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Yield stress of cemented paste backfill in sub-zero environments: Experimental results

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ABSTRACT

Current technical knowledge on the rheological behaviour of cemented paste backfill (CPB) is available for mines that have temperatures above zero, but this information is often unreliable when transposed to mines in permafrost or cold regions. The assessment and understanding of the yield stress of CPB and its evolution with time when exposed to sub-zero environmental temperatures are critical for applying CPB technology to underground mines in cold and permafrost regions. Therefore, the aim of this study is to investigate and develop a better understanding of the combined effects of time and sub-zero temperatures on a key rheological property (yield stress) of CPB. Several CPB mixtures of various compositions are exposed to various sub-zero-temperatures (−1 °C, −6 °C and −12 °C) or placed in room temperature up to 4 h. The yield stress of the CPB is determined after specific times. Furthermore, microstructural analyses and electrical conductivity monitoring are conducted on the CPB samples. It is found that the yield stress for the CPB samples exposed to the studied sub-zero temperatures is much lower than that of the sample placed in room temperature. Increases in the water cement ratio and sodium chloride concentration, and decreases in the sub-zero curing temperatures lead to lower yield stress. The results also show that the yield stress of CPB is strongly affected by the mineralogical and chemical compositions of the tailings. The findings of this study have significant implications for backfill practices in permafrost and cold regions.

1. Introduction

First used in the Bad Grund Mine in Germany in the late 1970s, cemented paste backfill (CPB) technology has since then been extensively used in many underground mines worldwide (Australia, Canada, China, etc.) (Yilmaz et al., 2004; Fall and Benzaazoua, 2005; Cihangir et al., 2012; Ghirian and Fall, 2013). Typically, CPB consists of a mixture of dewatered tailings with a solid percentage of 70–85%, water which is either fresh or mine processed, and a hydraulic binder, which is usually 3–7 wt.% (Benzaazoua et al., 2004; Pokharel and Fall, 2013). In addition to the efficient disposal of mine or processing waste, other benefits of the CPB technology include improved working environment, increased resource recovery and improved ground controls (e.g., Kesimal et al., 2005; Yilmaz, 2010). Furthermore, this technology is also considered superior to conventional slurry backfill methods in terms of both the economic and environmental benefits (Landriault, 1995; Hassani and Archibald, 1998). All of these technical, economic and environmental advantages associated with the use of CPB have resulted in wider acceptance of its application.

Typically, once homogeneously mixed in a backfill plant that is often located at the mine surface, fresh CPB is transported by gravity and/or pumped through pipelines to underground mine excavations (stopes). The transportation of fresh CPB through pipelines is one of the crucial stages of tailings backfill operations in mines. Therefore, one of the key performance properties of fresh CPB is its flowability, which is related to its fluidity (Wu et al., 2013). Indeed, freshly mixed CPB should be sufficiently fluid enough to enable efficient pumping/delivery from the backfill paste plant to the underground backfill stopes (Simon and Grabinsky, 2013). CPB with poor flowability impacts the efficiency of pumping/delivery to stopes as well as leads to pipe clogging, which has considerable financial consequences for the mine (e.g., loss of productivity, delay in mine schedule, increase in operation costs) (Wu et al., 2013) Therefore, the transportability of fresh CPB is crucial for efficient and cost-effective mine backfill operations (Fall et al., 2008).

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A key parameter used in the evaluation of the flowability or transportability of CPB is yield stress. The yield stress, as a good indicator of the magnitude of the particle–particle forces, is defined as the minimum shear stress required to initiate the flow (Simon and Grabinsky, 2013). It can be employed as a quantitative criterion for quality control and evaluation (Liddel and Boger, 1996). In pipeline design, changes in the yield stress of fluid CPB are commonly associated with changes in friction loss and due to the diameter of the pipes (Li and Moerman, 2002). Another important parameter for the evaluation of the transportability of CPB is viscosity. In pipeline design the ability to transport a specific paste is significantly influenced by the paste viscosity. High viscosity affects the pump performance and can lead to high pressures in pipelines. Moreover, excessive viscosity can result in pipeline blockages and shutdown (e.g., Andrade, 1947; McKetta, 1992; Hassani and Archibald, 1998; Jacobsen et al., 2008). The study of the viscosity is outside the scope of the present paper.

Several studies have been performed in past years to assess the yield stress of CPB and factors that affect the yield stress. These studies have shown that the yield stress of CPB is affected by external (e.g. warm temperatures, loading pressure) and internal (e.g., pH, density and concentration of the CPB mixtures, characteristics of the CPB mixture constituents, surface potential of solid particles) factors as well as time (Wang et al., 2004; Huynh et al., 2006; Mahlaba et al., 2011; Yin et al., 2012; Wu et al., 2013).

