Cement & Concrete Composites 32 (2010) 819–828

Contents lists available at ScienceDirect

Cement & Concrete Composites

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

Coupled effects of sulphate and temperature on the strength development of cemented tailings backfills: Portland cement-paste backfill

Mamadou Fall *, Mukesh Pokharel

Department of Civil Engineering – University of Ottawa, Ottawa, Ontario, Canada

ARTICLE INFO

Article history:
Received 2 September 2009
Received in revised form 28 July 2010
Accepted 3 August 2010
Available online 10 August 2010

Keywords:
Cemented paste backfill
Temperature
Sulphate
Coupling
Portland cement
Tailings

ABSTRACT

Cemented paste backfill (CPB), which is a mix of tailings, water and cement, is subjected to the combined actions of temperature and sulphate during its service life. There is a need to acquire solid knowledge on the coupled effects of temperature and sulphate on the strength of CPBs for a safe, durable and cost-effective design of CPB structures. Hence, the main objective of this paper is to use an experimental approach to study the combined effect of temperature and sulphate on the strength development and microstructure (mineralogical composition of the hardened cement paste) of CPBs. About 200 CPB specimens with various initial sulphate contents (0, 5000, 15,000, and 25,000 ppm) and cured at different temperatures (0 °C, 25 °C, 20 °C, 35 °C, and 50 °C) are tested at different curing times (28, 90, and 150 days). The results show that the coupled effect of temperature and sulphate has a significant impact on the strength and mineralogical composition of the CPB. Depending on the curing time, temperature and initial sulphate content, the sulphate can have a positive or negative impact, i.e., leads to an increase or decrease of CPB strength. The obtained results show a strong indication that the absorption of sulphate by calcium–silicate–hydrate (C–S–H) could lead to the formation of lower quality C–S–H, thereby decreasing the strength of the CPB. This study has demonstrated that the coupled effect of sulphate and temperature on CPBs is an important factor for consideration in the designing of cost-effective, safe and durable CPB structures.

1. Introduction

During the last decade, cemented paste backfill (CPB), a relatively new cemented tailings material, has become increasingly popular in underground mining operations around the world. In addition to its ground support contribution during mining operations, CPB is now an indispensable tailings management method [1–5]. CPB is a mixture of thickened and filtered tailings from the processing operation of mines, water, and a hydraulic binder. It contains between 70% and 85% solids (tailings + binder) by weight. The binder creates cohesion in the CPB through binder hydration. Binders can represent up to 75% of the cost of CPBs. Ordinary Portland cement is traditionally used as a binder in a proportion that is commonly 2% to 7% by total weight. Proportions up to 10% are sometimes used to increase early strength [6]. The components of CPBs are combined and mixed in a plant that is usually located on the mine surface and transported (by gravity and/or pumping) to the underground openings (Fig. 1). To carry fresh and hydrating CPB materials during stope filling and thereby prevent CPB from flowing into the mine working areas, permeable retaining walls; otherwise known as barricades, or retaining walls that are impermeable; known as bulkheads, are built in each of the access ways into the stope prior to stope filling.

One of the most important quality criteria for a CPB structure is mechanical stability at a given time. Once placed in the mine opening (Fig. 1), CPBs have to satisfy certain dynamic and static load resistance requirements to ensure a safe underground working environment for all mining personnel. Mine backfill and/or barricade failures can have considerable financial ramifications and also often result in fatalities or injuries as reported in Canada and around the world [7]. The uniaxial compressive strength (UCS) is undoubtedly the most often used geotechnical property to evaluate mechanical stability of CPBs in underground mine backfill practices because the testing of UCS is relatively inexpensive and can be incorporated into routine quality control programs at the mine [8]. For example, the 28 days compressive strength that is required to maintain backfill stability is generally lower than 1 MPa [7] in cut and fill mining. When the CPB is used for roof support, strength values higher than 4 MPa are required [7]. However, when the CPB is simply used to fill voids or for underground disposal, backfill strength values between 150 kPa and 300 kPa are often used as target values at several mines sites [9] in order to eliminate the risk of liquefaction at an early stage. Furthermore,

* Corresponding author. Address: Department of Civil Engineering, University of Ottawa, 161 Colonel by, Ottawa (Ontario), Canada K1N 6N5. Tel.: +1 613 562 5800x6558.
E-mail address: mfall@eng.uottawa.ca (M. Fall).

0958-9465/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.cemconcomp.2010.08.002

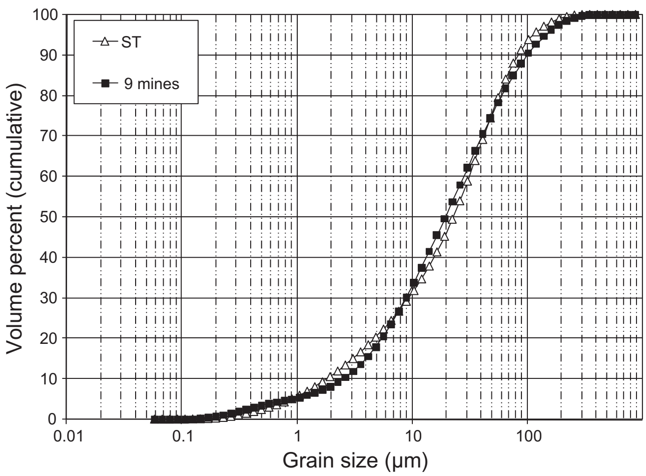

Fig. 1. Grain size distribution curve of the tailings material used.

a high rate of early backfill strength gain is especially important for opening of the barricades and thus, reduces the mining cycle, and increases production, i.e., for increasing the profitability of the mine [10]. Therefore, the designed and built CPB structure should be capable of achieving the desired UCS for ground support as early as possible.

