Modeling the heat development in hydrating CPB Structures

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ABSTRACT

Cemented paste Backfill (CPB) is a mixture of dewatered tailings, hydraulic binders and water. In addition to its contribution to the stability of mine workplace, CPB has a great benefit to the environment by minimizing surface tailings disposal. So, it becomes one of the most commonly used ways in mine backfilling around the world. Temperature can significintly affect the mechanical properties of cemented backfill. One source of heat in CPB is the heat produced by the binder hydration. Hence, a FLAC based numerical model was developed to analyse the heat developed by hydrating CPB structures. In order to validate the model, results of the developed FLAC were compared with three case studies (mathemetical, laboratory, and field works). The validation results show a good agreement between the developed model and these cases. The effect of stope geometry, thermal properties of both rock and CPB, filling rate, binder content and initial boundary conditions were also investigated.

RÉSUMÉ

Le remblai en pâte cimenté (RPC) est un mélange de résidus miniers, de liant hydraulique et d'eau. En plus de sa contribution à la stabilité des cavités souterraines, le RPC a aussi un grand apport pour l'environnement en réduisant au minimum le dépôt des résidus miniers en surface. Ainsi, le RPC est devenu une des techniques de remblayage minier la plus utilisée dans les mines souterraines du monde. La température peut affecter considérablement les propriétés mécaniques du remblai cimenté. Une source de chaleur dans le RPC est la chaleur produite par l'hydratation du ciment. Ainsi, un modèle numérique (FLAC) a été développé pour prédire et analyser la chaleur développée par les ouvrages de RPC et les transferts de chaleur entre le RPC et le milieu environnant. Afin de valider le modèle, les résultats découlant du modèle développé ont été comparés avec ceux provenant de trois études de cas (mathématiques, de laboratoire et de travaux terrain). Les résultats de la validation montrent une correspondance étroite entre les valeurs prédites et celles mesurées. Les effets de la géométrie des chantiers miniers, des propriétés thermiques des roches et des RPC, de la vitesse de remblayage, de la proportion de liant et de différentes conditions aux limites ont été aussi étudiées.

1 INTRODUCTION

One of the most important processes in the mining operation is the extraction of the valuable minerals from the earth. This process requires the excavation and removal of the ore bodies, leading to the creation of very large voids in underground, or on the surface, which cause a source of instability for the mining workplace as well as for the mining area. On the other side, only a small percentage of the excavated rock or soil is separated as valuable minerals, the rest is considered as a waste. Thus, a large amount of tailings waste material is accumulated at the surface. This may cause some environmental and/or geotechnical problems such as acid mine drainage or tailing dams failures. One of the solutions for these problems is the filling of the voids with the tailings by the process of backfill. Mine backfill allows returning much (up to 60%, Fall et al 2005) of the waste material to the underground mine as well as providing a structural element participating in the ground support. For these reasons, mine backfill has become a widespread practice in mining operations around the world and can play a significant role in the overall of mine operation (Fall and Benzaazoua 2005, Sivakugan et al 2005). Cement can be used as a binder to achieve better and faster mechanical properties, thereby increasing ore recovery under safer conditions. During the last decade, cemented past backfill (CPB) has become a common way in mine backfilling in many areas around the world. In general, CPB is a mixture of dewatered tailings (contains between 70% and 85 % solid by weight (Fall et al 2005) from the milling or processing operation of the mine, water and hydraulic binders (usually 3% to 7 % by weight) (Hassani and Archibald 1998). As a cemented material, the mechanical properties of CPB can be affected by many factors, such as tailings grain size and mineralogical composition (Fall et al 2005), water to cement ratio, binder content and curing temperature (Fall and Samb 2006). For cemented materials like CPB, curing temperature has a significant effect on the mechanical properties ((Fall and Samb 2006). This effect can be positive by increasing the compressive strength or negative by decreasing the compressive strength at advanced age of CPB for too high curing temperatures. One of the main sources of temperature in CPB is the heat produced by the cement hydration. When CPB is placed in the ore opening under field conditions, heat will be generated in the CPB and then transferred from the CPB to the surroundings, thereby influencing both the environmental working temperature and the mechanical behaviour of the material at early ages. Despite numerous studies and numerical models on the binder's

