Numerical modeling of the coupled thermo-chemo-mechanical response of cemented paste backfill structures in deep mine temperatures conditions

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ABSTRACT: The gradual depletion of ore available at shallow depths in a number of underground mines in various parts of the world means that underground mining operations are increasingly being carried out at greater depths. This is naturally associated with an increase in the temperature of the rocks surrounding the mine, due to the geothermal gradient. Since, heat can significantly affect the performance properties (e.g. structural stability, design cost) of any cementitious material and structure, questions about the impact of deep mine temperatures conditions on the performance of cemented paste backfill (CPB: a mix of tailings, binder and water) structures need to be solved. In this paper, a mathematical model is developed (and implemented into FLAC software) for predicting strength development and distribution within undrained hydrating CPB structure, temperature development and distribution within the CPB structures, heat transfert between CPB structures and deep mine rock temperatures by coupling the strength (mechanical factor), the temperature (thermal factor) and binder hydration (chemical factors) development of CPB structures. The validation tests show good agreement between the predicted and experimental results. The developed tool is then used to simulate the performance of CPB structure in several practical cases of deep mine backfill operations. The developed tool can contribute to more cost-effective and safer design of CPB structures in deep mine temperature conditions.

1 INTRODUCTION

One of the most important technological innovations in the last two decades, with aims to increase the productivity of mines, manage mine waste cost effectively and contribute to the improvement of health and safety in mine operations with a sustainable perspective, is the technology of cemented paste backfill (CPB). CPB (also known as pastefill) allows the limiting of caving, subsidence and supporting of pillars and walls. It is also an effective means of tailings disposal because it reduces the need for constructing large tailings dams at the surface (Sivakugan et al. 2006), thereby greatly limiting environmental costs (Fall et al. 2007a, 2008). The CPB is an engineered mixture of tailings from the processing operations of the mine, water and binders (2% to 7% by weight usually). It contains typically between 70 % and 85 % solids. Its components are mixed in a plant usually located on the mine surface and subsequently transported (by gravity and/or pumping) to the underground openings. CPB is extensively and increasingly used in underground mine operations. This is because of the technical and economic advantages as it is usually more profitable and/or safer than the other types of mine cemented backfills. Cement consumption using CPB is generally about 40–70% of what would be used in alternative backfills with comparable mechanical properties (Landriault 2001).

Mechanical stability and economical performance represent important performance criteria for CPB. Once placed, CPB has to satisfy certain mechanical stability requirements to ensure a safe underground working environment for all mining personnel. This is because mine backfill failure not only has considerable financial ramifications, but can also result in several injuries and/or fatalities. Hence, the mechanical stability of CPB is a safety concern in underground mining operations. As a structural element, the mechanical stability of the CPB is mostly evaluated in practice based on its unconfined compressive strength (UCS). This is because the UCS test is relatively inexpensive and quick, and can be easily incorporated into routine quality control programs at the mine (Vergne 2001). Knowing the time at which the CPB reaches its reasonable strength is very important for reducing the mining cycle (i.e. higher productivity) and ensuring the safety of mine workers. The required UCS for the CPB in a typical underground mining operation is 0.7-2 MPa (Brackebusch 1994). This UCS largely varies, depending on the dimensions of the CPB, application or function of the CPB and mine characteristics. Binder consumption is the factor that has the most significant influence on the cost or economical performance of CPB. The binder can represent up to 75% of the cost of CPB (Grice 2001).

Despite extensive use of the technology of CPB, many fundamental factors affecting the design of safe and economical CPB structures are still not understood well. Among these aspects, the effects of in situ and/or backfill temperatures on the above performance properties of CPB structures are not well known. Most of the past research efforts on mechanical stability and economical performance of CPB have concentrated on evaluating the performance properties of CPB in room temperature. Little attention has been devoted to study the isolated impact of temperature (Fall et al. 2007b), especially of deep mine temperature on CPB properties. There is a need to increase our understanding of the response of CPB structures in higher thermal loadings conditions.

Indeed, the progressive depletion of ore available at shallow depths in a number of underground mines in Canada and around the world means that underground mining operations are increasingly being carried out at greater depths and therefore at higher temperatures (due to the geothermal gradient). In other words, future mining activities will increasingly be undertaken where the temperature conditions are significantly higher. These hot temperatures, associated with deep mining infer that one of the most challenging engineering tasks in deep mine ground support, is the design of stable and economical CPB structure. Furthermore, since the CPB structures are often very large (several tens of meters in height and width), binder hydration can release (depending on the cement content and type) a significant quantity of heat inside the cemented backfill structure, as shown in field studies conducted by Williams et al. (2001). This is an additional heat load source in backfill operations. Consequently, there is a need to increase our understanding of the impacts of high temperature on the performance of CPB and of the development of tools to assess and predict them.

