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Strain-Hardening and Cracking Behavior of Fiber-Reinforced Sustainable Cement Composites under Direct Tension

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Abstract

This paper describes the fresh and hardened properties of polyvinyl alcohol (PVA) fiber reinforced sustainable cement composite incorporating fly ash as a binder. For the fresh and hardened properties, flow value, compressive and direct tensile performance, cracking and crack-healing behavior of sustainable strain-hardening cement composite (SHCC) were investigated. For the SHCC mixes, three mixtures with various water-to-cementitious materials ratio (*w/cm*) were used and the PVA fiber volume content was fixed at 2.0%.

Keywords: Strain-hardening cement composite (SHCC), Sustainable materials, Direct tensile performance, Cracking behavior, Crack-healing behavior

1 Introduction

During the past two decades, a new class of fiber-reinforced cement composite (FRCC) that exhibits multiple cracking and tensile strain-hardening behaviors under

direct tension have been developed, studied and improved [1]. The use of the special FRCC, called as strain-hardening cement composite (SHCC), in a variety of applications proved to be very promising. In USA, Japan and Korea, SHCCs have been applied for repair and strengthening of existing structures in order to simplify the reinforcement details and improve the seismic performance of critical members in infrastructure and buildings [2-4].
To achieve strain-hardening behavior, the innovative class of FRCC, i.e. SHCC, requires the high cement content to control the mortar rheology for improving fiber distribution and mortar fracture toughness. Coarse aggregates are typically omitted for producing the cement composite also, resulting in two or three higher cement content, compared with conventional concrete [5]. The high cement content in the SHCC leads to the higher heat of hydration, autogenous shrinkage, cost, energy consumption and carbon dioxide emission. Construction industry, which is one of the most significant sources of carbon dioxide emissions, has faced heavy pressure and new challenges, as well as mandatory upgrades in the durability and sustainability of conventional materials for reducing the greenhouse gases.

A suitable solution can be found in the use of supplementary cementitious materials such as fly ash. These sustainable materials have been used to replace cement in the concrete. Their replacement is intended to prevent the emissions by producing the cement and additional emissions by reusing the industrial wastes. Also, the feasibility of replacing a part of cement in the SHCC with industrial by-products was investigated and observed [7]. It is commonly known that the burning temperature, coal type and some other factors have a significant effect on the chemical compositions and particle size distribution of fly ash. These properties of fly ash influence the microstructure and mechanical performances of hydrated cement paste replaced a part of cement with fly ash [8].
In this paper, three types of specific compressive strengths (27, 40 and 70 MPa) were selected to establish strain-hardening behaviors of sustainable SHCCs mixed with the fly ash from South Korea. The effect of water-to-cementitious materials ratio (*w/cm*) on the compressive, direct tensile and cracking behaviors of sustainable SHCCs was evaluated.

2 Experimental Investigation

Materials
The sustainable SHCC materials used in this test were ordinary Portland cement (OPC), fly ash, silica sand and PVA fibers. The chemical compositions of OPC, fly ash and silica sand were provided in Table 1. OPC from a Korean company was similar to ASTM Type I. The fly ash was supplied from Boryeong power plant in the west of South Korea. Silica sand with a mean grain size of 110 μm was used for all SHCC mixtures. PVA fibers with a length 8 mm and a diameter of 39 μm were incorporated to redistribute the tensile stress and control the cracks in the cementitious matrix.

Table 1. Chemical composition of OPC, fly ash and silica sand

Ingredients	OPC	Fly ash	Silica sand
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	0.90	2.20	1.51
Physical properties			
Specific gravity	3.15	2.35	2.10
Blain fineness (m^2/kg)	364.0	341.0	-

Mixture proportions and mixing procedure

The mixture proportions of the sustainable SHCCs with different specific compressive strengths are provided in Table 2. Three sustainable SHCCs with various *w/cm* were investigated in this investigation. In all SHCC mixtures, PVA fibers content and fly ash replacement ratio (FA/C) were constant at 2% by volume and 0.25, respectively. The adding amount of polycarboxylate superplasticizer (SP) in the each mixture was controlled to achieve consistent rheological properties for better PVA fiber distribution and workability.

