- Technical Paper -

EFFECTS OF FREEZE-THAW ACTION ON THEMECHANICAL PROPERTIES OF STRAIN-HARDENING CEMENT COMPOSITE

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ABSTRACT

This paper describes a laboratory investigation into the effects of freezing-and-thawing exposure on the mechanical properties of strain-hardening cement composite (SHCC). Four kinds of SHCCs, with different water-to-binder ratio (W/B), reinforcing fiber volume and combination, were considered. Experimental results showed that freezing-and-thawing within 300 cycles had little effects on compressive performance of SHCC, while multiple cracking and deformability of SHCC under uniaxial tensile and flexural loadings were negative affected by the freezing-and-thawing exposure.
Keywords: fibers, freezing-and-thawing, strain-hardening cement composite (SHCC), durability

1. INTRODUCTION

Concrete is weak in tension, though it is an effective and strong material in compression. Cracks exist in concrete materials due to processing, shrinkage, and thermal effects. In reinforced concrete (RC), the presence of a load-induced tensile stress field causes existing internal cracks to propagate and reach the exposed surface of concrete, and existing external cracks to penetrate deeper [1]. Wider surface cracks increase migration of aggressive agents into concrete and make the concrete cover more permeable to moisture, oxygen, and carbon dioxide. Consequently, RC can be experience reinforcing bar corrosion, cover concrete spalling, strength lose, or progressive disintegration [2]. Therefore, wider surface cracks are the origin of the deterioration of RC infrastructures. The control of surface cracking becomes very important for improving the durability of RC structures.

Fig. 1 based on the statistical information of Korea Ministry of Land, Transport, and Maritime Affairs [3] shows the present state of bridge construction on the national roads in Korea. In the late 1980s, the bridge construction increased abruptly because the 10th Seoul Asian Game in 1986 and the 24th Seoul Olympic Game in 1988 were close at hand and Korea Government made a much budget for the construction of social infrastructures. Park et al. [4] reported that the average life of bridge on the national roads in Korea would be thirty years under present maintenance and management system for bridges and it was very short compared to an average life of bridges on the Korea Tax Law (30-50 years) and in OECD nations (50-100 years). After the year 2015, Korea Government will face several problems such as traffic jam, the much expense of infrastructure construction, and environment destruction due to the demolition and

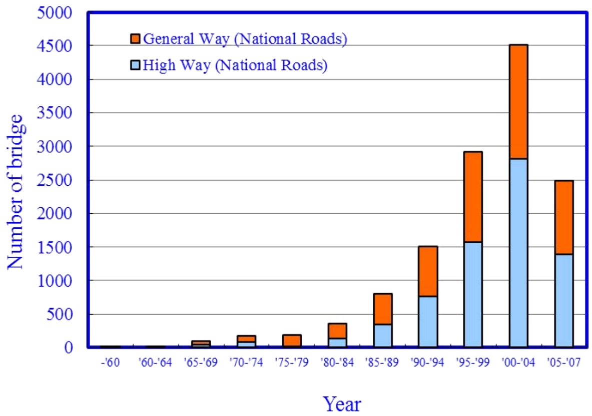

Fig.1 Present state of bridge construction in Korea

construction of bridges. Therefore, Korea Government and construction industries have recognized the necessary of new effective maintenance management system for infrastructures and the repair and rehabilitation method to improve the durability of infrastructures, especially, bridges.

Recently, a new class of fiber reinforced cementitious composites (FRCCs), which exhibit multiple cracking and strain hardening behavior under uniaxial tensile loading, are developed [5-9]. These FRCCs are called High Performance Fiber Reinforced Cementitious Composite (HPFRCC), Engineered Cementitious Composite (ECC) or Strain Hardening Cementitious Composite (SHCC) etc..

As aforementioned, the common deterioration to concrete infrastructures usually starts from the surface and progresses into the structure. It has been recognized that by the new repair materials such as SHCCs with the characteristics of cracking damage mitigation, the overlay or replacement of the deteriorated concrete can

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Table 1. Mixture proportions of matrix

Composite	W/B (%)	Fiber volume fraction (%)		Fly ash/ Binder (wt.%)	Sand/ Binder (wt.%)	Polymer/ Cement (wt.%)	SP/ binder
		PE	PVA				
45-PVA1.30+PE0.20	45	0.20	1.30	35.0	50.0	5.0	1.2
45-PVA0.75+PE0.75		0.75	0.75				
55-PVA1.30+PE0.20	55	0.20	1.30				
55-PVA0.75+PE0.75		0.75	0.75				

Agents in binder : silica fume, antifoaming agent, shrinkage-reducing agent, superplasticizer, multi-functional agent

increase the service life of deteriorated infrastructures [10-13]. Almost infrastructures are exposed to external environments and experience various environmental effects such as freezing-and-thawing cycles. The SHCCs subjected to repeated cycles of freezing-and-thawing may deteriorate rapidly. For durable repair of aged infrastructures, the freeze-thaw resistance of SHCCs should be considered an important parameter.