heat of hydration for conventional concrete, the results of these studies can not be directly applied to CPB due to relatively high differences between CPB materials and conventional concrete materials. Furthermore, the mathematical approach for the analysis and modeling of the heat developed by the hydration of CPB materials has not been considered until now, nor has the prediction of the coupled thermo-chemical (interactions between temperature and cement hydration) behaviour of CPB been done. There is a crucial need to develop a model that will allow to predict the heat produced by hydrating CPB structures as well as to predict the heat transfer between the CPB structures and the surroundings in any mine thermal conditions. Hence, in this paper, a FLAC model was developed to predict the heat of hydration of CPB structures and the temperature distribution during the early age of filling process as well as the heat transfer between CPB and the surrounding media.

This paper is organized as follows. The first part is dealing with the development of the numerical model. The next presents the model validation results, and then some model applications will be presented. Finally we present our conclusions.

2 DEVELOPMENT OF THE NUMERICAL MODEL

By using FLAC [Itasca2005], a numerical model was developed to study the heat of binder hydration in CPB as well as the temperature distribution and temperature history. The model uses two main categories of heat equations, first category is FLAC built – in equations, which are responsible for the principle of heat transfer calculations such as the conduction equation and energy balance equation. Second category, is external equations " User Defined " equations, which are added to FLAC by using the FISH language to implement the hydration process, model generation, rate of backfilling and some other processes in the model as described in the following sections.

2.1 Built -in equations

For the purpose of thermal analysis two main built in equations are used by FLAC, first of all is the energy balance equation, the second equation is the heat transport. Details about the mathematical and numerical approach are published in Itasca2005.

2.2 External codes and equation "User Defined"

Because of the cement hydration, heat will be generated, and the thermal properties of CPB, including, volumetric heat source and thermal conductivity will be time dependent properties. In order to put these changes with time into operation, some external equations were implemented in FLAC by using the FISH programming language. The following are the main external equations.

2.2.1 Binder hydration equations

The degree of hydration α is defined as the cement fraction that has reacted (De Schutter 1999). Due to difficulties in experimentally determining the degree of hydration α , it is often approximated by the degree of heat liberation or the degree of reaction which can be expressed by the fraction of released heat related to the total heat of reaction. As early as 1930s, the liberated heat of hydration has been used as an indicator of the degree of hydrations processes equations used in this model are described below.

2.2.1.1 Degree of hydration

The value of the degree of hydration can be represented by the degree of reaction, which can be expressed by the fraction of released heat related to the total heat of reaction (De Scutter 1995):

$$r(t) = \frac{Q(t)}{Q_{\text{max}}} \approx \frac{1}{Q_{\text{max}}} \int_0^t q(t) dt \dots [3]$$

Where:

r : degree of reaction

 $Q_{: released heat}$

 $Q_{
m max}$: total heat of reaction

q(t) : rate of released heat

Schindler et al (2004) suggested the following equation to evaluate the degree of hydration:

$$r(t) = e^{-(\ln \tau)^{-\kappa}}$$
......[4]

where :

$$\tau = 1 + \frac{t_{eqi}}{t1} \tag{5}$$

 t_{eqi} : equivalent time $oldsymbol{\mathcal{K}}$, t_1 : hydration parameters

The coupled effect of time and temperature can be introduced either in term of equivalent age [1]:

$$t_{eqi} = \int_{t=0}^{age} e^{\left[-\frac{\phi}{R}\left(\frac{1}{T+273} - \frac{1}{T_r+273}\right)\right]} \Delta t$$
......[6]

where :

 ϕ ...or...Ea : activation energy

- R : universal Gas constant
- T: temperature

T_r : reference temperature

Or it can be introduced directly in term of Arrhenius' law equation 7(D'Aloia and Chanvillard 2002), which was adopted in this model.

where :

