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Evaluation of the effect of sodium silicate addition to mine backfill, Gelfill – Part 1

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ABSTRACT

In this paper, the mechanical properties of sodium silicate-fortified backfill, called Gelfill, were investigated by conducting a series of laboratory experiments. Two configurations were tested, i.e. Gelfill and cemented hydraulic fill (CHF). The Gelfill has an alkali activator such as sodium silicate in its materials in addition to primary materials of mine backfill which are tailings, water and binders. Large numbers of samples of Gelfill and CHF with various mixture designs were cast and cured for over 28 d. The mechanical properties of samples were investigated using uniaxial compression test, and the results were compared with those of reference samples made without sodium silicate. The test results indicated that the addition of an appropriate amount of an alkali activator such as sodium silicate can enhance the mechanical (uniaxial compressive strength) and physical (water retention) properties of backfill. The microstructure analysis conducted by mercury intrusion porosimetry (MIP) revealed that the addition of sodium silicate can modify the pore size distribution and total porosity of Gelfill, which can contribute to the better mechanical properties of Gelfill. It was also shown that the time and rate of drainage in the Gelfill specimens are less than those in CHF specimens made without sodium silicate. Finally, the study showed that the addition of sodium silicate can reduce the required setting time of mine backfill, which can contribute to increase mine production in accordance with the mine safety.

1. Introduction

The process of filling the void created by underground mining activities with waste materials is defined as mine backfilling. Mine backfill has become an integral part of underground mining methods all around the world. Mine backfilling is primarily used to increase ore extraction, increase ground mine stabilization, and deposit waste materials. The increase of demand for minerals and increase of the depth of mining operations are the main challenges facing the mining industries. These challenges require to apply innovative methods that can meet the mining operation requirements in an environmentally friendly manner. At the same time, consistently increasing environmental standards and mine closure regulations require innovative approaches in mine waste disposal technology.

Mine backfill basically consists of tailings, binder and water. Gelfill is an underdeveloped mine backfill material which uses an alkali activator such as sodium silicate in its binder formulation. Although sodium silicate has been used in concrete manufacture, the use of this material in mine backfill is relatively new. Until very recently there have been only a few isolated publications, mostly out of McGill University, regarding Gelfill (Kermani et al., 2009, 2010, 2014). These previous studies investigated some basic mechanical properties of Gelfill. For instance, it was found that an elevated mixing time can have detrimental effect on the Gelfill mechanical strength (Kermani et al., 2011). Razavi and Hassani (2007) showed that the addition of sodium silicate to the sand pastefill might reduce the uniaxial strength of fill materials. Kermani and Hassani (2012) reported that the hydration process of slag/cement binder can be accelerated by the addition of sodium silicate. Although some of basic mechanical properties of Gelfill were understood, more research had to be conducted to clearly show the advantage of Gelfill over cemented hydraulic fill (CHF) if such advantages are proven. As a result, the main objectives of this paper are to measure the physical properties of Gelfill in various conditions, i.e. various binder and sodium silicate concentrations. Moreover, the microstructures of Gelfill and CHF specimens were

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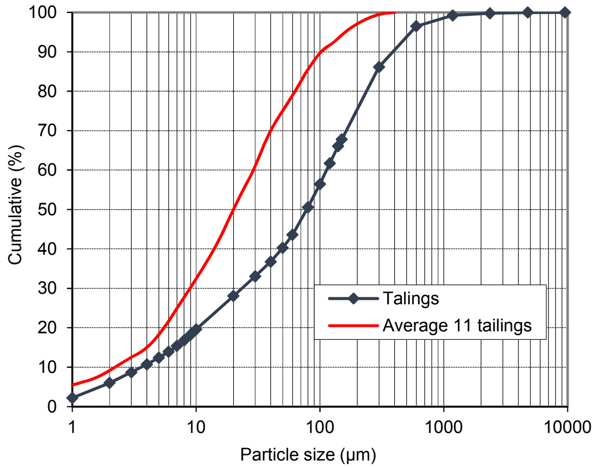

Fig. 1. Particle size distributions of tailings and average size of 11 mine tailings.

studied and compared to discover the possible reason behind the difference of the mechanical behaviour of Gelfill and CHF specimens. Finally, the amount of running water from Gelfill and CHF specimens was measured to investigate the possible advantage of Gelfill over CHF specimens. The final outcome of this laboratory research would help to better identify the mechanical properties of Gelfill and its benefits.

