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Mechanical Properties and Behavior of Early-Age Fiber-Reinforced Cemented Paste Backfill

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Abstract - Cemented paste backfill (CPB, a mixture of tailings, cement, and water) has been extensively adopted in underground mines around the world. As a major underground support measure, CPB is required to provide sufficient ground support to the underground mined-out space (called stopes). To improve the mechanical behavior of CPB, fiber reinforcement technique has been considered as a promising approach. However, as the key design parameters, mechanical properties, and behavior of fiber-reinforced CPB (FR-CPB) have not been systematically investigated. This study aims to experimentally investigate the tension and compression behavior of FR-CPB and associated mechanical properties including elastic modulus, tensile strength, and unconfined compressive strength at early-age curing time (1, 3, and 7 days). Moreover, an experimental program was designed and performed to measure the electric conductivity and matric suction in FR-CPB. The monitored results were used to explain the evolution of the mechanical properties and behavior of FR-CPB. The obtained results show that a significant improvement of mechanical properties and behavior of CPB has been achieved due to the fiber inclusion in the CPB matrix. Moreover, the FR-CPB shows an enhanced energy absorption to resist material failure. Additionally, the substantial improvement of mechanical properties and behavior (hardening and softening stages) at early-age curing time indicates the key role played by the cement hydration in the CPB matrix. The obtained results from the present study can improve the understanding of the mechanical behavior of FR-CPB and thus contribute to the successful implementation of the fiber reinforcement technique.

***Keywords*:** Cemented Paste Backfill; Tailings; Fiber Reinforcement; Mechanical Behavior.

1. Introduction

The backfilling technology has been widely used in the underground mines to fill the galleries (stopes) left after excavating the ore, enabling more rapid ore recovery and better structural stability [1]. One of the possible materials used by this technology is cemented paste backfill (CPB) which consists of mine tailings, binding agent, and water [2]. After preparation, fresh CPB is usually transported to the target stope through reticulated pipelines and/or gravity. As curing time elipses, the hardening CBP works as a support pillar to the surrounding rock mass [3]. Also, the CPB mass can be used as floors or roofs during subsequent mining operations [2,3]. Therefore, mechanical stability is one of the most important design criteria for the backfilling operation [4]. Correspondingly, extensive studies were conducted to investigate reinforcement options that could enhance the mechanical behavior and performance of CPB materials. It has been found fiber reinforcement can be considered as a promising approach [5].

Due to the complexity of field loading conditions, compressive and tensile stresses widely exist in CPB. For instance, when the underhand cut and fill method is adopted, the CPB mass is used as a roof and thus tensive stress develops along the bottom surface of CPB mass [6]. However, when the confining rock walls are removed as mining operation proceeds to the adjacent stopes, the side-exposed CPB will act as a support pillar subjected to compressive loadings [7]. Therefore, to ensure the efficiency of fiber reinforcement and stability of resultant fiber-reinforced CPB (FR-CPB), the compressive and tensile behaviors of FR-CPB must be systematically investigated. In this study, a series of laboratory tests were conducted to study the compressive and tensile constitutive behaviors and strengths of FR-CPB at early ages. Specifically, splitting tensile (ST) tests were performed to understand the tensile behavior of FR-CPB, and unconfined compressive strength (UCS) tests were conducted to retrieve information about compression behavior. Moreover, the development of electrical conductivity and matric suction were monitored to facilitate the understanding of the evolutive mechanical behaviors of FR-CPB.

