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Effect of deep mine temperature conditions on the heat development in cemented paste backfill and its properties

M Fall *University of Ottawa, Canada*

D Wu *China University of Mining & Technology-Beijing, China*

M Pokharel *University of Ottawa, Canada*

Abstract

As ore reserves available at shallow depths are diminishing in several countries, underground mining operations are moving to greater depths. This greater depth is naturally associated with heat influx increases because of the geothermal gradient. The exposed rock mass is the primary heat load source in any deep level mining operation. In this study, a numerical model is developed and validated to assess the heat transfer between deep mine rocks and cemented paste backfill (CPB) structures, as well as the heat development in CPB structures in deep mine temperature conditions. The numerical modelling results have shown that the initial deep mine rock temperatures significantly affect the heat or temperature development inside the CPB. Furthermore, experimental tests were carried out to study the effect of high temperatures on CPB properties. Different types of CPB specimens were tested at different curing times and temperatures. The strength, deformation behaviour, resistance to sulphate attack and hydraulic conductivity of these CPBs were evaluated by laboratory tests. Results showed that deep mine temperatures have a significant effect on the properties of CPB. Increasing the curing temperature increases the rate of CPB strength development and leads to higher early CPB strength and lower binder consumption. Moreover, the effect of temperature depends on the binder type, the curing time, the water content and the sulphate content of the CPB. Hence, the deep mine temperature is an important factor that should be considered in deep mine CPB operations in order to better optimise CPB mixtures and design cost-effective and durable CPB structures.

1 Introduction

CPB is a vital component of underground mine operations. Its key functions are the ground support of underground mine openings and the maximisation of safe and economic ore recovery. In addition, the maximum underground disposal of tailings and decreased acid generation represent significant environmental benefits. The key performance characteristics of CPB include mechanical stability (e.g. commonly evaluated by its strength, deformation behaviour), cost (binder consumption), durability (e.g. resistance to sulphate attack) and environmental performance (e.g. evaluated by its hydraulic conductivity).

Despite the tremendous progress that has been made in understanding the factors that affect the aforementioned key performance characteristics of CPB during the past years, major technological challenges still remain. The major challenges include investigations of the thermal interactions between the deep mine rock mass and CPB and the effect of deep mine temperatures on the key performance properties of CPB. The progressive depletion of ore available at shallow depths in several underground mines worldwide means that underground mining operations occur more and more often at greater depths, and thus at higher temperatures (due to the geothermal gradient). Also, taking a futuristic view where production would take place at a vertical rock breaking depth of 4,000-5,000 m, the significance of the effect of deep mine temperatures on CPB properties cannot be neglected or underestimated. The exposed rock mass is the primary heat load source in any deep level mining operation (Figure 1). In other words, future mining activities will increasingly be undertaken where the temperature conditions are significantly higher, i.e. the CPBs will increasingly be exposed to high curing temperatures. However, our understanding of the thermal interactions between the deep mine rock temperatures and the CPB and the effect of deep mine temperatures on the key properties of CPB, is still limited. There is a need to address this issue for both economical reasons and for the safety of mine workers.

Therefore, in this paper, a numerical model has been developed to predict the heat development in CPB and analyse the thermal interactions between rock mass and hydrating CPB structures in deep mine temperature conditions. The model and its validation against field and laboratory results are also presented. Following this, the model is applied to simulate some practical examples of the impact of deep mine rock temperatures on the heat development within CPB structures. Furthermore, in this paper, the results of experimental investigations of the impact of high temperatures on the key properties (strength, deformation behaviour, hydraulic conductivity, durability) are presented and discussed.

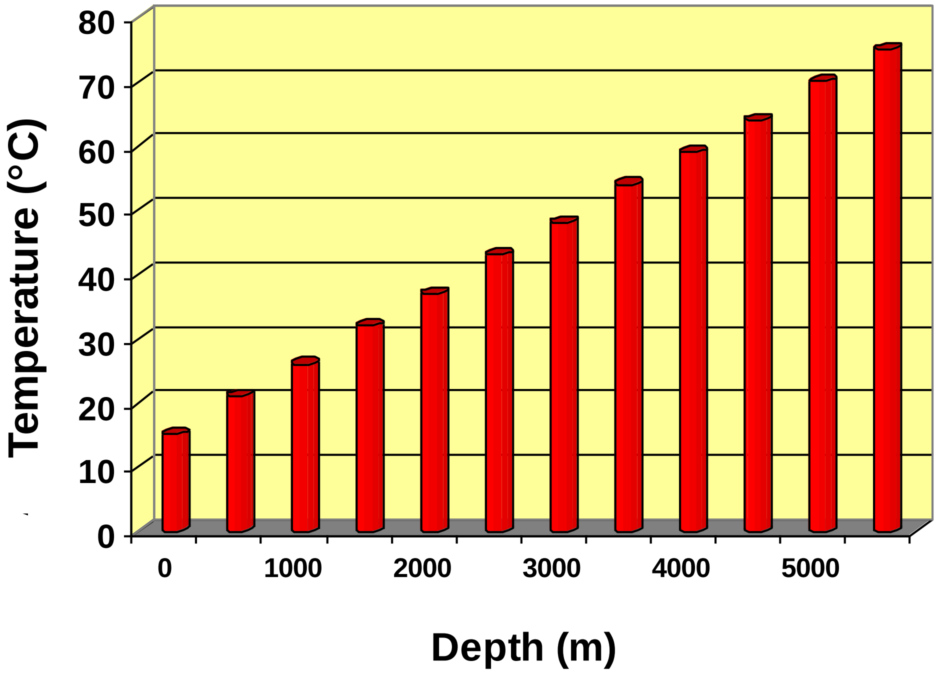


Figure 1 **Variation of geothermal temperature with depth in a South African gold mine (data from Rawlins & Philips 2001)**

2 Developed numerical tool and simulation results

A coupled thermo-hydro-chemical (THC) model has been developed and implemented into COMSOL Multiphysics software (COMSOL Inc. 2011) to predict and study the heat development within a hydrating CPB structure and its thermal interactions with the surrounding environment, e.g. deep mine rock mass, mine atmosphere. The THC model can capture and describe the thermal (e.g. heat generation by binder hydration and transfer between CPB and its surrounding media, thermal conductivity evolution), hydraulic (e.g. fluid flow, water consumption and self-desiccation, hydraulic conductivity) and chemical (e.g. binder hydration) processes that occur within a CPB. The developed modelling approach, the main governing and constitutive equations of the model, some examples of model verification and simulations results with regards to heat development within CPB in deep mine temperature conditions are presented and discussed below.

2.1 Modelling approach

The THC model is based on the coupling of the following processes – only the strong or moderate coupled processes are considered.

