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Modeling the thermal response of hydrating cemented gangue backfill with admixture of fly ash

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ABSTRACT

Cemented gangue backfill (CGB), which is a composite material mixed by coal gangue, binder and water, is used for coal mine backfill to control strata movement and thus, reduce ground surface subsidence. Whether a CGB structure can successfully play the role of supporting the overlying roof or not is dependent on its mechanical strength, which is significantly affected by the temperature development in it. The temperature of CGB is influenced by the heat generated by binder hydration and the heat transfer between the CGB and its surroundings. In this paper, a numerical model is proposed to predict the temperature development and distribution within the hydrating CGB structure. Results from an experimental study are employed to validate the developed model. This validation outcome indicates that the model simulation is in a good agreement with the experiment investigation. The validated model is then used to analyze the effects of various factors on the temperature development within the CGB structure versus curing time.

1. Introduction

Cemented gangue backfill (CGB), which is a kind of cement-based materials, is made with coal gangue, binder, and water [1,2]. Generally, the freshly prepared CGB mixtures are placed underground to fill mined-out areas through pipelines [3]. Once placed, the plastic CGBs begin to harden and after a given time, the hardened CGB structures, which have already possessed certain mechanical strength, are able to perform their role of supporting the overlying roof and thus prevent the upper strata from caving. Thereby, the coal pillars adjacent to the CGB structures can be mined. In addition, the CGB technology can also manage coal gangues, which are mine solid wastes and traditionally dumped in cone-shaped heaps on ground [4], causing serious social and environmental problems (e.g., dust pollution, spontaneous combustion) [5]. Since the CGB technology has its advantages in recovering coal resources, controlling land subsidence, and managing solid waste, it is regarded as an environmentally friendly solution incorporated into coal mine backfill and is being utilized increasingly in China.

One of the most important indicators to judge the quality of hardened CGB is its mechanical strength, which is affected by the binder hydration. This is because the binder hydration generates hydration products to improve bonding between particles of aggregate, contributing to the hardening and strength development of the CGB. Several studies have stated that temperature is a significant factor affecting the binder hydration process, and in turn the strength development in cement-based materials (such as concrete [6–8] and cemented tailings backfill (CTB), or cemented paste backfill (CPB) [9–11]). A properly high temperature can accelerate the hydration progress and thus more hydration products are generated to contribute to the strength development, but a relatively low temperature (especially when the temperature is lower than 0 °C) is unfavorable to the binder hydration. However, an overly high temperature may cause cracking in the cemented structures, which is a damage to the mechanical performance of the cement-based materials. For instance, in Fall and Samb's investigation [11], when the temperature is lower than 200 °C, the uniaxial compressive strength (UCS) of the CPB increases with increasing the temperature; while if the temperature is higher than 200 °C, the UCS decreases. Since CGB is also a cement-based material, it is necessary to understand the temperature evolution of the CGB.

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The temperature of a CGB structure is mainly affected by two processes. One is the binder hydration, and the other is the heat exchange between the CGB and its surrounding circumstance. For the former process, the binder hydration is an exothermal reaction, releasing heat to raise the temperature within CGB. As to the latter one, the heat transfers between the CGB and its surroundings due to their temperature difference. The initial temperature of the backfilled CGB varies, depending on the temperatures of its component materials (i.e., coal gangue, binder, and water), and the frictional heat generated during the transportation of the CGB. The underground environmental temperature around the CGB depends on the mine geothermal properties and the ventilation conditions.

Fly ash, which is a kind of industrial by-products, is commonly used as mineral admixture in cementitious materials to improve the stability and durability of these materials [12–14]. Additionally, considerable economic benefits can be achieved by replacing the cement with an appropriate proportion of fly ash in the binder. In terms of refuse reclamation and environment protection, the addition of fly ash in CGBs is an effective contribution in managing the solid waste, and thus reducing its pollution to the environment. For these reasons, in the current study, fly ash is utilized as mineral admixture for preparing the CGB.

In addition to CGB, numerous researchers have conducted modeling studies on the thermal properties of other types of cement-based materials, such as concrete [15–18] and CTB [19–21]. However, the results obtained from those studies are not applicable to the current CGB, due to the fact that CGB is different from CTB and concrete in many aspects, including aggregate used, mix proportion and binder usage. Moreover, these three kinds of materials (i.e., CGB, concrete, and CTB) are respectively applied in different situations. To date, there has been no model predicting the thermal behavior of hydrating CGB that contains fly ash responding to the coupled thermo-chemical effect (integration of temperature and binder hydration). It feels essential to develop a model to analyze the thermal response of the hydrating CGB. For this reason, a mathematical model is proposed in this paper, for predicting the heat generation and temperature development in the hydrating CGB, as well as the heat transfer between the CGB and its surroundings. The developed model is validated against an experimental study and thereafter, this model is used to simulate some engineering concerned problems. In engineering practice, engineers mainly concern about cost and efficiency. Specifically in terms of coal mine backfill, the usage of backfill materials and the time taken to finish backfilling are the primary concerns. This encourages the authors to reveal the effects of materials characteristics (this study focuses on the thermal property, i.e., the initial temperature of the materials), binder dosage (including the contents of cement and fly ash as well as their matching ratio), water-to-binder ratio, and backfilling rate on the thermal behavior of CGB. The obtained results can contribute to the design, preparation, and backfill of CGB mixtures.

