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Combined influence of sulphate and temperature on the saturated hydraulic conductivity of hardened cemented paste backfill

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ABSTRACT

This paper presents an experimental study that focuses on the investigation of the coupled effects of temperature and sulphate on the permeability of hardened cemented paste backfill (CPB). Hydraulic conductivity tests and a microstructural analysis are conducted on mature CPBs prepared with various amounts of sulphate (0, 5000, 15,000, and 25,000 ppm) and cured at various temperatures (2 °C, 20 °C, 35 °C, and 50 °C). Important findings and valuable results are gained. It is found that the coupled effects of sulphate and temperature can lead to decrease (i.e. improvement of the environmental performance of CPBs) or increase of the hydraulic conductivity of CPBs. There is competition between the permeability decreasing and increasing factors. The dominant influencing factors depend on the curing temperature and initial sulphate content.

1. Introduction

Cemented paste backfill (CPB) is one of the most important emerging and innovative technologies for sustainable mine waste management. It is a heterogeneous material produced by mixing tailings with a solid percentage between 70% and 85%, water that is either fresh or mine processed, and a hydraulic binder, which is usually 3–7 wt.%. This technology has economical as well as environmental benefits for the mining industry [1–5]. In addition to this, the hardened CPBs provide ground support for the surrounding mine structure and also a safe working environment for the mine workers [1,2,6–8]. Aside from mechanical stability (commonly evaluated by the strength of CPB), environmental performance is a relevant quality criterion for the CPB. Susceptibility to acid mine drainage (AMD) [9–11] and ability to release contaminants into the mine areas and/or groundwater (after mine flooding) are relevant environmental design criteria for CPB structures.

Permeability is one of the main parameters which control the environmental performance and durability of CPB [e.g., 12–14]. In addition, permeability can give relevant information about the pore structure, such as coarseness and connectivity, and the cracking of the CPB. Less desirable pore structures, which include coarse pores and high connectivity of the pores, and cracks, can allow and accelerate fluid transfer, such as oxygen and water, between the CPB and surrounding media, thereby resulting in increased potential oxidation of the sulphide minerals contained in the tailings and reducing service-life through sulphate attacks [e.g., 12,14]. The permeation properties of CPB can be assessed by using knowledge of the saturated hydraulic conductivity of the CPB. The hydraulic conductivity describes the ease with which a fluid (e.g., water, air) can flow through the pores or cracks within a porous medium (CPB in this study). It is a function of the permeability and degree of saturation of the porous medium, the density and viscosity of the fluid. Thus, for a saturated porous medium and given fluid density and viscosity, the hydraulic conductivity is controlled by the permeability, which depends on the microstructure or pore structure of the porous medium only.

During the past 15 years, several experimental studies [1–3,5,11,15–17] have been performed to investigate the strength of CPBs and the factors that affect CPBs, whereas only few studies [e.g., 12,13] deal with the hydraulic conductivity of CPBs. Furthermore, all of these studies ignore the combined effects of sulphate and temperature on hydraulic conductivity. There is a need to address these issues. Indeed, in reality, the CPB is simultaneously subjected to various thermal (temperature) and chemical (sulphate) loading conditions at the mine site [18,19]. This means that technical information with regards to the hydraulic conductivity of CPBs available in the literature will not simulate a field condition for establishing standard design criteria for CPB structures.

Considering the problems mentioned above and the fact that several underground CPB structures in Canada and worldwide are subjected to various coupled chemical and thermal loads during their lifetime, the main objectives of this study are:

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- to investigate the coupled effects of curing temperature and sulphate on the hydraulic conductivity of CPBs; and
- to better understand the coupled effects of sulphate and temperature on the hydraulic conductivity of CPBs.

2. Material, testing procedures and equipment

2.1. Materials

2.1.1. Binder

Commercially available ordinary Portland cement type I (PCI) was used to prepare the CPB samples. The binder was added in the mix at a rate of 4.5 wt.% in all samples. Table 1 shows the chemical composition of the cement as well as its relative density (Gs).

2.1.2. Mixing water

Distilled water was used to prepare all specimens. The purpose of using distilled water is to accurately maintain the desired concentration of sulphate in the sample. Required amounts of sulphate salt ($FeSO_4 \cdot 7H_2O$) with a molecular weight of 278.01 was added to the distilled water in order to achieve 5000 ppm, 15,000 ppm and 25,000 ppm of sulphate concentration.

2.1.3. Tailings

Artificial silica tailings (TS) were used as tailings materials. The main objective of selecting TS is to accurately control the concentration of sulphate, and the chemical and mineralogical composition of the tailings. This maintains a minimal level of uncertainty. Some natural tailings may contain chemically active or reactive minerals (e.g., pyrite) that can interact with the cement hydration process and products, and thus considerably increase the uncertainty in the results. Furthermore, sulphide-rich tailings can be oxidized during the preparation of the CPB and change the sulphate content. In turn, this sulphate can significantly affect the analysis and interpretation of the study results. TS shows a grain size distribution (Fig. 1) close to the average of nine mine tailings (which come from eastern Canada). With about 43 wt.% of fine particles (<20 μm), TS can be classified as medium tailings. TS is made of quartz (one of the dominant minerals in Canadian hard rock mines) and has a relative density of 2.7. The main chemical properties of TS are given in Tables 2. It should be emphasized that the sulphate and temperature exclusively affects the cemented matrix and cement hydration products of CPB.

