Construction and Building Materials 158 (2018) 326–336

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

A coupled THMC modeling application of cemented coal gangue-fly ash backfill

Di Wu [a,b,*], Tengfei Deng [a], Runkang Zhao [a]

[a] College of Resources and Safety Engineering, China University of Mining and Technology, Beijing, China
[b] State Key Laboratory of Coal Resources and Safe Mining, China University of Mining and Technology, Beijing, China

HIGHLIGHTS

- We develop a THMC model to analyze the coupled thermo-hydro-mechanical-chemical behavior of CGFB.
- The developed model can analyze the temperature, pore water pressure, water drainage, lateral pressure, as well as stress-strain development of hydrating CGFB.
- This study can contribute to a better design of stable, durable and environment-friendly CGFBs.

ARTICLE INFO

Article history:
Received 12 June 2017
Received in revised form 27 September 2017
Accepted 2 October 2017

Keywords:
Backfill
THMC
Coupling
Modeling
Coal mine

ABSTRACT

Cemented coal gangue-fly ash backfill (CGFB) is prepared by mixing coal gangue, fly ash, cement and water. The CGFB mixtures are filled into mined-out areas of coal mines for ground control and waste disposal. Once placed underground, the performance of CGFB is subjected to the thermal (T), hydraulic (H), mechanical (M) and chemical (C) processes and THMC coupling effects. Understanding the coupled THMC influence on CGFB is crucial for predicting the behavior of CGFB. This paper develops a THMC coupling model to describe and analyze the coupled THMC processes that occur in CGFB. The developed model considers the courses of thermal conduction and convection, fluid flow, suction development, chemical shrinkage, thermal expansion, and binder hydration. The simulation and prediction results of the developed model are compared with the experimentally tested data from 3 case studies. Good agreement is found between the modeling results and experimental data, validating the capability of the developed model to well characterize the properties of CGFB under coupled THMC loadings. The modeling results can also contribute to a better design of stable, durable and environment-friendly CGFB structures.

1. Introduction

In recent two decades, China has always been the leading producer of coal all over the world. Due to the geological and occurrence conditions, more than 90% of these coal resources are extracted from underground mines. Massive and intensive underground coal mining operations result in the creation of large quantities of mined-out areas and waste rocks (coal gangues). The disposal of coal gangues on the ground surface occupies land and also causes serious environmental contamination [1–4]. Moreover, the underground voids may induce ground subsidence or even collapse [5,6]. Therefore, cemented backfill technology, which uses the mixtures of solid waste and hydraulic binder to fill underground voids, has been introduced to solve the above problems [7–11]. For coal mines, a common practice is utilizing cemented coal gangue-fly ash backfill (CGFB, a mixture of coal gangue, fly ash, binder and water) as the filling material [12,13]. Once prepared and placed underground, the CGFBs should possess satisfactory stability, durability and environment-friendly properties, and these properties are strongly affected by the thermal (T), hydraulic (H), mechanical (M) and chemical (C) processes as well as the THMC couplings.

Understanding and modeling of the coupled THMC processes that occur in CGFB are crucial for evaluating the performance of CGFB and thus designing stable, durable and environment-friendly CGFB structures.

Recently, multiple processes coupled modeling has gradually become a research focus in cemented backfill materials, especially

---

[*] Corresponding author at: College of Resources and Safety Engineering, China University of Mining and Technology, Beijing, China.

E-mail address: ustb_wudi@hotmail.com (D. Wu).

https://doi.org/10.1016/j.conbuildmat.2017.10.009

CPB (cemented paste backfill, which is a mixture of dewatered mill tailings, binding agent, and water). Helinski et al. have proposed a fully coupled model (coupling the effects of filling, consolidation, cement hydration, and arching) for simulating the multiple processes that occur within a CPB filled stope, and the applicability of this model has been verified by comparing the modeling results with the field monitoring data from an operational pastefill stope [14]. Nasir and Fall have developed a numerical model of undrained CPB, coupling strength development, temperature and degree of hydration [15]. Wu et al. have proposed a mathematical model to predict the evolution of the rheological properties of fresh CPB under the coupled effects of temperature and binder hydration [16]. Wu et al. have established a thermo-hydro-chemical (THC) coupling model to analyze the thermal and hydraulic processes within hydrating CPB [17]. In addition, Wu and Cai have also developed a coupled THC model to predict and assess the hydraulic behavior of CPB [18]. Cui and Fall have presented a multiphysics model to predict the coupled THMC response of CPB and its evolution with time [19]. This model includes full coupling between the thermal, hydraulic, chemical (binder hydration) processes and CPB deformation as well as changes in CPB properties. Lu et al. have proposed a coupled THMC-viscoplastic cap model to describe the behavior of CPB under blast loading [20]. This model can not only evaluate the evolution of CPB properties in curing processes with coupled THMC factors, but also capture the nonlinear and rate-dependent behaviors of CPB under blast loading.

