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Tensile behavior of synthetic fiber-reinforced strain-hardening cement-based composite (SHCC) after freezing and thawing exposure

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ABSTRACT

Strain-hardening cement-based composites (SHCC) are distinguishable from ordinary fiber-reinforced cement-based composites (FRCC) because they have a tensile stress versus strain behavior that exhibits pseudo strain-hardening accompanied by multiple cracking. SHCC materials have become an appealing possibility as building materials in a wide variety of civil engineering projects. Freeze–thaw cycles pose a serious problem for the successful application of SHCCs in cold environments. This paper describes the direct tensile properties of SHCC before and after rapid freezing and thawing exposure in a controlled environment. The primary objective of this research is to provide comprehensive laboratory data on the influences of freeze–thaw cycles on the tensile performance of SHCC materials. The SHCC specimens used in the present study were reinforced with polyvinyl alcohol (PVA) and ultra-high molecular weight polyethylene (PE). The total percentages of fiber reinforcement in the SHCCs with PVA and PE were 2.0% and 1.5%, respectively. Cylindrical SHCC specimens with a diameter of 100 mm and height of 200 mm were made and tested for direct tensile strength. The freeze–thaw testing used in the study followed the recommendations found in Procedure A (frozen and thawed in water) of Korean Industrial Standard (KS) F 2456, which is similar to the ASTM C 666 Procedure A, and included 200 freeze–thaw cycles. The test results for freezing and thawing within 200 cycles indicated that the freeze–thaw cycles had a slight effect on the tensile response of the SHCCs. By increasing the number of freeze–thaw cycles, the tensile strength of the SHCC materials under monotonic and cyclic axial loading increased, while the tensile strain capacity decreased. This phenomenon is noticeable for PVA-SHCC materials.

1. Introduction

An inherent weakness of cement-based materials, such as mortar and concrete, is their brittle fracture behavior when exposed to tension with low tensile strength and ductility. The most effective means of imparting ductility to cement-based materials is fiber reinforcement. Although the fracture toughness of concrete is significantly improved by fiber reinforcement, most fiber-reinforced cement-based composites (FRCCs) still show quasi-brittle post-peak tension-softening behavior under tensile loads where the load decreases with increasing crack opening. The tensile strain capacity therefore remains low, same as that of normal concrete, i.e., about 0.01% (Yang, 2008).

Over the last couple of decades, considerable efforts have been made to convert this quasi-brittle behavior of FRCCs to ductile strain-hardening behavior resembling ductile metal. Recently, a new class of FRCCs that exhibits multiple cracking and strain-hardening behavior after first cracking under uniaxial tensile loading has been developed (Li and Wu, 1992; Naaman and Reinhardt, 1996; Krstulovic-Opara and Malak, 1997; Rokugo et al., 2002; Yun et al., 2007). Pseudo strain-hardening behavior, i.e., a post-cracking strength larger than the first-cracking strength as shown in Fig. 1, is generally accompanied by multiple cracking and related large energy absorption capacity. These new innovative FRCCs are called high performance fiber-reinforced cementitious composites (HPFRCCs) or strain-hardening cement-based composites (SHCCs) and currently include materials such as engineered cementitious composites (ECCs), slurry infiltrated fiber concrete (SIFCON), and slurry infiltrated mat concrete (SIMCON).

SHCCs are promising for structural applications and repair in a wide variety of infrastructures and buildings. The main applications of SHCCs can be categorized into selected zones of RC structures (Parra-Montesinos and Wight, 2000), new RC members (Yun et al., 2008), and repair/rehabilitation of RC structures (Yun et al., 2010). However, almost all concrete infrastructure components are exposed to external environmental conditions and experience various environmental effects, such as seasonal cycles of freezing and thawing. Even SHCCs subjected to repeated cycles of freezing and thawing may