However, an accurate and reliable prediction of performance of the CPB structures under these various thermal loadings conditions requires a modeling of the coupled thermo-chemo-mechanical (TCM) processes that occur in CPB. These factors are commonly viewed individually, when, in fact, in most cases they are strongly interrelated or coupled. Reproducing these phenomena simultaneously in a laboratory on a CPB structure measuring several dozens of meters is technically very difficult, and extremely costly. Similarly, it is quite difficult to reproduce different thermal stresses, chemical loadings (binder hydration) which CPB structures are subjected throughout their life cycle. Therefore, it is necessary to predict the response of CPB to the different aforementioned TCM processes from results of experimental tests performed on CPB samples or small-scale models. This transition (laboratory to field) can only be rigorously done if the TCM processes in CPB are well understood and modeled. Unfortunately, there is currently no tool to predict the TCM behaviour of CPB, or the performance of CPB under coupled TCM loadings.

In consideration of the facts that are mentioned above, a research program has been conducted at the University of Ottawa to study the coupled effects of temperature (thermal factor), binder hydration (chemical factor) and mechanical loadings (mechanical factors) on the performance of CPB structure and to develop model to predict the TCM behaviour of CPB structure. A part of the obtained results will be presented in this paper. In this paper, a mathematical model is developed (implemented into FLAC software and validated) for predicting strength development and distribution within undrained hydrating CPB structure, temperature development and distribution within the CPB structures, heat transfert between CPB structures and deep mine rock temperatures by coupling the strength (mechanical factor), the temperature (thermal factor) and binder hydration (chemical factors) development of CPB structures.

2 MODEL DEVELOPMENT AND VALIDATION

2.1 *Model development*

By using FLAC (Itasca 2005), a numerical model was developed to predict and study the thermo-chemo-mechanical (TCM) response of CPB structure in any thermal loading conditions. The model is based on the coupling of following processes (Figure 1):

- Chemical processes (C); describe and capture the chemical reactions (binder hydration) that occurs in hydrating undrained CPB structure;
- Thermal processes (T); describe and capture heat generation and transfer within the CPB structures as well as the evolution of the thermal properties of the CPB;
- Mechanical processes (M) (limited to strength); describe and predict the strength (UCS) development and distribution within the CPB processes;
- CPB Filling processes (F); to take into account the effect of the CPB filling rated on the TCM processes.

Most of the mathematical equations used in the development of the TCM are external equations ("*User Defined*"equations; i.e. are not FLAC built), which are implemented into FLAC by using the FISH language. The main approaches and equations used to model and couple the aforementioned processes are explained below.

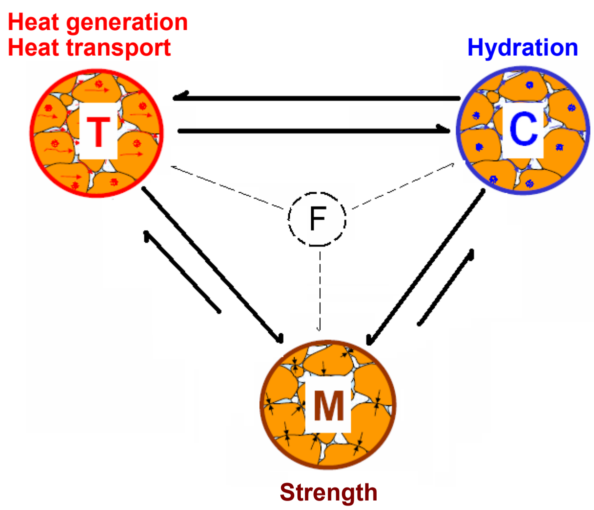

Figure 1. Schematic representation of the main coupled thermo-chemo-mechanical factors in hydrating undrained CPB structure considered in this study. F: Filling rate of the CPB; long arrow: strong coupling; short arrow: weak coupling; dashed arrow: one way effect