Although CGFB and CPB are similar in cementation and consolidation, they are still different from each other in some properties, such as aggregate used, composition and working conditions. The knowledge on multi-field coupled modeling of CGFB is very limited. Wu et al. have presented a THC coupled model to describe and predict the thermo-hydro-chemical behavior of CGFB [21]. However, this model is not able to assess the mechanical performance of CGGB. To date, no comprehensive study has been conducted to model the multiple processes that occur in CGFB as well as to predict the coupled THMC performance of CGFB. Therefore, the objective of this study is to develop a numerical model to analyze and assess the THMC behavior of CGFB. The numerical simulation results predicted by the THMC model are compared with the data of 3 case studies.

2. Mathematical formulation of the THMC model

2.1. Thermal equations

The temperature of CGFB is mainly affected by two factors, which are self-heating and heat exchange between the CGFB and its surroundings. The former factor results from the exothermic reaction of binder hydration, and the latter one includes thermal convection, thermal conduction, and heat radiation. It should be stated that the heat radiation is insignificant and thus not considered in the present study.

2.1.1. Binder hydration

Binder hydration is an exothermal reaction generating heat within CGFB. A previous study conducted by De Scutter and Taerwe has provided a formula to describe the hydration heat generating process [22]:

$$q_h = q_{\max} \cdot a_1 \cdot [\sin(\pi \cdot \alpha)^{a_2}] \cdot \exp(-a_3 \cdot \alpha) \cdot \exp\left[\frac{E_{\mathrm{ap}}}{R} \cdot \left(\frac{1}{T_r} - \frac{1}{T_c}\right)\right] \tag{1}$$

where, q_h is the binder hydration heat produced per unit time by weight; $q_{\max}$ is the maximum rate of heat production at the temperature of 20 °C; a_1, a_2, and a_3 are constants determined by experiments; α is the degree of binder hydration; T_r is the reference temperature; T_c is the CGFB temperature; R is the universal gas constant; and E_{ap} is the apparent activation energy, which is dependent on the temperature of CGFB and can be calculated by the following expressions [23]: when $T_c < 20$ °C, $E = 33500 + 1470(20 - T_c)$; otherwise when $T_c \geq 20$ °C, $E = 33500$ (J/mol).

2.1.2. Thermal convection

A CGFB skeleton is a kind of porous medium, which is formed by solid grains as well as liquid water and dry air in pores. Thermal convection within CGFB occurs when heat transfer through both liquid water and dry air flow. Since the convective heat interaction between the solid grains and dry air is insignificant. Therefore, the heat transfer process via dry air is ignored in this study. The convective heat through liquid water flow (Q_w) can be expressed by the following equation:

$$Q_w = \rho_w C_w u_w \cdot \nabla T \tag{2}$$

where, ρ_w is the density of liquid water, C_w is the specific heat capacity of liquid water at constant pressure, u_w is the velocity field of liquid water, and ∇T is the gradient of temperature.

2.1.3. Thermal conduction

Fourier's law is employed to characterize the heat conduction process between CGFB and its surroundings [24]:

$$q = -k_{\mathrm{eq}} \cdot \nabla T \tag{3}$$

where, q denotes the conductive heat flux vector, and k_{eq} refers to the equivalent thermal conductivity of CGFB.

Somerton et al. have provided an equation for calculating k_{eq} as follows [25]:

$$k_{\mathrm{eq}} = k_{\mathrm{d}} + \sqrt{\omega_e} \cdot (k_{\mathrm{s}} - k_{\mathrm{d}}) \tag{4}$$

where, k_{d} is the thermal conductivity of the porous medium (like CGFB in this study) in a completely dry condition, k_{s} is the thermal conductivity of the porous medium when it is fully saturated with water, and ω_e denotes the effective saturation degree of the porous medium.

Côté and Konrad have proposed the following expression to predict k_{s} of porous media [26], and this equation has been successfully applied in the prediction of k_{s} of CPB [27]. Therefore, this equation is continued to use here for calculating k_{s} of CGFB:

$$k_{\mathrm{s}} = k_{\mathrm{g}}^{1-\phi} \cdot k_{\mathrm{w}}^{\phi} \tag{5}$$

where, k_{g} and k_{w} denote the mean thermal conductivity values of the coal gangue grains and water, respectively, and ϕ is the porosity.

The condition that all the pores of a porous medium are completely dry can refer to the situation that these pores are fully saturated with air. As a consequence, the above Eq. (5) can be derived to calculate k_{d} [19]:

$$k_{\mathrm{d}} = k_{\mathrm{g}}^{1-\phi} \cdot k_{\mathrm{a}}^{\phi} \tag{6}$$

where, k_{a} is the value for the thermal conductivity of air.

2.1.4. Integrated expression

In consideration of the heat conduction and convection in CGFB, the heat conduction between the CGFB and its surroundings, as well as the heat generation from binder hydration, the following expression can be derived:

$$(\rho C)_{\mathrm{eq}} \frac{\partial T}{\partial t} + Q_w + \nabla q = Q_H \tag{7}$$

where, $(\rho C)_{\mathrm{eq}}$ is the equivalent volumetric heat capacity of the porous CGFB skeleton at constant pressure, and Q_H refers to the heat generated by binder hydration and can be obtained by using the following equation: