International Journal of Mineral Processing 162 (2017) 12–18

Contents lists available at ScienceDirect

International Journal of Mineral Processing

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

# Thermal, hydraulic and mechanical performances of cemented coal gangue-fly ash backfill

Di Wu [a,*], Yunbing Hou [a], Tengfei Deng [a], Yizhou Chen [b], Xiaolong Zhao [a]

[a] College of Resources and Safety Engineering, China University of Mining and Technology-Beijing, Beijing, China
[b] Institute of Building Fire Research, China Academy of Building Research, Beijing, China

ARTICLE INFO

*Article history:*
Received 19 October 2016
Received in revised form 16 February 2017
Accepted 2 March 2017
Available online 03 March 2017

*Keywords:*
Underground voids
Cemented coal gangue-fly ash backfill
Lateral expansion
Temperature
Drainage

ABSTRACT

Cemented coal gangue-fly ash backfill (CGFB, a mixture of binder, coal gangue, fly ash and water) is introduced and applied to fill underground voids in coal mines. Once placed, the CGFB mixtures should have favorable stability and environmental performance, and these are closely related to the thermal, hydraulic and mechanical properties of the CGFBs. In this study, column and block experiments are conducted to investigate the coupled evolutions of the main performance characteristics (thermal, hydraulic and mechanical) of CGFB structures. A test apparatus is designed and equipped to investigate the thermal (temperature development), hydraulic (water drainage) and mechanical (lateral expansion) performances of CGFB columns under pressure in drained and laterally constrained conditions. The CGFBs are cured at room temperature and monitored for 30 days. Additionally, water drainage and uniaxial compressive strength (UCS) of CGFB blocks at different curing temperatures (20 and 50 °C) are also tested. The results indicate that the hydraulic and mechanical behaviors of the CGFBs are significantly affected by thermal factors (heat generated by binder hydration and heat transfer between the CGFB and its surroundings). This study will contribute to a better understanding of the thermo-hydro-mechanical behavior of underground CGFB structures, and thus a better design of stable and environment-friendly CGFBs.



## 1. Introduction

Extraction of underground coal resources will certainly create underground voids and mine waste discharged on ground surface, resulting in subsidence, land occupation, and environmental pollution (e.g., spontaneous combustion of coal gangue heap causes air pollution, toxic or harmful substance contained in coal gangue causes water pollution) (Szczepanska, 1999; Tiwary, 2001; Bian et al., 2009; Wu et al., 2009; Liu and Liu, 2010; Ribeiro et al., 2010). These consequences have made engineers and researchers think of using mine wastes to fill underground mined-out areas to provide ground support, not only reducing the risk of surface subsidence, but also affording an environment-friendly approach for disposing the hazardous mine wastes. In recent decades, cemented backfill technology, which utilizes the mixture of binder, mine waste (such as coal gangue and tailing) and water to fill underground voids, has been widely used in mining operations all over the world (Kesimal et al., 2003; Sivakugan et al., 2006; Fall et al., 2008; Ercikdi et al., 2009; Mahlaba et al., 2011; Park et al., 2014; Wu et al., 2015a, b). As to coal mine backfill, except for using coal gangue as aggregate, fly ash is often admixed into the backfill materials. This is mainly ascribed to three reasons as listed below:

- The output of coal gangue from one coal mine is not able to prepare enough backfills for full filling of the gobs, therefore, fly ash, which is by-product of coal burning and convenient to obtain, is used to supplement the insufficiency of the coal gangue quantity.
- The coal gangue particles are relatively coarse while the fly ash particles are fine, the admixture of fly ash helps to improve the grain composition of the backfill materials.
- As a pozzolanic material, fly ash chemically reacts with calcium hydroxide (which is primary binder hydration products) to create cementitious compounds (such as calcium-silicate-hydrate or C-S-H, which is secondary hydration products), contributing to the hardening and strength gain of the backfill materials. For this reason, cement is often partially replaced by fly ash to make blended cement, and this is also a contribution of reducing the binder cost.