2. Materials and Methods
2.1. Materials
The FR-CPB specimens were prepared through a mixture of quartz tailings, Portland cement, tap water, and polypropylene microfibers. The quartz tailings are composed of 99.8% silicon dioxide and are inert materials which can reduce the uncertainties (e.g., the effect of sulphate anions on the cement hydration and microstructure of CPB) to a minimum level [8]. The particle size distribution of the quartz tailings was analyzed and the results were plotted in Fig. 1. Based on the obtained results, the D-values (D_{10}, D_{30}, and D_{60}), the uniformity coefficient ($C_U=D_{60}/D_{10}$), and the curvature coefficient ($C_{Coef}=D_{30}^2/(D_{10}\times D_{60})$) were extracted and presented in Table 1. General Use Portland cement was employed due to its wide availability [9]. Additionally, the tap water was used to prepare FR-CPB specimens. Microfibers with 13 mm of length were adopted in this study. The detailed information about the microfibers are summarized in Table 2.

Table 1: Particle size distribution parameters of quartz tailings.

D_{10} (µm)	D_{30} (µm)	D_{60} (µm)	C_U (-)	C_{Coef} (-)
1.87	8.47	25.67	13.72	1.50

-: dimensionless.

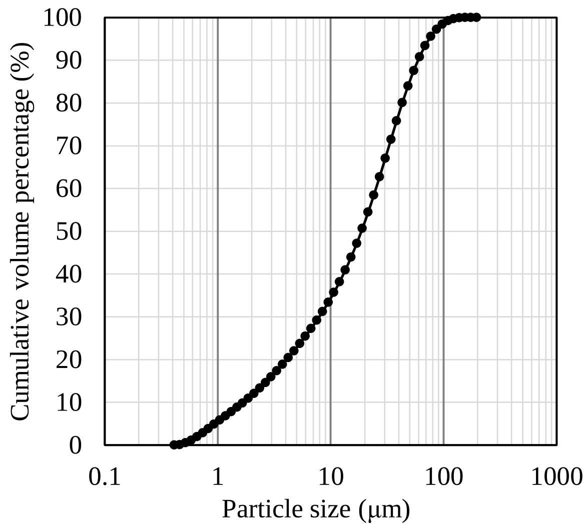

Fig. 1: Silica sand (quartz tailings) particle size distribution curve.

Table 2: Properties of Polypropylene microfibers.

Properties List (Unit)	Value
Length (mm)	13
Diameter (µm)	54
Specific Gravity (-)	0.91
Melt Point (ºC)	160

-: dimensionless.

2.2. Mix Formulation and Specimen Preparation

The mix formulation is presented in Table 3. According to ASTM C192 [10], the dry materials were first mixed for five minutes and then wet mixing through addition of tap water for were performed for eight minutes. Then, the fresh paste was casted into two types of plastic molds: 5cm (D)×10cm(H) and 10cm (D)×20cm(H), which were used to prepare the specimens for UCS and ST tests, respectively.

Table 3: Mixture formulation of the tested FR-CPB.

Fiber length (mm)	Fiber content (%)	Cement content (%)	Water-to-cement ratio (-)	Curing time (days)
13	0.5	4.5	7.6	1, 3 and 7

-: dimensionless.

2.3. Testing Methods

In this study two different laboratory tests were conducted: 1) splitting tensile (ST) tests and 2) unconfined compressive strength (UCS) tests. The ST tests were performed according to ASTM D3967-1 [11], and UCS tests were conducted in accordance with ASTM C39 [12]. For the data acquisition, a load cell with 1000 pounds of capacity from ARTECH Industries, Inc., and a displacement transducer with 25 millimeters of capacity from A-Tech Instruments Ltd. were employed to record the load and displacement during the tests. The tests were operated at a displacement rate of 1 mm/minute and, for each curing time, a minimum of three specimens were tested to ensure the replicability of results.

