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Coupled effect of cement hydration and temperature on rheological properties of fresh cemented tailings backfill slurry

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Abstract: The fluidity of fresh cemented tailings backfill (CTB) slurry depends on its rheological properties. Hence, it is crucial to understand the rheology of fresh CTB slurry, which is related to the cement hydration progress and temperature evolution within CTB mixtures. For this reason, a numerical model was developed to predict the evolution of the rheological properties of fresh CTB slurry under the coupled effect of cement hydration and temperature. Experiments were conducted to investigate the rheological behaviours of the fresh CTB slurry. By comparing the simulated results with the experimental ones, the availability of this developed model was validated. Thereafter, the model was used to demonstrate the coupled effect of cement hydration and temperature on the evolution of fresh CTB slurry's rheological properties, under various conditions (initial CTB temperature, cement to tailings ratio, and water to cement ratio). The obtained results are helpful to better understanding the rheology of CTB slurry.

Key words: cemented tailings backfill (CTB); hydration; temperature; rheology; coupled model

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1 Introduction

Cemented tailings backfill (CTB) slurry is one kind of non-Newtonian fluid, which is prepared by mixing cement, tailings and water [1]. The utilization of CTB technology allows waste tailings to be placed underground, which not only reduces the surface discharge of solid waste, but also provides underground supports [2]. Because of these advantages of CTB technology, it is being widely and intensively employed in global mining industry [3].

Generally, the freshly made CTB slurry is transported into underground stopes through pipeline. Therefore, the fresh CTB slurry should be flowable and transportable enough to ensure the delivery smoothly and efficiently. Otherwise, some problems (e.g., pipeline clogging) may occur, which would cause serious consequences, such as delaying mining production and increasing cost. However, the fluidity and transportability of fresh CTB slurry are dependent on its rheological properties [4], which are not only influenced by its own characteristics (e.g., solid concentration and mix proportion of the CTB mixtures), but also affected by some external factors, such as temperature and cement hydration process.

Of these factors, the internal properties of the fresh CTB slurry can be easily modified and adjusted (e.g., changing the solid percentage of the slurry) to improve its fluidity and thus to meet the transportation requirement. Nevertheless, the external factors are difficult or even impossible to adjust. For instance, friction between the fresh CTB slurry and inner walls of the pipe is inevitable. This causes thermal loading on the flowing slurry, thus increasing its temperature. This temperature rise will significantly affect the slurry's rheological properties [5].

Mining depth is another significant factor. Due to the geothermic gradient, the underground environmental temperature increases in direct proportion to the mining

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depth. This temperature rise will in turn affect the underground CTB temperatures, thus exerting an influence on the evolution of CTB slurry's rheological behaviour. For these reasons, it is essential to study the effect of various temperature loading conditions on the rheology of CTB slurry.

As one of the most significant heat sources, cement hydration process releases considerable amount of heat, contributing to the temperature development [6] within CTB mixtures, which in turn affects the CTB slurry's rheological properties. This temperature rise caused by cement hydration then affects the hydration process since a higher temperature is favourable for accelerating the cement hydration process [7].

Therefore, it can be determined that within fresh CTB mixtures, the cement hydration and temperature development interact with each other and together affect the rheological behaviours of CTB slurry. For this reason, it is vitally important to study the coupled effect of cement hydration and temperature rise on the rheology of fresh CTB slurry.

However, after being placed into underground stopes and naturally cured for a certain period, the fresh CTB mixtures should form hardened CTB structures to support roofs that provide a safe working environment for miners, as well as support pillars for improving recovery. Therefore, the adjustment of CTB slurries' internal features should fulfill the strength requirement of hardened CTB structures. Accordingly, the uniaxial compressive strength (UCS) is introduced to evaluate the mechanical stability of CTB structures [6]. Thus, to develop a favourable design for preparing CTB mixtures, both the rheological properties of fresh CTB slurries and the mechanical characteristics of hardened CTB structures should be considered at the same time. Although this paper is focused on the rheology of fresh CTB slurry, the UCS of hardened CTB structures is taken into consideration as well.

This paper is organized as follows: first, a mathematical model was numerically developed by coupling the equations of cement hydration, heat transfer and rheology; secondly, an experimental rheometer test was conducted on the freshly prepared CTB slurry; thirdly, the developed model was validated against the previous experimental results and put into application, and the coupled effects of cement hydration and temperature variation on the rheological properties of fresh CTB slurry under different boundary conditions were discussed and demonstrated; finally, the conclusions were presented.

2 Development of mathematical model

As demonstrated above, the rheological behaviour of fresh CTB slurry is affected by cement hydration and accompanied thermal process. Besides, the progress of cement hydration and the thermal process also interact with each other: the progress of cement hydration releases significant amount of heat to contribute to temperature development and at the same time high temperature can accelerate the hydration progress. The engineering simulation software COMSOL Multiphysics [8] is widely applied to conducting coupled modeling. Consequently, in the present study, the built-in "Heat Transfer Module", "CFD Module" and "Chemical Reaction Engineering Module" within COMSOL Multiphysics can be coupled together to analyze the coupled effect of cement hydration and the temperature variation on the rheological behaviour of fresh CTB slurry. The basic mathematical equation is applied to the modeling as follows:

$$\rho_c C_c \frac{\partial T_c}{\partial t} + \rho_c C_c u_c \cdot \nabla T = \nabla \cdot (k \nabla T) + Q \tag{1}$$

where ρ_c, C_c and k are the density, specific heat capacity and thermal conductivity of the fresh CTB slurry, respectively; u_c is the velocity field (i.e., the volumetric flow rate) of the fresh CTB slurry; Q is the heat source term.

2.1 Hydration equations

Cement hydration starts when the cement is mixed with water. The extent of this hydration progress can be described by the degree of cement hydration [9], which is introduced to represent the proportion of reacted cement, and its definition [10] can be expressed by the following equation:

$$\alpha(t) = \frac{H(t)}{H_\mathrm{T}} \tag{2}$$

where $\alpha(t)$ is the degree of cement hydration at the time t; $H(t)$ is the accumulated heat released by cement hydration until time t; H_T is the total heat when all the cement reacts ultimately.

In order to reveal the effect of time t on the degree of cement hydration, SCHINDLER and FOLLIARD [11] obtained the following expression:

$$\alpha(t) = \alpha_\mathrm{f} \cdot \exp\left[-\left(\frac{\tau_T}{t}\right)^{\beta}\right] \tag{3}$$

where t_T is the time parameter of cement hydration when the temperature of fresh CPB is T; β is the shape parameter of cement hydration; α_f is the ultimate degree of cement hydration, which can be calculated in the following form [12]:

$$\alpha_\mathrm{f} = \frac{1.031 w/c}{0.194 + w/c} \tag{4}$$