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Coupling temperature, cement hydration and rheological behaviour of fresh cemented paste backfill

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ABSTRACT

In this paper, a mathematical model is developed to predict and assess the evolution of the rheological properties of CPB under the coupled effects of temperature and progress of binder hydration. The model is implemented into the numerical software COMSOL Multiphysics. Then, the prediction ability of the model is assessed by comparing the predicted values with available experimental data from various rheological or flowability tests (rheometer, vane shear, and slump tests) on CPB. The model validation test results show that there is good agreement between the predicted and experimentally measured rheological properties of CPB. The simulation results emphasise that the temperature and progress of cement hydration have significant impact on the rheological behaviour and flowability.

1. Introduction

Mine backfilling has been introduced and designed to take advantage of waste tailings as a means to fill underground voids, which not only reduces or even eliminates surface tailings storage, but also provides miners with safe underground working conditions (e.g., Archibald et al., 2000; Rankine et al., 2001; Yilmaz et al., 2003, 2004; Le Roux et al., 2005; Huang et al., 2011; Abdul-Hussain and Fall, 2011). Therefore, this useful mining operation which is associated with the technology of cemented paste backfill (CPB, a mixture of binders, water and tailings) is being widely and intensively employed in the practice of underground mining around the world (e.g., Bloss, 2002; Kesimal et al., 2003; Kesimal et al., 2005; Fall et al., 2005; Fall and Benzaazoua, 2005; Helinski et al., 2006; Sivakugan et al., 2005; Klein and Simon, 2006; Huang et al., 2011; Cihangir et al., 2012).

After the preparation of fresh CPB by mixing tailings, binders and water in a backfilling plant which is usually located at the surface of the mine, the CPB forms a kind of slurry with relatively high density. The key objective of mine backfill is to place these fresh CPB mixtures into underground open stopes to produce hardened CPB structures, which can support the adjacent ore body and rock, and ensure a safe mining environment. One of the key performance properties of fresh CPB is its transportability, which is related to its fluidity or flowability. The fresh CPB must show acceptable flowability to enable efficient pumping/delivery from the CPB plant (usually located on the mine surface) to the underground stopes. Therefore, the flowability or the transportability of fresh CPB is crucial for efficient and cost-effective mine backfill operations, in which the cost represents 20% (on average) of the total mine operation costs (Fall et al., 2008). Fresh CPB with poor flowability not only affects efficiency in pumping/delivery to stopes, but can also result in pipe clogging which is associated with significant financial ramifications for the mine. For instance, if the fresh CPB is not flowable enough and pipe clogging occurs, the transportation system should be temporarily discontinued and the pipeline network disconnected (if necessary) to clear the pipes, which otherwise results in unfavorable consequences in which production progress is delayed and the operating costs of the mining companies are increased. Therefore, fluent transportability of fresh CPB should be ensured in order to avoid the occurrence of pipe clogging.

It is well known that characterising the rheological properties and behaviour of fresh CPB is the key step toward ensuring the good flowability of CPB. This stems from the fact that the transportation, pumping and placement of fresh CPB depends on its rheological properties or behaviour. In addition to external factors such as temperature and loading pressure, the rheological behaviour of transported fresh CPB also depends on internal elements (e.g., density and concentration of the CPB mixtures, characteristics of the CPB mixture constituents, and pH). However, almost all of the past studies (e.g., Wang et al., 2004; Huynh et al., 2006;

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Mahlaba et al., 2011; Yin et al., 2012) on the rheology of CPB have only focused on the effects of one isolated factor (e.g., cement content, shear time, addition of slag and/or fly ash, and pH value) on the rheological properties of CPB. The effect of temperature and the coupled effects of temperature and time (e.g., progress of cement hydration and shear time) have been ignored. Furthermore, there is no model that is available to predict the effects of temperature and temperature versus time on the rheological behaviour of fresh CPB flow. Therefore, there is the need to better understand the rheological behaviour of fresh CPB under various thermal loading conditions and their changes with time. This is because every single underground mine and backfill transportation system is unique with regards to differences in temperatures (Fall and Samb, 2007, 2008, 2009), and fresh CPB flow can be subjected to various thermal loading conditions during its transport from the plant to the underground stopes.