2. FREEZE-THAW DURABILITY OF SHCC

The freeze-thaw resistance of three ECC mixes with different replacement levels of fly ash showed superior to that of regular non-air-entrained concrete. After exposed to 300 freeze-thaw cycles, the ECC tensile specimens retained much of their initial tensile ductility. All the ECCs subjected to freeze-thaw showed an average ultimate strain capacity close to 2.4-3.0% strain capacity of specimens not subjected to freeze-thaw conditions [14].

According to JSCE's Recommendations for design and construction of HPFRCC with multiple fine cracks [15], no significant reduction of relative dynamic elastic modulus and mass were found over 300 freeze-thaw cycles. Also it is reported that 300 freeze-thaw cycles had little effects on the relative dynamic modulus of elasticity, mass loss, and flexural behavior of HPFRCC prisms without or with pre-flexural cracks occurred under almost 1.5 time cracking loads.

Study on the freeze-thaw durability of SHCC has been reported in Reference 16. After 354 cycles of freezing and thawing, SHCC column reinforced with a blend of polyvinyl alcohol (PVA) and polyethylene (PE) fibers showed only minor reductions in the relative dynamic modulus of elasticity and mass. For dumbbell specimens, 144 freeze-thaw cycles and pre-strain level induced before freeze-thaw cycles had little effects on the tensile performances of SHCC, providing evidence for the high resistance of SHCC to repeated freeze-thaw cycles.

This paper presents the mechanical properties such as compressive, flexural and tensile behavior, of SHCCs after experiencing 300 freezing-and-thawing cycles.

3. EXPERIMENTAL PROGRAMS

3.1 Materials and specimens curing

The SHCC matrix used in this particular study utilizes synthetic fibers, such as ultra-high molecular weight PE and PVA, cement, fine aggregate, and fly ash. The fiber combinations and details of composites are given in Table 1. Each mix has been labeled according to the ratio of water to binder, fiber type and fiber volume fraction. The SHCC matrix's total fiber content by volume is 1.50 percent. The elastic modulus, the tensile strength and fiber density of PE and PVA were 75 and 40GPa, 2,600 and 1,600MPa, and 1.0 and 1.3, respectively. The length and diameter of PE and PVA fibers were 15 and 12mm, and 0.012 and 0.04mm, respectively.

After testing the fresh mix for workability (KS F 2594) and air content (KS F 2421), specimens for each test were cast in molds and compacted through external vibration. For each mix, eight dumbbell specimens shown in Fig. 2, six cylinders, and three prisms were made. After curing for 28 days at 23±3℃ and 95-100% RH, tests for mechanical properties of specimens non-exposed to freeze-thaw cycles were conducted and freeze-thaw tests for the other specimens were started.

3.2 Testing procedure

(1) Compressive tests

The compressive tests of cylindrical specimens with 100mm diameter and 200mm height were carried out on the cylinder specimens according to KS F 2405.

(2) Four-point bending tests

The four-point loading flexural tests were carried out at a loading rate of 0.05mm/min on the 100 x 100 x 400 mm prisms according to the requirements of KS F 2408.

(3) Uniaxial tensile tests

Uniaxial monotonic tensile tests were performed on the dumbbell-shaped specimens to investigate the effects of freeze-thaw cycles on the crack pattern and tensile behavior of SHCC materials according to JSCE's Recommendations (Chunking mechanism using clamp jigs) [15]. The uniaxial tensile tests were conducted by a displacement- controlled testing machine, as shown in Fig. 2. The displacement of the center 100mm region of the dumbbell-shaped specimen was measured by means of two linear variable differential transducers (LVDTs), and the tensile strain was calculated by dividing this measured displacement by the reference length of 100mm. All specimens were tested up to complete tensile failure.

