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Initial temperature-dependence of strength development and self-desiccation in cemented paste backfill that contains sodium silicate

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ABSTRACT

Advanced knowledge of the effect of the initial temperatures of cemented paste backfill (CPB) on its strength development and self-desiccation ability is needed to provide a rational basis for mixture proportioning as well as the cost-effective design of CPB structures and speeding up of the mining cycle. An experimental testing and monitoring program has been undertaken to determine the influence of various initial temperatures (2 °C, 20 °C, 35 °C and 50 °C) on the strength development and evolution of the self-desiccation (measured by the volumetric water content and suction) of the CPB that contains sodium silicate as the admixture (S-CPB) at early ages (up 28 days). The evolution of the temperature, electrical conductivity (gives information about the cement hydration progress), volumetric water content and suction of S-CPB samples with the specified initial temperatures have been monitored for 28 days. Moreover, mechanical tests and microstructural analyses are performed on these S-CPB specimens after specific curing times (6 h, 1 day, 3 days, 7 days and 28 days). The results obtained show that the initial backfill temperature has a significant influence on the curing temperature of S-CPB, its strength development and self-desiccation. Furthermore, the results reveal that the temperature-time history, cement hydration, self-desiccation and strength development of S-CPB are strongly coupled. The initial S-CPB and these couplings should be taken into account for a safe and economical design of S-CPB structures and the speeding up of mining cycles.

1. Introduction

One of the most important technological innovations in the last two decades, with the aims to increase the productivity of mines, manage mine waste cost effectively and contribute to the improvement of health and safety in mine operations, is the technology of cemented paste backfill (CPB) [1]. CPB is a mix of tailings, water and binder. Its components are combined and mixed in a plant usually situated on the mine surface and transported (by gravity and/or pumping) to the underground mine openings (stopes) [2–4]. To carry fresh and hydrating CPB materials during stope filling and thereby prevent CPB from flowing into the mine working areas, retaining wall structures called barricades or bulkheads are built in each of the access ways into the stope prior to stope filling [5–7].

The most common binder used in the preparation of CPB is Portland cement (PC). PC is not only a costly binder, but its production generates a large amount of carbon dioxide (CO_2) (CO_2 is a by-product of a chemical conversion process used in the production of clinker; CO_2 is also released during cement production by fossil fuel combustion) [8]. The cement consumption can represent up to 80% of the cost of CPB. These factors mentioned above have compelled mining companies to seek for alternatives to cement that increase the strength of the CPB, decrease the cement content and reduce the carbon footprint of the mining industry. Sodium silicate is one of the most recent chemical additives that are used to reduce the binder content in cemented backfill and increase its strength [13]. This new product, sodium silicate cemented paste backfill (S-CPB) (also named gelfill), is a mix of tailings, water, cement and sodium silicate (usually 0.3–0.4% by weight of solids).

Mechanical stability is one of the key performance properties of any CPB. Once placed, the CPB has to satisfy certain mechanical stability requirements to ensure a safe underground working

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environment for all mining personnel [9–14]. Moreover, a mechanically stable cemented backfill structure at the early ages is especially important for the opening of the barricades, thereby for reducing the mining cycle time, and thus increasing mining efficiency and improving production. So to say, the designed and built CPB structure should be capable of achieving the desired mechanical stability for ground support as early as possible.

As a structural element, the assessment of the mechanical stability of a CPB structure is mainly based on the (undrained) unconfined compressive strength (UCS). This is because the UCS test is relatively inexpensive, and can be easily incorporated into routine quality control programs at the mine [15]. The 28-day compressive strength that is required to maintain backfill stability is generally between 0.7 and 2 MPa [16]. However, the required UCS value largely varies, depending on the application and/or function of the CPB.

Moreover, the understanding and assessing of pore water pressure development in the CPB at the early ages are also critical for a safe and cost-effective design of the barricades or bulkheads. Indeed, the mechanical stability of the barricade or bulkhead walls is significantly affected by the pore water pressure developed in the CPB [7,17]. An excess of positive pore water pressure can considerably increase the loads applied onto these retaining structures [18]. It is well known that self-desiccation (induced by cement hydration) happens in the CPB. This self-desiccation results in the reduction of the positive pore water pressure or the development of negative pore pressure (suction) in the hydrating CPB structure. This means that a clear understanding of the pore water pressure changes induced by self-desiccation is critical for the proper assessment of the mechanical stability and safety of the barricades, and thus for their cost-effective design. In addition, suction has a direct impact on the strength of porous materials, and thus on CPB strength [19–21]. Moreover, pore water pressure decrease or suction development will change the effective stress in the CPB, which will affect the mechanical behavior of the CPB [9,18,20,21].