Consequently, cement, coal gangue, fly ash and water are mixed to prepare cemented gangue-fly ash backfill (CGFB) mixtures, which are often applied to fill the mined-out areas of coal mines for ground support. Therefore, the mechanical performance is one of the most significant criteria for evaluating CGFB structures. In general, the roofs of

* Corresponding author.
*E-mail address:* DiWu@cumtb.edu.cn (D. Wu).

http://dx.doi.org/10.1016/j.minpro.2017.03.001
0301-7516/

mined out areas in coal mines are relatively soft in comparison with that in hard rock mines. The mined out areas of coal mines need to be backfilled immediately after mining operations. For this reason, the CGFB materials are required to be self-standing and gain strength quickly to support the roofs. Normally, the required uniaxial compressive strength (UCS) value for a CGFB structure is often up to 0.1 MPa after it is being placed underground for 4–8 h, and 4 MPa for 28 days. In addition, since the CGFBs are designed and utilized to alleviate the pollution induced by surface discharge of solid wastes, it should also be ensured that the backfilled CGFBs exert the lowest negative impact on the underground environment. This requires the CGFBs possessing favorable environmental performance, however, to date there have been few studies considering the environment-related properties of CGFBs, such as water drainage and hydraulic conductivity. This stimulates the present study to concern the environmental performance of CGFB. Fall et al. (2009) have conducted a laboratory investigation to study the saturated hydraulic conductivity of CPB (i.e., cemented paste backfill, which is another type of backfilling materials made by mixing binder, tailings and water, and particularly applied to fill the underground voids of metal mines such as gold mines and copper mines), and Abdul-Hussain and Fall (2011) have investigated the unsaturated hydraulic conductivity of CPB. Moreover, Yilmaz et al. (2014) have demonstrated the effects of curing and stress conditions on final gravimetric water content of CPB. Although these studies listed above can provide references for similar investigations on CGFBs, but after all CGFBs and CPBs are different in many aspects such as aggregate used, compositions and operating conditions. Hence, the correspondingly obtained results from CPBs may not necessarily be applicable to CGFBs. It feels necessary to conduct an investigation on the hydraulic characteristics of CGFBs.

Mechanical and hydraulic properties of cemented backfill materials are closely related to temperature, and this has been discussed by a lot of researches. Fall et al. (2010) have carried out an experiment to reveal the effect of curing temperature on the mechanical properties of CPB structures. Wang et al. (2016) have undertaken an experimental test to determine the influence of various initial CPB temperatures on the mechanical strength development of CPB. Nasir and Fall (2010) have developed a numerical model and thereby utilized corresponding simulations to illustrate the influence of initial temperature of CPB on the strength development in CPB. Fall and Samb (2009) have also considered the effect of abnormally high curing temperature (100–600 °C) on the strength of CPB. Pokharel and Fall (2013) have experimentally demonstrated the effect of curing temperature on the permeability of CPB. Wu et al. (2013) have numerically discussed the effect of initial CPB temperature on the evolution of water drainage of CPB versus curing time. Furthermore, multi-field coupling analysis has been introduced and thus applied to cemented backfilling materials. Abdul-Hussain and Fall (2012) have carried out tests to investigate the thermo-hydro-mechanical behavior of CPB. In addition, Ghirian and Fall (2013, 2014) have further considered chemical effect (binder hydration) and thus analyzed the thermo-hydro-mechanical-chemical behavior of CPB. Cui and Fall (2015) have proposed a coupled thermo-hydro-mechanical-chemical model to predict the mechanical and environmental performances of CPB. Nevertheless, few studies have considered the influence of temperature on the mechanical and hydraulic properties of CGFB, and multi-field coupling analysis on the performance of CGFB is extremely limited. For this reason, there is a need to conduct these kinds of studies, which are expected to provide information for better understanding the behavior of CGFBs.

