

The uniaxial compressive strength of fiber-reinforced frozen backfill

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ABSTRACT: The possible application of using fiber-reinforced frozen (-15°C) mine backfill was investigated using a series of laboratory experiments. Sisal fiber, Basalt fiber, and Bio-filament were added to the tailings and water that constituted primary backfill, which served as the reference material. Samples differed in terms of fiber type, fiber content, and curing temperature. The mechanical properties of samples were investigated using the uniaxial compression strength (UCS) test. The UCS of fiber-reinforced frozen backfill exceeded that of primary backfill and reached as high as 5.95 MPa. The UCS stress-strain behavior of mine backfill was markedly affected by freezing and fiber addition. Frozen backfill exhibited more ductile behavior and a higher elasticity modulus than unfrozen backfill, which showed brittle behavior. Fiber-reinforced backfill could absorb more energy before total failure.

Keywords: Sisal fiber, Basalt fiber, Bio-filament, fiber-reinforced backfill, frozen backfill, uniaxial compressive strength

1 INTRODUCTION

The practice of filling the void created by underground mining activities with waste materials is termed mine backfilling and is generally an integral part of the underground mining process. Mine backfill is mainly used to increase ore extraction and underground mine stabilization and to reduce the volume of deposited waste materials. Mine backfill mostly comprises tailings (waste), water, and binders—usually Portland cement (PC) (Weaver & Luka 1970; Benzazoua et al. 2004b; Wang & Qiao 2019). PC accounts for up to 75% of the cost of mine backfill (Hassani & Bois 1989; Potvin et al. 2005; Li et al. 2019), and PC production contributes a large amount of carbon dioxide to the atmosphere. Furthermore, increased demand for minerals and depletion of more accessible minerals forces mining companies to expand operations to more remote areas (e.g., higher latitudes in Canada). These challenges require innovative methods to meet the requirements of a mining operation in an environmentally friendly manner. Thus, exploring alternative binders to fully or partially replace PC to reduce the cost and carbon footprint (as well as improve the mechanical strength) of mine backfill has been

the focus of several research projects (Benzaazoua et al. 2004a; Kesimal et al. 2005; Mohamed Abdel-Mohsen et al. 2007; Singh et al. 2019).

Examples of alternative binders are pozzolanic products (Ercikdi et al. 2010), fly ash, and slag (Bouzoubaa & Foo 2004). Samples containing fly ash exhibited higher uniaxial compressive strength (UCS) than samples containing PC (Hassani et al. 2007). Cemented paste backfill (CPB) containing a mixture of fly ash (40%) and PC (60%) showed improved sulphate resistance (Benzaazoua et al. 1999). Among paste backfill samples prepared with PC, fly ash, and slag, slag-based samples had higher triaxial compressive strength (Belem et al. 2000). Other important factors affecting the physical properties of CPB are tailings properties (Kesimal et al. 2004; Fall et al. 2005; Kesimal et al. 2005), binder types and dosage (Kesimal et al. 2004; Ercikdi et al. 2009; Ercikdi et al. 2014), curing time (Yilmaz et al. 2015), and other additives (Mitchell & Stone 1987; Kermani et al. 2015; Koohestani et al. 2016; Mangane et al. 2018).

In cold and remote environments, application and transportation of cementitious materials are costly and logistically challenging. For instance, the hydration of cementitious material can dramatically decelerate or even cease in cold ambient temperatures (Jiang et al. 2020). Limited research has explored the feasibility of using ice as the main cementitious agent in mine backfill in cold climates. Although this method appeared to be feasible in terms of meeting strength and stiffness requirements, the cost of frozen backfill was low compared to conventional backfill (Daniel & Kazakidis 2012). Han (2011) compared the performance of frozen tailings backfill, with mechanical properties strongly influenced by water content, tailings fineness, and compaction pressure, to that of frozen cemented paste backfill with mechanical properties significantly affected by cement content, curing age, and binder type. The frozen tailings backfill displayed strain softening behaviors and a relatively brittle failure mode, whereas the frozen cemented paste backfill displayed strain hardening behaviors and was ductile.

