Construction and Building Materials 185 (2018) 555–566

Contents lists available at ScienceDirect

Construction and Building Materials

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

Effect of sodium-silicate activated slag at different silicate modulus on the strength and microstructural properties of full and coarse sulphidic tailings paste backfill

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HIGHLIGHTS

- Cemented paste backfill (CPB) is among the best available waste management techniques.
- Silicate modulus (Ms) of sodium-silicate significantly influences the strength gain rate of CPB.
- Optimum Ms value is around 1.25 irrespective of tailings particle size distribution.
- Decrease in Ms was observed to cause the formation of secondary gypsum minerals.
- Increase in Ms and use of coarse tailings significantly refined the microstructure of CPB.

ARTICLE INFO

Article history:
Received 26 March 2018
Received in revised form 13 July 2018
Accepted 13 July 2018

Keywords:
Cemented paste backfill
Alkali-activated slag
Sodium-silicate
Silicate modulus
Acid attack
Sulphate attack
Ca/Si ratio
Durability

ABSTRACT

In this study, strength and microstructural development of full (FT) and coarse sulphidic tailings (CT) cemented paste backfill (CPB) produced from sodium-silicate activated slag (SSAS) at different silicate modulus (Ms) were investigated in the short- and long-term. SSAS samples (SSASs) with varying Ms for both FT and CT produced 1.5–3.5 fold unconfined compressive strengths in the long-term compared to ordinary Portland cement samples (OPCs). Optimum Ms values were 1.0–1.25 for FT and 1.25–1.50 for CT considering the short- and long-term strength gain and microstructural properties of CPBs based on the polymerization degree and balance of C–S–H gel. Strength losses were observed in OPC-CT and in SSASs at Ms = 0.75 for FT and CT in the long-term. Formation of secondary expansive minerals such as ettringite, decalcification of C–S–H gel and the weakening of microstructure were found to be the main reasons for the strength losses due to the coupled effect of acid and sulphate attack. The use of CT and SSAS together significantly improved the microstructure of CPB. Increase in Ms decreased the porosity, refined the pore structure providing more compact microstructure and alleviated the decalcification of C–S–H gels in consequence of higher rate of polymerization.

1. Introduction

Cemented paste backfill (CPB) is an engineered mixture of mineral processing tailings, hydraulic binders and water. Tailings can contain sulphidic minerals such as pyrite and hazardous chemicals used during the processing stages of the sulphide-bearing precious minerals. CPB especially enables the filling of the large underground voids created during ore extraction as a part of underground mining. Therefore, CPB has received great attention since it allows environmentally friendly management of vast quantities of such tailings. Owing to the environmental, economic and technical advantages [1–6], CPB was regarded as one of the best available tailings management techniques by the European Union Commission in 2009 [7].

Design characteristics (i.e. binder type and dosage, consistency etc.), properties of tailings (i.e. sulphidic mineral (such as pyrite) content, amount of fine material etc.) and microstructural properties (i.e. pore structure, deleterious mineral formations etc.) significantly affect the mechanical strength development and durability properties of CPB. Mechanical strength is of critical importance for the safe production of adjacent blocks around the blocks filled with CPB for underground mines. High porosity (32–43%) and moisture content (15–23%) kept up for a long time

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https://doi.org/10.1016/j.conbuildmat.2018.07.105
0950-0618/

[8,9] in CPB generate acid and sulphate products due to the oxidation of sulphidic minerals [10–13]. During the first 56 days, the sulphate ions are completely consumed by CH (portlandite) [9,10,14] which is a hydration product of ordinary Portland cement (OPC). Sulphate bearing products react with other hydration products causing weaker C–S–H gel formation with poor quality [14]. Sulphate ions were found to increase after 56 days which is an indication of complete consumption of CH. On the other hand, pH begins to decrease after 14 days as an indication of pyrite reactivity and the consumption of CH [9,10]. Therefore, while C–S–H products disintegrated as a result of sulphate attacks and decalcified due to the acid products, secondary mineral precipitations [15] cause heterogeneous structure in the long-term which adversely affect the durability of CPB [11,16]. In recent years, besides the use of mineral and chemical additives to prevent acid and sulphate effects and to enhance the durability of CPB [11,12,16–18], the use of alkali-activated slags (AASs) have been reported to produce higher strengths and more resistant CPB to aggressive medium [9,10,19]. In case of durability problems, mine accidents may occur due to the collapse of CPB blocks [20]. These accidents can cause property and, the vital one, life losses. In practise, the durability performance of CPB is commonly evaluated by unconfined compressive strength in the short- and long-term.