2. Materials

2.1. Tailings

Tailings are waste materials produced in ore processing plants. The materials consist primarily of finely ground host rock. The physicochemical properties of tailings have a significant effect on the mechanical performance of mine backfill (Benzaazoua et al., 2004; Kesimal et al., 2004). In this research, the classified tailings were delivered from one of Vale's mines in Sudbury, Ontario. The mineralogical content of the tailings generally consists of quartz, albite and slight quantity of calcite, muscovite, pyrrhotite, chalcopyrite, anorthite, and chlorite. The particle size distribution of the tailings was determined by using the laser diffraction methods (ASTM, 1996). The result is presented and compared with the average size of 11 mine tailings from the provinces of Quebec and Ontario, reported by Ouellet et al. (2008) in Fig. 1 as well as Table 1, and it was observed that the tailing was coarser than the average size of 11 mine tailings.

2.2. Binder

Binders are mainly used to increase the mechanical stability of fill materials. The most expensive part of mine backfill is the binders, and the cost of binder used in backfill could represent up to 75% of backfill costs (Hassani and Archibald, 1998). Normal Portland cement, fly ash and blast furnace slag have been mainly used for mine backfill. In this research, a combination of 90% blast furnace slag and 10% type 10 Portland cement, both provided by Lafarge Canada, was used. This combination is generally used in the Vale mines in Ontario, Canada. The densities of the slag and Portland cement used were 2.89 g/cm^3 and 3.07 g/cm^3, respectively. The Blaine specific surface areas of the slag and Portland cement were 5998 cm^2/g and 3710 cm^2/g, respectively. The chemical compositions of the blast furnace slag and Portland cement are shown in Table 2.

Table 2
Chemical compositions of the Portland cement and blast furnace slag provided by Lafarge.

Chemical composition	Blast furnace slag (wt%)	Portland cement (wt%)
CaO	37.129	61.13
SiO_2	36.127	19.39
Al_2O_3	10.385	4.61
MgO	13.246	3.3
SO_3	3.362	2.27
Fe_2O_3	0.668	2.01
Na_2O	0.424	2.03
K_2O	0.489	0.71

Note: wt% is the percentage by total dry weight.

Blast furnace slag has been generally associated with three main setbacks, identified as: (i) low hydration rate, (ii) low early strength, and (iii) a relatively slow strength development. In order to overcome these setbacks, blast furnace slag must be activated. Sodium silicate is one of the main alkali activators that have been used to activate pozzoloanic materials. The results of many studies show that blast furnace slag can be successfully activated by alkali activators such as sodium silicate.

2.3. Sodium silicate

Various types of sodium silicates are manufactured from varied proportions of Na_2CO_3 and SiO_2 by smelting the silica with the sodium carbonate at temperatures around 1100–1200 °C. The general formula of sodium silicate can be manifested as $Na_2O\cdot n$-SiO_2. Theoretically, the ratio of n can be any number; however, the range of n is between 1.6 and 3.85 for most commercially available sodium silicate material. Sodium silicate has been used for various purposes including as an alkali activator of slag and fly ash, glue, cements, paints, detergents, a hardening agent for natural and artificial stones (Shi et al., 2006). Many researchers believe that sodium silicate is the most effective alkali activator for most pozzolans including blast furnace slag and fly ash (Anderson and Gram, 1998; Bakhareva et al., 1999; Brough and Atkinson, 2002; Hilbig and Buchwald, 2006; Chen and Brouwers, 2007).