3. Results and Discussion

3.1. Tensile and Compressive Behavior of Early-Age FR-CPB Specimens

The typical tensile and compressive constitutive curves are presented in Fig. 2. It can be found that the tensile and compressive behaviors of early-age FR-CPB are affected by the curing time. Specifically, as shown in Fig. 2(a), the slope of force-displacement increases with curing time, which indicates the improvement of material stiffness. Moreover, it can be observed that the hardening behavior become more obvious with curing time. Therefore, the stiffer and stronger FR-CPB will provide more immediate secondary ground support to the surrounding rocks walls as curing time ellipses. At post-failure stage, the softening behavior is kept unnoticeable at the early ages. It should be noted that softening behavior is commonly featured in the CPB materials without addition of fibers [13]. However, with the introduction of fibers into CPB matrix, it can be clearly observed that the material becomes more ductile, evidencing a clear residual strength. Additionally, the softening behavior improves as time elapses. At the seventh day, FR-CPB not only shows a substantial improvement of residual strength, but also manifests a pseudo hardening behavior (i.e., the second peak point). This can be attributed to the gradual development of crack bridging stress induced by the fiber inclusion at the post-failure stage. The crack bridging effect is dependent on the fiber-CPB matrix interfacial interaction which can be strengthened as the progress of cement hydration. As a result, the pseudo hardening behavior becomes more obvious at 7 days. Compared with the tensile behavior of FR-CPB, the compression behavior (Fig. 2(b)) shows similar evolutionary trend at the pre-failure stage, which includes the improvement of slope of constitutive curves and enhanced hardening behavior. However, no pseudo hardening behavior was observed from FR-CPB under compressive stress. Correspondingly, the strain softening behavior is observed at the post-failure stage and becomes more apparent as curing time increases. Based on the obtained results, it can be found that the addition of fibers mainly affects the post-failure behavior of CPB materials and improve its tolerance capacity of permanent deformation with curing time.

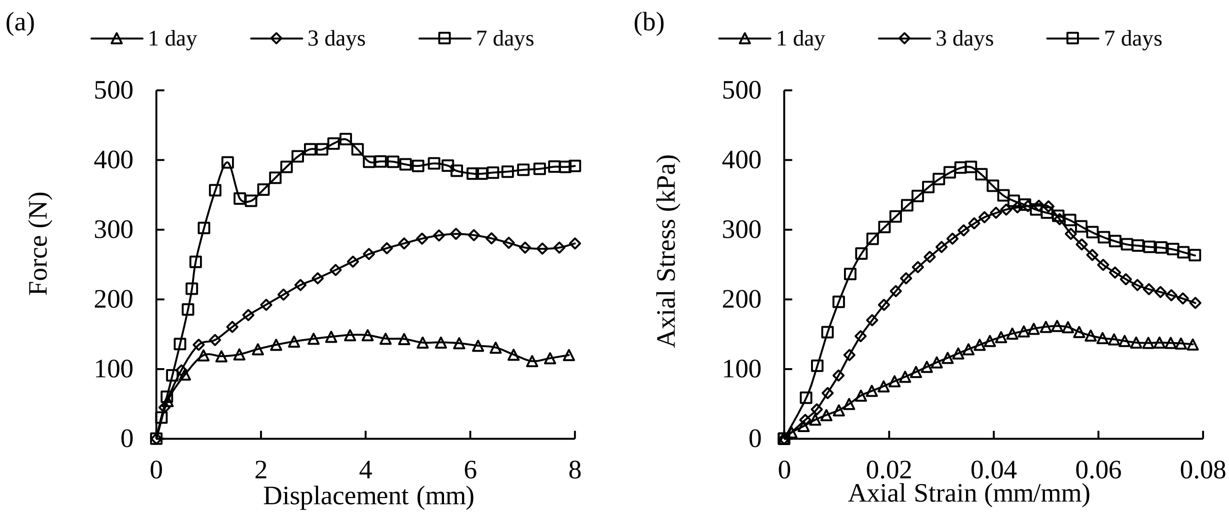

Fig. 2: Results from early-age FR-CPB specimens: (a) tensile behavior (force-displacement curves) and (b) compression behavior (stress-strain curves).