Although the OPC is commonly used as main binder in CPB applications, it is vulnerable to acid and sulphate attack due to the high CaO content. Alkali-activated slag binders (AAS) were reported to be more durable against acid and sulphate attack owing to having aluminum-containing calcium silicate hydrate gel (C–A–S–H (C–S–H was used as abbreviation instead for AAS after this point)) [21] compared to OPC. The strength and durability performance of AAS depends on many factors such as the type and concentration of the activators, silicate modulus (Ms:SiO_2/Na_2O) of sodium-silicate (liquid sodium silicate (SS: $Na_2O{\cdot}nSiO_3$)), curing conditions, water to slag ratio, slag chemistry and fineness, etc. [8–10,22–25]. Ms of the activator, the mass ratio of SiO_2 to Na_2O (the chemical constituents of SS), has an influential effect on the strength development of AAS together with the composition of slag [21,24,26–29]. Wang et al. [28] conducted a study on acidic, neutral and basic slags with varying Ms (i.e. in the range of 0.75–3.0). They obtained the highest strengths at 1.0 Ms for acidic and neutral slags, and at 1.25 Ms for basic slag at 28 days. Ms significantly influences the hydration degree of blast furnace slag for a given activator concentration, as well. Shi and Li [26] kept the activator concentration (Na_2O) at 3 wt% and obtained the maximum strength values in the range of 0.5–1.5 Ms, where below and above this range resulted in lower strengths. Escalante García et al. [30] found highest strengths at Ms = 1.5 and lowest strengths at Ms = 2.0 at 8.0 wt% Na_2O concentration for blast furnace slag. Bakharev et al. [31] studied on varying Ms ratios (0.75–1.0–1.25 and 1.5) of SS at 4 wt% Na_2O concentration. They found that the strength increases with decreasing Ms in the early ages while the highest strength was obtained at 28 days at Ms = 1.25. Similarly, Krizan and Zivanovic [32] performed a study using 1:3 slag/sand samples where Ms was chosen as 0.6–0.9–1.2–1.5. Lower strengths were obtained at curing times before 7 days whereas highest strengths were reached with increasing Ms at 90 days at a constant activator concentration (3 wt%). The strength values were relatively higher than those of OPCs depending on Ms. However, drying shrinkage cracks were seen to increase at higher Ms. Duran Atis et al. [23] found that the maximum strengths varied in the range of 0.75–1.25 Ms based on the activator concentration. Therefore, determination of the optimum Ms of SS is of significance for the polymerization of silicate anions for better hydration of slag, leading to the formation of C–S–H with less porous structure which affect the strength development of AAS [24,26].

Beneficial effects of AAS on the mechanical and microstructural properties of CPBs of sulphide-rich tailings were reported in some studies [8–10]. These studies were focused on the activator type-concentration, slag chemistry, binder dosage and the particle size of tailings which affect the strength development of CPBs produced from AAS. However, the effect of Ms of SS on the mechanical strength performance and microstructural properties of CPB of sulphide rich tailings has not been studied, yet. Therefore, the objective of this study is the investigation of the effect of SSAS with different Ms on the strength and microstructural properties of CPB produced from coarse (CT) and full sulphidic tailings (FT) to provide beneficial knowledge for mine operators and contribute to design/produce CPB in better quality. Mechanical strength performance of CPBs was correlated with microstructural properties (i.e. pore size distribution, total porosity etc. determined by mercury intrusion porosimeter (MIP), examination of microstructure by scanning electron microscope (SEM) equipped with energy dispersive spectrum (EDS)), and the results of pH and sulphate measurements during 360 days curing time.

2. Experimental studies

2.1. Properties of the tailings and binders

In this study; full tailings (FT) and coarse (deslimed) tailings (CT) were used for the preparation of CPBs. FT was collected from a sulphidic copper-zinc ore flotation plant located in the northeast of Turkey while CT was gathered from disc filter outlet of a sulphidic copper ore flotation plant located in the northwest of Turkey. CT was hydrocycloned and some of fine particles of the tailings were removed before disc filter inlet. FT and CT can be classified as medium ($-20\ \mu m \approx 54\%$) and coarse ($-{\approx}31\%$) tailings, respectively [33] according to the amount of fine material content under 20 µm (Fig. 1). Both tailings are well-graded considering the coefficients of uniformity (Cu) and curvature (Cc) [34] (Table 1).

Chemical compositions of FT and CT were determined at ACME labs (CANADA) using X-Ray fluorescence and wet chemical analysis methods. FT and CT approximately contain 56.4% and 77.3% pyrite minerals based on the sulphidic S^{-2} contents, respectively. FT includes higher amount of clay minerals than CT considering $SiO_2 + Al_2O_3$ content (Table 1). Major mineral phases are pyrite, quartz, calcite and ankerite for FT, and pyrite, chlorite, quartz and calcite for CT according to the X–Ray diffraction analysis (Table 1).

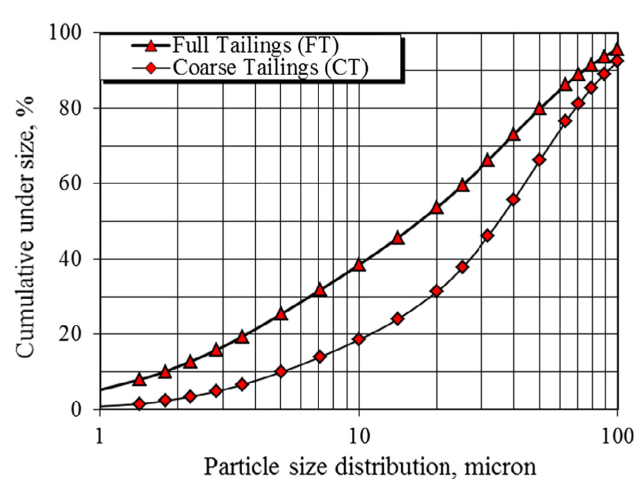

Fig. 1. Particle size distribution of the tailings.