In this research, type N® sodium silicate was used, provided by the PQ National Silicate Company. This type of sodium silicate is the most efficient activator for ground blast furnace slag. Table 3 shows the properties of the sodium silicate.

2.4. Sample preparation and curing

In order to investigate the effect of binder dosage and sodium silicate concentration, 171 cylinders of CHF and Gelfill specimens

Table 1
Physical properties of the tailings.

Material	D_{10} (μm)	D_{50} (μm)	D_{60} (μm)	D_{90} (μm)	C_U	C_C	Specific gravity, G_s
Tailings used in this study	4.1	82.1	52.4	116.5	28.4	2.39	2.85
11 mine tailings reported by Ouellet et al. (2008)	2.2	20	29	102	13.2	1.24	Not available

Note: D_{10}, D_{30}, D_{60}, D_{90} are the particle diameter sizes that 10%, 30%, 60%, 90% of the sample particles are finer than corresponding size of the sample particles, respectively; $C_U = D_{60}/D_{10}$; $C_C = (D_{30})^2/(D_{60}D_{10})$.

Table 3
The properties of sodium silicate (PQ National Silicate Company).

Value type	Na_2O content (%)	SiO_2 content (%)	Weight ratio (SiO_2/Na_2O)	Specific gravity at 20 °C	Viscosity at 20 °C (centipoise)	Solids (%)
Standard	8.9	28.66	3.22	1.394	177	37.56
Maximum	9.1	29	3.27	1.401	213	38.1
Minimum	8.7	28.2	3.15	1.388	141	36.9

with 18 different mixtures were prepared. Table 4 shows the mixture characteristics and symbolization corresponding to CHF and Gelfill samples. CHF and Gelfill samples were made with stilled water. The binder agents used for preparing the CHF samples were made of 90:10 of blast furnace slag and Portland cement, and the binder for the Gelfill samples was a combination of blast furnace slag, Portland cement and sodium silicate. CHF sample is made with 5% binder by total dry weight of tailings which is symbolized by wt %. The Gelfill samples were prepared by addition of 0.1, 0.2, 0.3, 0.4, 0.5, 0.7 and 0.9 wt% of sodium silicate. These samples were labelled as GF .1, GF .2, GF .3, GF .4, GF .5, GF .7 and GF .9 (Table 4). CHF-B5%, CHF-B7% and CHF-B9% were prepared with 5, 7 and 9 wt% binder and for the correspondence GF samples 0.3 wt% was added to the mixtures. The pulp density was kept constant at 70% as is practiced in Vale's mines in Sudbury. CHF and Gelfill mixtures were prepared in small batches in a 5-L stainless steel bowl. The mixtures were mixed for 5 min. A mixer with a stainless steel wire whip blade was used to mix the ingredients. Cylindrical, polyvinyl moulds 10 cm deep and 5 cm in diameter were used to cast the mixtures. The bottom of moulds were perforated by 25 uniformly distributed holes to simulate the drainage as it happens in the mines and a geotextile filter was installed to prevent the loss of fine particles. Those specimens were then cured in a curing chamber where the relative humidity was kept constant at (90 ± 2)% and the temperature was adjusted to (25 ± 1) °C unless otherwise stated. The specimens then were tested at 7 d, 14 d and 28 d, respectively.

3. Experimental setup

3.1. Unconfined compression tests

The mechanical strength of the cured specimens was measured. The test was conducted with a "Wykeham Farrance 100 kN" pressure equipped with a 50 kN load cell by conducting uniaxial compression tests (ASTM, 2006). A linear variable displacement transducer (LVDT) sensor was used to obtain the samples' vertical deformation rate (strain). Samples were taken out from the humidity room just prior to conducting the unconfined compression test. A data acquisition board and a computer setup were used to record and display the data. On a given curing day for each mixture, three samples underwent the unconfined compression testing and the average value of the three results was recorded as the overall result of the unconfined compression test.