Since the effectiveness of fiber reinforcement is dependent on the fiber-CPB matrix interfacial interaction, bond strength improvement by cement hydration will yield a more cohesive CPB matrix and thus strengthen fiber bridging effect. Moreover, as progress of cement hydration, the capillary water is gradually consumed and leads to the development of matric suction. The matric suction acts on the solid skeleton and fiber surfaces through surface tension induced by pore air-water interface, which will contribute to the enhancement of fiber-matrix interfacial interaction. The bond strength between tailings particles and matric suction are closely related to the cement hydration. Therefore, cement hydration plays a key role in the performance of fiber reinforcement. To demonstrate the progress of cement hydration, the electric conductivity and matrix suction were monitored in this study. The electrical conductivity (EC) is an efficient indicator of the ion motion, which can be used to assess the progress of binder hydration within cementitious materials. The measured EC and matric suction are plotted in Fig. 3. As shown in Fig. 3(a), a very short time is required to reach the peak EC and then EC shows a monotonically decreasing trend, which indicates the decrease in the hydration rate. Fig. 3(b) depicts the development of the matric suction inside CPB with curing time. It is evident that the matric suction evolves rapidly during the early age, and thus makes a greater contribution to the strength acquisition of FR-CPB.

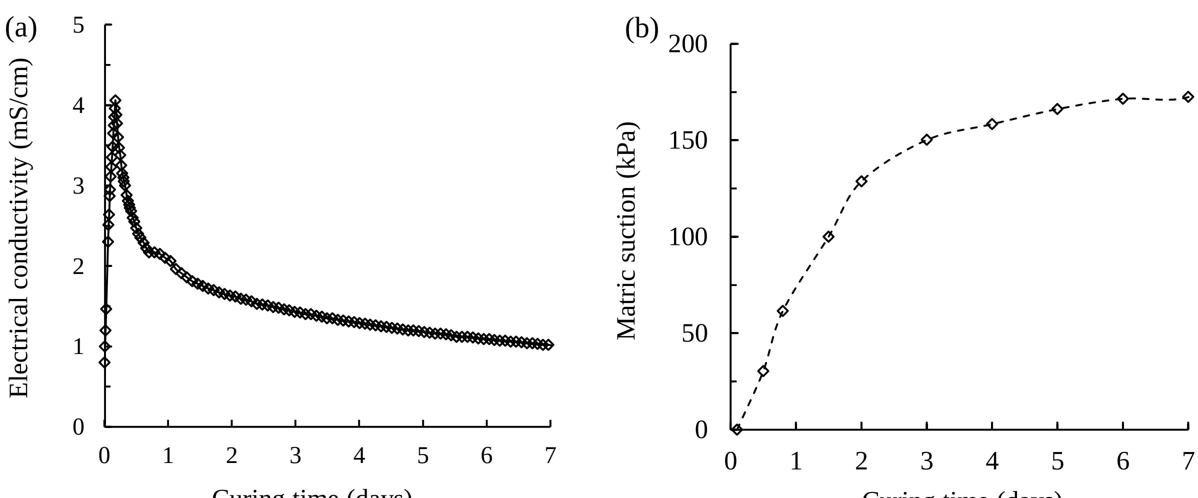

Fig. 3: Development of (a) Electrical conductivity and (b) matric suction development.

3.2. Tensile Strength and Unconfined Compressive Strength of Early-Age FR-CPB

The evolution of tensile and compressive strengths with time are shown in Fig. 4. It can be observed that material strengths increase with curing time. For example, compressive strength increases by 107% at 3 days, and 142% at 7 days relative to the compressive strength at the first day. Similar improvement can be observed from the tensile strength. Moreover, the ratio between compressive and tensile strengths is approximately equal to 4 at early ages. The higher compressive strength can be attributed to combined effect of bond strength, matric suction, fiber bridging, and shear resistance along the shear crack surfaces in FR-CPB specimens under compressive stress. However, the shear resistance does not exist along the tensile crack surfaces and tensile strength are governed by the combined effect of bond strength, matric suction and fiber reinforcement.