2. Model development

In the present study, the software COMSOL Multiphysics [22] is applied to conduct numerical analyses. COMSOL Multiphysics provides numerical tools for solving scientific and engineering problems, especially coupled applications. On the basis of partial differential equations (PDEs) for the laws of science, COMSOL Multiphysics carries out finite element analyses together with adaptive meshing and error control by using a variety of numerical solvers. The entire process for solving a specific problem in COMSOL Multiphysics is to set sequences to record all steps, including configuring geometry, setting boundary condition, meshing, studying, and visualizing results.

COMSOL Multiphysics gives a general mathematical model for describing heat transfer in porous media, which is written as follows:

$$\left(\rho C_{\mathrm{p}}\right)_{\mathrm{eq}} \frac{\partial T}{\partial t} + \rho C_{\mathrm{p}} u \nabla T = \nabla\left(k_{\mathrm{eq}} \nabla T\right) + Q_{\mathrm{H}} \quad (1)$$

where, ρ is the fluid density, C_p is the fluid heat capacity at constant pressure, $(\rho C_p)_{eq}$ is the equivalent volumetric heat capacity at constant pressure, k_{eq} is the equivalent thermal conductivity, u is the fluid Darcy velocity (namely, volume flow rate per unit cross-sectional area), and Q_H is the heat source (w/m^3).

As the hardened CGB structure is a porous medium, Eq. (1) is employed to analyze the heat generation and transfer within it.

Since CGB has a low permeability like other cementitious materials (e.g., CTB) [19], the heat transfer due to Darcy flow is assumed to be negligible (i.e., $u = 0$). So the above Eq. (1) can be rewritten in the following form:

$$\left(\rho C_{\mathrm{p}}\right)_{\mathrm{eq}} \frac{\partial T}{\partial t} - \nabla\left(k_{\mathrm{eq}} \nabla T\right) = Q_{\mathrm{H}} \quad (2)$$

where, $(\rho C_p)_{eq}$ and k_{eq} can be calculated by the following equations [22]:

$$\left(\rho C_{\mathrm{p}}\right)_{\mathrm{eq}} = \varphi \rho_{\mathrm{s}} C_{\mathrm{s}} + (1-\varphi)\, \rho_{\mathrm{f}} C_{\mathrm{f}} \quad (3)$$

$$k_{\mathrm{eq}} = \varphi k_{\mathrm{s}} + (1-\varphi)\, k_{\mathrm{f}} \quad (4)$$

where, φ is the CGB porosity, ρ_s and ρ_f are the densities of the solid matrix and the fluid, C_s and C_f are the heat capacities of the solid matrix and the fluid, and k_s and k_f are the thermal conductivities of the solid matrix and the fluid. It should be pointed out that in this study, the fluid is liquid water, excluding water vapor or dry air.

Abdul-Hussain and Fall [23] provides the following equation to calculate the porosity of cement-based materials:

$$\varphi = \varphi_0 + n\alpha \quad (5)$$

where, φ_0 is the initial porosity, n is an experimentally determined parameter, and α is the binder hydration degree.

Binder hydration, which is an exothermic chemical reaction, releases heat to contribute to the temperature development in CGB, and the released heat is exactly the heat source (Q_H) in Eqs (1) and (2).

Without considering thermal radiation and heat convection (this is because the heat due to radiation and convection is insignificant and thus can be negligible), heat transfer between the CGB and its surrounding environment is derived from Fourier's law of thermal conduction [19]:

$$q = -k_{\mathrm{c}} \nabla T \quad (6)$$

Generally, the ratio between the hydrated and the total binder is used to represent the degree of binder hydration [24]. According to this definition, the degree of binder hydration is difficult to obtain. Therefore, the fraction of released heat related to the total heat of hydration is used as an indicator of the degree of binder hydration [25], which can be expressed in the following form [19]:

$$\alpha(t) = \frac{Q(t)}{Q_{\max}} \approx \frac{\int_0^t q_{\mathrm{h}}(t)\,\mathrm{d}t}{Q_{\max}} \quad (7)$$

where, $\alpha(t)$ is the degree of binder hydration at time t, $Q(t)$ is the cumulative heat released by the binder hydration at time t, Q_{max} is the total heat of binder hydration, and $q_h(t)$ is the heat releasing rate.

Specifically, the following model is developed to evaluate the degree of binder hydration [26]:

$$\alpha(t_{\mathrm{e}}) = \alpha_{\mathrm{u}} exp\left[-\left(\frac{\tau}{t_{\mathrm{e}}}\right)^{\beta}\right] \quad (8)$$