Table 4
Binder mixtures characteristics of backfill samples.

Sample No.	Blast furnace slag (wt%)	Portland cement (wt%)	Sodium silicate (wt%)	Binder concentration (wt%)
CHF	4.5	0.5	0	5
GF .1	4.5	0.5	0.1	5
GF .2	4.5	0.5	0.2	5
GF .3	4.5	0.5	0.3	5
GF .4	4.5	0.5	0.4	5
GF .5	4.5	0.5	0.5	5
GF .7	4.5	0.5	0.7	5
GF .9	4.5	0.5	0.9	5
CHF-B5%	4.5	0.5	0	5
Gelfill-B5%	4.5	0.5	0.3	5
CHF-B7%	6.3	0.7	0	7
Gelfill-B7%	6.3	0.7	0.3	7
CHF-B9%	8.1	0.9	0	9
Gelfill-B9%	8.1	0.9	0.3	9

3.2. Mercury intrusion porosimetry (MIP)

Mercury intrusion porosimetry (MIP) is a technique extensively used to investigate the microstructure of cemented materials like backfill and concrete (Aligizaki, 2006). This technique is based on the theoretical foundation of Washburn (1921) which describes that a non-wetting liquid will only penetrate into pores under pressure, and this penetration is directly dependent on the amount of the applied pressure. Washburn developed a relationship between applied pressure and pore size as follows:

$$r = -\frac{2\gamma \cos \phi}{P}$$

where r is the radius of the capillary, P is the absolute applied pressure, γ is the surface tension of the liquid (approximately 0.48 N/m for mercury), ϕ is the wetting angle or contact angle between the liquid and solid material (approximately 140° for mercury).

Nevertheless this technique has some drawbacks, MIP technique is commonly used to determine pore size distribution and pore structure data (Ouellet et al., 2007).

Since evaluating the microstructure of the cemented backfill is important in understanding the mechanical properties and durability of cemented mine backfill (Belem et al., 2001). Therefore, a total of 12 samples of CHF and Gelfill cured for 28 d were subjected to the MIP test using a 9320-PoreSizer porosimetry manufactured by Micromeritics.

To study the microstructure of CHF and Gelfill specimens, samples were cured for 28 d. Consequently, small particles in dimension of 5–7 mm of samples were carefully taken from the centre of the samples which previously tested for the unconfined compression test. The selected samples were then dried in a vacuum desiccator.

4. Results and discussion

4.1. Effect of sodium silicate concentration on the Gelfill strength

Fig. 2 shows the result of the unconfined compression tests obtained from CHF and Gelfill specimens tested at 7 d, 14 d and 28 d of curing. As expected, the unconfined compression strength (UCS) values increased with increasing curing time (due to the hydration of normal Portland cement and blast furnace slag). The results show that for a given curing time, the UCS values increase by increasing the amount of sodium silicate up to 0.3% of the total dry weight (wt %). However, the UCS values decrease with any further increase of sodium silicate over this 0.3 wt% point. Moreover, the UCS values significantly decrease when the amount of sodium silicate surpasses 0.5 wt% and the specimens made with 0.7 wt% and 0.9 wt% sodium silicate have no measurable strength within the first 14 d of curing. This could be due to the increase in the total porosity of samples and the amount of moisture trapped in the samples. Furthermore, Fig. 2 also shows that the acquisition of mechanical strength for Gelfill samples is more rapid than the CHF samples which could be beneficial due to the fact that mining cycle could be reduced and consequently mining operation would be more efficient.