In addition to mechanical and environmental performances of backfills, the stability of barricades should also be considered in mine backfill operations. Ghirian and Fall (2013) think that the loads exerted onto the barricades are strongly affected by the pore water pressure (PWP) and suction that develop within the backfills behind the barricades, and a deeper understanding of the coupled effects of mechanical, thermal and chemical (e.g., binder hydration) processes on the hydraulic performance (e.g., PWP, suction) of CPBs is important for a better design of barricades. Wu et al. (2016) have presented a numerical model to predict the suction development in CGFB under the coupled effects of binder hydration and temperature. In terms of inspecting the stability of barricades, the lateral expansion behavior of the backfills should also be considered, especially when the backfills are subject to vertical loads. However, few studies have investigated the lateral pressure of CGFBs. Thus, the present study is going to describe the thermal (temperature variation), mechanical (uniaxial compressive strength, lateral pressure) and hydraulic (water drainage) behaviors of CGFB, as well as the interaction and coupling of these behaviors.

## 2. Experimental programs

### 2.1. Materials

The CGFB mixtures are comprised by the coal gangue, fly ash, cement and water. The coal gangue used is from a coal mine in northwest of China, the fly ash used is from a power plant near the coal mine, the cement used is ordinary Portland cement 425# that is bought from the market, and the water used is tap water. Table 1 illustrates the particle size compositions of the coal gangue and fly ash. Table 2 exhibits the main chemical compositions of the cement used, and Table 3 shows the chemical properties of the coal gangue and fly ash.

### 2.2. Test device developed for CGFB column experiments

An experimental apparatus (as shown in Fig. 1) is designed and fabricated to investigate the behavior of CGFB during its curing under pressure. A transparent acrylic column (Fig. 2) that is 15.0 cm in internal diameter, 16.0 cm in external diameter and 23.0 cm in height is used to place the freshly prepared CGFB sample, and the acrylic column is inserted into a steel column (7 in Fig. 1) that is 16.0 cm in internal diameter, 17.0 cm in external diameter and 23.0 cm in height. An internal circular slot, which is 17.0 cm in diameter and 0.5 cm in depth, is cut in a steel portable plate (13 in Fig. 1) for placing the steel column. The portable plate, which is embedded in a steel base plate (14 in Fig. 1), is designed and made for the convenience of casting the CGFB sample (9 in Fig. 1). Before the CGFB casting, the portable plate is pulled out from the base plate, and after completing the casting, the portable steel plate along with the CGFB sample and the two (steel and acrylic) columns are inserted into the base plate. Prior to pouring the CGFB into the acrylic column, a discoid permeable stone (12 in Fig. 1), which is 15.0 cm in diameter and 0.5 cm in thickness, is placed at the acrylic column bottom (above the circular slot of the portable steel plate). Afterwards, the CGFB sample is filled into the acrylic column, until the CGFB height reaches to 20.0 cm, and the top freeboard of the acrylic column (with the thickness of 2.5 cm) is left uncovered. This is in accordance with real underground mining conditions.

A circular through-hole, which is 2.2 cm in diameter and used for water drainage (from inside the CGFB sample), is opened at the center of the portable plate, and beneath this through-hole, another circular through-hole, which has the same inner diameter (2.2 cm) with the one in the portable plate, is opened at the center of the base plate. An aqueduct (15 in Fig. 1) is utilized to link the through-holes with a bottle (16 in Fig. 1), which is used to contain the drained water from the CGFB sample. Until no more water comes out from the CGFB sample, the already gathered water in the bottle is weighed by an electronic scale.

**Table 1**
Particle size compositions of the coal gangue and fly ash.

| | $D_{10}$ (μm) | $D_{30}$ (μm) | $D_{50}$ (μm) | $D_{60}$ (μm) | $D_{90}$ (μm) |
|---|---|---|---|---|---|
| Coal gangue | 204.722 | 856.589 | 1952.857 | 2736.752 | 6634.312 |
| Fly ash | 10.779 | 43.826 | 82.471 | 112.358 | 400.008 |