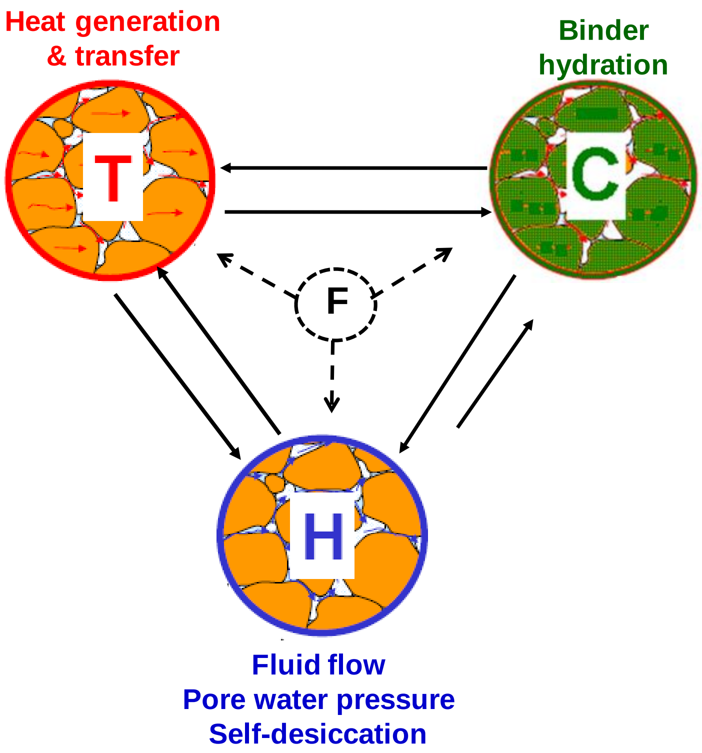


Figure 2 **Schematic representation of the main coupled THC factors in the hydrating CPB structure considered in the model development; F: Filling rate of the CPB; long arrow: strong or moderate coupling, i.e. very significant or significant effect; short arrow: weak coupling, i.e. minor effect; dashed arrow: one way effect**

2.1.1 *Thermal (T) process*

As presented in Figure 2, the thermal process mainly involves heat generation (binder hydration) and heat transfer between the CPB and its surrounding environment, such as rock mass and the mine atmosphere. Equation (1) (Schindler & Folliard 2003) is used to calculate the time and temperature related heat production rate of the hydrating CPB:

$$Q_H = H_T \cdot \left(\frac{\tau_T}{t}\right)^{\beta} \cdot \left(\frac{\beta \cdot \tau_T}{\tau \cdot t}\right) \cdot \alpha(t) \cdot \frac{E}{R}\left(\frac{1}{273+\mathrm{T}_r} - \frac{1}{273+T_c}\right) \tag{1}$$

Where:

H_T = the total ultimate heat of binder hydration in a CPB.

τ = the hydration time parameter at the reference temperature.

T_r = the reference temperature; T_c is the temperature of the CPB.

R = the universal gas constant (8.314 J/(mol·K)).

E = the apparent activation energy, which is related to the temperature of the CPB (Wu et al. 2012).

The temperature developments strongly influence the hydraulic properties of fresh CPB, leading to variations in hydraulic conductivity and suction, and saturation degree. Furthermore, changes in the hydraulic properties, e.g. suction, permeability, saturation degree, of the CPB can influence its fluid flow, which further impacts the thermal processes or properties, such as heat transfer in the fluid and thermal conductivity of the CPB. Moreover, the temperature has considerable effects on the rate of cement hydration and the amount of cement hydration products formed within the CPB mixtures (Nasir & Fall 2010).

The following equation is adopted to describe the thermal processes in hydrating CPB:

$$(\rho C)_{\mathrm{eq}}\frac{\partial T}{\partial t}+\rho_{\mathrm{F}}C_{\mathrm{F}}\mathrm{u}\cdot\nabla T=Q_H+\mathrm{q_d}+\mathrm{q_v} \tag{2}$$

Where:

$(\rho C)_{\mathrm{eq}}$ = the equivalent volumetric heat capacity of the CPB at a constant pressure.

ρ_{F} = the fluid density.

C_{F} = the fluid heat capacity at a constant pressure.

U = the Darcy velocity.

Q_H = the heat production rate of hydrating CPB.

$\mathrm{q_d}$ = the conductive heat flux.

$\mathrm{q_v}$ = the convective heat flux.

2.1.2 Chemical (C) processes

The chemical processes describe and capture the chemical reactions (binder hydration) that occur in hydrating CPB structures. The binder hydration, quantity and quality of the cement hydration products formed within the CPB will also be affected by the chemical interactions between the tailings, mixing water (fresh, mine processing waters) and binder (various types of cement). The hydration of CPB is controlled by coupled thermal (heat generation and transfer), hydraulic (e.g. fluid flow and water consumption) and chemical (chemical reactions) processes. Moreover, the binder hydration rate and progress will significantly affect the amount of heat generated within the CPB, as well as the hydraulic properties of CPB. For CPB materials, the degree of binder hydration can be mathematically expressed in the following form (Schindler and Folliard 2003; Wu et al. 2012):

$$\alpha(t)=\frac{H(t)}{H_T} \tag{3}$$

Where:

$\alpha(\mathrm{t})$ = the degree of binder hydration at time t.

$H(t)$ = the cumulative heat of binder hydration released at time t, (J/m^3).

H_T = the total ultimate heat of binder hydration of the cement-based materials (J/m^3).

2.1.3 Hydraulic (H) processes

The hydraulic processes describe and predict the fluid flow, the evolution of the pore water pressure and the self-desiccation of the CPB. The hydraulic processes are also strongly coupled to the thermal and chemical processes. When binder hydration within a CPB structure proceeds, self-desiccation occurs at the same time, which consumes the capillary water, and thus increases the capillary pressure and can reduce the effective saturation degree. In turn, the decrease in saturation degree can result in the development of negative pore water pressure or suction within the CPB (Wu et al. 2013). The equations adopted to capture the hydraulic processes are published in Wu et al. (2013).

2.1.4 CPB filling processes (F)

CPB filling processes (F) are used to take into account the effect of the CPB filling rate on the THC processes. The rate of backfilling can be defined as the rate of the pumping of paste into the stope. From a numerical point of view, this backfilling rate is converted by a simple calculation into the rate of increase in the height of the backfill structure, and then to a change in the element properties. This rate is mainly dependent on the cross sectional area of the stope.

2.2 Governing equations

The details of the developed governing equations are given in Wu et al. (2012). The final developed thermo-hydro-chemical coupled model can be presented in the following form:

$$\left[[1-(\mathrm{G}\alpha+\emptyset_0)]^2\rho_t C_p+(\mathrm{G}\alpha+\emptyset_0)\mathrm{S}_{\mathrm{eff}}\rho_W C_W+(\mathrm{G}\alpha+\emptyset_0)(1-\mathrm{S}_{\mathrm{eff}})\frac{\mathrm{M_A}}{\mathrm{R_A}T}\mathrm{p_A}C_A\right]\frac{\partial T}{\partial t}-$$

$$\left\{\frac{\sqrt{\mathrm{S_{eff}}}\left[1-\left(1-\mathrm{S_{eff}}^{1/\mathrm{X}}\right)^{\mathrm{X}}\right]^2}{0.6612(\mathrm{T}-229)^{-1.562}}\rho_W C_W+\frac{\sqrt{1-\mathrm{S_{eff}}}\left(1-\mathrm{S_{eff}}^{1/\mathrm{X}}\right)^{2\mathrm{X}}}{3.85\times10^{-8}}\cdot\frac{\mathrm{M_A}}{\mathrm{R_A}\mathrm{T}^2}\mathrm{p_A}C_A\right\}[\mathrm{K_T}\cdot\mathrm{A}\cdot(\alpha)^{\mathrm{B}}]\cdot\nabla\mathrm{p_c}\cdot\nabla T+\nabla\cdot\left(-k_{\mathrm{eq}}\nabla T\right)=$$

$$H_T\cdot\left(\frac{\tau_T}{t}\right)^{\beta}\cdot\left(\frac{\beta\tau_T}{\tau t}\right)\cdot\alpha(t)\cdot\frac{E}{R}\left(\frac{1}{273+\mathrm{T}_r}-\frac{1}{273+T_c}\right)\cdot v\cdot t\cdot A_s \qquad (4)$$

Where:

ρ_w = the water density.