(4) Freezing and thawing tests

Freeze-thaw tests were performed following Procedure B (frozen in air and thawed in water) of KS F 2456 similar to ASTM C 666 or JIS A 1148 "Resistance of concrete to rapid freezing and thawing."

Table 2. A summary of test results

Items \ SHCCs		45-PVA1.30+PE0.20	45-PVA0.75+PE0.75	55-PVA1.30+PE0.20	55-PVA0.75+PE0.75
Table Flow[1] (mm)		166 x 164	144 x 146	173 x 172	148 x 143
Air content[1] (%)		10.40	13.10	10.40	10.00
Compressive Strength (MPa)	0[2]	48.80	43.95	39.94	35.73
	100	48.50	45.21	33.66	34.08
	200	52.30	46.05	42.93	39.48
	300	46.73	46.73	45.80	34.08
Bending strength(MPa)	0	11.25	15.39	12.36	12.16
	300	12.44	13.44	12.38	10.80
Direct tensile strength[3] (MPa)	0	3.77	2.35	2.89	2.95
	100	2.83	2.22	2.99	4.01
	200	4.28	4.64	2.40	2.54
	300	4.68	3.16	3.55	3.57
Direct tensile capacity[4] (%)	0	0.64	0.44	0.92	0.29
	100	0.38	0.54	0.80	0.43
	200	0.65	0.47	0.36	0.25
	300	0.61	0.34	0.42	0.75

[1] an average value of three time tests, [2] the number of freeze-thaw cycles (curing times are 39, 68, 121, and 151 days for 0, 100, 200, and 300 freeze-thaw cycles, respectively), [3] an average value of test results of two specimens, [4] an average value of tensile strain of two specimens at tensile strength

In a single cycle, temperature of the specimens cools from 4 to -18℃ and then warms to 4℃, all within 3 to 4hr. In this study, the machine for rapid freeze-thaw cycles was as shown in Fig. 3. Damage to the specimens is assessed periodically by visual observation and by measurement of the dynamic modulus of elasticity.

For the compressive and bending performance of SHCCs, a single specimen was tested at pre-decided freeze-thaw cycles and couple specimens were tested to investigate direct tensile performance of each SHCC after 100, 200, and 300 freeze-thaw cycles. The size of each specimen is as described in section 3.2.

4. EXPERIMENTAL RESULTS

A summary of the test results, including the air content, flow value, compressive strength, bending strength, and direct tensile strength, is presented in Table 2. Discussion of the test results is divided into four sections: (1) frost resistance; (2) compressive performance, (3) flexural performance, and (4) direct tensile performance.

4.1 Frost resistance

To estimate the frost resistance of SHCCs, two criteria have been adapted. The losses of both the relative dynamic modulus of elasticity and the mass in the SHCCs after each decided freeze-thaw cycles were measured and recorded.

Fig. 4 presents the effects of water-to-binder ratio and the condition of reinforcing fiber blending on the relative dynamic modulus of elasticity and mass loss of SHCC with an average air content of 11 percent.

For each SHCC specimen exposed to freeze-thaw cycles, relative dynamic modulus of