2.2. Specimen preparation

Required amounts of tailings and binder were mixed in a dry container until a homogeneous colour was obtained. Required amounts of water with different sulphate concentrations (0 ppm, 5000 ppm, 15,000 ppm and 25,000 ppm) were then added to the dry mix of binder and tailings, and mixed together until obtaining a homogeneous paste. Then, the consistency of the paste mixtures was measured by the slump test in accordance to ASTM C 143-90. A total of about 60 CPB specimens with a slump of 18 cm and a water–cement (W/C) ratio of 7.5 were prepared. The binder content was kept constant at 4.5 wt.%. The prepared CPBs were then poured into a plastic cylinder sized 5 cm in diameter and 10 cm in height. The CPB cylinders were vibrated manually to remove the entrapped air from the moulded samples. The prepared samples were sealed with a plastic cover to prevent the evaporation of water. They were cured in an environmental chamber with controlled temperatures of 2 °C, 20 °C, 35 °C and 50 °C for 90 days. After the specific curing times, the CPB samples were subjected to various tests (hydraulic conductivity, microstructural).

Table 1
Chemical composition and relative density of the cement (PCI) used.

Binder	MgO	CaO	SiO_2	Al_2O_3	Fe_2O_3	SO_3	Gs
PCI	2.65	62.82	18.03	4.53	2.7	3.82	3.1

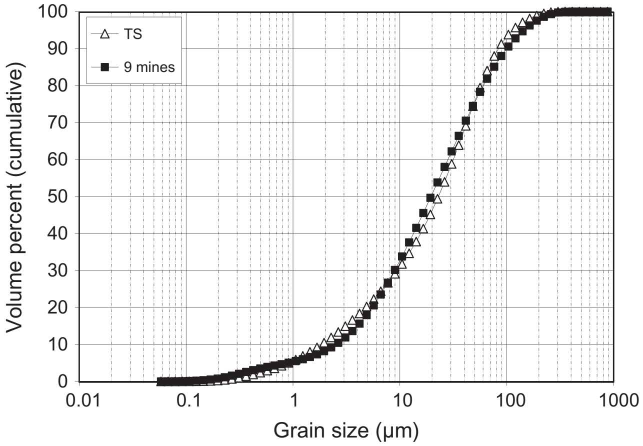


Fig. 1. Grain size distribution of the tailings used (TS) and the average grain size distribution of tailings from 9 eastern Canadian mines.

Table 2
Chemical properties of the silica tailings by percentage. *Source:* US Silica Company.

SiO_2	Fe_2O_3	Al_2O_3	TiO_2	CaO	MgO	Na_2O	K_2O	LOI	pH
99.8	0.035	0.05	0.02	0.01	<0.01	<0.01	0.02	0.1	7

2.3. Testing of specimen

2.3.1. Hydraulic conductivity tests

The flexible wall permeameter principle was used following ASTM D 5084-00 to perform hydraulic conductivity tests on the CPBs which contained various sulphate contents (0, 5000, 15,000, and 25,000 ppm), and cured at various temperatures (2 °C, 20 °C, 35 °C, and 50 °C) for 90 days. The procedure for this method is described in ASTM D5084-00 and was conducted in the constant head mode. The effluent head was kept constant at 10 kPa, while the influent head was calculated from a desired gradient to be applied as a function of the sample thickness. Saturation was achieved by bridging the influent and effluent lines and applying backpressure. Saturation was judged complete by verifying influent intake against effluent water volume supply until they became equal, and also by determining the degree of saturation of the samples at the completion of the hydraulic conductivity tests. The samples showed average final degrees of saturation higher than 98%. Each hydraulic conductivity test was repeated at least three times (a new sample was used for each test) and the average value was considered as the saturated hydraulic conductivity of the sample tested.

2.3.2. Microstructural analysis

The microstructure of the studied CPB samples was investigated mainly by XRD tests and a scanning electron microscopy (SEM) analysis. The samples contained various sulphate contents (0, 5000, 15,000, and 25,000 ppm) and were cured at various temperatures (2 °C, 20 °C, 35 °C, and 50 °C) for 90 days. XRD tests and the SEM analysis were carried out on CPB samples as well as prepared hardened cement pastes with a high W/C ratio (W/C = 2; to simulate the cement matrix of CPBs). The samples for SEM analysis were first dried at 50 °C to constant mass in a vacuum oven to remove the free water. Drying at this temperature did not appear to cause cracking. After that, the samples were vacuum impregnated with low viscosity epoxy, polished and then observed in backscatter electron mode. XRD tests were carried out by using a Scintag XDS 2000 XRD, whereas the SEM observations were done with a Hitachi S4800 FEG-SEM. The XRD tests and SEM allowed the studying of binder hydration products, and sulphated and expansive minerals which formed in the CPB system. Furthermore, mercury intrusion porosimetry (MIP) tests and a thermal analysis (TG, thermogravimetric) were performed on some CPB and cement paste samples (samples cured at 20 and 35 °C) to study the pore structure and binder hydration products of the tested CPB samples. MIP measurements were performed using a Micromeretics AutoPore III 9420 mercury porosimeter. Before MIP-testing, all samples were first dried at 50 °C up to mass stabilization. Drying at this temperature did not appear to cause cracking. The thermal analysis was undertaken by using an SDT apparatus from TA Instruments which allows simultaneous registration of weight loss and heat flow along the thermal treatment of the sample.