C_w = the water heat capacity at constant pressure.

$\alpha(t)$ = the degree of binder hydration at time t.

$(\rho C)_{\mathrm{eq}}$ = the equivalent volumetric heat capacity of the solid-fluid system at constant pressure.

k_{eq} = the equivalent thermal conductivity of the solid-fluid system.

$\nabla\mathrm{p_c}$ = the capillary pressure gradient.

$\mathrm{S_{eff}}$ = the effective saturation degree, $\emptyset_0$, is the initial porosity.

$\mathrm{K_T}$ = the permeability of the tailings being used.

$\mathrm{M_A}$ = the molar mass of air, $\mathrm{R_A}$, the universal gas constant of air.

H_T = the total ultimate heat of binder hydration of the cement-based materials.

T_r = the reference temperature.

T_c = the temperature of the cement-based materials.

E = the apparent activation energy.

R = the universal gas constant.

As shown in Equation (3), the mathematical model couples the thermal, hydraulic and chemical (THC) processes. On the one hand, when the binder hydration of the CPB mix proceeds, the exothermic chemical reactions begin to generate heat, which in turn, have an effect on the thermal process (e.g. temperature increment) within the CPB mix. In contrast, the chemical reactions will be influenced by the temperature – "a higher temperature accelerates the binder hydration" (Nasir & Fall 2010). On the other hand, the chemical reactions consume water, which affects the hydraulic process (e.g. desaturation). Conversely, the chemical process, i.e. binder hydration, is influenced by the water content. In addition, the thermal process influenced by the temperature evolution will exert an effect on the hydraulic process. For example, the relative permeability, density and viscosity are temperature dependent. On the contrary, change in hydraulic parameters will affect the fluid flow, which further influences the thermal process through heat transfer in the fluid.

2.3 Examples of model validations

In order to test and verify the ability of the developed coupled THC model to predict the temperature development within a CPB and its thermal interactions with the surrounding environments, the model was applied to simulate heat development within CPBs subjected to various thermal boundary conditions, and the simulation results were compared with the experimental data. Three categories of experimental data were used: (i) data from experimental tests performed on various types CPB samples (from different mines, different mix components) at the University of Ottawa and in other laboratories; (ii) data obtained from tests performed on small scale models of CPB at the University of Ottawa and in other laboratories; (iii) field data. The validation results have shown that there is good agreement between the predicted and experimental results, i.e. the ability of the developed THC model and simulation tool to predict the temperature and binder hydration development within CPB structures as well as to predict heat transfer between CPB and the surrounding media (rock mass, mine air). Some examples of validation results are presented in Figures 3-5, whereas further results are published elsewhere (Wu et al. 2012, 2013). Figure 3 illustrates a comparison between the temperature profile measured within a field CPB structure by Williams et al. (2001) and that predicted by the THC model. It should be pointed out that the binder type for the field study is Portland cement type I. Figure 4 shows an example of validation of the temperature predicted by the developed model against the temperature data measured within a small laboratory scale model of CPB (Wu et al. 2013). This laboratory study utilised PCI/fly-ash (50:50), i.e. the mass ratio of Portland cement type I (PCI), to fly-ash (FA), is 50 to 50%, and PCI/SLAG (50:50), i.e. the mass ratio of PCI to slag is 50 to 50%. Figure 5 demonstrates a comparison between the temperature profile measured by De Souza and Hewitt (2005) within a small scale CPB model and that predicted from the model. From the validation results presented in Figures 3-5 it can be seen that there is a good agreement between the predicted and the measured temperature profiles in both field and laboratory verification tests.

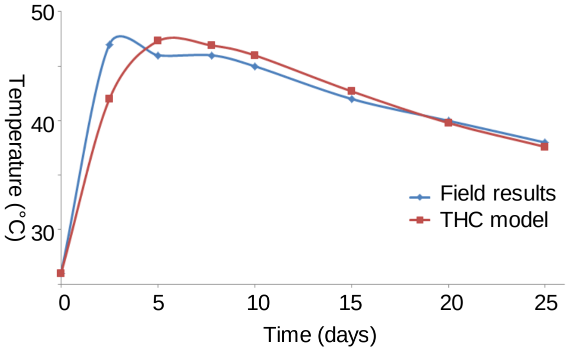
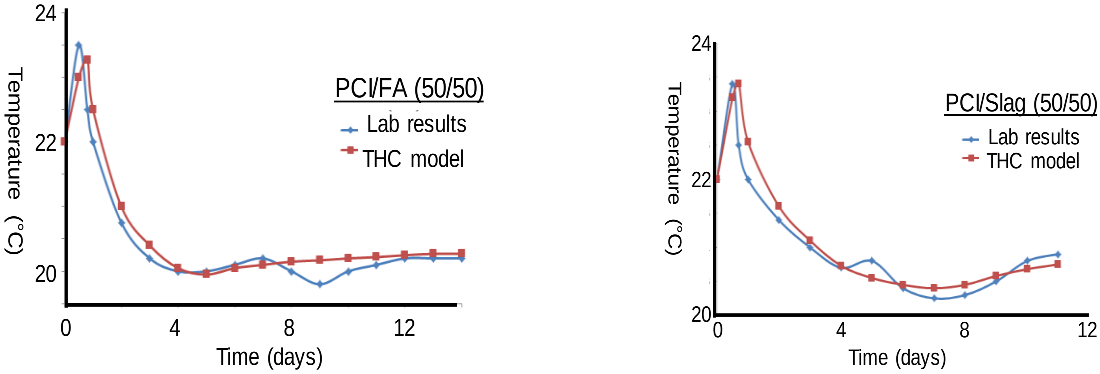


Figure 3 Comparison between the results of simulation and field study (field data from Williams et al. 2001)



(a) (b)

Figure 4 An example of comparison between the results of the THC model simulation and laboratory study; (a) the mass ratio of PCI to FA is 50:50%; (b) the mass ratio of PCI to slag is 50:50%

