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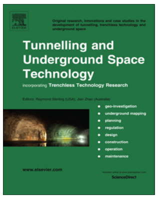

A coupled thermo–hydro-mechanical–chemical model for underground cemented tailings backfill

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ABSTRACT

Cemented paste backfill (CPB), a mixture of tailings, water and binder, is extensively used in underground mines worldwide for ground support and tailings disposal. The prediction of the behavior of CPB structures from early to advanced ages is of great practical importance. Once placed underground, the behavior of CPB is controlled by complex multiphysics (thermal, hydraulic, chemical and mechanical) processes. Modeling of the coupled THMC processes that occur in CPB are crucial for reliably assessing and predicting the performance of CPB structures. Yet there is currently no tool to predict the thermo–hydro-mechanical–chemical (THMC) behavior of CPB, or the performance of CPB under coupled THMC loadings. Therefore, a new multiphysics model is presented in this paper to describe and predict the coupled THMC behavior of CPB and its evolution with time. The governing equations of the model result from a combination of a set of conservation and constitutive equations. Four balance equations (water and air mass, momentum (mechanical equilibrium) and energy conservation equations) are taken into consideration. The model considers full coupling between the thermal, hydraulic, chemical (binder hydration) processes and CPB deformation as well as changes in CPB properties resultant of these phenomena, such as stress–strain relationship, thermal conductivity, permeability, porosity, and strength. The model coefficients are identified in terms of measurable parameters. The prediction capability of the developed model is then tested against laboratory and field tests conducted on CPB. Good agreement between the modeling results and experimental data confirms the capability of the developed model to well capture the THMC behavior of CPB and its evolution.

1. Introduction

With the rapid development of backfill technology in the mining sector, the application of cemented paste backfill (CPB) has become a standard practice around the world (Yilmaz et al., 2004; Sivakugan et al., 2006; Fall and Nasir, 2009; Ghirian and Fall, 2014). CPB is an engineered mixture of tailings from the processing operations of the mine, additives such as Portland cement, blast furnace slag and fly ash, and water. After preparation, the CPB is usually delivered into the mined-out stope by means of reticulated pipelines or gravity. Consequently, the backfilled stope not only provides support for the adjacent stopes, but also ensures a higher recovery of resources as less ore is left behind in the pillars. Compared to other types of mine backfill, such as hydraulic fill and rockfill, CPB is more versatile for mine designers. First, the water content of CPB is extremely reduced but it is still able to be transported through high-pressure positive displacement pumps (Le Roux et al., 2005). Moreover, the tailings, as the major ingredient of CPB, are pumped into underground space, which can, to an extreme extent, eliminate the need for constructing large surface storage tailings dams (Sivakugan et al., 2006) and minimize the associated cost and environmental issues (Fall et al., 2004; Yilmaz et al., 2004; Ghirian and Fall, 2014). Furthermore, another benefit is the faster and higher mechanical strength acquisition of CPB as compared to rockfill and hydraulic fill (Yilmaz et al., 2003; Nasir and Fall, 2010; Veenstra, 2013), which, in turn, means that it is more economical. Therefore, CPB has started to replace both hydraulic fill and cemented rockfill in underground mining operations.

The critical design criteria of CPB structures consist of structural stability, durability, design cost and environmental performance (Pierce, 1999; Williams et al., 2001; Fall and Nasir, 2009; Ghirian and Fall, 2013a). Once prepared and placed underground, the CPB structure is simultaneously subjected to mechanical (**M**, e.g., geomechanical conditions of the mine, filling rate and strategy, backfill self-weight), hydraulic (**H**, e.g., suction, pore water

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pressure (PWP) development, water drainage), chemical (**C**, e.g., cement hydration), and thermal (**T**) loads from early to advanced ages (Fall and Ghirian, 2014) as explained in Section 2. For instance, the temperature of the surrounding rocks naturally increases with depth due to the influence of the geothermal gradient. Moreover, binder hydration can generate significant amounts of heat (internal source of heat) inside the CPB structure (Fall et al., 2010). These external and internal sources of heat will directly affect the binder hydration rate, and thus influence the strength development of CPB as well as cause mechanical deformation through thermal expansion. In addition, as the binder hydration reaction proceeds, some of the pore water will be consumed by the binder hydration, which contributes to the dissipation of the excess pore water pressure within the CPB. Consequently, there will be a gradual transition from saturated to unsaturated conditions in the backfill medium, which can result in an increase of the effective stress in the CPB. Moreover, the CPB structure can also experience mechanical deformation under gravity (backfill self-weight), and shrinkage strain induced by binder hydration. Hence, the performance of the CPB structure is controlled by complex coupled multiphysics processes, including thermal (T), hydraulic (H), mechanical (M) and chemical (C) (THMC) processes. These complex and varying coupled THMC processes create their own special challenges for the design of stable and cost-effective CPB structures. Understanding and modeling of the coupled THMC processes that occur in CPB are crucial for reliably assessing and predicting the performance of CPB structures.