2.1.1 *Modeling the binder hydration within CPB structure*

The degree of hydration α is defined as the cement fraction that has reacted (De Schutter, 1999). The hydration of cement is distinguished as a physicochemical process. As this process is affected by many parameters, many models have been developed to quantify the degree of hydration which try to cover all the affecting parameters (Bentz, 2006). One of these parameters is the water to cement ratio (w/c). w/c of CPB is much higher than that of concrete. Therefore, it is important to take into account the w/c in hydration processes. The model by Bentz (2006) is adopted in this study to evaluate the degree of hydration. This model takes into account the w/c in the hydration process. Bentz (2006), based on the Powers model (1946), suggested the following:

$$\frac{\partial \alpha}{\partial t} = A\frac{(B-\alpha)^2(1-\alpha)}{(C-\alpha)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots [1]$$

with:

$$\begin{cases} A = \dfrac{k_3\left(f_{\exp} + \rho_{cem} CS\right)^2}{f_{\exp}\left[1 + \rho_{cem}(w/c)\right]^2} \\[2ex] B = \dfrac{\rho_{cem}}{f_{\exp} + \rho_{cem} CS}\left(\dfrac{w}{c}\right) \\[2ex] C = \dfrac{\rho_{cem}}{f_{\exp}}\left(\dfrac{w}{c}\right) \end{cases}$$

E : Activation Energy
R : Universal gas constant

where:
α: degree of hydration
t: time
k_3 : constant (= 0.061 for sealed curing conditions)
$f_{\exp}$: volumetric expansion coefficient for the solid cement
ρ_{cem} : specific gravity of cement
CS: chemical shrinkage per gram of cement
w/c : water to cement ratio

The above equation is based on the principles of the Powers model (1946), the value of water (w) is defined as the amount of water available for hydration processes. A value of w/c of at least 0.42 should be available for complete hydration Jensen and Hansen (2001).
Temperature greatly influences the chemical reaction of the hydration process. Experimental studies conducted on cement (De Schutter 1999, Schindler et al. 2004, De Scutter and Taerwe 1995) have shown that the curing temperature greatly influences the hydration process. In this paper, the effect of temperature (θ) on the hydration process is introduced into Equation 1 by means of Arrhenius law by the following formula:

$$f(\theta) = \exp\left[\frac{E}{R}\left(\frac{1}{293} - \frac{1}{273+\theta}\right)\right] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots [2]$$

With the effect of temperature, Equation 1 can be represented as:

$$\frac{\partial \alpha}{\partial t} = A\frac{(B-\alpha)^2(1-\alpha)}{(C-\alpha)} \times \exp\left[\frac{E}{R}\left(\frac{1}{293} - \frac{1}{273+\theta}\right)\right] \ldots\ldots\ldots\ldots\ldots [3]$$

The chemical reaction of the binder reaction is also coupled with the strength of the CPB as explained below.

2.1.2 *Modeling the thermal processes within the CPB structure and surrounding rockmass*

The thermal processes modeled include the heat generated by the binder hydration, the heat transfer and the change of the thermal properties of the CPB with time under coupled loading conditions. The model developed uses two main categories of heat equations: (i) the first category is FLAC built (in equations), which are responsible for the principle of heat transfer calculations, such as the conduction and energy balance equation; (ii) the second category includes external equations implemented into FLAC by using the FISH language; these equations describe the heat generated by the chemical reaction of the binder or the change of the thermal properties of CPB with time.

2.1.2.1 *Built-in equations*
For the purpose of thermal analysis, two main built-in equations are used by FLAC. The first equation is the energy balance equation which has the form:

$$-\nabla \cdot q^T + q_v^T = \rho C_\upsilon \frac{\partial T}{\partial t} \quad \text{[4]}$$

where:

q^T : is the heat-flux vector in [W/m2],

q_v^T : is the volumetric heat-source intensity in [W/m3],

ρ : density

C_υ : specific heat

t : time

T : temperature

Equation 4 relates the change in temperature $\frac{\partial T}{\partial t}$ to heat flux q^T and volumetric heat source q_v^T. In cement hydration, heat is produced and can be introduced in Equation 4 as volumetric heat source q_v^T. The second equation describes the heat transport. Fourier's law is the basic law that FLAC uses to define the relation between the heat-flux and the temperature gradient. This law is given in the form:

$$q^T = -k^T \nabla T \quad \text{[5]}$$

where: k^T : the thermal conductivity tensor in [*W/m.C*].