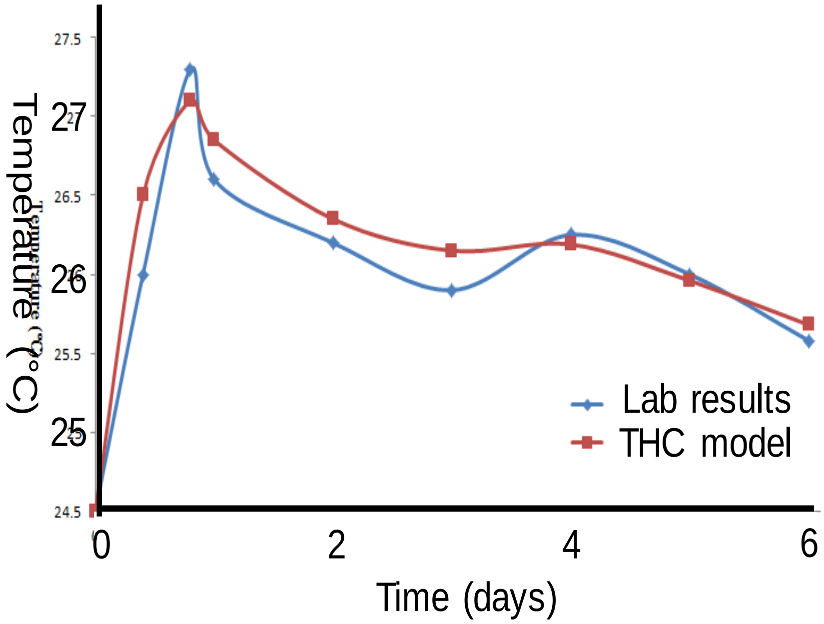


Figure 5 **Comparison between the simulation results and laboratory study by De Souza and Hewitt (2005)**

2.4 Examples of numerical simulation results

After the successful verification and demonstration of the developed THC model's ability to predict the heat development within CPBs under various thermal boundary conditions, the model was applied to simulate the thermal response of hydrating CPB structure surrounded by rock mass with various initial temperatures (cold to hot rock temperatures). An illustrative example of the simulated models is shown in Figure 6, where T0 is the initial CPB temperature, T1 is the initial rock temperature, T2 is the initial air temperature, W is the width of the backfilling stope, and H is the height of the stope. It should be noted that three types of binders were selected to conduct the study: PCI/FA (50:50), PCI/SLAG (50:50) and PCI (100%), i.e. the mass ratio of PCI is 100% in the binder. Further details on the CPB mix components are given by Wu et al. (2012). Figure 7 shows a typical example of simulation results with regards to the effect of initial rock temperatures on the heat development within CPB structures. The temperature development at the point located 2 m above the bottom of the backfill stope is investigated, which shows that the initial rock temperatures significantly affect the temperature variation within the CPB. Figure 8 demonstrates the effect of initial rock temperatures on temperature distribution after 30 days of curing. From these figures, it can be noted that, regardless of the type of binder used, higher initial rock temperatures lead to greater temperature rises and longer times to keep the higher temperatures within the CPB structures. The reason is that a high curing temperature is beneficial to the temperature rise within CPB by accelerating binder hydration, which is consistent with the results obtained by Fall et al. (2010) in which it was found that more hydration products are formed with higher curing temperatures. The observations are very useful to backfilling operations in practice: due to the geothermal gradient, the rock temperature in a deep underground mine is high (Figure 1), which is helpful for curing CPB by providing a significant temperature rise, and thus, an alternative for reducing binder content. The obtained simulation results (Wu et al. 2012) have also shown, regardless of binder type, initial rock temperatures have no significant effect on the temperature rise and distribution in the middle of large CPB structures, but affect the temperature variation near the interface between the CPB and its surrounding rock. This is due to the fact that the middle part of the large CPB structure is less influenced by its surrounding media.

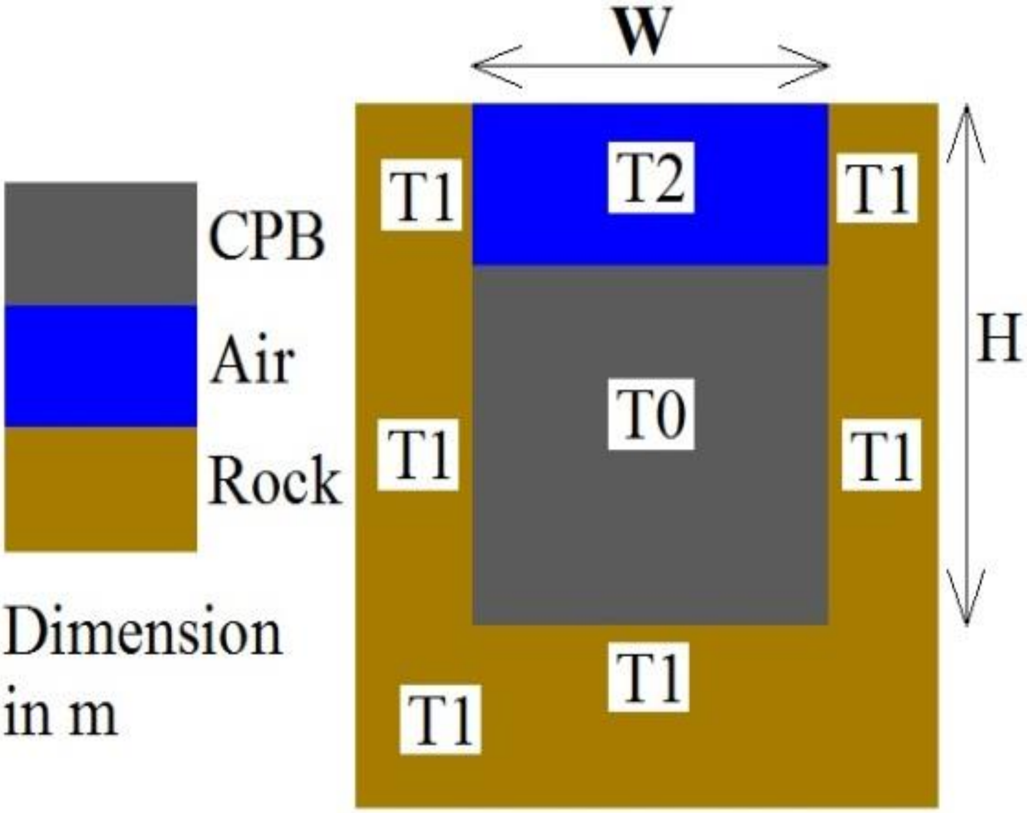
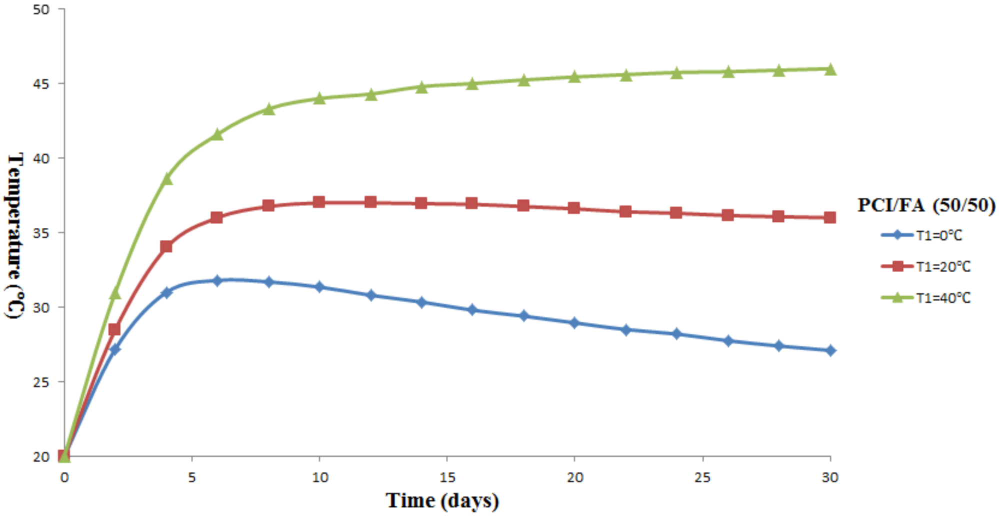