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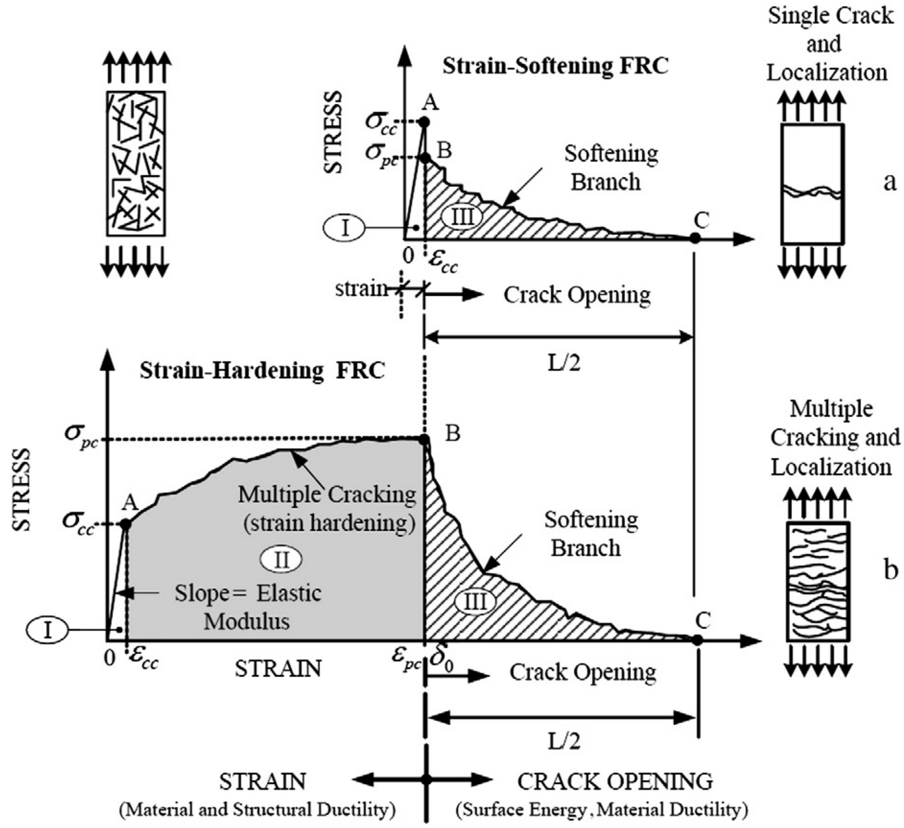

Fig. 1. Typical stress–strain behavior in tension of SHCC: (a) Conventional strain-softening FRC composites; (b) strain-hardening cement-based composite (Naaman and Reinhardt, 1996).

deteriorate rapidly. Therefore, for practical applications of SHCCs to social infrastructures in cold climates, the freezing and thawing resistance of SHCC materials should be considered as an important parameter.

It has been reported that after 300 cycles of exposure to freezing and thawing, the wet-cured tensile specimens of three ECC mixes with different replacement levels of fly ash exhibit a strain capacity of roughly 3% under direct tensile testing and retain much of their initial tensile ductility (Li et al., 2003). A study by Rokugo et al. (2008) showed that for dumbbell-shaped SHCC specimens reinforced with a blend of PVA and PE fibers, 144 freeze–thaw cycles and a pre-strain level induced before freezing and thawing had little effect on the tensile performance of the SHCC specimens.

A limited number of research studies regarding the mechanical properties of SHCC exposed to freeze–thaw cycles have been published. However, further research needs to be conducted on the mechanical properties of various types of SHCCs exposed to severe environments. The main purpose of the present investigation is to explore the effect of freeze–thaw cycles on the tensile properties of cylindrical SHCC specimens with different types of reinforcement fibers.

2. Experimental program

2.1. Scope

The main intent of this investigation is to evaluate the tensile properties of SHCC materials after exposure to freezing and thawing environments. The experimental program was designed to examine the effects of reinforcing fiber types on the tensile properties of cylindrical SHCC specimens that have undergone freeze–thaw cyclic testing. In order to conduct direct tension tests of SHCC materials after freeze–thaw cycles, all prepared specimens were cylindrical with a 100-mm diameter and 200-mm height.

2.2. Materials

The main components of the dry mixes used in this study were cement, silica sand, silica fume, Calcium Sulfa Aluminate (CSA) expansive additives and fly ash. Type I Portland cement, conforming to ASTM C 150, was used to produce the SHCC mixtures. Silica sand, with a specific gravity of 2.61 and grain sizes ranging from 105 to 120 μm, was used in the study. Silica fume (Elkem Microsilica, grade 940) and acrylic polymer (Forton BV) were used for the matrix modifications. A CSA-based expansive admixture (Denka) was used to reduce autogenous shrinkage and internal tensile stress in the cement-based matrix. ASTM C 618 Class F fly ash was used as a mineral admixture. The chemical composition and physical properties of cement, fly ash, and silica fume are shown in Table 1. The chemical additives used were a dry viscosity agent (methyl cellulose), shrinkage-reducing agent, and superplasticizer (polynaphthalene sulfonate). A small amount of antifoaming agent was also added to control the microvoids generated by the methyl cellulose.

Table 1
Chemical composition and physical properties of cement, fly ash, and silica fume.

	Cement	Fly ash	Silica fume
CaO (wt%)	63.25	5.54	0.30
SiO_2 (wt%)	20.80	47.58	96.02
Al_2O_3 (wt%)	4.61	26.42	0.30
Fe_2O_3 (wt%)	2.59	12.19	0.80
MgO (wt%)	4.17	0.90	1.10
Na_2O (wt%)	0.16	1.50	0.70
K_2O (wt%)	0.50	1.90	1.60
SO_3 (wt%)	2.70	1.08	0.20
Loss on ignition (wt%)	0.90	2.20	1.51
Blaine fineness (m^2/kg)	364	341	–
Specific gravity	3.15	2.35	2.10