A : Arrhenius' law constant

2.2.1.2 Heat of hydration

Scutter and Taerwe (1995) suggested the following formula to consider the coupled effect of temperature and time to the heat of hydration :

$$q(r,\theta) = q_{\max,20} \times f(r) \times g(\theta)$$
[8]

Where:

 $\theta_{:temperature}$

 $q_{\max,20}$: maximum rate of released heat at temperature of 20°C

$$f(r)$$
: is the function of degree of reaction "time"
 $f(r) = c.[\sin(r\pi)]^a.\exp(-b.r)$[9]

a, b and c : constant, and can be estimated based on laboratory tests (Scutter and Taerwe 1995)

 $g(\theta)$: is the function of temperature, Arrhenius' law equation 7 was adopted to represent this function (Scutter and Taerwe 1995). After rearrangement, equation 7 can be written as:

$$g(\theta) = \exp\left[\frac{E}{R}\left(\frac{1}{293} - \frac{1}{273 + \theta}\right)\right]_{\dots\dots\dots\dots[10]}$$

Putting equation 9 and 10 into equation 8 results in:

$$q(r,\theta) = q_{\max,20} \times c.[\sin(r\pi)]^a . \exp(-b.r)$$
$$\times \exp\left[\frac{E}{R}\left(\frac{1}{293} - \frac{1}{273 + T}\right)\right]$$
.....[11]

2.2.2 Activation energy

As shown in equation 11, an adequate estimate of the heat of hydration is directly linked to a correct determination of the activation energy. D'Aloia and Chanvillard (2002) stated that "for cement there is a unique parameter, which characterises the cemented mixture and which can be found in the Arrhenius' law", in case of cement hydration, several interdependent

chemical reactions are involved. So the expression of hydration equation is just an approximation of the whole processes. For this reason the activation energy is sometimes called "apparent Ea". Ea characterises the whole cemented molecule mixture including the type of cement, but also the water to cement ratio w/c, etc D'Aloia and Chanvillard (2002). Freiesleben Hansen and Pedersen (1977) proposed the apparent activation energy according to the following equations (Jin *et al* 2001):

for
$$T^{C} < 20$$

 $E(T^{C}) = 33,500 + 1470(20 - T^{C})J / mol,[12]$
And for $T^{C} >= 20$
 $E(T^{C}) = 33,500J / mol,[13]$
Where:
 T^{C} ; is the computed material temperature (°C).

2.2.3 Time dependant thermal conductivity and grid generation

Laboratory tests show that the thermal conductivity of the CPB is a time and temperature dependent property (Celestine and Fall 2008). By using the laboratory results of the thermal conductivity (Celestine and Fall 2008) for a wide range of time and temperature, a special FISH code was designed to take into account the change in this property in the process of thermal analysis.

Grid generation is the process of dividing bounded field into elements. This part is an important process of FLAC for the solution of partial differential equations (PDE). In this paper, a special code was designed by using FISH to simplify the process of grid generation by using simple input data.

2.2.4 Rate of backfilling

The rate of backfilling can be defined as the rate of pumping of paste backfill into the stope; this role can be converted by simple calculation into the rate of increasing in the height of the backfill. This rate is mainly dependent on the cross sectional area (A) of the stope as shown in equation (14):

Where:

H : height of backfill

$$\frac{\Delta p}{\Delta t}$$
 : pumping rate (tons/hour)

 A_r : cross section area of the stope

In case of large backfill volume, the filling process may take long time. Therefore, there will be a considerable variation in the degree of hydration between the layers of filling. For this reason, a special code was designed by using FISH language to simulate the rate of backfilling.

3 MODEL VALIDATION

To validate the results of the developed FLAC model, three examples from three different studies were selected. The selected examples represent three different types of study: numerical, laboratory and field study. Validation with the field study will be presented in this paper.

3.1 Example: Field study

Williams et al (2001) performed a field study on cemented backfill by measuring stress and strain changes in the backfill and reinforcing members during undercut mining, in order to evaluate if the temperature compensation was required for the instrumented strain gauges. The temperature developments due to the heat of cement hydration of the solidifying filling masses were recorded.