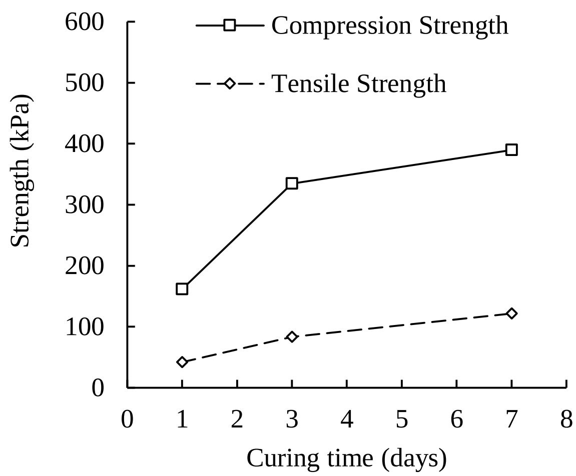

Fig. 4: Evolution of tensile and compressive strengths of early-age FR-CPB.

3.3. Elastic Modulus of Early-Age FR-CPB

Elastic modulus represents the material resistance to non-permanent deformation. The secant modulus (E_{50}) at 50% peak stress are determined in this study. Fig. 5 depicts the development of the elastic modulus (E_{50}) of early-age FR-CPB. Substantial improvement of E_{50} can be observed at early ages. The E_{50} reaches 3.91 MPa at the first day, and then increases to 10.13 MPa (increased by 159%) and 18.84 MPa (increased by 86%) at 3 and 7 days, respectively. As the resistance to elastic deformation increases with curing time, the stiffer FR-CPB can provide more immediate ground support when FR-CPB is subjected to loading from surrounding rock mass.

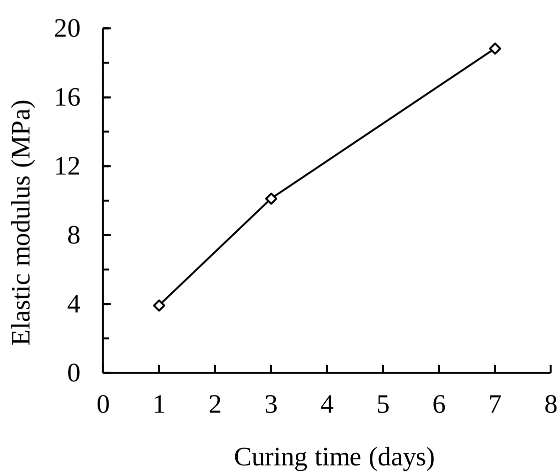

Fig. 5: Development of the elastic modulus of early-age FR-CPB.

4. Conclusion

A series of laboratory tests was conducted to investigate tensile and compressive behaviors of FR-CPB at different curing times. Based on the obtained results, it has been found that the pre-failure behavior is dominated by the progress of cement hydration. Correspondingly, the improvement of elastic modus and hardening behavior become more obvious with curing time. The stiffer FR-CPB indicates the backfill materials can provide more immediate ground support to the surrounding rock mass as curing time elapses. Moreover, the pseudo hardening behavior is commonly featured at the post-peak stage of tensile tests, which significantly improves the residual strength of FR-CPB. However, no pseudo hardening was observed from the unconfined compressive strength tests. The effectiveness of fiber reinforcement is dependent on the fiber-CPB matrix interfacial interaction. Consequently, the progress of cement hydration can yield a more cohesive matrix and thus strengthen the fiber-CPB matrix interfacial interaction. In addition, the evolution of electric conductivity indicates the rapid cement hydration at the very early ages and thus results in significantly improvement of bond strength between tailings particles. Meanwhile, the development of matric suction can also contribute to the fiber-CPB matrix interfacial interaction. Therefore, this study can significantly improve the understanding of mechanical behavior of FR-CPB and thus contributes to the successful implementation of fiber reinforcement technique in the mine backfilling design.

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