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Unsaturated hydraulic properties of cemented tailings backfill that contains sodium silicate

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A B S T R A C T

Recycling the mine waste (tailings) into cemented tailings backfill has economical and environmental advantages for the mining industry. One of the most recent types of cemented tailings backfill is gelfill (GF), a backfill that contains sodium silicate as chemical additive. GF is typically made of tailings, water, binder and chemical additives (sodium silicate gel). It is a promising mine tailings backfill technology. From a design point of view, the environmental performance or durability of GF structures is considered as a key factor. Due to the fact that GF structures are cementitious tailings, their durability and environmental performance depend on their ability to resist the flow of aggressive elements (water and oxygen). Thus, understanding the unsaturated hydraulic properties of GF is essential for a cost-effective, environmentally friendly and durable design of GF structures. However, there is a lack of information with regards to unsaturated hydraulic properties of GF, the factors that affect them and their evolution with time. Hence, the unsaturated hydraulic properties (water retention curve (WRC) or water characteristic curve, air entry value (AEV), residual water content, unsaturated hydraulic conductivity) of GF are investigated in this paper. GF samples of various compositions and cured in room temperature for different times (3, 7, 28, and 90 days) are considered. Saturated hydraulic conductivity and microstructural tests have been conducted; WRCs are measured by using a WP4-T dewpoint potentiameter and the saline solution method. Unsaturated hydraulic conductivity is predicted using the van Genuchten (1980) equation. The water retention curve (WRC) is determined as the relationship between volumetric water content and suction for each GF mix and curing time. The van Genuchten (1980) equation is used to simulate the WRC to best-fit the experimental data. AEV and residual water content are also computed for each mix and curing time. Furthermore, functions are developed to predict the evolution of AEVs, residual water content and fitting parameters of the van Genuchten model with degree of hydration. Important outcomes have been achieved with regards to unsaturated hydraulic properties. The unsaturated hydraulic conductivity of GF was calculated to decrease when the suction, binder content, and degree of hydration increase. The effects of binder content and degree of hydration are more obvious at low suction ranges. The obtained results would contribute to a better design and assessment of the durability and environmental performance of GF structures.

1. Introduction

The generation of acid mine drainage (AMD) which results from the oxidation of sulphide-bearing tailings is considered as one of the major environmental problems that is challenging the mining industry. A massive amount of sulphide-bearing tailings are generated by mine activities around the world each day. These tailings should be perfectly controlled to avoid destructive impacts on the environment. Therefore, ways to effectively and economically limit the environmental impacts caused by AMD have always been a main issue for all mining operations (Yilmaz, 2007; Orejarena and Fall, 2008; Fisseha et al., 2010). It is worth mentioning that Georgius Agricola wrote in his 16th century classic, De Re Metallica, that 'when the ores are washed, the water that has been used poisons the brooks and streams and either destroys the fish or drives them away'(Davis and Ritchie, 1986).

Several techniques have been developed in recent years to mitigate the problem associated with AMD. One of the techniques that have become increasingly popular in underground mining operations around the world is recycling the tailings in the form of cemented paste backfill (CPBs). CPBs are heterogeneous material produced by mixing tailings (70–85 wt.%) with fresh or mine processed water, and hydraulic binder (3–7 wt.%). The cost of the binder consumption is high. It can represent up to 75% of the cost of cemented backfill (Fall et al., 2008, 2009; Nasir and Fall, 2009). This factor has compelled mining companies to seek for alternatives that can increase the strength of the fill and reduce the binder content. Sodium silicate is the most recent chemical additive that is used to reduce the binder content in CPBs. This new product is named gelfill (GF).

GF is a new cemented tailings backfill material. It is typically made of tailings, water, binder and chemical additives (sodium silicate gel).

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According to previous studies on GF (Doucet et al., 2007; Hassani et al., 2007), the chemical additive, sodium silicate, (like a gel, therefore the name GF) has the ability to absorb a large amount of water (cemented tailings are always prepared with excessive water to allow easy transport to underground voids), to accelerate binder hydration and promote the formation of additional binder hydration products. This contributes to a substantial increase in GF strength.

Mechanical, environmental performance and durability are the most important design criteria of cemented tailings backfill structures (Grabinsky et al., 2008; Nasir and Fall, 2008; Fall et al., 2009). Permeability is the key parameter that most affects the environmental performance and durability of cemented backfill (e.g., GF). Vulnerability of GF to AMD is dependent on the reactivity of tailings contained in the GF. The reactivity in turn is reliant on the types and quantity of sulphide minerals present in the GF as well as hydraulic properties of the GF (seepage of water and diffusion of oxygen through the GF matrix). These properties can be evaluated by investigating the hydraulic conductivity of GF, in particular, the unsaturated hydraulic conductivity. In addition, the hydraulic conductivity controls the leaching and transport of pollutants through the GF to the ground water (Fall and Samb, 2008; 2009). The hydraulic conductivity can also give information about the GF pore structure, such as coarseness, connectivity, and cracking.

