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Coupling binder hydration, temperature and compressive strength development of underground cemented paste backfill at early ages

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ABSTRACT

Cemented paste backfill (CPB) is an engineered mixture containing up to 60% solid tailings, and 3–7% binder (often) and water. CBP is used in backfilling underground mine voids. It receives great interest as one of the most commonly used ways in mine backfilling around the world. The usage of CPB greatly contributes to the disposal of mining tailings waste from the surface, increasing working place stability to extract more minerals safely. The key parameter for the design of CPB structure is its strength; namely, unconfined compressive strength (UCS). Knowing the time at which the CPB reaches its reasonable strength is very important for reducing the mining cycle and ensuring the safety of mine workers. As a cemented material, CPB strength is time and temperature dependent, and a function of the degree of hydration. The objective of this paper is to develop a numerical model for predicting the UCS of undrained CPB. Strength development is coupled with temperature and degree of hydration. For validation purposes, the predicted UCS will be compared with three groups of experimental results. The results show a good agreement between the predicted and measured values, and a new formula is suggested for including the effect of temperature into the UCS of CPB.

1. Introduction

Extracting valuable minerals from the earth is considered one of the main objectives of mining operations. In most cases, the percentage of the valuable minerals in underground ore is small in comparison to excavated ore materials. This fact leads to two main side effects: (i) the accumulation of waste tailings on the ground surface and (ii) the creation of underground large voids.

Surface tailings disposal can have negative effects on the environment, such as acid rock drainage (ARD) and the geotechnical hazards of tailings dam failures. As an economic and environmental friendly solution, the underground voids can be backfilled with tailings. The process of mine backfilling allows to return a significant amount of waste material to the underground mine, as well as providing a structural element for ground support. For these reasons, mine backfilling has become a widespread practice in mining operations around the world, and can play a significant role in overall mine operations (Yilmaz et al., 2004; Fall and Benzaazoua, 2005; Kesimal et al., 2005; Sivakugan et al., 2005; Fall et al., 2004, 2008). Mine backfilling can be done mainly in three different ways, based on the backfill material consistency (rock, slurry or hydraulic backfill and paste backfill). Hydraulic backfill (HB) is a mixture of alluvial sand and/or mill tailings and a relatively small percentage of cement. The mixture is generally about 60–75% solids by weight. Rockfill is usually a mixture of waste rock, tailings/or sand, water and cement. The cemented paste backfill (CPB), first used at the Bad Grund Mine in Germany in the late 1970s (Lerche and Renetzeder, 1984), is an engineered mixture of tailings from the processing operation of the mine, water and binders (3–7% by weight usually). It contains typically between 70% and 85% solids.

In response to the high hazards posed by hydraulic backfills (failures of backfill barricades and subsequent mine fatalities), nowadays, the use of the hydraulic backfill is restricted and tends to disappear (Fall et al., 2007a). On the other hand the CPB is extensively used in underground mine operations and its use follows an increasing trend (Celestin and Fall, 2008). Some reasons that invoke more interest and popularity in CPB among many mining sites in Canada and around the world during the last two decades include: (i) the higher percentage of solids, allowing a return of up to 60% (Fall et al., 2008) of the tailings to the underground; (ii) faster and higher strength gain, in addition to lower dewatering after backfilling and (iii) the CPB confers economical advantages. Indeed, cement consumption using CPB is generally about 40–70% of what would be used in alternative backfills with comparable mechanical properties (Landriault, 2001).

As a structural element, the CPB structure is mainly designed based on the (undrained) unconfined compressive strength

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Nomenclature

r	degree of reaction
t	time
Q	released heat
Q_{max}	total heat of reaction
q	rate of released heat
τ	age parameter
κ	hydration parameter
t_{eqi}	equivalent age
t_1	hydration parameter
A	stope cross sectional area
γ	bulk density of CPB
Δt	time intervals
$\phi \ldots$ or $\ldots Ea$	activation energy
R	Universal Gas constant
T	temperature
T_r	reference temperature
A	Arrhenius' law constant
a, b, c	constants
$q_{max,20}$	maximum rate of released heat at temperature of 20 °C
$\frac{\Delta H}{\Delta t}$	rate of backfilling
$\Delta p/\Delta t$	rate of pumping