Given the strength limitations of frozen backfill noted in previous studies, the aim of this work is to investigate the effect on the UCS and deformation behavior of reinforcing frozen backfill with Sisal fiber, Basalt fiber, and Bio-filament. An orthogonal experiment design was used to study the effect of fiber type, fiber content, and curing temperature. This study is expected to provide a reference to evaluate the performance of fiber-reinforced frozen backfill and help reduce the usage of PC in mine backfill.

2 MATERIALS

2.1 Tailings

Tailings were obtained from a mine in northern Quebec, Canada. The specific gravity (G_s), particle size (D_i where $i=10, 30, 50, 60,$ and 90 mm), and coefficients of uniformity (C_u) and curvature (C_c) are summarized in Table 1. Figure 1 shows the particle size distribution of tailings, which were tested in according to ASTM C136/C136M-14 (2014). Table 2 lists the chemical composition analyzed by X-ray fluorescence.

2.2 Binder

Both primary and fiber-reinforced samples were made with 0% and 2% (dry mass of solid materials) General Use Type 10 Portland cement as binder.

Table 1. Physical properties of Westwood tailings.

G_s (g/cm ³)	D_{10} (μm)	D_{30} (μm)	D_{50} (μm)	D_{60} (μm)	D_{90} (μm)	C_u	C_c
2.93	3.95	8.6	12.1	14.0	23.0	3.5	1.3

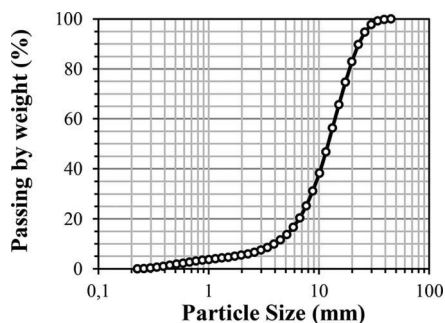


Figure 1. Particle size distribution of tailings.

Table 2. Chemical composition of Westwood tailings.

Oxides	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	SO ₃	CaO	MgO	K ₂ O	Na ₂ O
Content (%)	49.02	17.67	9.15	7.29	6.52	3.97	2.70	1.50
Metal element	P	Ni	Cu	Cl	Cr	Zr	Sr	Rb
Content (ppm)	677	648	406	319	115	108	90	44

2.3 Fiber

Sisal fiber (Figure 2) is extracted from the Sisal plant and has the advantages of high strength, easy processing, good dispersion, and low cost. The tensile strength and Young's modulus (Table 3) are mostly influenced by filament diameter and length (Deák & Czigány 2009; Jiang et al. 2014). Basalt fiber (Figure 2) is melted at 1450–1500°C and drawn through a platinum-rhodium alloy plate at a high speed, giving it high strength, electrical insulation, corrosion resistance, high



Figure 2. Photographs of Sisal fiber, Basalt fiber, and Bio-filament.

Table 3. Physical properties of Sisal and Basalt fiber.

Fiber type	Young's modulus (GPa)	Tensile strength (MPa)	Filament length (mm)	Filament diameter (μm)
Sisal	9–26	5500–6500	10	300–500
Basalt	28–110	400–4800	10	7–15

Soure: Tolêdo Filho et al. (2000); Ku et al. (2011); Ratna Prasad and Mohana Rao (2011); Alves Fidelis et al. (2013); Ramesh et al. (2013); Sultan (2005); Deák and Czigány (2009); Lopresto et al. (2011); Colombo et al. (2012); Jiang et al. (2014).

temperature resistance, and degradability. The tensile strength is lower for short than continuous Basalt fibers (Table 3). The Bio-filament was supplied by Performance Bio-filaments Inc., who produce cellulose filaments from wood pulp. The process results in cellulose filaments of exceptional strength and purity, with an extraordinary high and unique aspect ratio. Bio-filament is a “wet fluff” (Figure 2) with 4% solid content and is dispersible in solvents like water.