Due to the low permeability of the rock and CPB (Celestin 2008), and by assuming that no significant air flow will occur in the stope voids, heat transfer due to convection is assumed to be negligible

2.1.2.2 *Modeling the heat of hydration*
Scutter and Taerwe (1995) suggested the following formula for considering the coupled effect of temperature and time on the heat of hydration:

$$q(r,\theta) = q_{\max,20} \times f(r) \times g(\theta) \quad \text{[6]}$$

where:

θ : temperature

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

$f(r)$: is the function of degree of reaction " time"

$$f(r) = c.\left[\sin(r\pi)\right]^a.\exp(-b.r) \quad \text{[7]}$$

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 is adopted to represent this function (Scutter and Taerwe 1995). After rearrangement, the Arrhenius' equation can be written as:

$$g(\theta) = \exp\left[\frac{E}{R}\left(\frac{1}{293} - \frac{1}{273+\theta}\right)\right] \qquad [8]$$

where

E : Activation Energy

R : Universal gas constant

Putting Equations 7 and 8 into Equation 6 results in:

$$q(r,\theta) = q_{\max,20} \times c.\left[\sin(r\pi)\right]^a.\exp(-b.r) \times \exp\left[\frac{E}{R}\left(\frac{1}{293} - \frac{1}{273+T}\right)\right] \qquad [9]$$

2.1.2.3 Predicting the evolution of the thermal properties of CPB with time

Laboratory experimental studies conducted by Celestin and Fall (2009) showed that the thermal conductivity of CPB is a time and temperature dependent property. By using the laboratory results of the thermal conductivity for a wide range of times and temperatures, a special FISH code was developed to take into account the temperature and time dependent changes of the CPB's thermal properties in the process of thermal analysis.

2.1.3 *Modeling compressive strength development within the CPB structure*

Exothermic reactions are accompanied by volume shrinkage and increasing bound forces (Paulini 1990). The bound forces are responsible for the development of the mechanical properties of the CPB during the hydration reaction. This reaction is best described by means of degree of hydration as a fundamental parameter. Therefore, at any time, the mechanical development in cemented materials is a function of the degree of hydration ($\mathrm{UCS(t)} \propto (\alpha)$).

Many factors affect the development of the degree of hydration and mechanical properties of CPB, such as cement type, age, temperature, water to cement ratio and more. Due to the high number of variables, there is no mathematical model that can reproduce the quantitative effect of all of these factors on strength development (Zelic et al. 2004). Knudsen (1984) presented a simple analytical model for developing hydration of Portland cement, and this model is represented by:

$$t_o + t_1 A + t_2 A^2 = t \qquad [10a]$$

where:

t_o: length of the dormant period

t_1 and t_2: rate constants

A : hydration ratio (ratio of hydrated to unhydrated cement)

t : time

Thus, Equation 10a can be re-written in the following form as a function of the degree of hydration:

$$t_o + t_1 \frac{\alpha}{1-\alpha} + t_2\left(\frac{\alpha}{1-\alpha}\right)^2 = t \qquad [10b]$$

This equation can be re-written in terms of compressive strength, by substituting: α with f_c, t_o with t_o', t_1 and t_2 with k_{k1} and k_{k2} respectively in equation 10b, so that equation 11 can be obtained (Zelic et al. 2004):

$$t_o' + k_{k1} \frac{fc}{fc_\infty - fc} + k_{k2}\left(\frac{fc}{fc_\infty - fc}\right)^2 = t \qquad [11]$$

where:

fc : compressive strength at time t

fc_∞ : final compressive strength

t_o' : age at start of strength development

k_{k1} and k_{k2} : rate constants

Zelic et al. (2004) provided an empirical expression for the relationship between the degree of hydration and compressive strength:

$$\frac{\alpha}{1-\alpha} = k_{fc2}\left(\frac{fc}{fc_{\infty} - fc}\right) + k_{fc3} \quad [12]$$

where:

k_{fc2} and k_{fc3} are constant (Zelic et al. 2004)]

In order to use Equation 12, the value of the above two constants was assumed to be 0.099 and 4.14 respectively (Zelic et al. 2004). Now, to predict the compressive strength (or UCS) at any degree of hydration (or time), the value of fc_{∞} is required because of the long curing time to obtain this strength. To simplify the application, the short term fc_t (UCS at curing time of " t " days at 20 °C, fc_{28} is recommended) is used to predict the fc_{∞} using Equations 1 and 12. If the available data for the short term fc_t was not cured at 20 °C, the concept of equivalent degree of hydration (α_{eqi}) can be used to predict the equivalent fc_t at 20 °C.