Figure 6 Geometry of the simulated model for application to practical situations; T0: initial CPB temperature; T1: initial rock temperature; T2: initial air temperature; W: width of the backfilling stope; H: height of the stope

Figure 7 also reveals that the temperature rise and evolution within the CPB structures is affected by the supplement of mineral admixtures regardless of the initial rock temperatures. By replacing 50% of the PCI with FA or slag, the maximal temperature decreases because the heat released by the hydration of PC is much more than that of FA or slag. The results presented in Figures 7 and 8 can also be verified by several other studies (Buffo-Lacarriere et al. 2007; Wang & Lee 2010). From Figures 7 and 8, it can also be seen that the maximum temperature generated within the CPB made of PCI/FA (50:50) is lower than that produced within the CPB made of PCI/SLAG (50:50). This is due to the fact that heat generation by slag hydration is more than that as a result of FA (Wang & Lee 2010). In addition, Figures 7 and 8 show that although the addition of mineral admixtures into PCI will decrease the heat generation within the CPB, the mixed binder can still bring about a significant temperature rise. Therefore, in practical backfilling operations, it could be favourable to proportionally replace PCI with FA or slag in the binder, which can reduce the preparation cost of the CPB. Furthermore, by mixing a certain amount of mineral admixture with PCI, this can control and adjust the maximum temperature in the CPB, thus avoiding the occurrence of overly high temperatures which could be harmful to its strength development.


50
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40
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30
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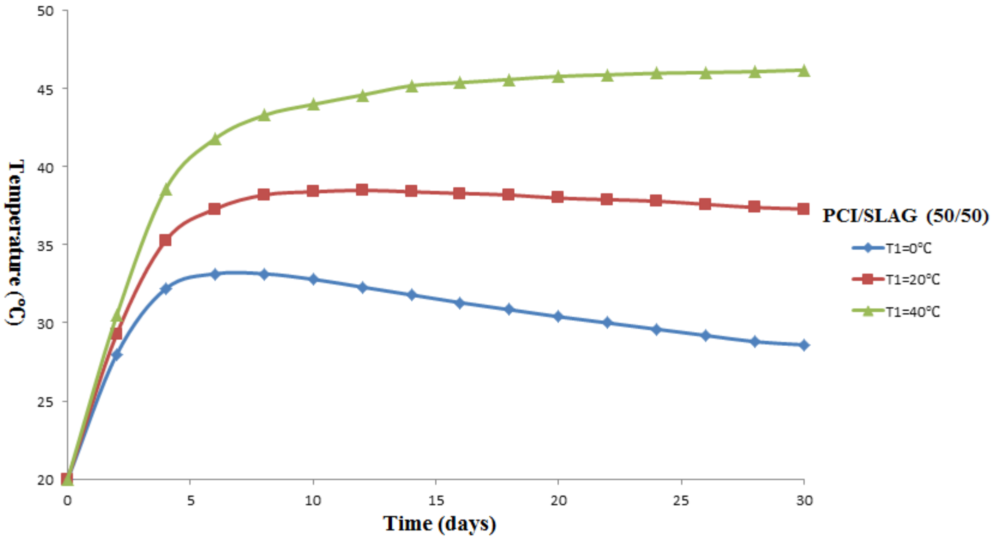
20
0
5
10
15
20
25
30
Temperature (°C)
Time (days)
PCI/FA (50/50)
T1=0°C
T1=20°C
T1=40°C

(a)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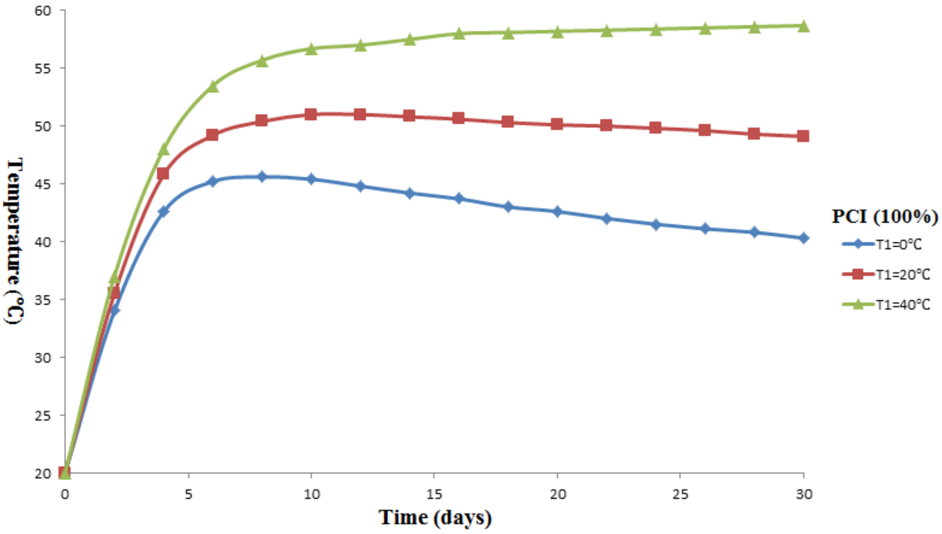
Temperature (°C)
Time (days)
PCI/SLAG (50/50)
T1=0°C
T1=20°C
T1=40°C

(b)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Temperature (°C)
Time (days)
PCI (100%)
T1=0°C
T1=20°C
T1=40°C

(c)

Figure 7 Effect of initial rock temperatures on the heat development within CPB with (a) PCI/FA (50:50); (b) PCI/SLAG (50:50); (c) PCI (100%)

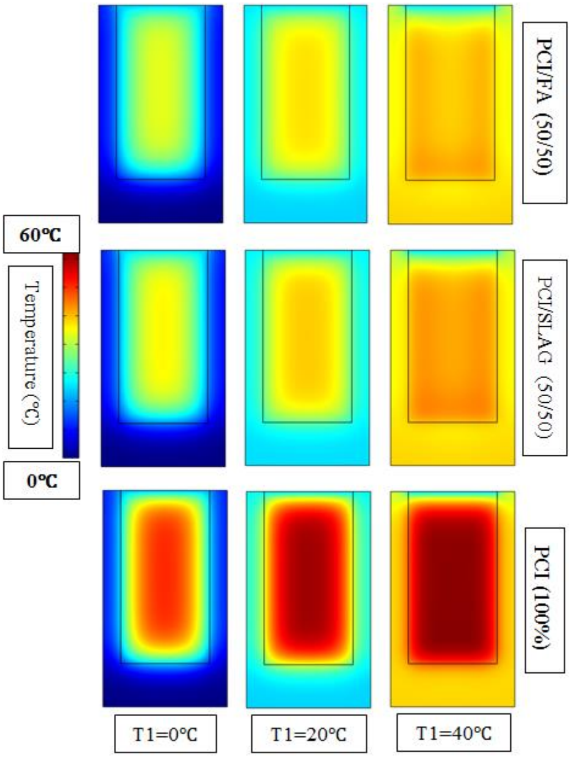


Figure 8 Temperature distribution in CPB structure and the surrounding rock after 30 days