3. Results and discussions

Fig. 2 illustrates the hydraulic conductivity of the CPB samples which contain 0 ppm, 5000 ppm, 15,000 ppm and 25,000 ppm of sulphate cured at 2 °C, 20 °C, 35 °C and 50 °C for 90 days. From this figure, it is clear that, for a given curing time, the hydraulic conductivity of the CPB samples depends upon both temperature and sulphate concentration as discussed below.

3.1. Temperature-dependent evolution of the hydraulic conductivity of the sulphated CPB

From Fig. 2, it can be observed that generally, regardless of the sulphate content, higher curing temperature results in lower hydraulic conductivity of the CPB (except for samples with 15,000 ppm and 25,000 ppm of sulphate and cured at 50 °C; this will be discussed later). This is because high temperatures accelerate the cement hydration process [20–22]. Consequently, the amount of hydration products (e.g., C–S–H, CH, calcite) increases with temperature, thereby resulting in the refinement of the pore structure. This increase of the amount of hydration products formed with higher temperature is demonstrated by the experimental evidence which is shown in Fig. 3. This figure represents the results of the thermal analysis (TG) performed on the cement pastes of the CPB samples cured at 20 °C and 35 °C, respectively. A comparison of the TG diagrams of the cement paste CPB cured at 20 °C and 35 °C shows that the weight losses are higher for cement paste cured at 35 °C. This means that higher amounts of hydration products are formed in the 35 °C CPB samples. Indeed, it is well known that weight losses located between 100 °C and 180 °C result from the dehydration reactions of the hydrates, such as C–S–H, carboaluminates, ettringite, and gypsum [23–26], whereas the major weight losses situated at 400–500 °C and 650–750 °C characterize the decomposition of CH and calcite, respectively [23,24]. Moreover, the refinement of the pore structure of CPBs with precipitation of a higher amount of cement hydration products is demonstrated by the results of the MIP performed on the sulphate-free CPB samples cured at 20 °C and 35 °C, respectively, which is presented in Fig. 4. From this figure, it can be noticed that CPB samples cured at 35 °C have finer pore structures and lower total porosity than CPBs cured at 20 °C. In other words, the hardened cement matrix cured at 20 °C is more permeable. Fig. 2 also shows that the samples cured at 2 °C have the highest hydraulic conductivity values. This is due to the formation of low amounts of hydration products in the cement matrix because of the inhibition of cement hydration by the low temperature [21,22]. From the results presented above, it can be concluded that higher curing temperatures decrease the fluid transport ability of the CPBs (except for the highly sulphated samples (15,000 and 25,000 ppm) cured at 50 °C), and thus improve its environmental performance and durability.

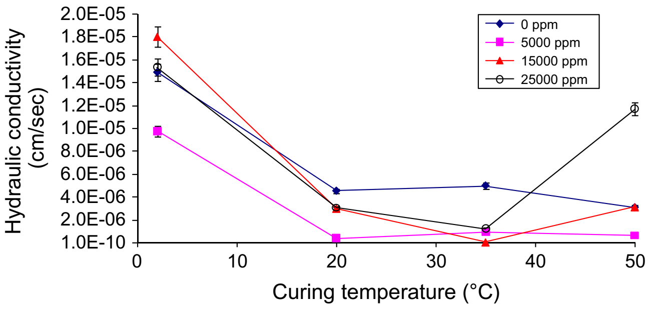


Fig. 2. Coupled effects of sulphate and curing temperature on the hydraulic conductivity of CPB.

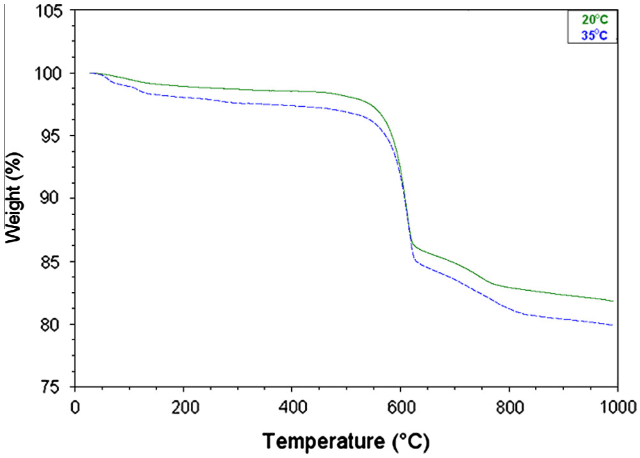


Fig. 3. TG diagrams for cement pastes of CPB cured at 20 °C and 35 °C.

3.2. Effect of the initial sulphate content on the saturated hydraulic conductivity of CPB for a given curing temperature

From Fig. 2, it is also clear that the hydraulic conductivity of the CPB for a given temperature is strongly dependent on the initial

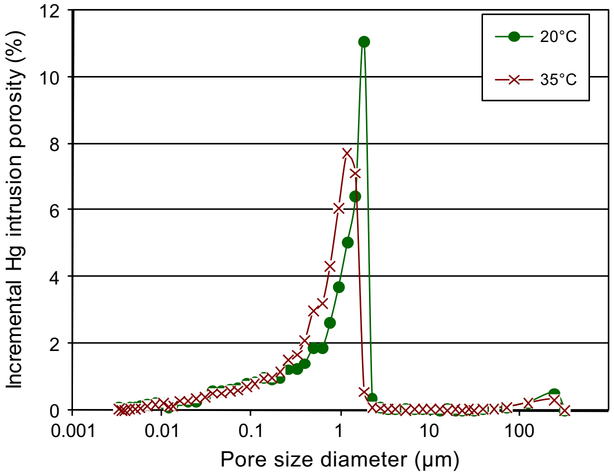


Fig. 4. MIP porosity and pore size distribution of mature CPB vs. curing temperature.

sulphate content of the samples. Furthermore, it can be noticed that, the nature and magnitude of the effects of the initial sulphate content on the hydraulic conductivity are function of the values of the curing temperature (cold, room, moderated and high temperature) as discussed in the following sections.

