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Coupled thermo-hydro-mechanical–chemical behaviour of cemented paste backfill in column experiments
Part II: Mechanical, chemical and microstructural processes and characteristics

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ABSTRACT

The evolution of coupled thermal (T), hydraulic (H), mechanical (M) and chemical (C) (THMC) properties of underground cemented paste backfill (CPB) has been studied by means of experiments with insulated–undrained high columns. This paper which compliments Part I (Ghirian and Fall, 2013), presents the mechanical, chemical and microstructural processes and characteristics. Two columns have been built and filled with a specific CPB mix and equipped with different sensors. The vertical deformation and drying shrinkage for a period of 150 days are measured. Also, four other columns are cured for 7, 28, 90 and 150 days and then small samples are taken out from the columns to investigate the evolution of unconfined compressive strength (UCS), shear strength parameters, microstructural properties, and pore fluid chemistry. The combined results of the two part experiment show that strongly coupled THMC processes control CPB behavior. This study has demonstrated that mechanical properties are coupled to chemical reactions due to cement hydration and temperature changes inside the columns. Also, suction development due to self-desiccation can significantly increase the uniaxial compressive strength values with time. Chemical analysis including ion concentration measurements with time has revealed that change in pore fluid concentration affects the refinement of pore voids, and thereby results in improvement in hydro-mechanical performance as well as microstructural evolution of the CPB. External environmental loading, such as surface evaporation, can affect the durability performance of CPB structures. The results show that there is degradation of strength following surface shrinkage as well as an increase in saturated hydraulic conductivity due to existence of micro-cracks. The obtained results support that coupled THMC effects should be taken into account in field conditions to understand CPB behavior where stronger interplay reactions take place.

1. Introduction

Extraction of ore bodies from the ground creates large underground voids (stopes) which are backfilled by using appropriate materials and backfilling methods to provide ground support, dispose the tailings in a safe manner and reduce the risk of surface subsidence. Among the different methods of backfilling, cemented paste backfill (CPB) technology has become increasingly popular around the world (e.g., Kesimal et al., 2003; Sivakugan et al., 2005; Orejarena and Fall, 2008, 2011). CPB is an engineering mixture of dewatered tailings generated during mineral processing, hydraulic binder (e.g., cement) and water. Once CPB is placed into a mine stope, cement hydration contributes to the development of mechanical stability within the CPB structure so that it remains self-supporting during the recovery of the adjacent stopes to guarantee the safety of mine workers (Yilmaz et al., 2003). Mechanical properties are considered a key factor for a safe and efficient design of CPB structures, such as unconfined compressive strength (UCS) and stress–strain behavior (Archibald et al., 2000; Klein and Simon, 2006; Fall et al., 2007; Fall and Samb, 2009; Huang et al., 2011). These properties are significantly affected by several coupled THMC factors, such as heat of cement hydration (T), hydraulic factors (H) (e.g., suction, pore water pressure [PWP]), chemical reactions (C) (e.g., pore fluid chemistry) and mechanical (M) load (e.g., self-weight load). For instance, temperature rise due to the hydration process (or also higher curing temperature) affects the rate of UCS gain in backfills (Fall et al., 2010). Also, hydraulic factors such as suction development as a result of self-desiccation significantly influence the mechanical performance (e.g., Helinski et al., 2006; Abdul-Hussain and Fall, 2012). In addition, the physical properties (e.g., void ratio and degree of saturation) as well as CPB mix design proportion can significantly affect the mechanical behavior of CPB (Fall et al., 2004, 2008). There is therefore a need to understand these coupled THMC processes during the curing time of a CPB structure.

Furthermore, susceptibility to acid mine drainage (AMD), which results from the oxidation of sulphide-bearing tailings, is one of the most important environmental and durability issues of backfill structures. In the case where sulphide minerals are present in the tailings used in CPB preparation, there would be a potential of reactivity of these minerals with water and oxygen which can produce contaminants such as

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acidic leachate and toxic heavy metals. The contaminants can be transported into the surrounding environment, where water can flow through the backfill structure (Ouellet et al., 2005; Fall et al., 2009). For CPB structures exposed to the atmosphere, drying shrinkage due to surface evaporation can lead to micro-cracks development. This in turn can create preferential water and air paths in de-saturated backfill structure exposed to the atmosphere. (Holt and Leivo, 2004). It is an environmental issue when a durable CPB structure is needed to minimize susceptibility to AMD generation (MEND report, 2006). Furthermore, this is important in terms of mechanical strength degradation and fluid transport ability (Pokharel and Fall, 2011). Although the relationship between shrinkage cracks and strength loss is well documented in the concrete literature (i.e., Huo and Wong, 2006), yet to date, the effect of surface drying shrinkage and associated micro-crack development on CPB materials has not been addressed and there is the need to understand its effect on the coupled hydro-mechanical performance of CPB structures.

Chemical reactions due to the cement hydration process are one of the crucial factors in coupled THMC processes in CPB material. This hydration results in precipitation of cement hydration products into the pores, which in turn can lead to pore refinement and porosity reduction (Fall et al., 2009). This microstructural evolution contributes to the improvement of mechanical properties (e.g., strength, setting and hardening) and hydraulic properties (e.g., reduction in saturated hydraulic conductivity). There is therefore the need to understand the effects of chemical factors on coupled THMC processes in CPB materials.