For the validation purpose of the developed model, the temperature history at the middle of the backfill was investigated ("P.B") and compared with the simulated FLAC model. Figure 1 shows the geometry of the simulated FLAC model. The main properties and boundary conditions for the input used for the FLAC models are given in appendix A (for more details see Othman and Fall (2008).



Figure 1: Field example: geometry of the simulated model.

Figure 2 shows a comparison of temperature history between the current study model and the field data from the selected example.



Figure 2: Comparison between the results of developed FLAC model and Field tests (field data adopted from Williams et al 2001).

Generally, the comparison shows a good agreement between the developed FLAC model and the field test results, especially with the maximum temperature. Otherwise, the differences in temperature may be due to the varied boundary conditions in the field.

4 MODEL APPLICATIONS

After the validation of the model with different cases, the model was used to conduct some applications. The selected applications have been chosen to study the effect of some field factors and mix properties on the temperature development in the hydrating CPB and the heat transfer between CPB and rock. In this paper, one part of these applications will be presented. More details about the applications are published in Othman and Fall (2008).

4.1 Effect of stope geometry

4.1.1 Stope size

Since the size of backfilled stope can vary from small to large stopes, the effect of the CPB structure size on the heat released by hydration and heat transfer induced by CPB was investigated by taking different stope sizes. The selected range of the size was (0.5x1, 1x2, 2.5x5 and 5x10 m). Figure 3 shows the temperature development with time at point (p) located 2.5 m above the bottom of the stope with different stope sizes. Results have shown that the size of CPB structure has significant effect on the heat development for hydrating CPB structure. Increasing the stope size will increase the heat development and also keep the temperature high for longer time. There are two main factors controlling this behaviour: Firstly, increasing the size will delay the heat transfer from the hydrated CPB to the surroundings, which leads to the accumulation of heat and increasing in the temperature. Secondly, the increase in temperature itself will help in accelerating the cement chemical reaction according to Arrhenius' law as shown in equation 7. The increase in backfill temperature and the reduction in backfill heat loss associated with bigger stope size will lead to higher early age strength of the CPB. This is beneficial for the mining operations for safety and cost point of view.



Figure 3: Effect of stope size on the heat development of CPB (binder content: 107 kg/m³).

T effect of stope size on the temperature distribution after 28 days was also investigated as shown in Figure 4 (b, c)



Figure 4a: Effect of stope size on the Temperature distribution in CPB of size 5x10 m after 28 days.



Figure 4b: Effect of stope size on the temperature distribution in CPB of size 30x60 m after 28 days.

Figure 4: Effect of stope size on the temperature distribution in CPB

4.2 Effect of CPB thermal properties

In general, CPB is a porous material, with three main phases: solid, water and gas. Therefore, the thermal properties of the CPB depends on the individual thermal properties of these phases, mainly the solid phase "or the tailings". The variety in ore minerals leads to the variation in thermal properties of the tailings, hence in the thermal properties of the CPB. Furthermore, the value of both: void ratio and degree of saturation will have effect on the thermal properties of the CPB. The effect of thermal properties of CPB was investigated by studying the impact of the thermal conductivity and heat capacity on the heat development in hydrating CPB as shown in figure 5 and figure 6 respectively. The results show that the change in specific heat of the CPB has a significant effect on the heat development in the CPB, while the thermal conductivity has lower effect.



Figure 5: Effect of CPB thermal conductivity on the heat development of CPB (binder content: 107 kg/m^3).



Figure 6: Effect of CPB heat capacity on the heat development of CPB (binder content: 107 kg/m^3).

4.3 Effect of binder content

The binder content is the main factor that controls both the mechanical properties and cost of the CPB. The effect of binder content on the heat development of the CPB was investigated by taking a wide range of binder content values of: 75, 150, 200, and 250 kg/m3. Figure 7 shows the effect of binder content on the heat development in the CPB. Results show that binder content has a significant effect on the heat development of the CPB. Re-representation of the results shows that this effect increases non-linearly as shown in figure 8.