However, despite the extensive use of CPB and several past studies [e.g., 9,10,14,22–27] performed on CPB, many fundamental factors that affect its strength development and self-desiccation are still not well understood. Among these factors, the effect of the initial CPB temperature (i.e. fresh CPB temperature at time zero after its pouring into the mine stope) on its early age strength and self-desiccation is not well known. All of the past studies on the impact of temperature have only focussed on the effects of isothermal curing temperature [e.g., 8, 25] or high(fire)-temperature [(e.g. 28,29] on the strength of CPB. The influence of the initial temperature on the strength development and the self-desiccation of CPB with or without silicate sodium have been ignored. There is a need to address this issue for both economical reasons and the safety of mine workers. This is because every single CPB structure is unique with regards to differences in temperatures, and fresh CPB can have variable initial temperatures. Since CPB is a mixture of binders, water and tailings, its initial temperature is strongly affected by the initial temperatures of the mix components, such as the mixing water and tailings. The geographical location (e.g., warm/cold region) and/or the variations in temperature due to seasonal influence (e.g., winter/summer) can considerably change the temperature of the mixing waters (especially when lake or river waters supply the mixing waters for the preparation of the backfill), tailings (e.g., tailings stored outside before their use in CPB preparation) and thus that of the CPB mixtures [8]. Furthermore, an increase of the temperature in fresh CPB can occur during its transport in pipes from the surface to the underground working areas of a production section as described by Wu et al. [30]. In addition, when preparing CPB, moderate heat could be added to achieve a high early strength.

Thus, the objective of the present work is to experimentally study the influence of the various initial temperatures of CPB which contains sodium silicate on the evolution of its early age strength and self-desiccation (evaluated by the evolution of the volumetric water content (VWC) and suction in the backfill) within the S-CPB.

2. Materials and experimental program

2.1. Materials used

The materials used include water, binders, tailings and sodium silicate.

2.1.1. Water and binders

Tap water was used to mix the binders and tailings. Portland cement type I (PCI) and blast furnace slag (Slag) were used as the binders. PCI was blended with Slag. The blending ratio (weight) was 50/50. These binders are often used for CPB mixtures in mines located in eastern Canada. Table 1 shows the physical and chemical properties of the binders used.

2.1.2. Tailings

The physical and chemical characteristics of tailings can vary and are mainly dependent on the parent rock properties, ore mineralogy together with the physical and chemical processes used to extract the desired product [8]. Two types of tailings are used in this study, with the aim to reveal the relevance of tailings type in the response of S-CPB at early ages. These tailings include natural gold tailings (GT) and artificial (silica) tailings (ST). GT was collected from the CPB plant of a hard rock gold mine in eastern Canada. The particle size distribution of the GT is shown in Fig. 1. This figure shows that GT has about 42 wt. % fine particles (<20 μm) and can be classified as medium tailings. ST has the advantage of allowing the accurate control of the mineralogical and chemical compositions of the tailings, and thus reducing the level of uncertainties to a minimum level. Generally, natural tailings can contain several reactive chemical elements, and often, sulphide minerals, which can interact with cement and thus, affect the interpretation of the results [8]. ST contains 99.8% SiO_2 and shows a grain size distribution close to that of GT (Fig. 1) and the average of those from nine Canadian hard rock mines. It can be observed that ST has about 45 wt. % fine particles (<20 μm) and can also be classified as medium tailings. Tables 2 and 3 show the physical and mineralogical characteristics of GT and ST, respectively. GT is mainly made of chlorite, talc, quartz, magnetite, magnesite, dolomite and sulphides (particularly pyrite and a small amount of pyrrhotite) minerals. TS is made of quartz (one of the dominant minerals in Canadian hard rock mines). Furthermore, the tailings were tested for various index properties (e.g., liquid and plastic limits) by following ASTM standards. From the results obtained, GT and ST are non-plastic and classified as sandy silts of low plasticity, and ML in the Unified Soil Classification System (UCCS; [31]). Categorization as ML is typical for tailings from hard rock mines as also determined by Vick [32].

2.1.3. Sodium silicate

Soluble sodium silicates, also named water soluble glasses, are usually produced from varied proportions of an alkali metal and silicon dioxide (SiO_2). Aside from being used as an admixture for cement, soluble sodium silicate is also used for a number of applications in various industries or fields, such as the paper industry (e.g., for binding packaging), geotechnical engineering (e.g., soil grouting, mine backfill), soap and detergent manufacturing, waterproofing, textile processing, and foundries. Soluble sodium silicates are silicate polymers. It is a polymer liquid that is clear, colorless, and viscous. It is agreed that sodium silicates activate the