Some experimental studies were conducted to investigate the effect of curing temperature on the strength development of concrete, for example (Ezziane et al. 2007, Chanvillard and D'Aloia 1997, Kim et al. 1998). The experimental results showed that increasing the curing temperature will increase the early age compressive strength and reduce the ultimate strength. The reduction in the ultimate compressive strength is a function of the curing temperature and can be represented by the following (Chanvillard and D'Aloia 1997):

$$S_{c28}(T) = S_{c28}(20\deg C)[1 - k(T-20)] \quad [13]$$

where:

T : isothermal curing temperature

k : constant (adopted as 0.01 in some studies based on experimental data)

$S_{c28}(T)$:28 days strength obtained under isothermal curing temperatures

The reduction of the ultimate compressive strength due to higher curing temperatures is different when the same curing temperatures are applied at different ages. This effect occurred mainly during the first 7 days (Kim et al. 1998). Higher curing temperatures at early ages will cause rapid hydration and hence, act as a shell, which delays the diffusion of hydration products into the bulk cement paste matrix (Kim et al. 1998).

In the case of Portland Cement –CPB (i.e only Portland Cement used as binder) and also based on experimental data (Fall and Samb 2007, Celestin 2008, Pokharel 2008), the effect of higher curing temperatures (up to 50°C) at early ages on the ultimate compressive strength is not the same as concrete. It was noticed that the ultimate UCS (up to a curing age of 150 days) increases with temperature. The reason may be attributed to the higher water to cement ratio, which will allow the cement particles to be surrounded by more water and hence, more cement will be hydrated (Jensen et al. 2001).

The effect of the temperature on the UCS of CPB can be introduced by the constant k_{fc2} in Equation 12. By analysing three different experimental data (Fall and Samb 2007, Celestin 2008, Pokharel 2008), it was found that the constant k_{fc2} is temperature dependent, and can be modified by the following equation:

$$k_{fc}(T) = k_{fc2}(50°C) - \beta(50-T) \quad [14]$$

where:

$k_{fc}(T)$: temperature $(T°C)$ dependent constant to be used in Equation 12.

$k_{fc2}(50°C)$: reference value (at 50°C)

β : fitting parameter

2.1.4 *Modeling of rate of backfilling*

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

$$\frac{\Delta H}{\Delta t} = \frac{\Delta p / \Delta t}{\gamma . A_r} \quad \text{[15]}$$

where:

H : height of backfill

$\Delta p / \Delta t$: pumping rate (tonne/hour)

A_r : cross section area of the stope

In cases of large backfill volume, the filling process may take a 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 by the FISH language was designed to simulate the rate of backfilling, thereby incorporating the incremental backfill construction into the numerical model and analysis.

2.2 *Model validation*

To validate the developed TCM model, the predicted results obtained with the model were compared with results obtained from: (i) field tests; (ii) tests on large scale model of CPB; (iii) tests on CPB samples; (iv) theoretical studies. The validation results show good agreement between the predicted and experimental results. Some examples of validation results are presented below. Williams et al. (2001) performed a field study on CPB structure by measuring stress and strain changes in the backfill and reinforcing members during undercut mining to evaluate if temperature compensation was required for the instrumented strain gauges. The temperature developments resulting from the heat of cement hydration of the solidifying filling masses were recorded. For validation purposes of the FLAC model, the temperature history in the middle of the backfill was investigated ("P.B") and compared with the simulated FLAC model. Figure 2 shows a comparison of the temperature history between the current model and the field data (Example 3). It can be noticed that the curve of temperature rise within the CPB structure predicted by the FLAC model is close to that obtained from field measurements.