3.2.1. At a curing temperature of 2 °C ("cold" curing temperature)

Fig. 2 illustrates that the 15,000 ppm and 25,000 ppm samples at 2 °C show higher hydraulic conductivity than the 0 ppm sample, whereas the 5000 ppm sample has the lowest hydraulic conductivity. The higher hydraulic conductivity of the highly sulphated CPBs in comparison to the 5000 ppm samples is due, in addition to the inhibition of cement hydration by the low temperature, to the presence of high sulphate concentration which prevents the precipitation of a sufficient amount of hydration products in the pores of the cement matrix. This results in the formation of more porous structures. This sulphate induced inhibition of the cement hydration can be adequately explained on the basis of the reduced solubility of C_3A in solutions saturated with sulphate [25]. The lowest hydraulic conductivity of the 5000 ppm is attributed to the fact that, as mentioned in [17], a moderate sulphate content can contribute to the decrease of CPB porosity. This is because there is a reasonable amount of precipitation (but not excessive) of secondary hydrated minerals (such as gypsum, ettringite and brucite) in the empty capillary pores that are present in the CPB. This is graphically demonstrated by the results of SEM observations presented in [17]. From this study, it can be observed the pores within the CPB are filled with secondary hydrated minerals.

3.2.2. At 20 °C curing temperature ("room" curing temperature)

From Fig. 2, it can be observed that at 20 °C, the permeabilities of the sulphated CPBs are lower than that of the sulphate-free sample. The 5000 ppm sample shows the lowest hydraulic conductivity. As mentioned above, the lower hydraulic conductivity of the sulphated samples is due to the refinement of the pore structure of the CPB induced by the precipitation of expansive minerals that result from the reaction of sulphate ions with the cement hydration product, CH (which results in gypsum formation) and the tricalcium aluminate of the cement clinker phases, C_3A (which results in ettringite formation). Similar observations were also made by

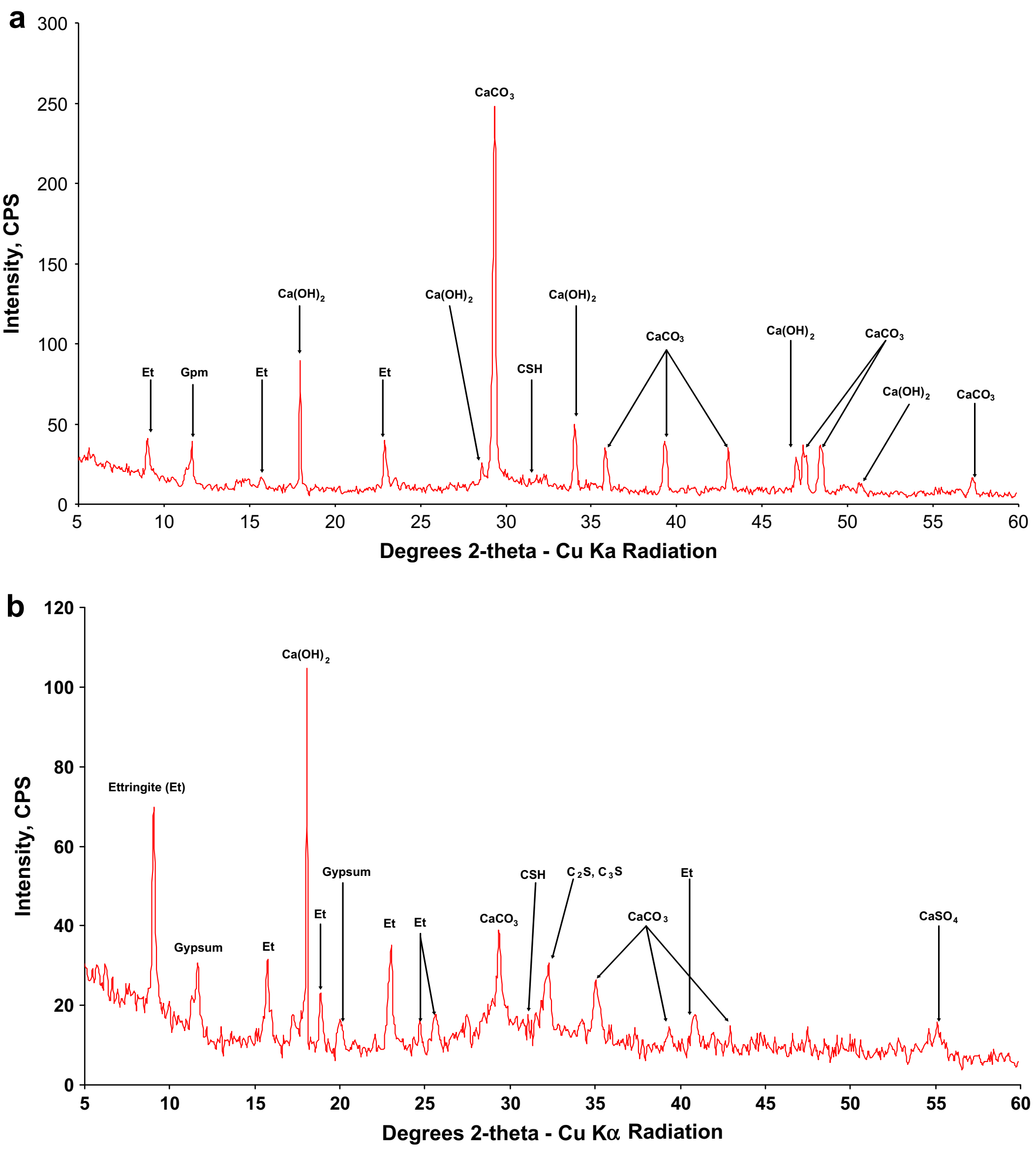
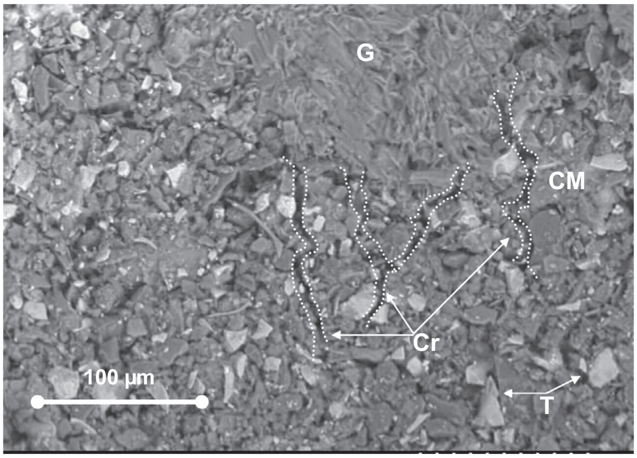