3 Experimental investigations of the effect of high temperatures on the properties of CPB

The numerical simulation results presented above have shown that the deep mine hot rock temperature has a significant impact on the temperature development within the hydrating CPB structure, i.e. on the CPB curing temperature. The simulation studies revealed that high temperatures can develop within CPB structures in deep mine temperatures conditions. These high temperatures may have significant impact on key performance properties of CPB, such as strength development, deformation behaviour, hydraulic properties and durability. Therefore, an extensive experimental program was conducted to investigate the effect of high temperature on the aforementioned properties of CPB. CPB specimens with different mix components (e.g. binder types and contents, W/C ratios, tailings types, sulphate content) were prepared. The specimens were then sealed, this avoids the evaporation of water, and cured in developed environmental chambers at specific curing temperatures and times. After the specific curing times, the CPB samples were subjected to various tests (mechanical, hydraulic, microstructural tests). More details about the mixes prepared and experimental program are given in Fall et al. (2009, 2010), Pokharel and Fall (2010), Fall and Pokharel (2010). Typical examples of results obtained are presented and discussed below.

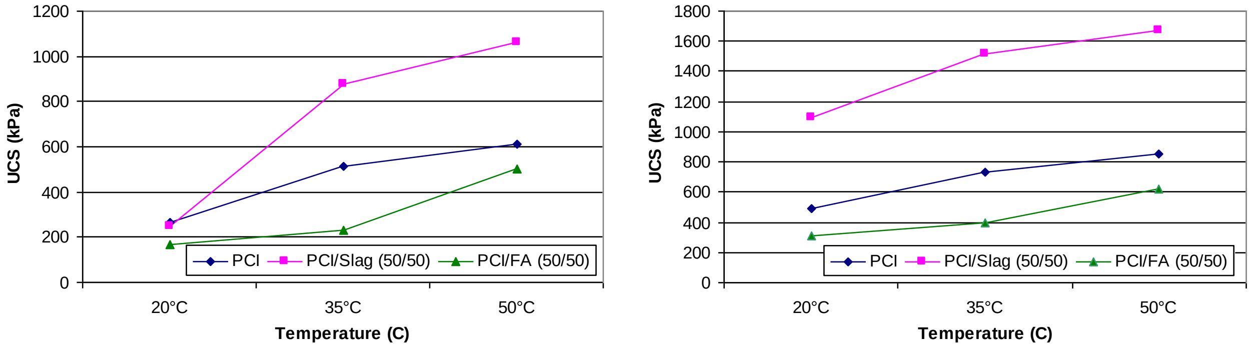
3.1 Effect of high curing temperatures on the strength development of CPB

The most important parameters used in practice to judge the mechanical stability of CPB structure include uniaxial compressive strength (UCS) (Hassani & Archibald 1998). However, UCS is not the only significant parameter showing the structural integrity of the CPB. In the ground support role, the deformation behaviour and stiffness (Young's modulus) of the CPB are also key design properties of interest. The effect of high curing temperature on the UCS, deformation behaviour and stiffness on various CPB mixes were investigated at three temperature levels (20, 35 and 50°C) during different curing times. The results obtained have shown that high curing temperatures significantly affect the aforementioned properties and behaviour of CPB. Figures 9(a) and (b) show a typical example of the results obtained with regards to the effect of high curing temperatures on the strength of seven and 28 days old CPBs, respectively. These figures highlight the effect of curing temperature on the strength of paste backfill cemented with PCI, PCI/slag (50:50), and PCI/FA. It can be observed that, regardless of the binder type, the UCS increases as the curing temperature increases. The reason for this is that a higher temperature accelerates the binder hydration (Fall et al. 2009). From this figure, it is obvious that the increases in strength of CPB mixtures containing a slag and PCI mix (in the weight ratio 50:50) far exceed those observed for CPB mixtures made using only PCI or a mix of PCI and FA (50:50). These results suggest that curing at elevated temperature gives a more significant contribution to (slag) pozzolanic reaction than that to PCI hydration. This is because hydration of slag is much more sensitive to temperature than PCI. Indeed, higher temperatures lead to the increase of the hydration reaction of PCI, and thus the formation of C-S-H and CH. The slag admixture reacts with the CH in varying degrees. Consequently, extra C-S-H is produced. This is positive for the CPB strength development. These results then imply that in the case of hot or deep mine curing temperatures (>20°C), the partial replacement of PCI by slag increases the compressive strength of CPB (up to 28 days). However, test results show that the FA significantly contributes to reducing the compressive strength of CPB at all curing temperatures (20, 35 and 50°C) (Figure 9). The reason for this disappointing compressive strength development of FA-CPB is that the FA blended cement CPB requires an extended curing time in order to take advantage of the beneficial effects of the pozzolanic activity and pore refinement. This observation is also supported by the results of MIP tests performed by Fall et al. (2009) on 28 day old PCI-CPB, slag-CPB and FA-CPB samples cured at 35°C. The MIP test results revealed that the slag-CPB samples show both the lowest porosity and finer pore structure (due to the formation of higher amount of hydration products), whereas the FA-CPB samples show the highest porosity and coarser pore structure (due to the formation of lower amount of hydration products). However, it should be emphasised that as underlined by many authors (e.g. Maltais & Marchand 1997), the FA/cement reaction processes significantly depend on the chemical and physical properties of FA. These properties tend to differ markedly from one source to another. Even within one source, individual grains are highly variable in nature (Maltais & Marchand 1997). The results presented above with respect to the effect of hot temperatures on the early age strength of CPB may have significant practical applications. A high rate of early backfill strength gain achieved in an economical manner is a target for all in the mining industry. Early strength gain is of special importance for opening of the barricades, scheduling the extraction of adjacent stopes and thus, reduction of the mining cycle time, hence increasing mining efficiency and production. This is obviously associated with economic benefit for mines. Furthermore, this high early age strength gain may play a significant role in reducing the potential for CPB liquefaction at early age of cure and thus decreasing barricade failure risk. This is because the binder hydration product is able to create bonds between individual tailings particles of the CPB and provides strength.