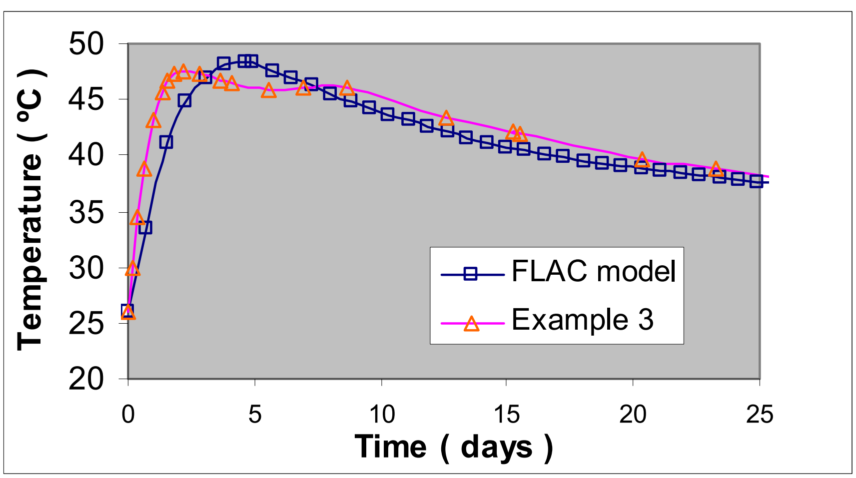

Figure 2. Comparison between the results of developed TCM model (FLAC model) and those obtained from field (Example 3) (data for Example 3 from Williams et al. 2001).

Figures 3 and 4 show examples of validation of the strength development of CPB. A set of available experimental results for the development of UCS for various CPB materials (originated from various mines) and cured at various temperatures (to simulate deep mine hot curing temperatures) was used for validation purposes. Figures 3 and 4 shows a comparison between the experimental results and developed FLAC model results. The results are presented in the form of normalized strength (UCSt / UCS28). The results show good agreement between the predicted and experimental results regardless of the curing temperatures and the types of CPB.

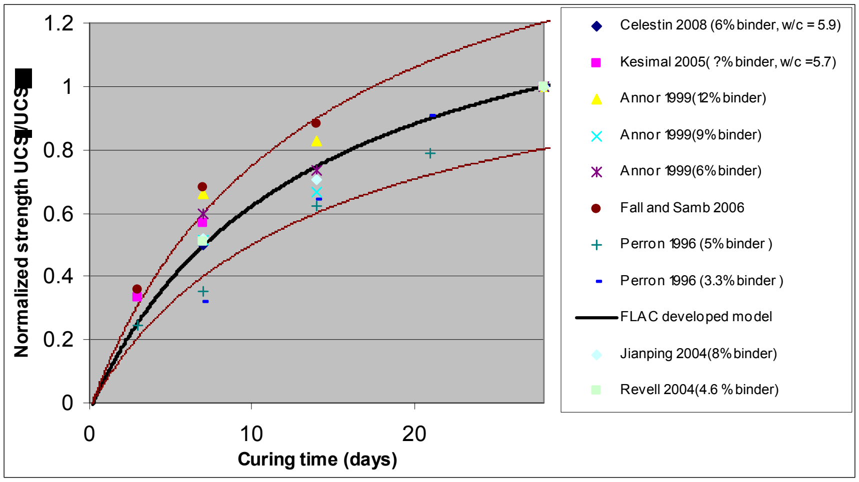

Figure 3. Comparison between the predicted and experimental UCS.

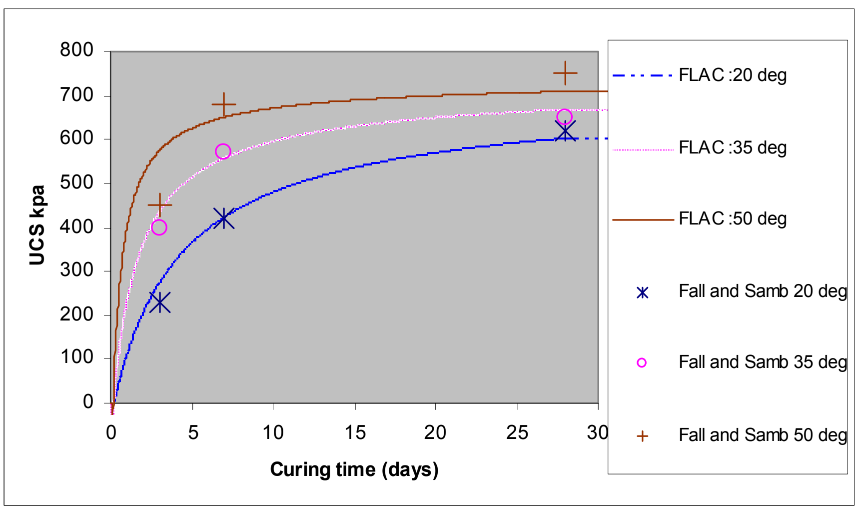

Figure 4. Comparison between the predicted and experimental UCS (CPB samples cured at various high temperatures).