3 SAMPLE PREPARATION AND EXPERIMENT SETUP

Fourteen batches of mine backfill samples were prepared with a solids concentration of 70% (Table 4). The fiber contents of the fiber-reinforced samples were 0.5 and 1.0 wt%. Reference samples contained no fiber.

To prepare the samples, dry materials were weighed and mixed for 2 min using a mixer with a stainless-steel wire whip blade. Water was added gradually and mixed for another 5 min. Cylindrical molds (100 mm deep and 50 mm diameter) were used to cast the specimens. Specimens containing 2 wt% of the binder PC (Group 1 in Table 4) were cured in a curing chamber where the relative humidity was kept constant at $(90\pm 2\%)$ and the temperature was adjusted to $(20\pm 1^\circ\text{C})$ for 3 days and then moved to a freezer where the temperature was kept constant at -15°C . Samples without any binder (Group 2) were cured directly in a freezer at -15°C . Moreover, unfrozen samples in Group 2 were prepared and dried at ambient temperature $(+20^\circ\text{C})$ for comparison to frozen samples.

The unfrozen samples in Group 2 was not consolidated until 50 days later. The UCS test was conducted after 56 days of curing to evaluate the mechanical properties of specimens according to ASTM C39/C39M-18 (2018). To minimize the influence of heat exchange between the specimen and the ambient environment on the UCS results of frozen backfill, the upper and lower plate of test device was also frozen at the same temperature as the samples.

4 RESULTS AND DISCUSSION

4.1 Reinforced effect of fibers on unfrozen dry and frozen backfill samples

Adding fiber to specimens dried and cured at $+20^\circ\text{C}$ did not affect the UCS (Figure 3). However, freezing all Group 2 specimens lacking PC binder (with or without fiber) enhanced the

Table 4. Experimental design.

Sample	Fiber		Binder (wt%)	Dry tailings (wt%)	Curing condition
	Type	Content (wt%)			
1	None	0	2	98.0	Group 1: cured for 3 days at 20°C and then frozen at -15°C .
2	Sisal	0.5	2	97.5	
3	Sisal	1.0	2	97.0	
4	Basalt	0.5	2	97.5	
5	Basalt	1.0	2	97.0	
6	Bio	0.5	2	97.5	
7	Bio	1.0	2	97.0	
8	None	0	0	100	Group 2: frozen: cured at -15°C .
9	Sisal	0.5	0	99.5	Group 2: unfrozen:
10	Sisal	1.0	0	99.0	
11	Basalt	0.5	0	99.5	Dried and cured at $+20^\circ\text{C}$.
12	Basalt	1.0	0	99.0	
13	Bio	0.5	0	99.5	
14	Bio	1.0	0	99.0	