During the past 15 years, several studies have been conducted to understand the factors that affect the UCS of CPBs [e.g., 1,2,4,7,10–15]. These studies have shown that the initial sulphate content can significantly affect the UCS of the CPB [15]. However, technical data about the effect of temperature on the UCS of CPBs is quite limited. Moreover, despite the tremendous progress made in understanding the effect of sulphate or temperature on the UCS development of CPBs, all of the previous studies have only investigated the isolated effects of sulphate [e.g., 10,11] or curing temperature [10] on the strength of CPBs. There are no studies on the coupled effect of sulphate and temperature on the UCS development of CPBs. Yet, there is a need to acquire such solid knowledge, since once built, in the engineering practice, the CPB structure is often simultaneously subjected to coupled thermal (temperatures) and chemical (sulphate) loads from early to advanced ages as explained below.

Various heat sources can significantly affect the temperature of CPB structures as described in [10]. These sources include: (i) the depth of the mine and geological conditions (the temperature of the rockmass which surrounds the CPB increases with depth [16,17]), (ii) the geographical location of the mine (e.g., permafrost region), (iii) the heat produced by the backfill hydration and/or transport (temperature within the CPB can reach 50 °C because of the binder hydration [6,18,19]), (iv) self-heating of the rocks and/or the hardened backfill, and (v) other human-induced temperature [20,21].

CPB materials often contain sulphate. The quantity of sulphate that can be present within the CPB system is usually much higher than that found in conventional concretes or mortars subjected to sulphate attacks. The initial sulphate content of CPBs can be low (<5000 ppm) to very high (25,000 ppm). Four main internal sources of sulphate in the CPB system can be identified. First, the CPB has a high proportion of tailings (75–80 wt.%) that can contain a high proportion of sulphide minerals (up to 60%, [e.g., 22]). The oxidation of the sulphide minerals [23,24] contained in the tailings (before mixing with cement and water) can produce sulphate in the tailings. However, the oxidations of the tailings in the CPB system is considered negligible due to the high water saturation of the CPB, binder hydration products that act as a physical barrier to oxygen and porosity reduction caused by the cement hydration process [21]. Secondly, another source of sulphate in a CPB system is the process of using sulfur dioxide/air for the destruction of cyanides in gold mining [25]. Furthermore, the addition of gypsum ($CaSO_4{\cdot}2H_2O$) or anhydrite ($CaSO_4$) to the clinker to control the setting of the cement can introduce small amounts of sulphate into the CPB mix [15,26]. Finally, the presence of sulphate in the CPB system can result from the use of mine processing waters that are often rich in sulphate in the preparation of CPBs.

In consideration of the facts that are mentioned above, a research program has been conducted at the University of Ottawa by the above authors to thoroughly investigate the effect of sulphate on the development of CPB UCS under various thermal loadings.

The main objectives of this paper are:

- to present the results of the coupled effect of sulphate and curing temperature on the strength of CPBs at early ages;
- to present the results of the coupled effect of sulphate and curing temperature on the strength of CPBs at advanced ages; and
- to develop an understanding of the mechanical performance (UCS) of CPBs when simultaneously exposed to sulphate attacks under various thermal curing conditions.

This study deals with CPB materials whose binder is made of ordinary Portland cement (Type I).

This paper is organized as follows. The experimental program, i.e., the materials used, the preparation of CPB specimens and the tests done are presented in the next section. This is followed by a presentation and discussion of the results obtained. Finally, we present our conclusions.

2. Experimental program

2.1. Materials

Silica tailings, binder and water with different amounts of sulphate were used to prepare the CPB specimens.

2.1.1. Tailings

Silica tailings (ground silica, ST) were used. This allowed the preparation of CPB samples with controlled mineralogical and chemical (e.g., sulphate) composition and physical characteristics (grain size). Natural tailings may contain various (uncontrollable) minerals and chemical elements that can influence the outcome of the study. The ST shows the same particle size distribution from the average of nine Canadian mine tailings (Fig. 1). The ST is made almost exclusively from 99.8 wt.% SiO_2. With 40% fine particles (particles with diameters lower than 20 μm), the ST can be classified as medium tailings. Further physical and chemical properties of the ST are given in Tables 1 and 2. The ST is well-graded with a coefficient of uniformity (C_u) of approximately 16.2 (Table 1) and free of sulphide minerals (Table 2).

2.1.2. Mixing water

Distilled water was used as the basic water. Specific amounts of sulphate salt ($FeSO_4{\cdot}7H_2O$) with a molecular weight of 278.01 were added to a specific volume of distilled water to create mixing water with well known sulphate concentrations (0 ppm, 5000 ppm, 15,000 ppm, and 25,000 ppm). Ferrous sulphate is the most common sulphate type found in cemented backfill mixes.

2.1.3. Binder

Portland cement Type I (PCI) in a weight proportion of 4.5% was used as the binding agent. The relative density of PCI is 3.1. The main chemical characteristics of the binder are shown in Table 3.