3 EXAMPLES OF MODEL APPLICATIONS

After validating the model with different case studies, the developed model was applied to simulate the performance (e.g. thermal response, strength development, heat transfer, thermal interaction with the rockmass) mechanical response) of CPB structures in various deep mine climates and the different factors affecting it. The factors studied include; stope geometry (size, shape, angle and height), rock and CPB thermal properties, initial CPB and rock temperature, binder consumption, rate of backfilling and curing time. Valuable results were obtained regarding the thermal-chemical-mechanical response of CPB structure and its optimal design taken into account the thermal loading conditions. The simulation results have shown the temperature has a significant effect on the thermal, chemical (binder hydration) and mechanical (strength) response of the CPB structure. Binder content, filling rate (e.g. Figure 5), stope size (e.g. Figure 6) and shape ratio, initial CPB temperature (e.g. Figure 7) and CPB specific heat have a significant impact on the heat development and distribution within CPB structures as well as on the strength development of CPB. The results show that the thermal properties of the rock surrounding the CPB and the stope angle have a negligible effect on the thermal response of CPB structures.

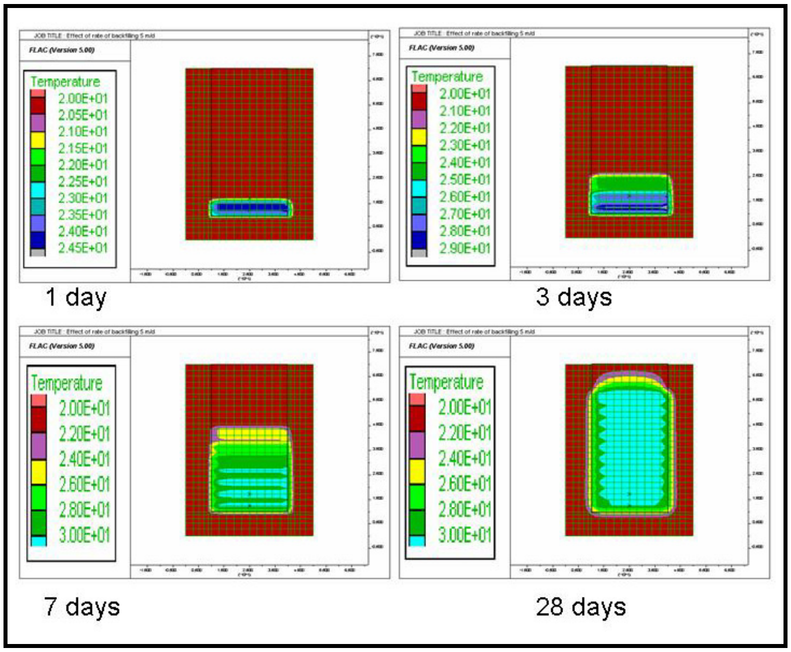

Figure 5. Temperature distribution during the filling process for rate of backfilling 5m/day for big stope of 30 x 60 m.

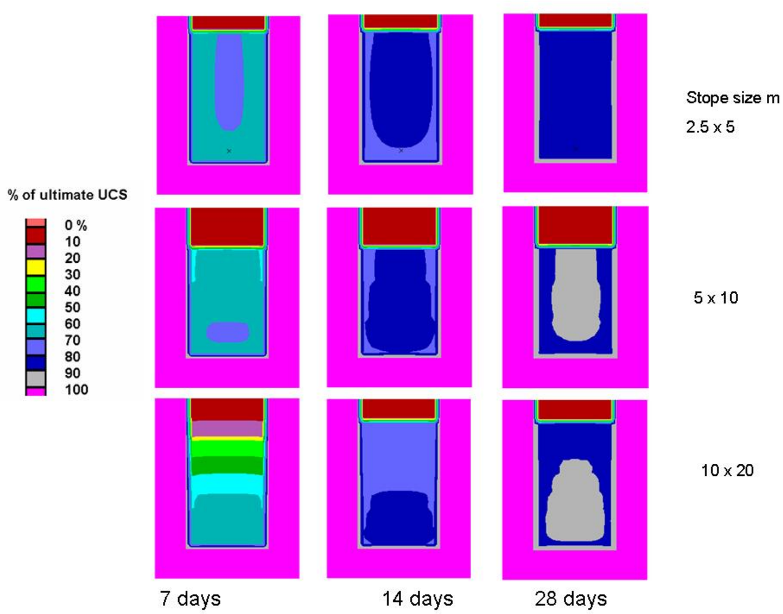

Figure 6.UCS development for different stope sizes (mix characteristics per Fall and Samb 2006). (CPB surrounding by the rock mass in pink color)