Fig. 1 shows that, regardless which system is in use, there is always friction between the inner sidewall of the pipe and the fresh CPB when it is transported through the pipeline; this contributes to heat generation within the fresh CPB (Fig. 1-①). Furthermore, depending on the depth of the underground opening stope, the transportation distance can be sometimes extremely long. Therefore, the cement hydration process may start when the fresh CPB is transported through the pipeline during a relatively lengthy amount of time, which can release non-negligible amounts of heat and thus increase the temperature of the CPB during its transport. Moreover, as ore reserves available at shallow depths are recently becoming more rare in several countries (e.g. Canada and South Africa), underground mining operations are moving to greater depths (Fall et al., 2009, 2010). This greater depth is not only associated with longer transport distance and time for the fresh CPB, but is also naturally associated with heat influx increases (Orejarena and Fall, 2008, 2011) because of the geothermal gradient (Fig. 1-②). The exposed rock mass is the primary heat load source in any deep level mining operation. These hot rock temperatures will obviously increase the temperature of the transported CPB because of the thermal interactions between the rock and the CPB contained in the pipe (Fig. 1-③). In addition, the geographical location of the mine is also a non-negligible factor that can affect the temperature of open pit mines and mines situated at relatively shallow depths, and thereby influence the temperature of the transported fresh CPB. The temperatures of these mines are strongly influenced by the climate of the region (Fig. 1-④). Particularly, in permafrost regions, these mines face permanent severe cold temperature conditions. Moreover, the geographical locations and/or the variations in temperature due to seasonal influence can considerably change the temperature of the mixing waters of CPB (especially when lake waters supply the mixing waters for the preparation of the backfill), and thus that of the CPB mixtures (Wu et al., 2012). These various temperatures, to which the CPB can be subjected during its transport, infer that one of the most challenging engineering tasks to ensure an efficient and cost-effective transport of CPB is the understanding and prediction of the effects of temperature on the rheological behaviour of CPB with time.

It is well known that a change in the temperature of fresh cementitious materials (e.g., CPB, cement paste and concrete) will affect the rate of cement hydration, which has strong influence on rheological properties (yield stress and viscosity), i.e. transportability of any fresh cementitious material (e.g. Petit et al., 2008, 2010). For instance, variations in yield stress and viscosity are directly associated with whether fresh CPB can be transported or how much load should be applied or energy (e.g. pumping) should be consumed to ensure flowability. Therefore, it is crucial to understand and model the rheology of fresh CPB under the coupled influence of temperature and time (cement hydration progress). This will contribute to better optimisation of CPB flow characteristics which could result in the improvement of CPB transportation parameters, and thereby reduce the risk of pipe clogging.

2. Mathematical modelling

2.1. Modelling approach and concept

By using COMSOL Multiphysics (COMSOL AB, 2005), a numerical model is developed to predict and study the flow or rheological behaviour of CPB under the coupled influence of thermal processes and progress of binder hydration. The model is based on the coupling of the following processes (only the strong or moderate coupled processes are considered; in Fig. 2, the long arrow represents strong or moderate coupling while the short arrow indicates weak coupling).

2.1.1. Thermal (T) process

As presented in Fig. 2, the thermal (temperature) process mainly involves heat generation (cement hydration and frictional

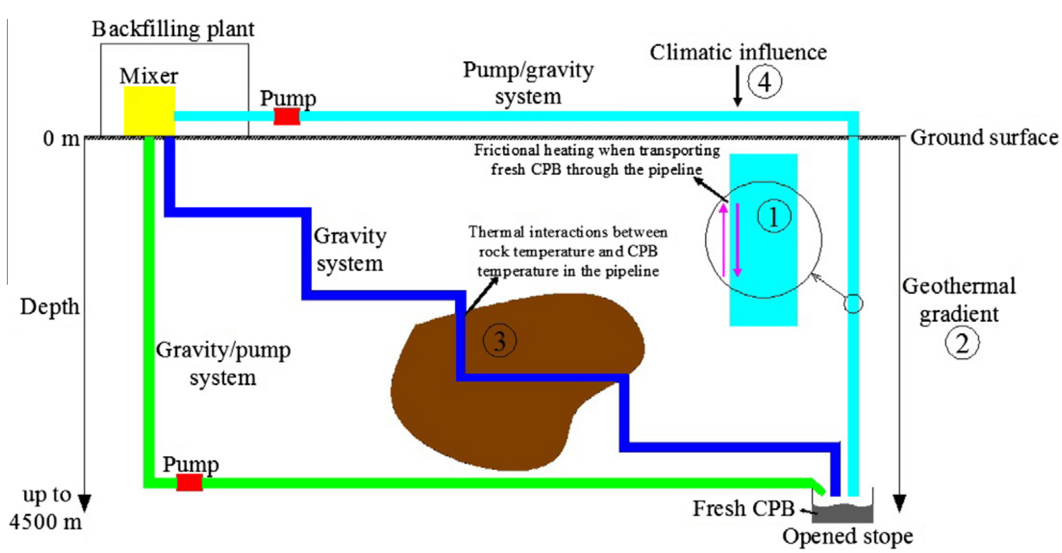

Fig. 1. Underground mine backfill transportation systems and thermal influencing factors.