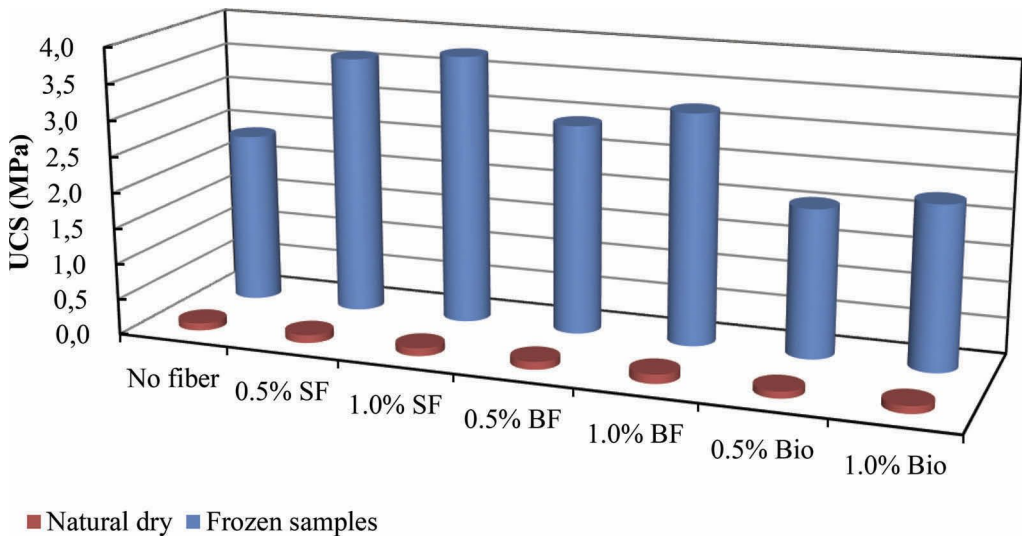


Figure 3. UCS of unfrozen and frozen dried backfill samples without and with reinforcement with Basalt fiber (BF), Sisal fiber (SF), and Bio-filaments (Bio).

UCS: Sisal fiber was associated with the highest UCS (3.76 MPa), whereas Bio-filament addition resulted in lower UCS than the no fiber treatment. For a given fiber type, the UCS of frozen specimens was higher at 1% than 0.5% fiber concentration. This indicates that the bond between ice and fibers formed after the phase transition from water to the crystalline ice.

After 56 days of freezing, the UCS of fiber-reinforced frozen backfill specimens containing 2 wt% PC (Group 1 in Table 4) was 43% (Sisal fiber) to 143% (Biofilament) higher than the UCS of specimens lacking PC (Figure 4). In the presence of PC, the fiber content (0.5 vs. 1.0%) did not affect the UCS as much as it did when PC was absent. This phenomenon can be attributed to the hydration of cement, the phase transition of water, and enhanced bond integration between tailings particles and fibers.

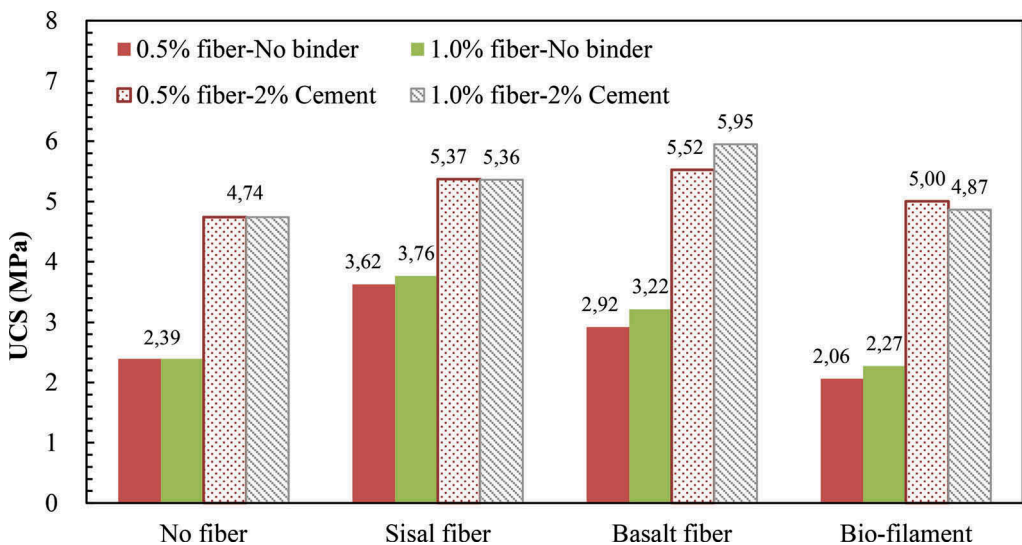


Figure 4. UCS of frozen backfill samples with and without binder cement.

The increase in UCS of backfill as result of inclusion of fiber reinforcement can be expressed as the UCS improvement factor, I_R , defined as:

$$I_R = \frac{\sigma_R - \sigma_U}{\sigma_U} \quad (1)$$

Where σ_R is the UCS of fiber-reinforced backfill and σ_U is the UCS of unreinforced backfill. The I_R represents the relative gain in UCS of backfill due to the addition of fiber. Table 5 presents the I_R of frozen backfill without and with PC, using σ_U values of 2.39 and 4.74 MPa, respectively (Figure 4).