Fig. 5. XRD results of (a) 5000 ppm and (b) 25,000 ppm CPB cured at 20 °C.

[27] on sulphated CPB cured at room temperatures. These authors have experimentally demonstrated that the precipitation of sulphated minerals with a CPB cured at room temperature can lead to the refinement of its pore structure. The interesting part of the findings here is that the highly sulphated CPB samples (15,000 and 25,000 ppm) show higher hydraulic conductivity than the 5000 ppm samples and lower hydraulic conductivity than the sulphate-free CPBs. The higher hydraulic conductivity observed for the 25,000 and 15,000 ppm samples at 20 °C can be attributed to the combined effect of two mechanisms that contribute to the coarsening of their pore structure (in comparison to the 5000 ppm samples) and thus counteract the beneficial effect of the porosity reduction of the cement matrix due to the precipitation of an appropriate amount of expansive minerals. First, because of the low sulphate concentration of the 5000 ppm samples (in comparison to 15,000 and 25,000 ppm), there is no (or insignificant) inhibition of cement hydration. The absence of inhibition will favour a more complete hydration of the cement, thereby resulting in a finer pore structure. This is in accordance with the XRD analysis results of the 5000 ppm and 25,000 ppm cemented paste samples cured at 20 °C as presented in Fig. 5a and b, respectively. An absence of dicalcium silicate (C_2S) and tricalcium silicate (C_3S) can be noted from Fig. 5a, which indicates an almost complete hydration of cement of the 5000 ppm CPB, whereas Fig. 5b confirms the presence of the clinker phases C_3S and C_2S in the 25,000 ppm CPB specimen; in other words, it shows an inhibition of cement hydration in highly sulphated samples. Secondly, a comparative analysis of the XRD results presented in Fig. 5a and b indicates that a high proportion of expansive minerals (ettringite and gypsum) are formed in the highly sulphated samples. The formation of large amounts of ettringite and gypsum may have produced excessive expansive pressure. This pressure could have started to physically damage the cemented matrix of the highly sulphated samples (which results in the formation of microcracks), and thus lead to the coarsening (in comparison to the 5000 ppm samples) of the pore structure of the highly sulphated samples. This is experimentally supported by the SEM micrograph of a highly sulphated mature CPB sample cured at 20 °C (Fig. 6). From this figure, it can be clearly seen that the cemented matrix of the CPB adjacent to the pore filled with secondary gypsum minerals are affected by microcracks that result from the destructive expansive action of gypsum.

It can be concluded that for a curing temperature of 20 °C, increasing the initial sulphate content has two opposite effects on the permeability of CPBs. On the one hand, low to moderate sulphate content (⩽5000 ppm in this study) is associated with the precipitation of an appropriate amount of expansive minerals (gypsum, ettringite) within the pores of the CPB. This leads to refinement of its pore structure and decrease of its permeability. However, on the other hand, the strong inhibition of cement hydration as well as the precipitation of large (excessive) amounts of expansive minerals (with respect to the available pore space) associated with high initial sulphate content (⩾15,000 ppm in this study) tend to damage and thus negatively affect CPB permeability. This counteracts the beneficial effect of the porosity reduction of the cement matrix due to the precipitation of appropriate amount of expansive minerals. At a certain level of initial sulphate content, the aforementioned negative effects of high initial sulphate on CPB permeability can outweigh the positive effect of the filling of the CPB pores by expansive minerals.



SEM image showing CPB damaged (see cracks, Cr) by the destructive action of the expansive mineral phase (gypsum, G) formed within the CPB pores. T: tailings grain; CM: cement matrix

Fig. 6. SEM micrograph showing secondary hydrated minerals that have damaged the CPB by their destructive expansive action.