Figure 10 gives a typical example of the results obtained with regards to the effect of high curing temperatures on the strength of CPB at advanced ages. From this figure, it is interesting to notice that up to 150 days of curing time, the studied PCI-CPB samples do not show any high temperature inversion in the compressive strengths as commonly observed in conventional concrete and mortar materials. Contrary to PCI-CPB samples, the Slag-CPB specimens show a decrease of their 150 days compressive strength for curing temperatures >35°C. The absence of a crossover effect on PCI-CPB samples cured up to 150 days is an important finding. This finding suggests that the effect of a high initial curing temperature on the strength development of PCI-CPB is not fully similar to that on conventional PC concrete and mortar materials. Most of the PC concretes cured at high temperatures show a drop in their strength or strength inversion after 28 days of curing time. The observed decrease in the long term strength (150 days) of slag-CPB cured at higher temperatures (>35°) is consistent with the results of the investigations conducted by Escalante and Sharp (2001), who concluded that 30°C is the optimum temperature for strength development in the slag cement paste blend. These authors attributed the lower long term strength of the blended slag-cement cured at temperatures ≥35°C to the formation of hydration rims around the unhydrated slag grain.

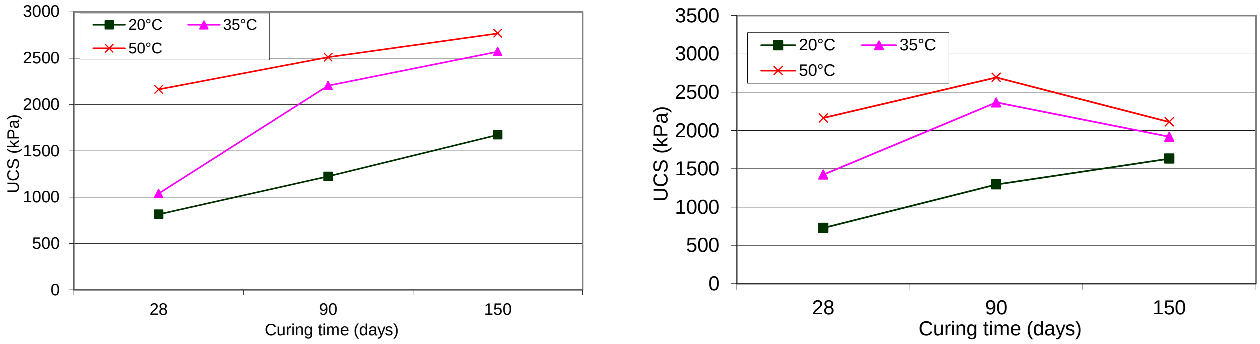
The findings regarding the effect of curing temperature on the long term strength (up to 150 days) of CPB presented above suggest that paste backfills cement with only PCI are less sensitive to the phenomena of the crossover effect than those made of PCI blended with slag. However, the drop in UCS appears for the studies slag-CPB only after three months of curing.

This implies that the mining of secondary stopes adjacent to backfilled stopes subjected to high curing temperatures (>35°C) after three months of curing could lead to backfill stability issues, when the CPB contains slag (in binder proportion of 4.5% and ratio of 50:50).



(a) (b)

Figure 9 Effect of curing temperature on the strength of CPBs made of various types of binders after (a) 7 days; and (b) 28 days of curing (W/C~7.5; slump~7")



(a) (b)

Figure 10 Effect of curing temperature on the development of the long term strength of CPB; (a) PCI-CPB (W/C = 7.5, slump ~ 17 cm; %cement = 4.5%); and (b) slag-CPB (W/C = 7.5, slump ~ 17.78 cm (7")); %cement = 4.5%)

3.2 Effect of high temperature on sulphate attack on CPB

CPB materials often contain sulphate. The quantity of sulphate that can be present within the CPB system is usually much higher than that found in conventional concretes or mortars subject to sulphate attacks. The initial sulphate content of CPBs can be low (<5,000 ppm) to very high (25,000 ppm). This sulphate can lead to the deterioration of the CPB through an internal sulphate attack. The sulphate attack not only decreases the strength (mechanical stability) of the hardened CPB structures, it may also contribute to the development of cracks in the CPB (Fall & Pokharel 2010), thus reducing its environmental performance. In contrast to conventional concrete, the sources of sulphate in CPBs are essentially internal. Most of the previous studies on sulphate on CPB were conducted on CPBs cured at room temperatures, which are not representative of deep mine high temperatures. Technical data on the effect of high curing temperatures on sulphate attack on CPBs is quite limited. This means that the impact of high temperatures on the resistance of CPB to sulphate attack is still not well understood. Therefore, several CPB specimens with various initial sulphate contents (0, 5,000, 15,000, and 25,000 ppm) and 4.5% binder contents (PCI; slag/

PCI (50:50)), and cured at different temperatures (2, 20, 35, and 50°C) were tested at 150 days curing times to study the impact of high temperatures and sulphate on the strength of CPB and its mineralogical composition.

The results obtained have shown that the effect of sulphate on CPB strength is strongly affected by the curing temperature. The sulphate-temperature-cement hydration interactions can have positive or negative effects on the mechanical resistance (strength). The magnitude of the effects depends on the amount of the initial sulphate content and the value of the curing temperature. It is found that for curing temperatures which are ≥ 20°C, sulphate concentrations up to 15,000 ppm have a beneficial effect on the strength of the studied 150 days old CPBs. This beneficial effect on the UCS value is attributed to the precipitation of expansive minerals that are not excessive in the empty pores, such as ettringite and gypsum, in the empty pores of the CPBs which contribute to their hardening as well as to the refinement (porosity reduction) of the pore structure of the CPB as demonstrated by Fall and Pokharel (2010) and Pokharel and Fall (2010). This hardening effect and porosity reduction result in strength increase. However, the results obtained have revealed that CPBs with 25,000 ppm initial sulphate content generally show lower strength, especially at high curing temperatures (50°C) (Figure 11). The mechanisms responsible for this lower strength of 25,000 ppm-CPBs depend on the curing temperature. For curing temperatures ≤35°C, the decrease in the strength of the 25,000 ppm-CPBs is due the combined effect of the inhibition of the cement hydration by high sulphate content and the physical damage of the CPBs due to the formation of excessive amounts of expansive minerals, as commonly observed in cemented materials (concrete, CPB, mortar) cured at room temperatures. However, it is found, that that the observed severe decrease in strength of 25,000 ppm-CPBs at 50°C cannot be attributed to the negative effect of the expansive minerals and cement hydration inhibition commonly observed in sulphate attacks on cemented material, e.g. concrete, CPB, mortar, in room temperature. The origin of this drop of strength is attributed to the combined effect of two mechanisms as demonstrated in Fall and Pokharel (2010) and Pokharel and Fall (2010). First, the high curing temperature (50°C) and initial sulphate content are associated with absorption of a larger amount of sulphate ions by calcium-silicate-hydrate (C-S-H). This absorption of sulphate by C-S-H could lead to the formation of lower quality C-S-H, thereby decreasing the strength of the CPB. Secondly, since the stability of ettringite decreases with higher temperatures, the destruction of ettringite phases at high temperatures (50°C), led to the coarsening of the pore structure of the 25,000 ppm CPB, thereby contributing to the decrease of its UCS (Fall & Pokharel 2010).

