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Yield stress and strength of saline cemented tailings in sub-zero environments: Portland cement paste backfill

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ABSTRACT

The objective of this study is to investigate the time-dependent evolution of the yield stress, strength and deformation behaviour of cemented paste backfill (CPB) that contains Portland cement as the binder with different saline concentrations in a sub-zero environment (−6 °C). Yield stress measurement with the vane method, uniaxial compressive testing and microstructure analysis have been conducted on various CPB samples with different sodium chloride (salt; NaCl) concentrations and cured in a sub-zero temperature for different times (0, 0.25, 1, 2 and 4 h for yield stress measurement; 7, 28 and 90 days for compressive strength testing). The results show that the yield stress decreases with an increase in salinity. The strength of CPB under freezing conditions decreases as the concentration of NaCl is increased. A shift from the strain-softening behaviour of CPB that has no salinity to the strain-hardening behaviour of CPB with high salinity is observed. Additionally, it is also noticed that with curing time, the deformation behaviour of the studied CPB becomes gradually less ductile. The microstructural analysis results show that the binder hydration products are affected by the salinity. There is strong indication that the absorption of the $Na+$ ions by calcium–silicate–hydrate leads to the decrease of the strength of CPB with different saline concentrations. The results of this investigation provide technical information for the designing of cost-effective, safe and durable CPB structures in sub-zero mining environments.

1. Introduction

Over the past few decades, cemented paste backfill (CPB), an innovative cementitious material, has been extensively employed for underground mine support (Fall and Benzaazoua, 2005; Fall and Pokharel, 2010; Ghirian and Fall, 2013; Tariq and Yanful, 2013). In addition to providing support for the surrounding mine structure, other potential benefits that could be obtained include increased mineral recovery, reduction of the mining cycle, increase in the mine production rate, and recycling of tailings. CPB is a homogeneous mixture produced by mixing dewatered tailings with a solid percentage of 70–85 wt%, water and a hydraulic binder (usually 3–7 wt%) (Benzaazoua et al., 2004; Fall, Célestin, Pokharel, and Touré, 2010; Pokharel and Fall, 2013).

Generally, the components of CPB are combined and mixed in a plant usually located on the mine surface and transported to the underground mine cavities (stopes) by gravity and/or pumping (Fall and Pokharel, 2010). Therefore, the transportability of fresh CPB at any given time is an important quality and design criterion for the paste backfill. Indeed, newly mixed cemented backfill should be sufficiently fluid to allow efficient pumping/transport from the backfill plant to the underground mine cavities (Simon and Grabinsky, 2013). A crucial factor used in the assessment of the flowability of CPB is yield stress (Haiqiang, Fall, and Liang, 2016). Yield stress, a rheological parameter, is defined as the minimum shear stress that must be applied to a material to induce flow (Liddell and Boger, 1996) and has been widely used as a useful parameter for quality control and evaluation in cement based systems (Ferraris, Obla, and Hill, 2001; Hanehara and Yamada, 2008). The yield stress is responsible for functional performance during mixing, transporting, placing and consolidating, but also controls in part, the properties of the final products (Wu and Roy, 1984; Nguyen and Boger, 1998; Liddell and Boger, 1996). Therefore, the measurement of yield stress is very essential to quantitatively evaluate the transportability and workability of fresh CPB.

On the other hand, mechanical stability is another important performance criterion for CPB (Fall et al., 2010). Once placed into mine openings, CPB must satisfy certain dynamic and static load resistance requirements to ensure a safe underground working environment (Fall, Adrien, Celestin, Pokharel, and Toure, 2009). The uniaxial compressive strength (UCS) of the CPB is widely used in practice to evaluate its stability because UCS testing is relatively inexpensive and can be incorporated into routine quality control programs at the mine (Fall and Benzaazoua, 2005; Vergne, 2000). Generally, CPB with a high rate of

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early strength gain and a favorable long-term durability is very important since it can reduce the mining cycle and thereby increase production. However, UCS is not the only important factor that demonstrates the structural integrity of CPB. In its role for ground support, the deformation behaviour (stress-strain behaviour) of CPB is also a key design property of interest (Fall et al., 2010).

In various parts of the world (e.g., Canada, China), ore that was once available at shallow depths is now nearly exhausted due to continuous and extensive mining operations. This has resulted in an increased interest within the mining community to exploit mineral resources in permafrost or cold regions, which are characterized by sub-zero mining environments. For example, in the Canadian far north, permanently frozen rocks can be found at depths of 1000 m (Haiqiang et al., 2016). However, one of the most challenging technical issues with backfilling in permafrost or cold regions is to ensure the transportability of fresh CPB since the CPB may not remain sufficiently flowable (possibility or danger of freezing of the CPB) for the period of time needed for its transport from the backfill plant to the underground mine cavity (Haiqiang et al., 2016). The freezing of the CPB during its transport can lead to pipe clogging which has significant financial ramifications for mines.