Figure 7: Effect of binder content on the heat development of CPB.



Figure 8: Effect of binder content on the increase in temperature within CPB at curing time of 5 days.

4.4 Effect of initial CPB temperature

In field, CPB initial temperature is mainly dependent on the initial temperature of tailings, cement and water. Different environmental temperatures from location, and/or from season to another will significantly affect the storage temperature, hence the initial CPB temperature. Moderate heat can be also added to CPB during its preparation to increase its early age strength as reported by Fall et al. 2007. A range of initial CPB temperatures of (2 to 35 °C) were selected to investigate the effect of initial CPB temperature on the heat development in CPB. Figure 9 shows the effect of the initial temperature of the CPB on the heat development at point (p) located 2.5 m above the bottom of the stope.



Figure 9 : Effect of initial temperature of the CPB on the increase in temperature of CPB at 2.5 m above the bottom of the stope.

Figure 10 shows the effect of the initial temperature of the CPB on the heat development at point (p) located 7.5 m above the bottom of the stope.



Figure 10 : Effect of initial temperature of the CPB on the heat development of CPB at 7.5 m above the bottom of the stope.

Re-analysing the above figures shows the effect of the initial CPB temperature on the increase in temperature of the CPB. As sown in figure 11, increasing the initial CPB temperature will increase non-linearly the increase in CPB temperature, mainly due to the effect of temperature function "Equation 7", which leads to more heat development.



Figure 11 : Effect of initial temperature of the CPB on the increase in temperature in CPB at 7.5 m above the bottom of the stope

5 CONCLUSIONS

In this paper, numerical studies were performed to investigate the heat produced by hydrating CPB structure. A numerical model was developed to analyze and predict the temperature development and heat transferred by CPB under various boundary conditions. Based on the results obtained from this study, the following conclusions can be drawn: (i) the model developed for this study is capable of predicting the thermal response of CPB reasonably well as compared with a similar theoretical, lab model and field results; (ii) binder content, filling rate, shape of stope, initial CPB temperature ad CPB specific heat have a significant impact on the heat development of the CPB. Results show that the thermal properties of the rock have a negligible effect on the heat development of CPB, while CPB thermal properties (heat capacity) have more effect on the hydration process.

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Appendix A (thermal properties)

Property		Value for the validation Example	Value for the applications	
Temperatures	T1 (ºC)	+32.2 ^h	20	
boundary conditions	T2 (ºC)	+32.2 ⁿ	20	
	T3 (ºC)	+26.0 ^h	20	
	T4 (ºC)	Variable ^h	-	
Backfill thermal	conductivity	Variable ^b	Variable ^b	
(W/(m.k))	,	Table A2	and controlled when	
			studying the effect of CPB	
			thermal properties	
Deal/fill apositic heat (1/(kg k))		050 ^c	1050	
Dackilli specific fieat (J/(Kg.K))		950	1250	
Rock thermal conductivity (W/(m.k))		2.67 ^s	2.67	
Rock specific heat (J/(kg.k))		1000 ^a	840	
Cement Activation Energy (J/mol)		Variable ^d	Variable ^d	
Cement content		(10%) ⁿ =239 kg/m ³	107 kg/m ³	
$q_{\mathrm{max,20}}$ (J/g.h)		7.9 ^e	7.9 ^e	

Table A1 - Properties of the simulated FLAC models

a - Khokholov and Kurilko 2004, b - Celestine and Fall 2008 c - Cerny etal 1996,

d - Eq. 12 & 13, e - De Schutter 1999, g - Clauser and Huenger 1995, h - Williams et al 2001

Table A.2 – Variation of backfill thermal conductivity with time and temperature(W/m.k)[Celestine and Fall 2008] .

	Time days				
Temperature ^e C	1	3	10	28	
2	2.2	2.2	2.2	2.2	
20		2.15	2.1	2.1	
35		1.75	1.7	1.2	
50		1.4	1.1	0.6	