All mixtures were mixed with same procedure. The sustainable SHCCs were prepared with a pan mixer with 60L capacity. Dry mixing of all solid constitutes including cement, fly ash and silica sand was first performed for 3 minutes. Water and SP admixture were then added to the dry mixture and the mixture was further mixed for another 3 minutes. After making sure that fresh mortar matrix is homogenous, PVA fibers were slowly incorporated into the mortar matrix and mixed until all fibers are evenly distributed. Fresh SHCCs were cast into molds.

Table 2. SHCC mixture proportions by weight

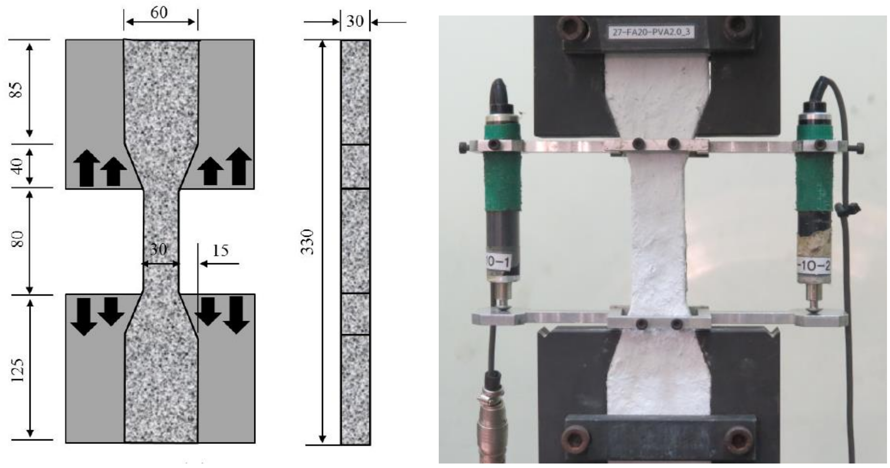
Mix designation	*w/cm* (%)	SP (%)	Unit weight (kg/m^3)			
			Cement	Water	Fly ash	Silica sand
SHCC27	48.0	0.2	735	441	184	588
SHCC40	45.0	0.3	832	469	208	416
SHCC70	31.5	0.8	965	380	241	508

Specimen preparation and testing procedure

To evaluate the workability of the fresh SHCCs investigated in this study, flow values for each SHCC mixture were estimated. To examine the hardened properties of each sustainable SHCC mixture, cylindrical specimen and dumbbell-shaped specimen were manufactured for compressive and direct tensile tests, respectively. For compressive tests, the cylinders with 50 mm in diameter and 100 mm in height were cast. To characterize the direct uniaxial tensile performance of sustainable SHCCs, direct tensile tests were conducted on dumbbell-shaped specimens with 100mm in measuring length, 30 mm in width and 30 mm in depth. After cylindrical and dumbbell-shaped specimens were cast, the specimens were stored in the atmosphere for 24 hours and then were demolded. After demolding, the specimens were cured in a water tank until one day before the day of testing. Just before testing, the specimens were left in the laboratory at ambient temperature.

Compressive tests were conducted in accordance with ASTM C 39 for compressive strength of cylindrical concrete specimens. For each mixture, three cylinders were tested to consider the fluctuation of compressive strengths in the cylinders. All of the compressive tests were performed at a constant rate of 0.5 MPa/s until maximum strength and then controlled by displacement up to failure.

The JSCE's recommendations were used for direct tensile tests on the dumbbell-shaped specimens. The configuration of tensile specimen and direct tensile loading apparatus are provided in Figure 1. The section of tensile specimens is 30 mm × 30 mm, and the gage length of the specimen is 80 mm. As shown in Figure 1, the displacement of the center 80 mm region of the dumbbell-shaped specimen was measured by means of two displacement transducers (DTs). All the specimens were tested up to complete tensile failure. All of uniaxial tensile tests were conducted at a constant engineering strain rate of 0.5 percent/min.



(a) Specimen's geometry(unit :mm) (b) Setup for direct tension

Fig. 1. Specimen configuration and setup for direct tension tests

3 Experimental Results and Discussions

The fresh and hardened properties of sustainable SHCCs were summarized in Table 3. To determine flow values of fresh SHCCs, mini slump tests were performed according to ASTM C 1437. In Table 3, the relative slump value was calculated from the following equation;

$$\Gamma_p = \left(\frac{d}{d_o}\right)^2 - 1$$

Where Γ_P is relative slump, d is the average of two measures diameters of the fresh SHCC spread and d_o is bottom diameter (100 mm) of the conical con with 70 mm in top diameter, 100 mm in bottom diameter and 50 mm in height used in this study. The relative slump value in Table 3 is an average of twice test results for each mixture. Compressive and direct tensile test results in Table 3 are average values of three cylindrical and dumbbell-shaped specimens, respectively. For the hardened properties, the standard deviation is also included.

