur-rich tailings and result in high strength acquisition of the paste backfill.

The mixing-water sulphate contents strongly affect the hydration processes depending on the binder type and the curing time. Also, the slag-based binder hydration seems to be inhibited by the presence of soluble sulphates in contrast to the Portland-cement-based binder.

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 particularly highlighted the complexity of paste backfill materials for which the compressive strength acquisition depends on three main components (tailings, binder and mixing-water characteristics). There is no typical recipe for all paste backfill mixtures. Each type of tailing and each type of mixing water requires laboratory optimization for choice of binder. The chemical properties of the three main components of paste backfill play an important role in its compressive strength acquisition and must be considered when designing and operating a paste backfill plant. This is because low compressive strength of the resultant paste backfill can directly affect the operation of a mine.

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