From the results presented above, it is evident that for a curing temperatures of 20 °C (room temperature), competition exists between factors of permeability decrease (refinement of the pore structure of CPBs) and increase (coarsening of the pore structure of CPBs caused by damage to the cemented matrix and/or by the strong inhibition of the cement hydration) as the initial sulphate content of the CPB increases. In other words, this means that the competition between permeability decrease and increase factors plays a major role in determining the environmental performance and durability properties of a CPB.

3.2.3. At 35 °C curing temperature (“moderate” curing temperature)

Fig. 2 reveals that for a temperature of 35 °C, the permeability values of the sulphated samples are relatively similar and lower than that of the sulphate-free samples. This indicates that the aforementioned positive effect of the filling of the CPB pores by expansive minerals outweigh the negative effects of the high initial sulphate on CPB permeability. In other words, there is less inhibition of cement hydration of highly sulphated CPBs as well as no precipitation of large amounts of expansive minerals within the pores of highly sulphated CPBs. This lower inhibition is due to the well known fact that as the curing temperature increases, the hydration rate of the cement increases, i.e., there is less C_3A whose reactions will be inhibited by high sulphate concentration [7]. This will contribute to the formation of more hydration products (e.g., C–S–H, CH) and thus the refinement of the pore structure. An absence of the precipitation of a large amount of expansive minerals is attributed to the combined effects of the following two mechanisms as discussed below in more details and demonstrated by Figs. 7 and 8: (i) higher curing temperatures lead to a higher absorption of sulphate by C–S–H [28], which thereby results in less availability of sulphate ions to form expansive minerals; and (ii) high curing temperatures favour the dissolution of ettringite [29], and thus contribute to the reduction of the amount of ettringite formed within the pores of CPB, i.e., decrease in its expansive pressure.

3.2.4. At 50 °C curing temperature (“high” curing temperature)

From Fig. 2, it can be observed that, there is an increase of the hydraulic conductivity of the highly sulphated CPBs. The permeability of the 15,000 ppm and 25,000 ppm samples is higher at 50 °C than at 35 °C and 20 °C which indicates a coarsening of the pore structure of the highly sulphated samples at 50 °C. This is due to the combined effects of the following factors: (i) the adsorption of sulphate by C–S–H gel at higher temperatures; and (ii) the destabilization of ettringite at high temperatures (since the solubility of ettringite increases with increasing temperatures; [28]). These factors lead to lower amounts of expansive minerals available to fill the empty pores of the sulphated CPBs thereby coarsening their pore structure. This argument with regards to