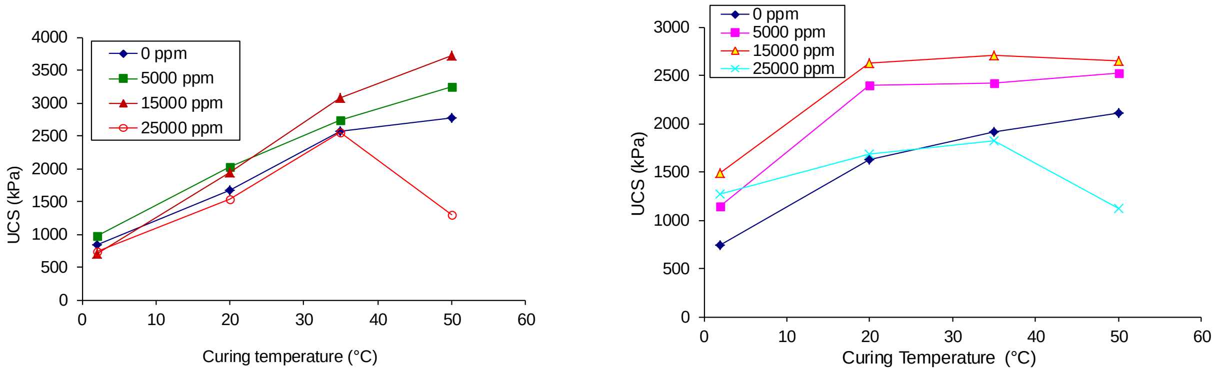


Figure 11 Coupled effect of temperature and sulphate on the 150 days UCS of CPB; (a) PCI-CPB (W/C = 7.6, slump ~ 17.78 cm (7″); %cement = 4.5%); and (b) slag-CPB (W/C = 7.6, slump ~ 17.78 cm (7″); %cement = 4.5%)

3.3 Effect of high temperature on the hydraulic properties of CPB

One of the most important parameters affecting environmental performance and durability of CPBs is permeability. Susceptibility to acid mine drainage (AMD) and ability to release contaminants into the mine areas and/or groundwater (after mine flooding) are relevant environmental design criteria for CPB structures. The sensitivity of CPBs to AMD is mainly dependent on the reactivity (oxidation potential) of the tailings contained in the CPB. In turn, this reactivity is not only dependent on the types and quantity of sulphide minerals present in the CPB system, but also the ease with which fluids, such as oxygen and water, enter and move through the CPB matrix, i.e. on the permeation properties of the CPB (Fall et al. 2009). These permeation properties can be assessed using knowledge of the hydraulic conductivity of the CPB. Furthermore, hydraulic conductivity is one of the main parameters controlling the groundwater flow rate through the CPB structure once it is flooded. In other words, it significantly affects the leaching potential and transport of contaminants through the CPB to groundwater (Levens et al. 1996). In addition, hydraulic conductivity can give relevant information about the pore structure, such as coarseness and connectivity, and the cracking of the CPB. Poorer pore structures, including 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 (Fall et al. 2009). Therefore, several CPB specimens with various mix components), and cured at different temperatures (2, 20, 35, and 50°C) were tested at different curing times (1, 7, 28, and 90 days) to study the impact of high temperatures on the hydraulic conductivity of CPB. Figure 12 provides an example of typical results obtained. In Figure 12, the hydraulic conductivity recorded on four groups of samples (1, 7, 28 and 90 days) made of 4.5% PCI and 4.5% PCI/slag (50:50) cured during the same period of time and temperature are presented to observe the effect of temperature. From Figure 12, it can be noted that the hydraulic conductivity decreases with curing temperature and time for the studied CPBs. The reason is that high curing temperatures allow CPB samples to form higher amounts of hydration products. These products fill the voids and reduce the porosity so that the sample has low hydraulic conductivity at higher curing temperatures (Fall et al. 2009). Figure 12 shows also that the changes in hydraulic conductivity with temperature are more significant in early age samples (up to 7 days). However, the effect of curing temperature on the hydraulic conductivity of CPBs depends on the binder type (Figure 12).

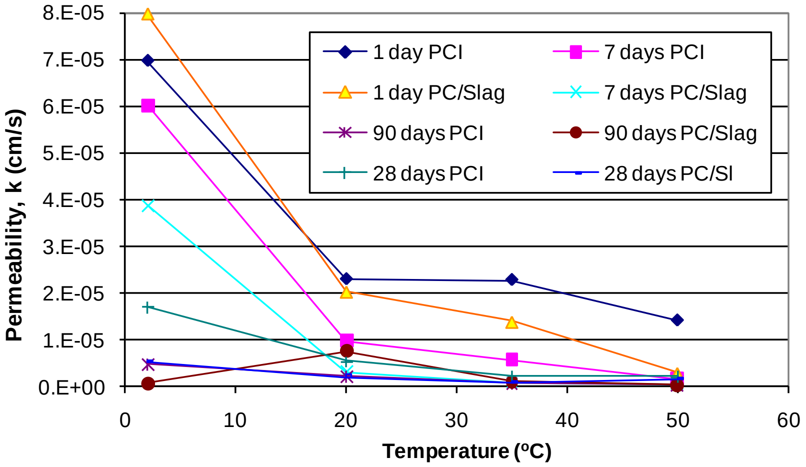


Figure 12 Effect of curing temperature on the hydraulic conductivity of CPB at various curing times (4.5% binder; w/c = 7.6; slump = 17.78 cm (7”))

4 Conclusions

This paper presents the results of a numerical and experimental study which aims to predict the heat development within hydrating CPB structures in deep mine temperature conditions and evaluate the effect of high temperature on key properties of CPBs.

In the numerical study, a coupled THC numerical model has been developed to simulate the temperature development of CPB structures, as well as heat transfer between CPB and its surrounding deep mine rock. According to the model and by considering several important practical situations, various simulation studies are conducted to assess the impact of deep mine hot rock temperatures on the temperature evolution and distribution in CPB. It is found that the initial rock temperatures have significant effects on the temperature development and distribution within CPB structures. High temperatures can develop in CPB structures surrounded by hot rocks.

In the experimental study, the impacts of high curing temperatures on the properties of various CPB mixes have been investigated. The results obtained reveal that the curing temperature has a significant effect on the strength development and deformation behaviour of CPB. However, this effect depends on the CPB mix components and curing time. It is also found that the hydraulic conductivity of CPBs is significantly influenced by the curing temperature. The hydraulic conductivity decreases with curing temperature and time for the studied CPBs. The results show also that the changes in hydraulic conductivity with temperature are more significant in early age samples (up to seven days). Furthermore, the results show that the temperature has a significant impact on the resistance of CPB to sulphate attack. Depending on the curing time, temperature and initial sulphate content, the sulphate can have a positive or negative impact, i.e. leads to an increase or decrease of CPB strength. A high curing temperature (50°C) and initial sulphate content are associated with absorption of a larger amount of sulphate ions by calcium-silicate-hydrate (C-S-H). The obtained results show a strong indication that the absorption of sulphate by C-S-H could lead to the formation of lower quality C-S-H, thereby decreasing the strength of the CPB.

This study has also shown that the effect of deep mine hot temperatures on CPB cannot be ignored in mine backfill operations. The curing temperature is an important factor that has to be considered in order to design more cost-effective, durable and environmental friendly CPB structures in deep mine environments. Results of this study could serve as background information for the development of optimal mine backfill design procedures.

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