The objectives of the present paper are to investigate the evolution of the coupled effects of mechanical, chemical and microstructural processes on CPB behavior, and understand the interactions of hydraulic, thermal (which are presented in paper Part I (Ghirian and Fall, 2013)) and mechanical properties on CPB performance. Also, this paper aims to address the influences of drying shrinkage on microstructural, mechanical and hydraulic performance and durability of CPB structures. Our literature review on recent studies (i.e., Belem et al., 2006; Fall and Samb, 2006; Helinski et al., 2006; Yilmaz et al., 2009; Nasir and Fall, 2010) shows that coupled THMC interactions have not yet been addressed. This has inspired the authors to conduct the current research to study the long term evolution of coupled THMC processes of CPB by column experiments, which include the effect of curing time and use of large curing specimens compared to conventional small cylinders. The findings of this study can contribute to a better understanding of CPB behavior, and thus lead to a more cost-effective, safe and durable design of CPB structures.

2. Materials, methods and experimental program

2.1. Materials

2.1.1. Binder and mixing water

In this study, ordinary Portland cement type I (PCI) was used as binder. Tap water was used to mix the binder and tailings.

2.1.2. Tailings

The ground silica (artificial) tailings (ST), which is made of quartz mineral (99.8% by weight) was used. The main objective of selecting the ST was to control the chemical and mineralogical composition of the tailings, and hence reduce the uncertainties of the results. Natural tailings such as sulfide-rich tailings may contain high amounts of sulfate and reactive minerals. The sulfate and these minerals can interact with cement. Moreover, these minerals can be oxidized during the preparation and curing processes of CPB. This will significantly affect the analysis and interpretation of the results (Pokharel and Fall, 2011). Silica tailings has about 45 wt.% fine particles (<20 μm) and can be classified as sandy silt with low plasticity in the ML group, according to the Unified Soil Classification System (USCS). Also, it has a grain size distribution close to the average of nine mine tailings from eastern Canadian mines.

2.2. CPB preparation and mix proportions

Required amounts of tailings, binder and water were mixed in a concrete mixer until a homogeneous paste was obtained. The mixing time was 10 min. The mix proportions adopted for this study were 4.5% PCI and a water to cement ratio (*w/c*) qual to 7.6. The slump or the consistency of the paste mixtures was equal to 18 cm, which is the most frequently used slump value in CPB preparation.

After the CPB mixtures were produced, the columns were filled up with the fresh backfill to the height of 150 cm in three filling sequences of 50 cm each. Each lift was allowed to set for 24 hrs, and then a new layer was added. This filling strategy allows us to understand the effect of several factors, such as filling rate, filling sequence, formation of a plug and unexpected backfilling interruption on CPB behavior. The *w/c* ratio, cement proportions and slump value were kept constant in all of the mixes used to fill the columns.

2.3. Experimental set-up of the column experiments

A schematic diagram of the column experimental set-up is shown in Fig. 1. The columns were constructed with cardboard form tubes with 20 cm inner diameter and 150 cm height. To construct each column, a tube with 20 cm diameter was placed in a tube with 30 cm diameter. The gap between them was then filled with expansive insulating foam sealant. It limited thermal interactions of the CPB mixture with the surrounding environment. The bottom of the column was fitted with an impermeable cap to maintain an undrained condition. The top of the column was open to atmosphere in order to consider the effect of evaporation on THMC behavior of CPB. It allowed us to simulate a backfilled mine stope conditions such that the surface of the backfill is exposed to the environment, while the sides and the bottom are surrounded by the adjacent rocks. Temperature and relative humidity of the curing room was continuously measured. In total, six columns were manufactured which comprised two columns for instrumentation and four columns for sampling purposes at 7, 28, 90 and 150 days. Each column was dismantled over a period of three days and then CPB samples were taken from different heights: 10, 25, 40, 60, 75, 90, 110, 125, 140 and 145 cm for the experimental testing program.

In order to prepare the samples with the required size for the different laboratory tests, the insulating layer was first removed and then the column was mechanically cut into small parts at the different heights mentioned above. Immediately, samples were taken for moisture content and density measurement at different heights. Then required samples for the engineering tests, such as uniaxial compressive strength (UCS), saturated hydraulic conductivity, direct shear tests were trimmed with coping saw and spatula into required size and shape. The whole column dismantling procedure was carried out in less than 3 hrs in order to minimize moisture loss. All the samples were kept in sealed plastic bags and cooler until tests. To determine the index properties of each sample, measured moisture contents were transformed into saturation degrees, based on the weight of water, solid parts, initial void ratio and specific gravity. Bulk density and porosity were determined gravimetrically. The time-dependent evolutions of the physical properties are detailed in Ghirian and Fall (2013).

2.4. Column instrumentation and monitoring

Monitoring columns were equipped with various sensors in order to investigate the variations of temperature, pore pressure, suction and settlement in different height of the column. The design locations of the sensors, filling sequence and sampling locations are illustrated in Fig. 1. The sensors were connected to a data acquisition system. Temperature sensors (model TH-T) were installed in the middle of each layer at