4.2 Deformation behavior of fiber-reinforced

The UCS stress-strain behavior of mine backfill was markedly affected by freezing (Figure 5). Frozen backfill not only obtained higher UCS values, but also exhibited more ductile behaviors and higher elasticity modulus, while the unfrozen backfill shows brittle behavior. The fiber-reinforced backfill is able to hold together for more deformation and therefore higher strength at failure. Therefore, the fiber-reinforced backfill can absorb more energy before total failure.

The brittle behavior of unfrozen tailings backfill (Figure 6) was transformed by freezing to a more ductile behavior (Figure 7). Unreinforced backfill samples failed at a relative low axial strain (approximately 2.4%), whereas backfill samples reinforced with Basalt fiber failed at approximately 3.3% axial strain and those reinforced with Sisal fiber failed at approximately

Table 5. Improvement factor, I_R , of frozen fiber-reinforced backfill.

No Cement		2% Cement	
Fiber	I_R (%)	Fiber	I_R (%)
0.5% Sisal	51.38	0.5% Sisal fiber	13.28
1.0% Sisal	57.13	1.0% Sisal fiber	13.03
0.5% Basalt	22.02	0.5% Basalt fiber	16.51
1.0% Basalt	34.36	1.0% Basalt fiber	25.43
0.5% Bio-filament	-13.83	0.5% Bio-filament	5.52
1.0% Bio-filament	-5.11	1.0% Bio-filament	2.63

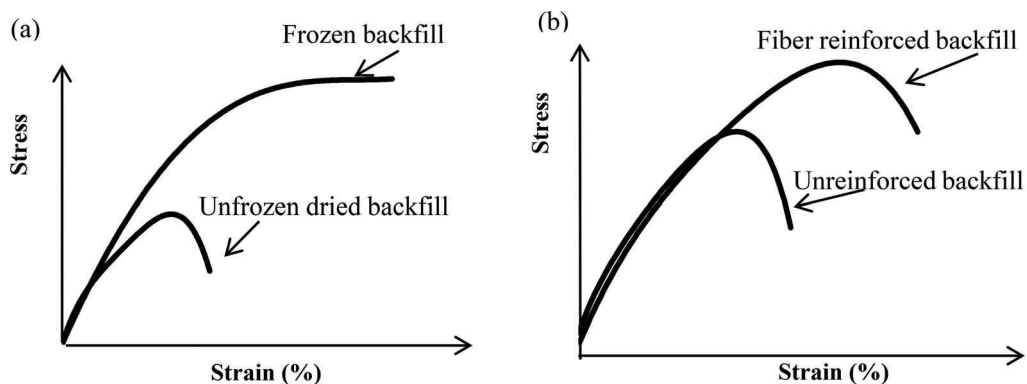


Figure 5. Typical unconfined compressive stress-strain curves for (a) unfrozen dried and frozen backfill; (b) unreinforced and fiber-reinforced backfill.

3.7% (Figure 6). The higher fiber content seems improve the UCS and elasticity modulus, but does not contribute to the ductility of unfrozen dried backfill.

The stress of frozen specimens rose faster than that of specimens dried without freezing during the elastic deformation stage (Figure 7). Fibers contributed to elevated UCS while the fiber content dominated the post-peak behavior. Among the three fibers, Sisal fiber had the strongest influence and Bio-filament had the weakest influence on the ductile behavior of backfill. The bond between tailings and fiber contributed to the enhanced ductility. All tests on reinforced specimens exhibited strain-hardening behavior with increasing strength as the strain increased.