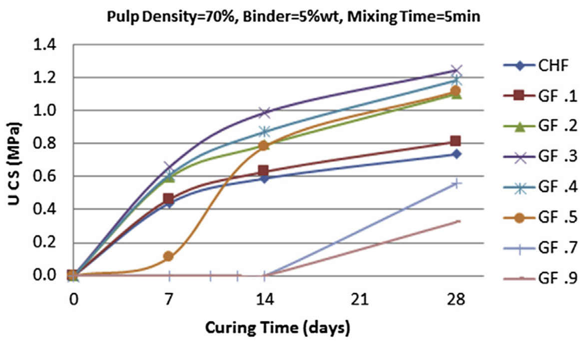

Fig. 2. Effect of sodium silicate dosage on the uniaxial compressive strength (UCS) of CHF and Gelfill.

4.2. Effect of binder concentration on the Gelfill and CHF mechanical strength

In order to investigate the effect of binder concentration on Gelfill and CHF, the binder dosage of 5 wt%, 7 wt% and 9 wt% were used and the samples were labelled CHF-B5%, CHF-B7% and CHF-B9%. It is important to note that 0.3 wt% sodium silicate was added to above mentioned CHF samples, which were labelled Gelfill-B5%, Gelfill-B7% and Gelfill-B9%.

Fig. 3 presents the results of the unconfined compression test performed on the specimens at 7 d, 14 d and 28 d of curing. As expected, the UCS values of CHF and Gelfill specimens were increased with the increase of binder dosage. The diagram also shows that the UCS values of Gelfill specimens are higher than those of CHF specimens made with the same amount of binder concentration. It can be concluded that the addition of an appropriate amount of sodium silicate to CHF can increase the mechanical strength of fill materials. Furthermore, backfill strength can rapidly reach to the required UCS of 1 MPa reported as minimum strength requirement for a cemented backfill in a typical underground mining operation (Brakebusch, 1994). This indicates that Gelfill could contribute to a more rapid mining cycle, therefore increase and improve the mining production.

4.3. Mercury intrusion porosimetry results

In order to investigate microstructural properties and also to explain the results of the unconfined compression tests, MIP tests were performed on CHF and Gelfill samples cured for 28 d, and the results are shown in Fig. 4. The total porosity of the CHF sample (38.93%) is higher than that of the Gelfill sample (34.11%). Moreover, both samples have two pore size families that dominate the pore size distribution. The size of pores reported in the Gelfill samples (20–0.1 μm) was smaller than the size of pores in the CHF samples (100–1 μm). These two differences can contribute to the higher UCS values and better mechanical behaviour of the Gelfill over the CHF samples. In fact, for a given overall porosity of a sample, as pore size decreases, the distribution of an applied stress is more likely to be homogeneous and uniform (Li and Aubertin, 2003; Kermani et al., 2009).

4.4. Effect of sodium silicate concentration on the drainage of Gelfill and CHF

The addition of extra water to hydraulic backfill is absolutely necessary to facilitate the transportation of fill materials. Fill materials are mixed with extra water to produce slurry. This water is then transported with fill material to the stopes where the backfill is placed. This extra water may cause many operational problems