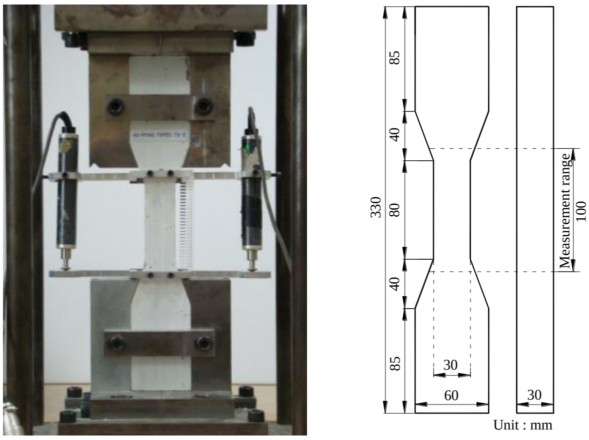
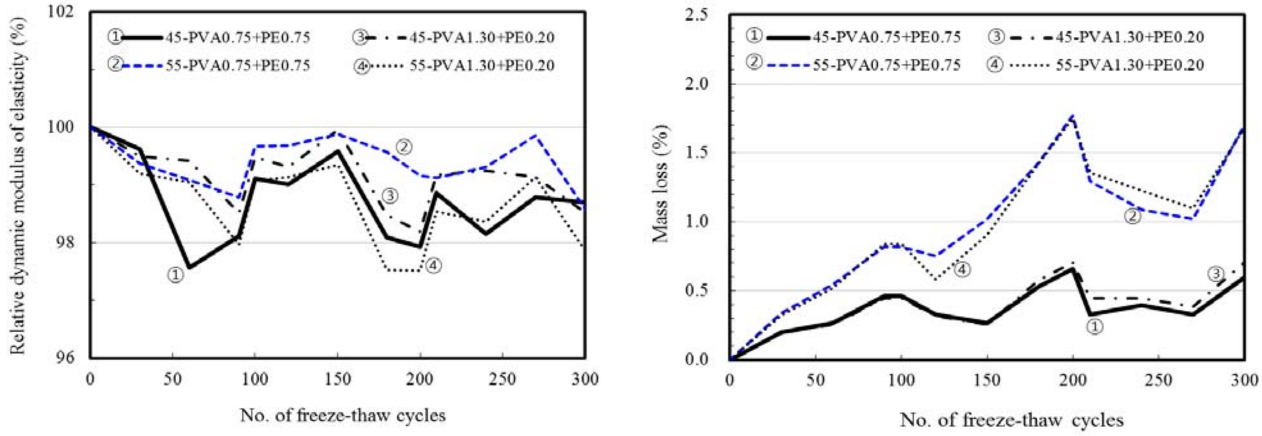


Fig. 2 Jig and configuration of direct tensile tests

Fig. 3 Machine for freeze-thawing tests



(a) Relative dynamic modulus of elasticity (b) Mass loss

Fig. 4 Frost resistance of SHCCs

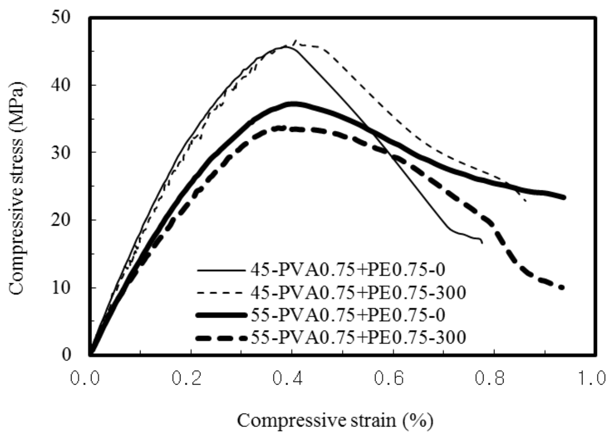


Fig. 5 Compressive behavior of SHCCs

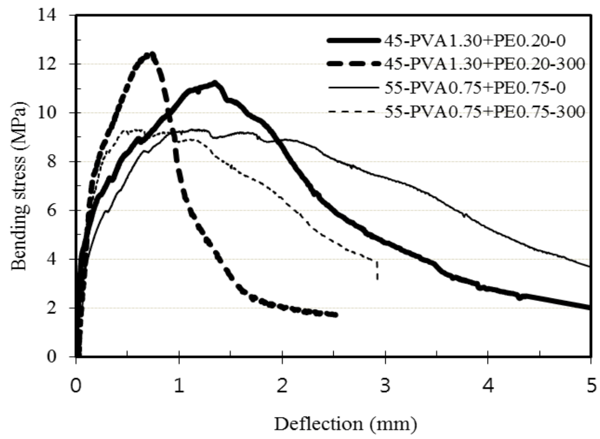
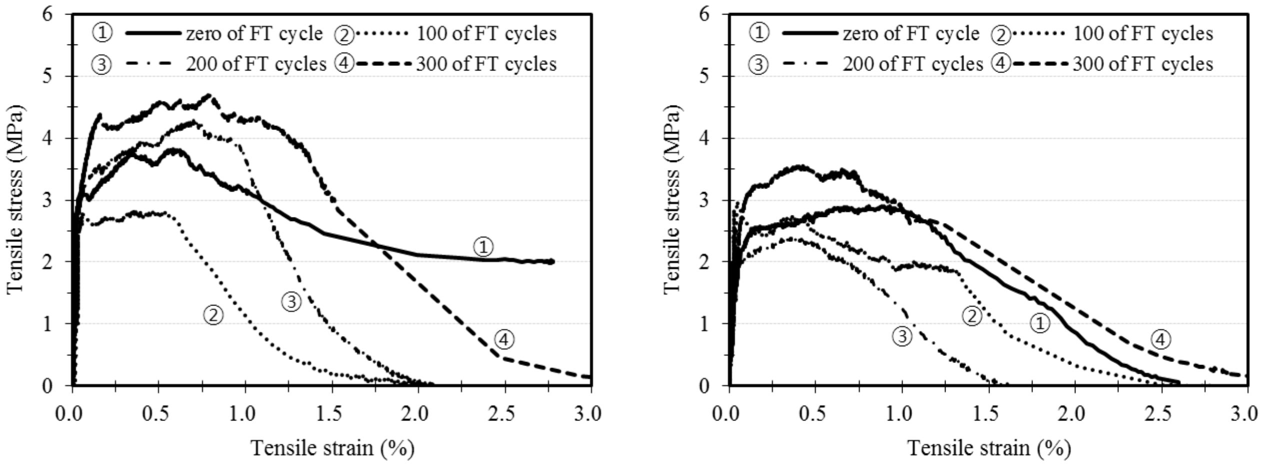