The E_{50} , deformation energy, and post-peak strength of typical frozen samples were considered as indices to evaluate the performance of frozen backfill, in addition to UCS. E_{50} is the secant modulus at 50% UCS and is considered the elastic index. The energy absorbed by a unit volume of backfill before peak strength is calculated by:

$$M_0 = \int \sigma d\varepsilon \tag{2}$$

M_{0P} is the other index to evaluate the performance of frozen backfill:

$$M_{0P} = \int_0^{\sigma_0} \sigma d\varepsilon \tag{3}$$

Where σ_0 is the peak strength of backfill.

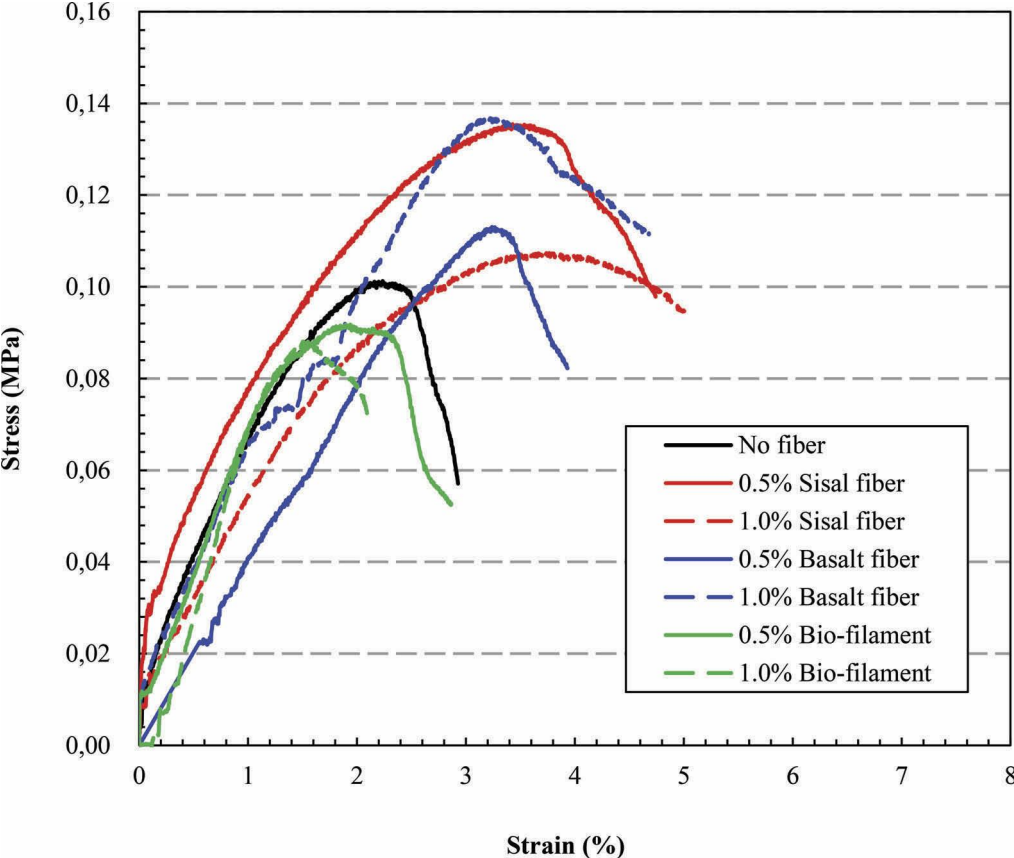


Figure 6. Typical stress-strain curves for unfrozen dry backfill samples without binder cement.