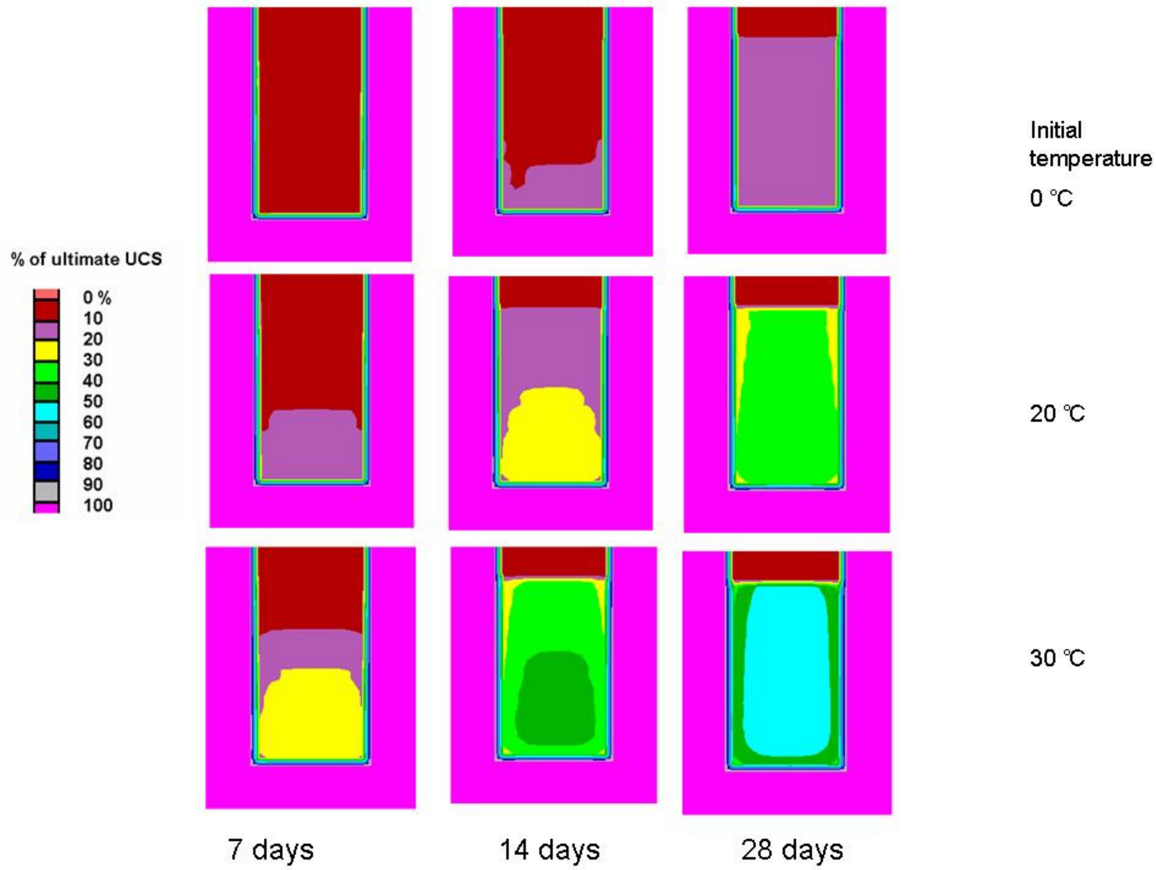

Figure 7. UCS development for different initial CPB temperatures (mix characteristics per Celestin, 2008). (CPB surrounding by the rock mass in pink color).

4 SUMMARY AND CONCLUSIONS

In this paper, a thermo-chemo-mechanical model is proposed to analyze and predict the temperature and strength development within CPB, and heat transferred by CPB structures under various boundary conditions. The developed model is useful in the prediction of the performance of CPB in deep mine temperature conditions. The developed model can provide useful information on the opening of the barricades at early ages, estimation of CPB strength, managing the mine climatic conditions and controlling the potential negative impact of overly high curing temperatures on CPB properties.

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