Mechanical properties (shear strength and uniaxial compressive strength (UCS)) are affected by the unsaturated conditions in GF structures. Increasing the suction in GF structures leads to an increase in the strength. Self-desiccation, which is mainly responsible for the development of suction at early ages of the GF, and occurs in all types of cementitious materials due to chemical shrinkage, has an influence on the properties of fresh GF as well as the long-term behaviour of the GF. During self-desiccation, the largest pores empty first. The menisci formed in these partially empty pores create capillary tension within the pore solution and reduce the internal relative humidity (RH) of GF structures (Bentz, 2008). As a result, the compression strength of the GF structure increases, which influences the stability and durability of the GF. Decreasing the moisture content of GF structures due to higher suction (low RH) can lead to more economical GF designs. A good understanding of the unsaturated properties of GF is needed to evaluate the mechanical properties of GF in unsaturated conditions.

As GF is a new cemented material, only a few studies have discussed its mechanical properties. However, no studies have addressed the relevance of unsaturated hydraulic properties. There is a lack of knowledge on the unsaturated hydraulic properties of GF for different curing times and binder contents. The determination of the unsaturated properties of GF is being a challenge for geotechnical engineers and engineering geologists. This has inspired the author to conduct the current study.

The objectives of this study are:

- to determine the water retention curve (WRC) for the GF and its evolution with time as well as to simulate the WRC to best-fit the experimental data; and
- to predict the unsaturated hydraulic conductivity of GF sample by using saturated hydraulic conductivity and WRC;
- to better understand the unsaturated hydraulic properties of GF.

The results presented in this paper will contribute to the design of safer, more economically and environmentally friendly GF structures.

2. Experimental programs

2.1. Materials

The materials used to prepare GF include binder, tailings, sodium silicate, and water.

2.1.1. Binder and mixing water

Portland cement type I (PCI) was used as the binder. It is the most common material used by the mining industry to produce cemented backfill. Table 1 shows the physical and chemical properties of the binder. Tap water was used to mix binders and tailings.

2.1.2. Tailings

Silica tailings (ground silica, TS) are used in this study. TS can be classified as medium tailings with 41–45 wt.% fine particles (<20 μm). The use of silica tailings allows accurate control of the mineralogical and chemical compositions of the tailings. This maintains the level of uncertainties at a minimum level. Indeed, natural tailings can contain several reactive chemical elements, and often, sulphide minerals (which oxide and produce sulphate during contact with oxygen) that can interact with sodium silicate and/or the cement and thus affect the interpretation of the results as well as study outcomes. TS contain 99.8% SiO_2 and show a grain size distribution close to the average of nine Canadian mine tailings (Fig. 1). Tables 2 and 3 show the physical and chemical properties of TS. TS are non-plastic and classified as sandy silts of low plasticity (Celestin, 2008; Fall et al., 2010) and the ML category in the UCCS. ML is typical for tailings from hard rock mines as also determined by Vick (1990).

2.1.3. Sodium silicate

Soluble sodium silicates are water soluble glasses generally manufactured from varied proportions of an alkali metal and SiO_2. Soluble sodium silicates are silicate polymers. It is manufactured by smelting sand with sodium carbonate at 1100 °C to 1200 °C. It is an inorganic chemical, a clear, colourless, and viscous liquid. 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 tailings backfill), soap and detergent manufacturing, waterproofing, textile processing, and foundries. In the present study, soluble sodium silicate is used as an admixture for the cement or binder for the preparation of cemented tailings backfill. A commercial solution of sodium silicate (type N) was used, in which the ratio of SiO_2 to Na_2O is 3:2. Table 4 shows the sodium silicate properties. Sodium silicate was added to the mix in a liquid form.

2.2. Preparation of materials and mix proportions

Around fifty GF samples were prepared to study the hydraulic properties. Tailings, binder, water, and sodium silicate were mixed using a B20F food mixer. The mixing time was 10 min for all mixes. Tailings, binder, and water were mixed first, followed by the addition of sodium silicate. Various binder proportions were used to prepare the mixes; 2%, 4.5%, and 6% PCI by weight with a solid mass concentration of 73% which correspond to water–cement (w/c) ratios of 18.5, 8.2, and 6.2, respectively. Then, 0.4% sodium silicate by weight of solids was added to the mixes. All mixes have the same slump. The produced GF was poured into curing cylinders which are 5 cm in diameter and 10 cm in height. The prepared samples were then sealed and cured at 20 °C ± 2 °C for periods of 3, 7, 28, and 90 days.

2.3. Testing and analysis methods

2.3.1. Water retention curve (WRC)

A WP4-T Dewpoint PotentiaMeter and the saline solution method were used to measure the WRC of the GF samples. The WP4-T was

Table 1
Characteristics of Portland cement type I.

Types of binder	MgO	CaO	SiO_2	Al_2O_3	Fe_2O_3	SO_3	Relative density	Specific surface (m^2/g)
PCI	2.65	62.82	18.03	4.53	2.70	3.82	3.10	1.30