To address and understand the multiphysics processes that occur in CPB and their effects on CPB behavior, comprehensive research with experimental analysis, field measurement and numerical modeling is needed. Until now, however, despite the tremendous progress made in understanding the behavior of CPB, most of the previous studies have only investigated the isolated effects of one influencing factor (mechanical, chemical, hydraulic, or thermal) on the behavior of CPB. For example, due to the significance of mechanical stability, many research efforts (e.g., Mitchell, 1989; Lawrence, 1992; Pierce, 1999; Fall et al., 2005; Simon, 2005; Fall et al., 2007; Nasir and Fall, 2008) have concentrated on investigating the mechanical properties (e.g., uniaxial compressive strength, shear strength, cohesion and internal friction angles), microstructural evolution and the corresponding influencing factors. Moreover, the evolution of the hydraulic process in CPB is also investigated via both laboratory experiments and in situ measurements (e.g., Yumlu, 2008; Fall et al., 2009; Thompson et al., 2012). For the thermal process, it has been observed that thermal properties such as thermal conductivity evolves with binder hydration (De Souza, 2006; Célestin and Fall, 2009), and the temperature rise and distribution in CPB are largely controlled by both the heat released by the binder hydration and thermal load exerted by the surrounding rock (Williams et al., 2001; Fall et al., 2008; Orejarena and Fall, 2008; Yumlu, 2008; Fall et al., 2010).

In response to the limited knowledge on the coupled processes in CPB, studies have been gradually carried out on the multiphysics processes in CPB at the experimental (laboratory, field) and modeling levels. Some experimental studies have been carried out to better understand the HM (e.g., Yilmaz et al., 2014), THM (e.g., Abdul-Hussain and Fall, 2012) or THMC (e.g., Ghirian and Fall, 2013a, 2014) behavior of CPB. As the understanding on the mechanisms of coupled processes in CPB is increasing, numerical modeling has also made progress in furthering the work in this area. Various partially coupled numerical models have been developed to predict the behavior of CPB. A thermo–chemo-mechanical (TCM) model (Fall and Nasir, 2009) was proposed to simulate the response of CPB under thermal loading conditions. In order to describe the coupled thermal and hydraulic processes within CPB, a thermo–hydro-chemical (THC) model was developed (Wu et al., 2013). A hydro–chemo-mechanical (HCM) model which couples cement hydration with conventional consolidation analysis was presented by Helinski et al. (2007). However, to date, no studies have been conducted on the development of a fully coupled multiphysics model to predict the THMC behavior of CPB. A reliable and effective assessment and prediction of the behavior and performance of CPB are vital for the coupling of all of these THMC factors. In addition, the assessing of such CPB structures and comparing of several possible CPB designs prior to their construction require a robust and reliable multiphysics (THMC) model or computational tool which incorporates knowledge of these various coupled mechanisms at the material level. Unfortunately, there is currently no tool to predict the THMC behavior of CPB, or the performance of CPB under coupled THMC loadings. Therefore, the objective of this study is to develop a multiphysics model to analyze and predict the THMC behavior of CPB.

2. Coupled THMC processes considered

CPB can be treated as a multiphase porous medium which consists of liquid (capillary water and physically adsorbed water), gaseous (pore air) and solid (binder, tailings and hydration products) phases. Once placed into a stope, a series of strong interactions between the coupled THMC processes immediately take place within the CPB structure. Fig. 1 depicts the main THMC processes that can affect the CPB behavior, which are taken into consideration in this study. The interaction between the coupling processes dominates the evolution of the material properties and behavior of the CPB structure.

2.1. Chemical process

Binder hydration commences right after the CPB is mixed and the progress of the chemical reaction influences the CPB properties and behavior in four key aspects: (i) as the chemical reaction proceeds, the resulting hydration products precipitate and refine the capillary pore space between the tailings particles. This pore refinement and connection between the solid particles significantly contribute to microstructural changes. The microstructural variation leads to the evolution of several material properties, such as thermal (e.g., thermal conductivity) (Abbasy, 2009), hydraulic (e.g., saturated hydraulic conductivity) (Fall et al., 2009) and mechanical (e.g., uniaxial compressive strength) (Yilmaz et al., 2015) properties; (ii) capillary pore water is gradually consumed during binder hydration, which not only contributes to the change in the degree of saturation, but also results in the evolution of the pore water pressure (Ghirian and Fall, 2013a); (iii) the heat released by exothermic binder hydration will influence the temperature distribution in the CPB structure and the binder hydration rate (Nasir and Fall, 2010). The evolution of the temperature can, to a certain extent, result in mechanical deformation via thermal expansion; and (iv) due to the fact that the volume of the hydration products is less than the combined volume of the reacted cement and water (Powers and Brownyard, 1947), binder hydration can directly cause mechanical deformation through chemical shrinkage.

2.2. Hydraulic process

The impacts of the hydraulic process result from the variation in water content within the CPB structure. There are several factors that contribute to the evolution of the water content, including self-desiccation, surface evaporation, water seepage from the surrounding rock, and pore water flow and drainage (e.g. Helinski et al., 2007; Abdul-Hussain and Fall, 2011; Ghirian and Fall, 2013a). Self-desiccation is induced by water consumption in