Table 3. Summaries of test results

Mix designation	Relative slump value (Γ_P)	Compression		Direct tension	
		Strength (MPa)	Strain (%)	Strength (MPa)	Strain (%)
SHCC27	2.90	40.2 ± 2.9	0.30 ± 0.05	3.87 ± 0.31	2.92 ± 0.99
SHCC40	3.84	45.3 ± 1.0	0.36 ± 0.02	4.97 ± 0.49	1.57 ± 0.65
SHCC70	2.33	66.2 ± 1.2	0.35 ± 0.01	6.23 ± 0.40	0.51 ± 0.21

Fresh properties

A different amount of SP was added into each SHCC matrix to adjust the slump value of cementitious matrix to 270 ± 20 mm. The SHCC40 among all SHCC mixtures shows the highest workability. The highest relative slump value of SHCC40 is due to least amount of silica sand.

Compressive properties

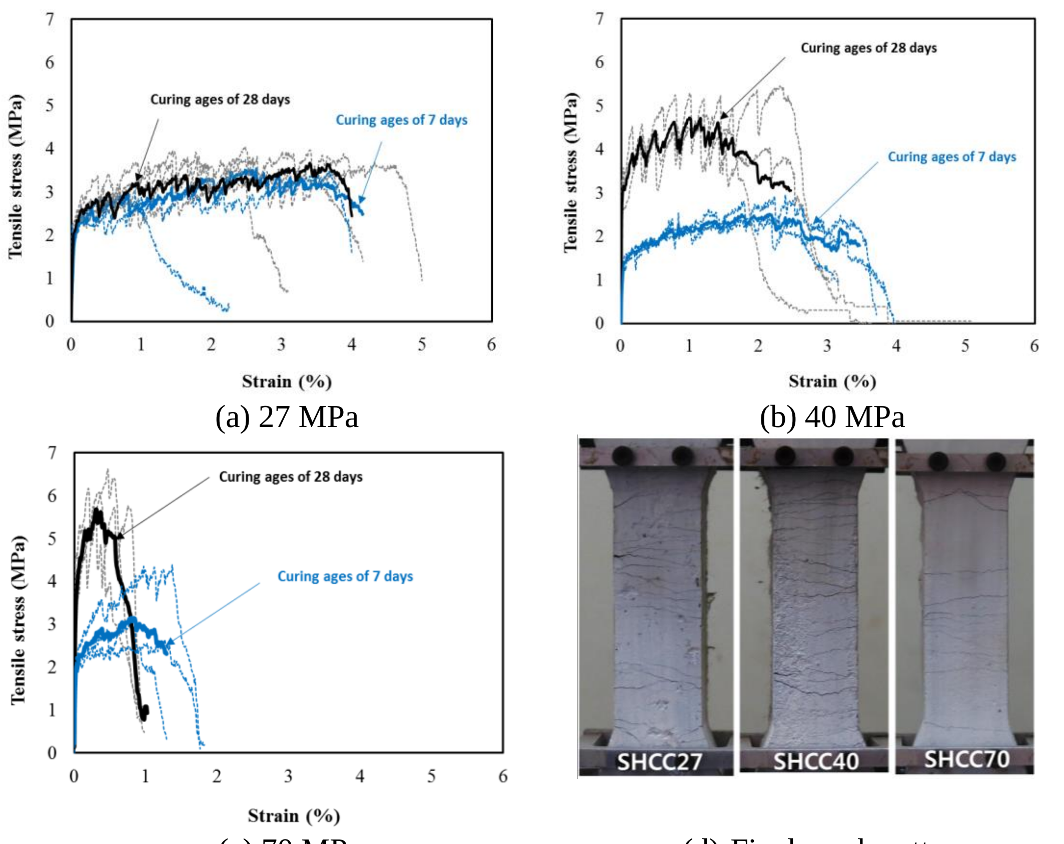
The compressive strengths of the SHCC27, SHCC40 and SHCC70 at a curing age of 28 days are 40.2 ± 2.9 MPa, 45.3 ± 1.0 MPa and 66.2 ± 1.2 MPa, respectively.

