Coupled effect of cement hydration and temperature on hydraulic behavior of cemented tailings backfill

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Abstract: Cemented tailings backfill (CTB) is made by mixing cement, tailings and water together, thus cement hydration and water seepage flow are the two crucial factors affecting the quality of CTB. Cement hydration process can release significant amount of heat to raise the temperature of CTB and in turn increase the rate of cement hydration. Meanwhile, the progress of cement hydration consumes water and produces hydration products to change the pore structures within CTB, which further influences the hydraulic behavior of CTB. In order to understand the hydraulic behavior of CTB, a numerical model was developed by coupling the hydraulic, thermal and hydration equations. This model was then implemented into COMSOL Multiphysics to simulate the evolutions of temperature and water seepage flow within CTB versus curing time. The predicted outcomes were compared with correspondent experimental results, proving the validity and availability of this model. By taking advantage of the validated model, effects of various initial CTB and curing temperatures, cement content, and CTB’s geometric shapes on the hydraulic behavior of CTB were demonstrated numerically. The presented conclusions can contribute to preparing more environmentally friendly CTB structures.

Key words: cemented tailings backfill; hydration; water seepage flow; pore water pressure; coupled model

1 Introduction

Cemented tailings backfill (CTB) is one kind of mixtures formed by tailings, water and cement [1–2]. The most significant application of a hardened CTB is to support underground stope, aiming to promote ore pillar recovery and provide secure workplaces for mining workers [3]. Therefore, after being delivered underground, CTB structures need to possess enough mechanical stability to exert their load bearing capability. But at the same time, the placed CTB structures should do less or even no harm to the underground environment. For this reason, it is also essential for a CTB structure to own favorable environmental performance [4], which is related to the hydraulic permeability of CTB [5]. This is because the processed tailings, which are used for preparing CTB, usually contain some hazardous ingredients (e.g., cyanide, and sulphate). These detrimental materials might be drained out with the water seepage flow from inside CTB (a type of porous media [6]), and thus pollute underground environment and groundwater [7]. Aside from this, for instance, with the water seepage flow, the sulphate can spread all through the pores or cracks within CTB, resulting in destroying the strength (mechanical stability) of CTB due to sulphate attack [7]. Moreover, if there is too much seepage water underground, the mine has to pump the water onto the ground surface. This is an unexpected increase in the operation cost of the mining company. Hence, there is a need to understand the hydraulic behavior of CTB, which is in favor of achieving stable and environmentally friendly CTB structures. The hydraulic conductivity (or permeability) of a CTB structure is affected by its temperature [8] and some other factors (such as the porosity of CTB). With regard to a general CTB structure, cement hydration is a typical kind of chemical process that generates significant amount of heat for contributing to the temperature development in CTB, and in the meantime, produces a certain number of hydration products to refine the pore structures in CTB [9]. These two effects together contribute to affecting the evolution of water seepage flow within CTB. This is because temperature variation influences the viscosity of water and the migration rate of water flow through the pores inside CTB. In addition, cement hydration also consumes
large amount of water [10], which directly affects the seepage field within CTB by reducing the water content.

During the past 20 years, lots of researchers conducted studies on the hydraulic behavior of porous media (CTBs in this work). LEE and CHO [11] designed an experimental program to study on the hydraulic characteristics of rough rock fractures under normal and shear load. OLSSON and BARTON [12] developed an improved hydro-mechanical model to discuss the hydraulic properties of rock joints. A research on the coupled thermal-hydrological-mechanical processes in sparsely fractured rock was conducted by NGUYEN and SELVADURAI [13]. XU et al [14] experimentally demonstrated the effects of temperature and pressure differences on water seepage in breccia, and they also obtained a linear relationship between seepage coefficient and temperature. THOMAS et al [15] numerically and experimentally carried out a research on the unsaturated soils and discussed the coupled thermo-mechanical-hydraulic behavior of the soils. QIAN et al [16] conducted a study on water seepage flow in concrete and analyzed the waterproofing capability of concrete. As mentioned before, all of the research objects of these studies were rock, soil or concrete. These materials or composites are essentially different from CTBs, so the previously developed models or experimental results achieved by these researches could not be applied to CTB directly.

For CTB or cemented paste backfill (CPB), FALL et al [9] conducted an experimental research on saturated hydraulic conductivity of CPB, and revealed the time-dependent evolution of the saturated hydraulic conductivity of CPBs. ABDUL-HUSSIAN and FALL [6] developed a research on the unsaturated hydraulic properties of CTB that contains sodium silicate, which revealed the evolutions of CTB’s unsaturated hydraulic conductivity and residual water content versus curing time and suction. The effect of temperature on the saturated hydraulic conductivity of hardened CPB was illustrated by POKHAREL and FALL [7]. However, the water seepage flow within CTB (or CPB) was not discussed in these three significant studies. For this reason, it is necessary to conduct a research on the water seepage flow in CTB, which is crucial for designing and preparing more environmentally friendly CTB structures. As a result, in this work, a numerical model will be developed to analyze the coupled effect of cement hydration and temperature variation on the evolutionary law of the water seepage field within CTB, with the validation and application of the developed model.

2 Numerical modeling

As one of the most advanced and powerful numerical simulation tools, the software COMSOL Multiphysics is being widely and intensively employed in various areas of science, technology and engineering. The key application of this software package is to simulate the coupled processes of different physical fields. COMSOL Multiphysics allows users to solve their own particular problems by writing partial differential equations (PDEs) in the built-in physics interfaces interactively. The sequence for COMSOL Multiphysics to solve a specific problem includes constructing geometric models, defining the physics, meshing, solving, and presenting the visualized results. Thanks to the excellent coupling and simulating function of this software, it was applied to conduct numerical modeling and simulation for the present work.

2.1 Hydration equations

In order to describe the progress of cement hydration within CTB, the following expression [17] is introduced:

$$\alpha(t) = \exp \left[ - \left( \frac{\alpha_f}{t} \right)^{\alpha_S} \right]$$  \hspace{1cm} (1)

where $\alpha(t)$ is the cement hydration rate at time $t$; $\alpha_f$ and $\alpha_S$ are two parameters representing the cement hydration process, of which the former is time ($t$) related and represents the progress of cement hydration at a reference temperature ($T_r$), while the latter relates to the shape of CTB structure; $\alpha_f$ is the final degree of cement hydration, which is a function of water-to-cement ratio ($\gamma$) used for preparing CTB [18]:

$$\alpha_f = \frac{1.031\gamma}{0.194 + \gamma}$$  \hspace{1cm} (2)

Since the final cement hydration degree ($\alpha_f$) indicates the ratio of the hydrated cement to total until the entire cement hydration process finishes, the value of $\alpha_f$ can never exceed 1. According to Eq. (2), $\alpha_f$ equals 1 when $\gamma$ is 6.258. Thus, if $\gamma$ is less than 6.258, this equation is mathematically valid and the value of $\alpha_f$ can be calculated accordingly. Otherwise, when $\gamma$ is greater than 6.258, the equation is invalid. In this case, the value of $\alpha_f$ is considered to be 1.

2.2 Thermal equations

A hardened CTB structure is a porous medium, so fluid (air and water) is permeated in its pores (or cracks). The heat inside and outside CTB can thus be transferred through the fluid flow. However, since the thermal conductivity of air is significantly less than (approximately 1/25) that of water [19], heat transferred by air flow will be ignored in this work.

The temperature evolution within CTB, as well as