Despite the significant progress made by these previous studies in understanding the time-dependent yield stress of fresh CPB, no study has been performed on the effect of sub-zero environmental temperatures as well as the combined effect of sub-zero temperature and time on the yield stress of fresh CPB. There is a need to address this issue because the gradual depletion of ores available at shallow depths in a number of underground mines in various parts of the world (e.g., Canada, China) means that underground mines are increasingly being carried out in permafrost or cold regions which are characterized by sub-zero mining environments (Orejarena and Fall, 2008, 2010). The pipelines that transport the CPB in such regions are often subjected to sub-zero environmental temperatures. For instance, in the Canadian far north, local rocks can be permanently frozen at depths as great as 1000 meters. These sub-zero environmental conditions pose a real challenge to the transportation of fresh CPB due to the risk that the CPB may not remain sufficiently flowable or fluid (risk of freezing of the CPB) for the period of time required for its transport from the CPB plant to the stopes.

To avoid the freezing of the CPB during its transport, insulated pipes can be used. However, these pipes are not only expensive, but also cannot guarantee that the CPB temperatures remain above zero (or freezing point) at extreme cold temperatures or during its transport. Furthermore, the use of heated pipes considerably increases the cost of backfill operations due to high energy consumption and cost, which may affect the profitability of the mine. Thus, a sufficient understanding of the yield stress of CPB transported in sub-zero environmental conditions is required to assess the flowability and optimize the transportation of CPB in cold and permafrost regions.

The main objective of this paper is therefore to experimentally study the time-dependent evolution of the yield stress of fresh CPB in sub-zero environments.

2. Experimental program

2.1. Materials used

The materials used this study include tailings, binders, a chemical admixture (sodium chloride) and water.

2.1.1. Binders

Portland cement Type I (PCI) is the most common binder agent used in the backfill industry. However, due to its relatively high cost, pozzolanic products, such as fly ash (FA) and blast furnace slag (Slag) are often used to partially substitute for PCI to reduce the backfill operation cost. Hence, PCI was used as a binder alone or blended with FA or Slag. The blending ratio of PCI and Slag or FA in this study is 50/50 or 50/50 in weight proportion. The primary physical and chemical characteristics of the binders are shown in Table 1.

2.1.2. Tailings

The physical, mineralogical and chemical characteristics of tailings can be very variable due to the variations in the parent rock properties, ore mineralogy and the physical and chemical processes used to extract the economic product (Fall et al., 2010). To obtain results and draw conclusions applicable to a wide range of tailings categories, three types of tailings, artificial silica tailings (ST), gold tailings (GT), and zinc tailings (ZT) are used in this study. Furthermore, the use of ST, GT and ZT allows for the evaluation of the effect of the changes in the mineralogical composition of the tailings on the rheological behaviours of fresh CPB in a sub-zero environment. ST is mainly made of quartz mineral (99.8% by weight; Table 3). The use of ST (non-reactive and non-acid generating tailings) allows the mineralogical and chemical compositions of the tailings materials to be accurately controlled and thus uncertainties in the results obtained are minimal. Natural tailings can contain numerous reactive chemical elements and often sulphide minerals (they oxide and generate sulphate during contact with oxygen) that can interact with the cement and thus affect the interpretation of the results (Fall et al., 2010). The GT was sampled from the CPB plant of a gold mine, while the ZT was collected from the plant of a zinc mine. The main physical properties and mineralogical compositions of the tailings are shown in Tables 2 and 3, respectively. The ST, GT and ZT can be classified as medium tailings. As illustrated in Table 2, the ST shows grain size characteristics close to those of the GT and ZT, and to the average of nine types of tailings from eastern Canadian mines.

2.1.3. Mixing waters

Tap water is mainly used to mix binders and tailings. However, to prepare a saline mixing water with specific amounts of sodium chloride, distilled water was used as the basic water. The addition of specific amounts of sodium chloride to the distilled water allowed preparation of the mixing water with various concentrations of sodium chloride (0, 5, 35 and 100 g/L).

2.2. Specimen preparation and mix proportions

CPB specimens with different binder contents and types, tailings types and water to cement (W/C) ratios were prepared. The

Table 1
Primary chemical and physical properties of the binders used.

	Mg (wt.%)	Ca (wt.%)	Si (wt.%)	Al (wt.%)	Fe (wt.%)	S (wt.%)	Relative density	Specific surface area (cm^2/g)
PCI	1.6	44.9	8.4	2.4	1.8	1.5	3.2	1300
FA	2.6	13.3	15.2	9.2	4.1	1.3	2.6	2200
Slag	6.9	26.6	18.9	3.9	0.5	1.2	2.8	2100