Direct tensile properties

Figure 2 presents direct tensile stress versus strain behaviors of three dumbbell-shaped specimens made with different compressive strength SHCCs at a curing age of 7 and 28 days. As shown in Figure 2, all sustainable SHCCs in direct tension, regardless of SHCCs' compressive strengths, exhibited strain-hardening behavior accompanied by multiple cracking that fine cracks are distributed over the tensile specimens after an initial tensile crack. In SHCC27 mixture, the curing age had no noticeable effect on the direct tensile response while in SHCC40 and 70, direct tensile behaviors depended on the curing age. As can be seen from Figure 2 and Table 3, the direct tensile strength of SHCC27 at 7 days is approximately 3.50 MPa, which is 10% less than that at 28 days. Tensile strain capacity of SHCC27 mixture at 7 and 28 days are 2.58% and 2.92%, respectively. The direct tensile performance of the sustainable SHCC developed in the study is comparable to those of the slag-based or the fly ash-based engineered cementitious composites (ECCs) by Lee et al. [8], Jang et al. [6] and Yang et al. [5]. However, for SHCC40 and 70 mixtures, the tensile strengths at 7 days are less than those at 28 days while the tensile strains are larger.

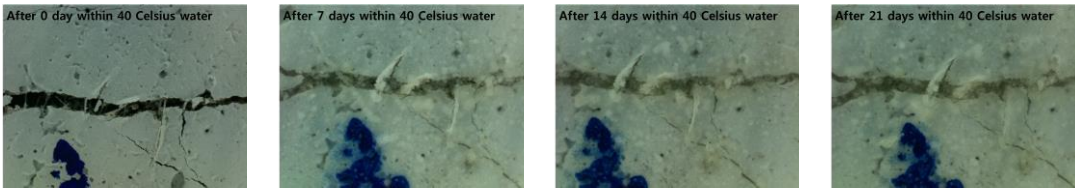
Cracking behavior

Typical multiple cracking patterns of each sustainable SHCC mixtures are shown in Figure 2(d). As can be seen in Figure 2(d), uniform and fine crack distribution over dumbbell-shaped specimens with SHCC27 and SHCC40 mixtures were observed. The multiple cracking behaviors exhibited on these SHCC specimens corresponds to their high tensile strain capacity. However, the tensile specimens of SHCC70 mixture with higher compressive strength showed relatively few fine and widely spaced cracks. These cracking characteristics of SHCC70 mixture led to significantly lower strain capacity with less than 1.0%.

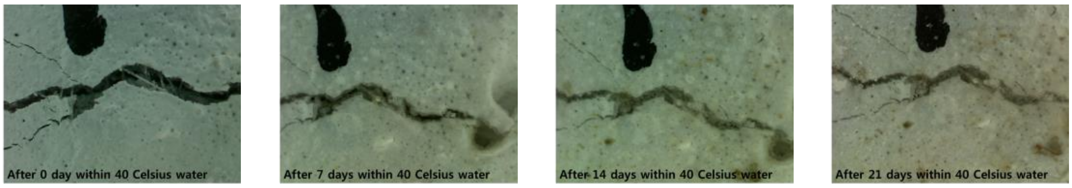


(a) 27 MPa (b) 40 MPa (c) 70 MPa (d) Final crack patterns

Figure 2. Tensile and cracking behaviors of sustainable SHCCs



(a) Healing processes of crack occurred at curing age of 7day



(b) Healing processes of crack occurred at curing age of 28day

Figure 3. Typical crack-healing behavior of SHCC27 in 40 Celsius water

Crack-healing behavior

Except for investigating the compressive and tensile performances of sustainable SHCCs with various compressive strengths, effect of cracking age, curing condition and compressive strength on the crack-healing behavior of SHCCs including 25% fly ash at the weight of cement was examined. Figure 3 shows typical crack-healing behavior of SHCC27 immersed in 40 Celsius water as a curing age increased. The formation of crystallization products in the cracks occurred at a curing age of 7 and 28 days was observed. Self-healing performance of cracks in the sustainable SHCCs was identified.

4 Conclusions

Compressive strength in the sustainable SHCC has a significant effect on the compressive as well as direct tensile performance. Crack self-healing feasibility in the sustainable SHCCs mixed in this study was also observed and confirmed. It is concluded that fly ash from power plant in Korea is feasible to produce the SHCC with higher strain capacity and crack self-healing performance.

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