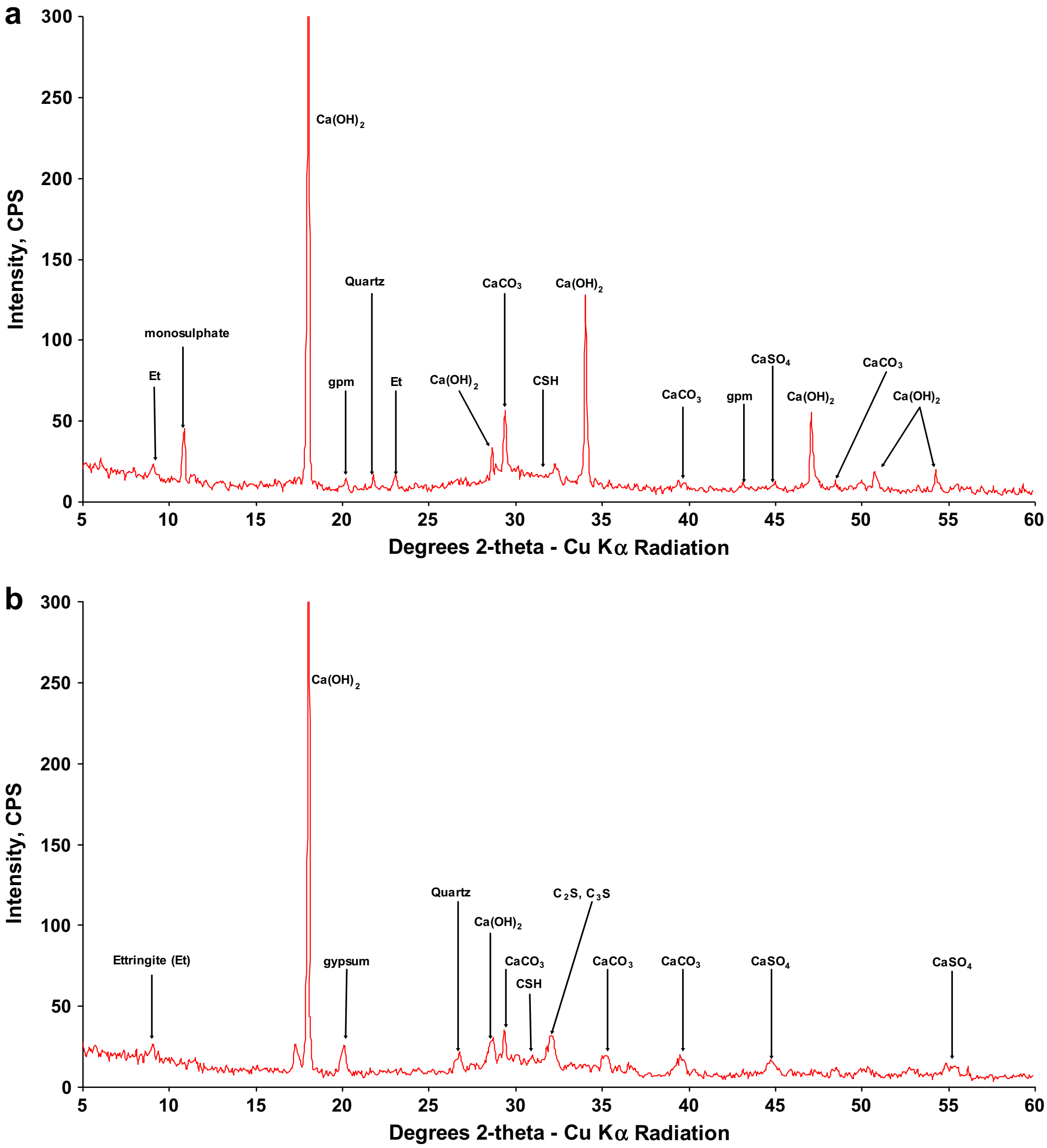


Fig. 7. XRD result of (a) 0 ppm and (b) 25,000 ppm cemented paste of mature CPB cured at 50 °C.

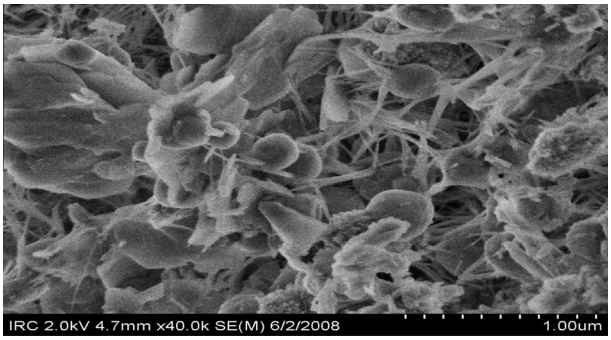
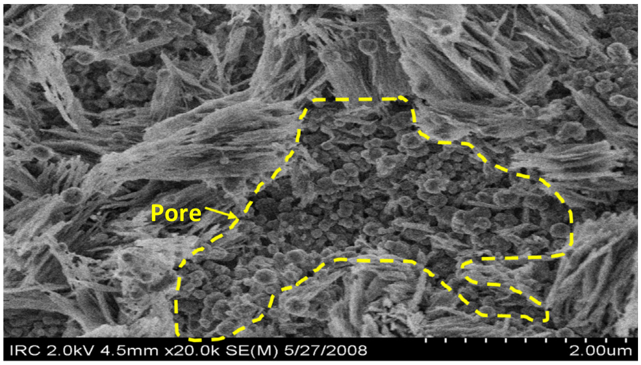
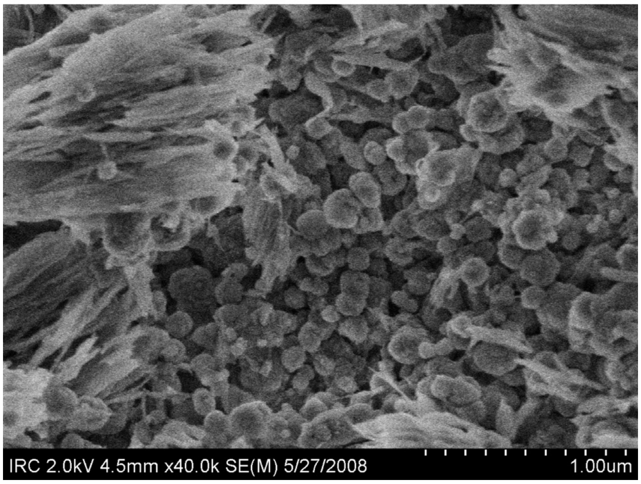


Fig. 8. SEM observation of 0 ppm sample made from PCI at 50 °C cured for 150 days.

the sulphate absorption by C–S–H is fully supported by the results of experimental investigations carried out by [28] which demonstrated that sulphate binding to C–S–H increases and is faster as the curing temperature increases, which is also consistent with the XRD result of the 25,000 ppm samples at 20 °C and 50 °C presented in Figs. 5b and 7b, respectively. The 25,000 ppm sample at 20 °C shows the presence of high amounts of expansive minerals due to availability of sulphate to react with CH and C_3A (Fig. 5b). This contributes to the refinement of the pore structure at 20 °C as discussed previously. The XRD result of the 25,000 ppm at 50 °C in Fig. 7b shows the presence of very low amounts of these minerals. The peak of CH is also high, especially at 18° 2-theta. The 25,000 ppm sample at 20 °C in Fig. 5b does not have any CH at 28.5° 2-theta whereas the ones at 50 °C contain CH. Hence, these XRD show clearly that at higher curing temperatures, sulphate is absorbed by C–S–H gel which results in higher permeability. This sulphate absorption and ettringite destabilization induced coarsening of the pore structure of highly sulphated samples is also clearly shown by comparing the SEM micrographs of the cemented pastes of the 0 ppm and 25,000 ppm CPBs cured at 50 °C provided in Figs. 8 and 9, respectively. From Fig. 8, it can be seen that the cement paste of the sulphate-free CPB is characterized by the presence of very small empty pores between the cement hydration products (C–S–H, CH); these small pores result from the full



(a) Large pore of tthe cement matrix is filled with a porous mass made of colloidal ettringite



(b) Details of the porous material made of colloidal ettringite

Fig. 9. SEM observation of 25,000 ppm samples at 50 °C.