(UCS). This is because the UCS test is relatively inexpensive, and can be easily incorporated into routine quality control programs at the mine (Vergne, 2000). A binder is used (usually 3–7% by weight) (Hassani and Archibald, 1998) to reach a better and faster UCS and through this, increase ore recovery under safer conditions. The prediction of the UCS of the CPB structure is an important step in the design process. Many studies have been conducted to investigate the strength development of the undrained CPB based on isothermal conditions (e.g. Amaratunga and Yaschyshyn, 1997; Yilmaz et al., 2004; Fall and Benzaazoua, 2003, 2005; Fall and Samb, 2008; Pokharel, 2008). These studies have revealed that several factors such as the mix components (e.g. cement content and type, tailings type and fineness, water to cement ratio, sulphate content) and the curing temperature, significantly affect the strength development of undrained CPB. This is mainly attributed to the facts that the aforementioned factors strongly influence the binder hydration degree, which, in turn, largely controls the strength development of CPB. However, despite the tremendous progress made in understanding the strength development of CPB and the factors affecting it, almost all these previous studies have only investigated the isolated effects of one influencing factor (e.g. one mix component, curing temperature) on the strength development of CPB. Moreover, these influencing factors and the strength development of CPB are commonly viewed individually in CPB technology, when, in fact, they are strongly coupled. Furthermore, these studies were mostly experimental and the change in temperature with time (i.e., temperature history: due to heat produced by the cement hydration, heat exchange between the surrounding rock and the CPB, etc.) was not included in all of these studies. Finally, the mathematical approach for the numerical analysis and modeling of the coupled effect of temperature and binder hydration on the UCS development of CPB materials has not been considered until now, nor has the prediction of the UCS of CPB structures under coupled thermo-chemical (interactions between temperature and cement hydration) loadings been done. For the reasons mentioned above, it was noticed in several underground mines (le Roux et al., 2002; Revell, 2004) that the UCS of in situ CPB core samples is generally much higher than that of equivalent CPB samples prepared in the laboratory.

In this paper, a FLAC (2D) model is developed for predicting UCS development and distribution of undrained CPB during the early ages, taking into account the coupled effects of temperature (thermal factor) and binder hydration (chemical factors).

2. Development of the numerical model

FLAC (2D) (Version 5.0, Itasca, 2005), a two-dimensional finite difference program based on an explicit Lagrangian calculation scheme, was used for the numerical studies. Explicit means it uses a time stepping procedure to solve the problem without forming the stiffness matrix. Furthermore, the program FLAC contains a powerful built-in programming language (FISH), which enables the user to implement his own functions or constitutive models, define quantities to be calculated and to control the analysis processes. By using FLAC, a numerical model is developed to study the development of the UCS within undrained CPB structures. The model is coupled with the thermo-chemical model (TC model) developed by Nasir and Fall (2009) in order to take the effect of temperature into strength development processes. The TC model is presented elsewhere (Nasir and Fall, 2009). Fig. 1 shows the main components of the developed numerical model. The details about the model components and their coupling are explained below.

2.1. Degree of hydration

The degree of hydration α is defined as the cement fraction that has reacted (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 (Powers and Brownyard, 1946). One of these parameters is the water to cement ratio (w/c). The w/c of CPB is much higher than that of concrete. Therefore, it is important to take into account the w/c of CPB in hydration processes. The model developed 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 (Powers and Brownyard, 1946), suggested the following:

$$\frac{\partial \alpha}{\partial t} = A\frac{(B-\alpha)^2(1-\alpha)}{(C-\alpha)} \tag{1}$$

$$\text{with :}\quad \begin{cases} A = \frac{k_3(f_{\exp}+\rho_{cem}\mathrm{CS})^2}{f_{\exp}[1+\rho_{cem}(w/c)]^2} \\ B = \frac{\rho_{cem}}{f_{\exp}+\rho_{cem}\mathrm{CS}}\left(\frac{w}{c}\right) \\ C = \frac{\rho_{cem}}{f_{\exp}}\left(\frac{w}{c}\right) \end{cases}$$

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.

In the above equation that is based on the principles of the Powers model (Powers and Brownyard, 1946), the value of water (w) is