Fig. 6 Flexural behavior of SHCCs



(a) 45-PVA1.30+PE0.20 (b) 55-PVA1.30+PE0.20

Fig. 7 Direct tensile behavior of SHCCs after freeze-thaw cycles

elasticity remained nearly constant and decreased only approximately 3% after 300 freeze-thaw cycles as shown in Fig. 4(a). From Fig. 4(b), It should be noted that mass losses in the SHCCs with higher water-to-binder ratio (W/B = 0.55) were higher than those of the SHCCs with lower W/B. Mass losses were mainly caused by surface scaling of the specimens.

4.2 Compressive performances

Typical compressive stress versus strain curves of the SHCCs cylinder specimens with different W/B and blending conditions are shown in Fig. 5. From Table 2 and Fig. 5, it can be seen from Table 2 that 45-PVA1.30+ PE0.20 composite was characterized by the highest compressive strength and the composites with more PE fibers were generally characterized by low compressive strengths. From this result and previous results [9], it is found that PE fibers have

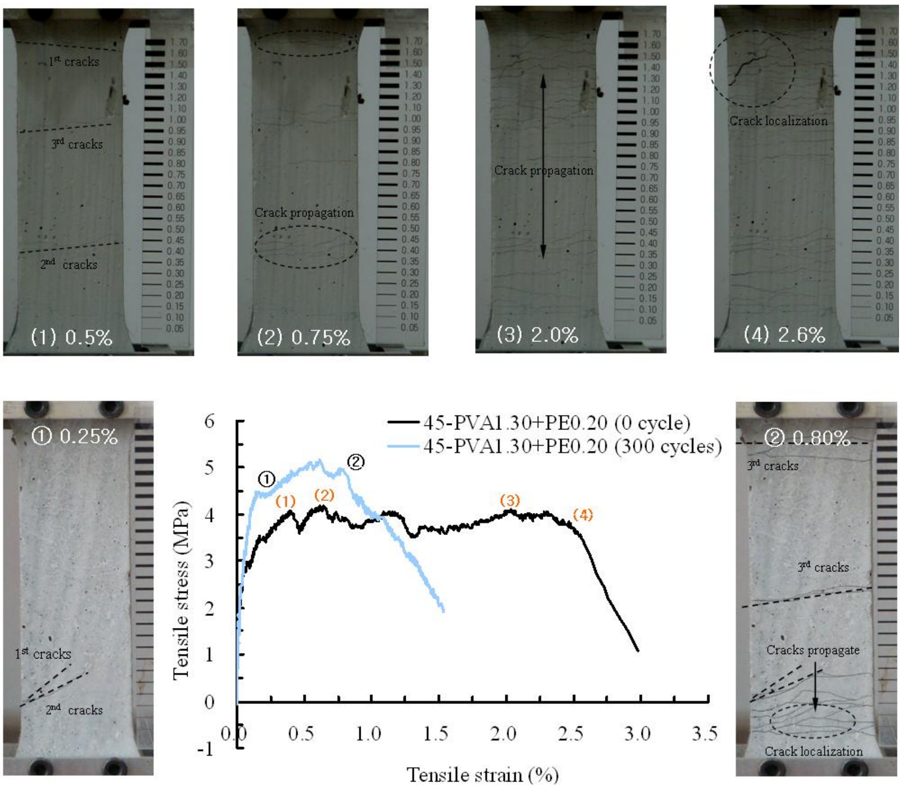


Fig. 8 Cracking propagation of SHCCs under direct tensile loading

negative effects on the compressive strength of SHCC composites.