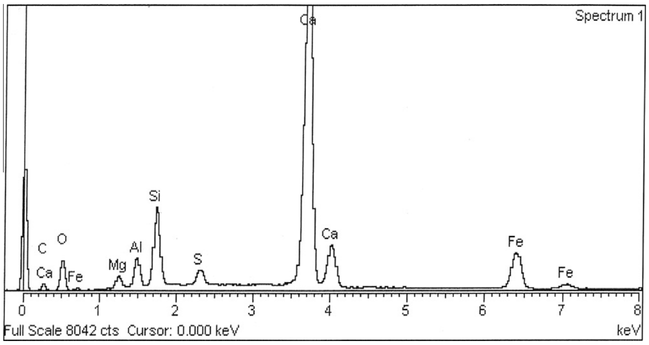


Fig. 10. EDAX of 25,000 ppm samples cured at 50 °C.

hydration of the Portland cement without any negative impact of the sulphate. In contrast to the 0 ppm samples, the SEM observations (Fig. 9a and b) of the 25,000 ppm sample cured at 50 °C reveal that the pore structure is characterized by the presence of large pores filled with a porous mass (details shown in Fig. 9b) made of colloidal ettringite. The energy dispersive XRD analysis (EDAX) of the same sample in Fig. 10 shows the major peaks of Ca, S, Al, and Si, which indicate the formation of ettringite. This porous mass is an indication that an inadequate amount of expansive minerals (ettringite) was available to fully fill the pores, which can be attributed to the dissolution of ettringite at high temperature and absorption of the sulphate by the C–S–H (less sulphate is available to form ettringite). Furthermore, it can be noticed from Fig. 2 that the 25,000 ppm samples have the highest permeability, i.e., the coarsest pore structure among the sulphated samples because the adsorption of sulphate by C–S–H gel also depends upon the concentration of sulphate as demonstrated by several studies [e.g., 30,31]. This absorption increases as the sulphate content increases, thereby leading to less formation of expansive minerals that can fill the CPB pores.

4. Summary and conclusions

This paper presents the results of a study which aims to evaluate the combined effect of sulphate and temperature on the hydraulic conductivity of CPBs. Several CPB mixtures with various sulphate contents (0, 5000, 15,000 and 25,000 ppm) are cured at different temperatures (2 °C, 20 °C, 25 °C, 35 °C, and 50 °C) for 90 days. Hydraulic conductivity tests and microstructural (mineralogical composition of the cement paste of CPBs, pore structure) analyses of these CPB mixtures provide valuable information of the effect of sulphate on environmental performance and durability of CPBs under various curing temperatures. Using this laboratory program, the following findings are determined.

- Regardless of the sulphate content (except for the highly sulphated samples cured at 50 °C), the hydraulic conductivity of the CPBs decreases as the curing temperatures increases because of the refinement of the pore structure of the CPB induced by the precipitation of a higher amount of hydration products with higher temperatures. This implies that the environmental and durability performance of the CPB improve with higher curing temperatures.
- Cold curing temperatures (2 °C) provide the highest hydraulic conductivity to the studied CPBs regardless of the initial sulphate contents; in other words, these temperatures decrease the environmental performance and durability of the concerned CPBs. This high permeability is caused by the coarsening of the CPB pore structure because of the inhibition of cement hydration by the low temperature and the high sulphate content ($\geqslant$15,000 ppm).
- For curing at room temperature (20 °C), the interaction between sulphate and temperature has two opposite effects on the fluid transport ability of CPBs. Factors of permeability decrease and increase compete as the initial sulphate content of the CPB increases. On the one hand, a decrease of the internal porosity (through the filling of CPB pores with a reasonable amount of expansive minerals, such as ettringite and gypsum; this is also known as the permeability decreasing factor) that is associated with an increase in the sulphate concentration leads to a decrease of the permeability of sulphated CPB. On the other hand, besides the higher inhibition of C_3A with a higher initial sulphate content, increasing the sulphate content (which favours precipitation of larger amounts of ettringite and gypsum) results in higher expansive pressure of the formed expansive minerals, and thus tends to negatively affect the permeability, i.e. environmental performance of a CPB. This counteracts the beneficial effect of the aforementioned permeability decreasing factor. In other words, the competition between permeability decreasing and increasing factors plays a major role in determining the environmental performance and durability properties of a CPB at this curing temperature.
- At high curing temperatures (35 °C and 50 °C), the sulphate CPBs show the lowest hydraulic conductivity because of the (i) refinement of their pore structure by the precipitation of a reasonable amount of expansive minerals within the pores, and (ii) the limitation of the formation of a large amount of expansive minerals within the pores of highly sulphated CPBs;

this limitation is caused by the absorption of sulphate by the C–S–H gel and the dissolution of ettringite at high temperatures. However, at 50 °C, the highly sulphated CPBs show high permeability which mainly results from the coarsening of the pore structure due to the absorption of sulphate by the C–S–H gel as curing temperatures and sulphate content increase as well as the destabilization of ettringite at high temperatures.

This study will provide useful information for understanding the fluid transport ability of CPBs in various coupled thermal–chemical loading conditions. The authors believe that the outcome of this research will help mining operators and the engineering community working in the CPB system field for consideration in the environmental and durability evaluation of the aforementioned structures.

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