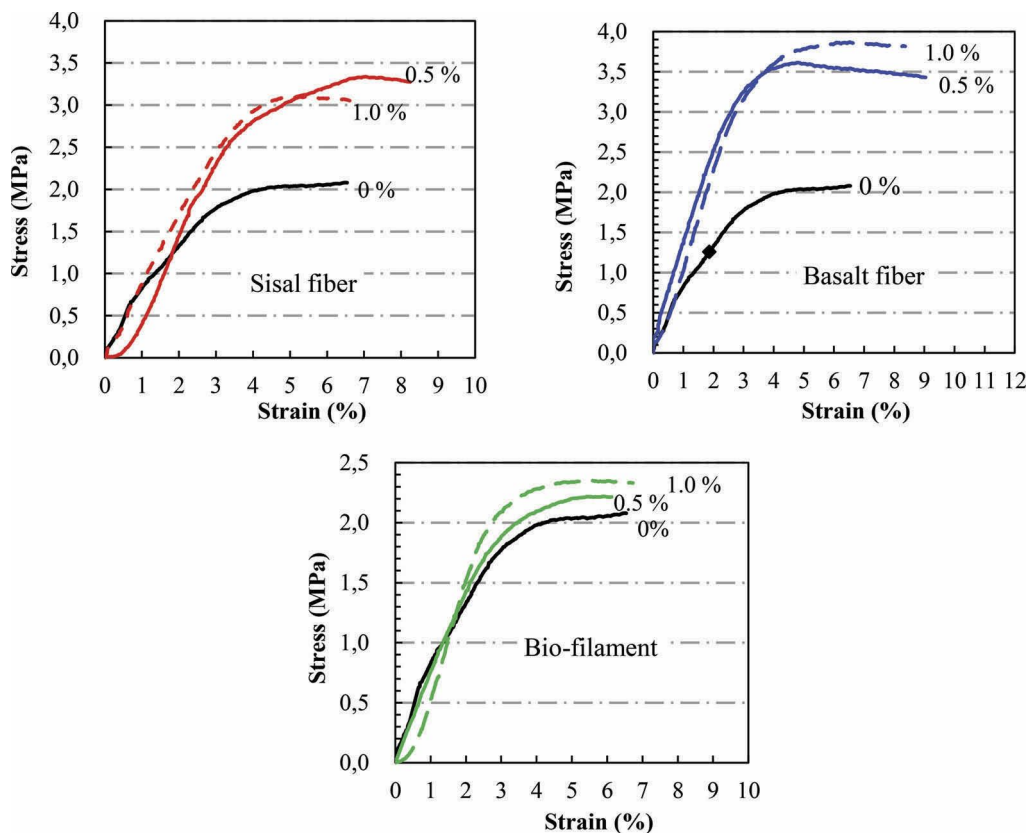


Figure 7. Typical stress-strain curves of frozen backfill samples without binder cement.

From Table 6, the fiber-reinforced frozen backfill absorbed more energy. The addition of Sisal and Basalt and fiber enhanced the UCS and residual strength, and improved the initial stiffness. The contribution of Bio-filament to frozen backfill performance was not significant.

Table 6. Strength performance of frozen fiber-reinforced backfill.

Frozen backfill type	E_{50} (MPa)	Energy absorbed before failure, M_{OP} (kJ)	Post-peak strength (MPa)
No fiber	0.74	71.4	2
0.5% Basalt fiber	1.24	117.84	3.42
1.0% Basalt fiber	1.14	184.81	3.81
0.5% Sisal fiber	1.02	147.61	3.27
1.0% Sisal fiber	0.87	96.16	3.05
0.5% Bio-filament	0.73	105.53	2.19
1.0% Bio-filament	1.02	86.97	2.33

5 CONCLUSION

A series of experiments explored potential application of frozen backfill with or without fiber (Sisal, Basalt, and Bio-filament) reinforcement as an alternative to CPB. The highest UCS (5.95 MPa) was achieved with frozen backfill containing 2% PC and 1% Basalt fiber. Freezing transformed the deformation behavior of backfill from brittle to more ductile. The fiber-reinforced frozen backfill absorbed more energy. Sisal and Basalt fiber addition not only enhanced the UCS and residual strength but also improved the initial stiffness. The contribution of Bio-filament to frozen backfill strength was not significant.

ACKNOWLEDGEMENTS

This work was supported by Geomechanics Laboratory in McGill University and Iamgold Inc. . Comments by Janice Burke improved an earlier version of the paper.

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