An approach that addresses the freezing of CPB during its transport is to use insulated pipes. But, these pipes are not only costly, but also cannot assure that the CPB temperature remains above the freezing point in particularly cold weather or during its transport (Haiqiang et al., 2016). Moreover, the use of heated pipes significantly raises the cost of CPB operations due to high energy consumption and cost, which could negatively influence the economic performance of mines (Haiqiang et al., 2016). Therefore, a cheaper alternative approach, which consists of adding anti-freezing agents (e.g. sodium chloride) to prevent the paste from freezing during transport, is used in the backfill practice. Furthermore, in Canadian permafrost, the water available for the preparation of mine backfill is often naturally saline (Hivon and Sego, 1993). Such conditions also often occur at field sites along the sea coast where no other source of water is available or where fresh water is costly to transport. Nevertheless, the presence of saline pore fluid in CPB may change the engineering properties (e.g., yield stress, strength) and the subsequent deformation behaviour of frozen CPB, which may affect the transportability and mechanical stability of the CPB.

However, to date, almost all previous studies performed to understand the rheological and mechanical properties of CPB (e.g., Yilmaz, Kesimal, and Ercidi, 2004; Cihangir, Ercikdi, Kesimal, Turan, and Deveci, 2012; Simon and Grabinsky, 2013; Ghirian and Fall, 2013) were conducted on CPB that has no salinity and/or CPB subjected to curing temperatures above zero. There are no studies on the evolution of the yield stress and mechanical behaviour (strength, deformation behaviour) of CPB that contains deicing salt (sodium chloride) subjected to sub-zero curing temperatures. For the reasons mentioned above, there is therefore the need to address this research gap. Therefore, the objectives of the present study are to experimentally investigate the evolution of the yield stress, UCS, and deformation behaviour of CPB made of Portland cement with different saline concentrations in a sub-zero environment.

2. Experimental program

2.1. Materials used

Tailings, binder and water with different concentrations of NaCl were used to prepare the CPB specimens.

2.1.1. Binder

Portland cement type I (PCI) with a specific gravity of 3.2 and 4.5% by weight was used to prepare the CPB specimens. Portland cement is one of the most commonly used binders in mine backfilling. The primary chemical composition and physical properties of PCI are shown in Table 1.

Table 1
Primary chemical composition and physical properties of PCI (wt%).

Element	SO_3	Fe_2O_3	Al_2O_3	SiO_2	CaO	MgO	Relative density
PCI	3.82	2.70	4.53	18.03	62.82	2.65	3.2

2.1.2. Tailings

Non-reactive silica tailings (ST) that contain 99.8% silicon dioxide are used in this study. The main physical and chemical properties of these artificial tailings are listed in Tables 2 and 3, respectively. The primary goal of choosing inert ST is to accurately control the chemical and mineralogical compositions of the tailings, and thus, to increase the reliability of the results. This is because natural tailings usually contain some reactive chemical elements, such as sulphide minerals, which can interact with cement hydration products (Fall et al., 2010), and thus could bring significant uncertainties to the results and their interpretation. Moreover, the ST used have a grain size distribution that is comparable to the average range of the grain size of nine types of mine tailings from eastern Canada (Table 2).

2.1.3. Mixing waters

Distilled water was used as the basic water to prepare all of the specimens. The required amounts of NaCl were added to the distilled water to achieve mixing waters with various NaCl concentrations (0, 5, 35 and 100 g/L).

2.2. Specimen preparation, mix proportions and curing conditions

The same water-to-cement ratio of 7.35 and binder content of 4.5% by weight were used for all of the mixes. The mixing water was added into the homogeneously mixed dry ingredients. The mixing time for all of the mixes was kept constant at 7 min. The solid percentage of all the mixes was 75%. All of the pre-weighed material was first placed inside a temperature-controlled environmental chamber 12 h before mixing to reach a temperature of −5 °C, so that all of the fresh CPB after mixing will have nearly the same initial temperature of 0 °C. For yield stress measurement, the fresh paste was poured into curing cylinders with a diameter of 10 cm and a height of 20 cm, and then placed into a temperature-controlled environmental chamber with a constant temperature of −6 °C. As for the UCS tests, curing molds (5 cm in diameter and 10 cm in height) were filled with the mixed fresh CPB and then stirred with a stirring rod for 30 s to remove trapped air from the mixture. Finally, the prepared specimens were cured in the aforementioned chamber at −6 °C ± 0.3 °C. A curing temperature of −6 °C was chosen to simulate the environmental temperature to which CPB is subjected during its transport from the backfill plant to the stopes as well as

Table 2
Physical properties of tailings.

Element	G_s	D_{10}	D_{30}	D_{50}	D_{60}	C_u	C_c
Unit	–	μm	μm	μm	μm	–	–
ST	2.7	1.9	9.0	22.5	31.5	16.6	1.3
Average of 9 mines	–	1.8	9.1	20.0	30.8	17.1	1.7

G_s: specific gravity; C_u: coefficient of uniformity; C_c: coefficient of curvature; S_s: specific surface area.

Table 3
Primary chemical composition of silica tailings used (wt%).

Element	SiO_2	Fe_2O_3	Al_2O_3	TiO_2	CaO	MgO	Na_2O	K_2O
ST	99.8	0.035	0.05	0.02	<0.01	<0.01	<0.01	0.02