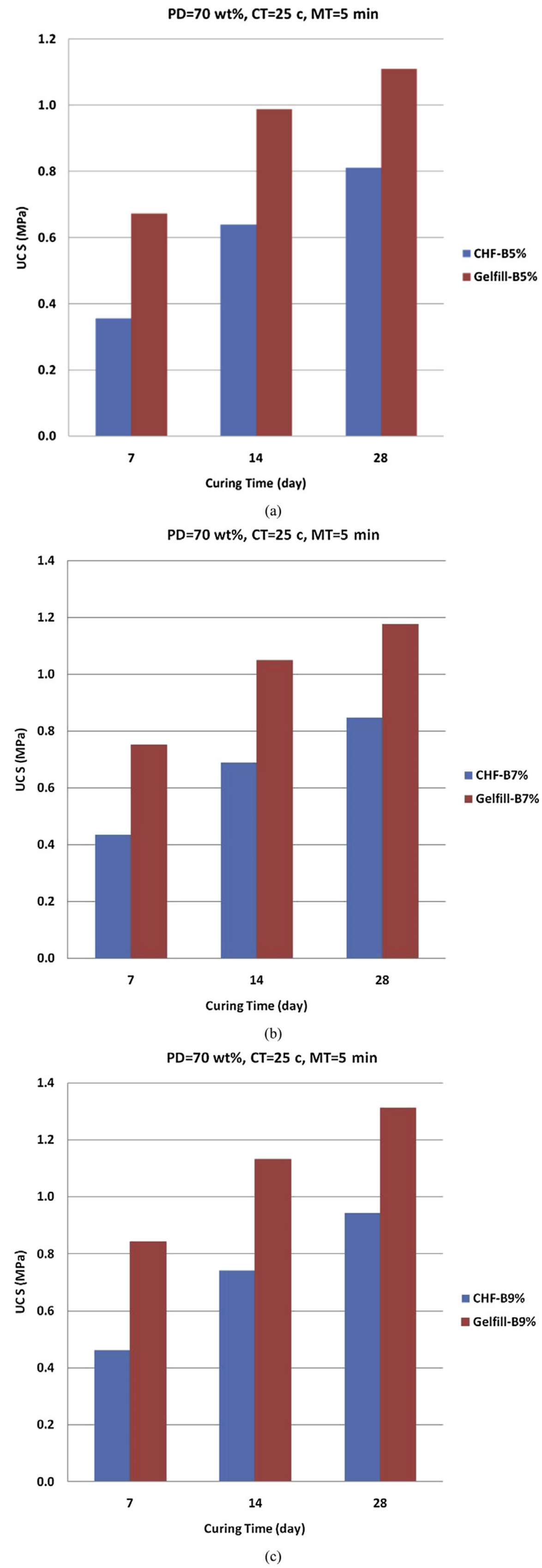

Fig. 3. UCS values of CHF and Gelfill samples made with various binder concentrations: (a) 5%, (b) 7%, and (c) 9%. PD is the pulp density, CT is the curing temperature and MT is the mixing time.

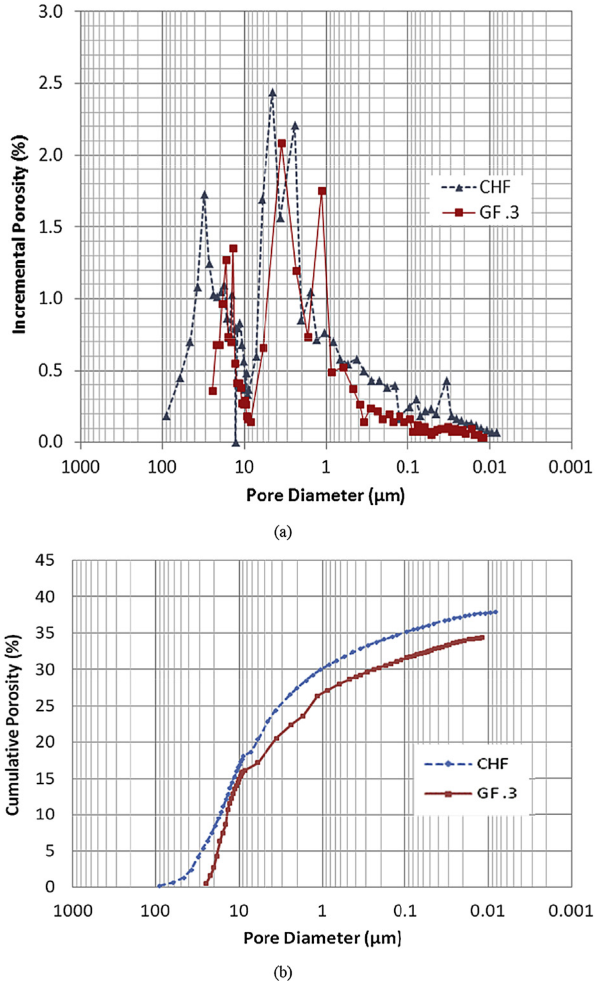

Fig. 4. Incremental pore size distribution (a) and overall porosity (b) of CHF and Gelfill containing 0.3 wt% sodium silicate after 28 days of curing.

underground, and the additional water has to be pumped out of the mine, which can be time-consuming and costly. For this reason, the amount of released water and the drainage time are among the most important properties of mine backfill.