Exposed to 300 freeze-thaw cycles, all the SHCC mixtures remain virgin in the overall compressive behaviors. From Fig.5 and Table 2, it is noted that the freeze-thaw environment within 300 cycles had little effects on the compressive performance of SHCC composites. Failure modes of two cases (i.e., with and without freeze-thaw exposure) were quite similar. Types of reinforcing fibers had little effects on the mass losses in the SHCCs.

4.3 Flexural performances

The equivalent elastic bending stress versus midspan deflections are shown in Fig. 6. An elastic response is observed up to the first cracking strength of the composite. After the first crack, the bending stress increases with an increase in the deflection; thus multiple cracks develop at the bottom surface of the specimen up to the maximum bending stress. Beyond the maximum stress, the bending stress drops gradually due to fiber pull-out, rupture or failure of the matrix near the localized crack.

From Table 2 and Fig. 6, it be seen that freeze-thaw exposure make initial slopes in flexural stress-deflection curves of SHCC prisms stiffer and decreased the deflection at the ultimate flexural strength in case of PVA1.30+PE0.20 composites. And Freeze-thaw cycles had significant effects on the cracking patterns on the tensile zone of flexural prisms. Under four-point loading, SHCC prisms non-exposed to freeze-thaw environments showed multiple cracking characteristics while SHCC prisms undergoing freeze-thaw cycles failed with a single crack.

4.4 Direct tensile performances

Fig. 7(a) shows a comparison of the typical tensile responses of 45-PVA1.30+PE0.20 composite. Each curve is average curve of two test results. Most of the specimens showed a similar trend, and all specimens demonstrated a clear pseudo strain-hardening behavior with strain capacities ranging from 0.50% to nearly 1.00%. An elastic response is observed up to the first cracking strength of the composites. After the first crack, the tensile stress increases with an increase in the strain, indicating the development of multiple cracks up to the peak tensile stress (post-cracking strength). The peak tensile stress is reached when the fiber bridging capacity is exhausted and the strain begins to localize at one crack as shown in Fig. 8. Beyond the peak tensile stress, the tensile stress drops gradually due to some fibers pulling out from the matrix and the fracture of fibers near the localized crack.

Comparison of Figs. 7(a) and (b) showed that as previous research results on the available literatures [14, 16], rapid freeze-thaw environment within the scope of this research does not make the tensile strength and ductility decrease while the ductility decreased a little for the composite 55-PVA1.30+PE0.2, with higher W/B and relatively more PVA fibers. From this result, it is seen that freeze-thaw exposure has little effect on the tensile performance of SHCC materials. But it is thought that the freeze-thaw environment could have a little effect on the ductility of SHCC materials with hydrophilic fibers and higher W/B because repeated freeze-thaw cycles damaged interfacial transition zone (ITZ) between matrix and fibers [17].

4.5 Multiple cracking characteristics under tension

Fig. 8 presents a typical tensile stress-strain curve and cracking sequence for 45-PVA1.30+PE0.20 composite.

For the composite non-exposed to rapid freeze-thaw cycles, the pseudo strain-hardening behavior continues until the strains reach nearly 2.4 percent and multiple fine cracks were distributed over the overall surface of the tensile specimen. After tensile strain of 2.4 percent, the first cracks on the upper of dumbbell specimen were localized and then tensile stress decreased gradually.

For the composite exposed to 300 freeze-thaw cycles, tensile strength was higher but multiple fine cracks were not distributed well over the specimen. Therefore, strain-hardening range also was shorter than that of the composite without freeze-thaw cycles.

5. CONCLUSIONS

The effects of W/B and types of fiber blending on the mechanical properties and freeze-thaw durability of strain-hardening cement composites (SHCCs) were investigated. Results indicated that SHCC provides superior resistance to deterioration under the rapid freeze-thaw environment. Rapid freeze-thaw cycles have little effects on the mechanical properties, such as compressive, flexural and tensile behavior, of SHCC materials. But multiple fine cracking characteristics under flexural and direct tensile loading, tensile strain capacity, and ductility were negatively influenced by freeze-thaw environment. This tendency is prominent in the composites with higher W/B or hydrophilic fibers.

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