To study the effect of sodium silicate concentration on the drainage of Gelfill, 5 samples with different mixing designs were made. The mixing designs correspond to the mixing designs already used for the study of the mechanical strength of Gelfill and CHF (Table 4). The water released from the bottom of the samples was collected and measured over the drainage period which lasted for 22 h. The amount of water collected for different mixtures is presented and compared in Fig. 5. As expected, the quantity of collected water increases gradually with time; however, the rate of drainage decreases. The results show that drainage has ceased after 22 h. It can be also observed that the quantity of collected water and the rate of drainage decreased with the increase of sodium silicate concentration. Finally, it should be mentioned that the maximum volume of collected water at the end of the drainage are 539.8 cm^3 for CHF and 481.85 cm^3 for Gelfill with 0.3 wt% sodium silicate. The results obtained for Gelfill could be positive due to the decrease of the amount of released water.

5. Conclusions

The influence of sodium silicate concentration and binder dosage on the mechanical and microstructural properties of CHF and Gelfill is presented in this paper. The investigation confirmed that Gelfill specimens produced by the addition of an appropriate amount of sodium silicate have higher mechanical strength in comparison to CHF specimens which can contribute to underground stabilization and mine safety. Moreover, the results demonstrated that strength development of Gelfill samples is more rapid than CHF specimens. Nevertheless, a high elevated amount of sodium silicate concentration has a detrimental effect on the strength of Gelfill samples.

The research also shows that the pore structures and pore size distributions of Gelfill and CHF samples are different which could mainly contribute to the better mechanical properties of Gelfill specimens.

Moreover, the results of this research demonstrate that the addition of sodium silicate to CHF can practically reduce the amount of released water from fill materials.

It was also demonstrated that binder dosage strongly influences the mechanical strength of Gelfill and CHF samples, however, adding an appropriate amount of sodium silicate to mine backfill binder can be beneficial regardless of the binder concentration.

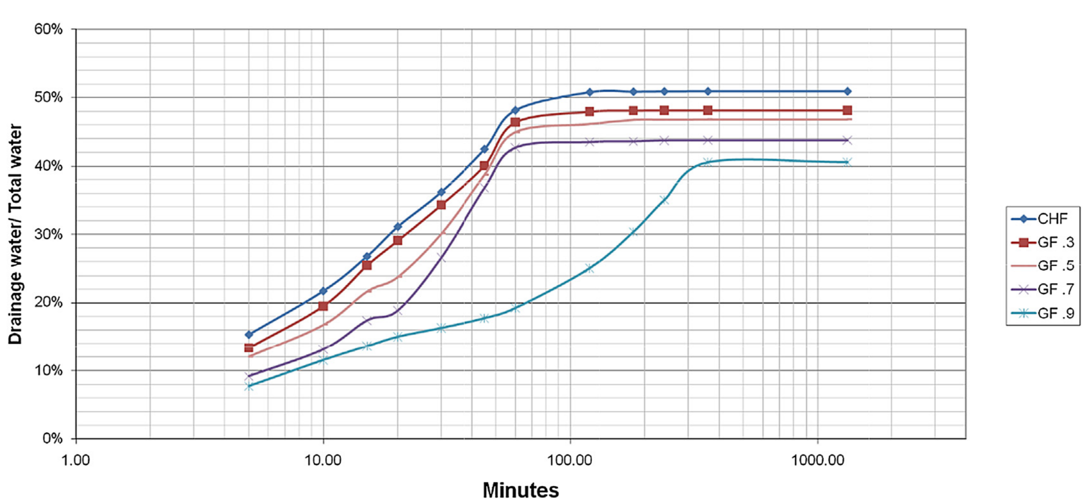

Fig. 5. The effect of sodium silicate concentration on the drainage of Gelfill and CHF.

In conclusion, use of Gelfill as mine backfill material could contribute to reduce the non-productive time of the mining cycle and to increase the mine production efficiency, and there is potential to improve the stability of the underground mines and improve hydraulic fill economics.

Conflict of interest

The authors wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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Ferri Hassani obtained his Bachelor of Mining Engineering and Ph.D. from Nottingham University, Nottingham England in 1976 and 1981, respectively. Ferri Hassani is a Webster Chair Professor of Mining Engineering at McGill University and director of Geo-mechanics labs and Earth/Mine Energy Research Group (EMERG), England. He was awarded a Fellow of the Canadian Institute of Mining and Metallurgy for his contribution to the mining industry in Canada. He has been at McGill University since 1983 and many years in a leadership role. His focus evolved from rock mechanics and mine design, to mining and energy and waste heat recovery from mining operation mine waste disposal, minefill and mining sustainability as well as microwave assisted rock breaking system. He was one of the pioneers of Pate backfill and he is the chairman of the International Mine Backfill Council. He was Co-founder and Chairman of the Canadian Mining innovation council (CMIC). He was given Canadian Rock Mechanics Award of Rock Engineering Society of CIM in 1992 and was also awarded Boleslaw Krupinski Gold Medal from the World Mining Organization of IOC 2013. He continues to maintain a strong interdisciplinary research and consulting activities with several million dollars of research and has graduated over 150 Ph.D. and MEng. Students, as well as research assistants, post-doctoral fellows, research associates and published over 160 scientific articles and reports. His research has led to obtaining several patents in the past 15 years.

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Mostafa Benzaazoua obtained his Master degree in 1990 (Lorraine University – Nancy, France), with specialization in applied mineralogy and metallogeny. He pursues his training with a Professional Master (DESS) in Mineral Processing (obtained in 1991); then in 1992 he obtained his geosciences Ph.D. around applied mineralogy and geochemistry applied to mine ores and others mine by-products for beneficiation and/or management purposes. M. Benzaazoua joined the University of Quebec (UQAT) in 1996 beneficiating of a postdoctoral fellow. He became Professor in 1997 at UQAT. He obtained a Canada Research Chair in 2003 in the field of Integrated Mine Waste Management. In 2008 he obtained an International Research Chair funded by the IDRC jointly with the CRC in collaboration with Marrakech University (Morocco). Since UQAT appointment, he worked on several government funded and industry sponsored projects dealing with mineralogy and geochemistry for mine pollution control, waste management, mine site rehabilitation, mineral processing and waste reuse. Between 2010 and 2012, He took a leave and joined the National Institute of Applied Sciences at Lyon in France as Professor in the field of Industrial environment (treatment and reuse of industrial wastes). Now he is part of the young Mine and Environment Research Institute in UQAT. Dr. Benzaazoua's background is in geosciences with a specialization in applied mineralogy, geochemistry and mineral processing. He develops strong skills in mining environment, waste management, waste treatment and reuse; especially through the use of cemented mine backfill technology.

Michelle Nokken obtained her Bachelor of Applied Science and Doctorate in Civil Engineering at the University of Toronto. She is an Associate Professor in the Department of Building, Civil & Environmental Engineering at Concordia University, Montreal, QC. Dr. Nokken's research interests are durability of concrete, use of alternate cementing materials and non-destructive testing. Dr. Nokken is a member of ASCE, CSCE, ASTM. She is a Fellow of the American Concrete Institute.