sustainability

MDPI

Article

The Effect of Shrinkage-Compensation on the Performance of Strain-Hardening Cement Composite (SHCC)

Seok-Joon Jang [1], Ji-Hyeon Kim [2], Sun-Woo Kim [3], Wan-Shin Park [3] and Hyun-Do Yun [2,*]

1 Research Institute for Infrastructure Performance, Korea Infrastructure Safety Corporation, Jinju 52856, Korea; jang@cnu.ac.kr
2 Department of Architectural Engineering, Chungnam National University, Daejeon 34134, Korea; ojtmk0@naver.com
3 Department of Construction Engineering Education, Chungnam National University, Daejeon 34134, Korea; sw.kim@cnu.ac.kr (S.-W.K.); salshin@cnu.ac.kr (W.-S.P.)
* Correspondence: wiseroad@cnu.ac.kr; Tel.: +82-42-821-5622

Received: 27 December 2018; Accepted: 4 March 2019; Published: 8 March 2019

Abstract: This study investigated the effects of shrinkage compensation on the tensile and cracking responses of strain-hardening cement composite (SHCC) by adding calcium sulfoaluminate (CSA)-based expansive additive (EXA) to the mixture. Such responses are closely related to the durability of concrete structures, of dumbbell-shaped SHCC specimens, and reinforced SHCC ties. For this study, two SHCC mixtures and a conventional concrete mixture with a specific compressive strength value of 30 MPa were prepared and measured in terms of shrinkage history, compressive strength, flexural strength, and direct tensile strength. The test results show that the mechanical properties of shrinkage-compensated SHCC with 10% CSA-based EXA are superior to those of conventional SHCC and concrete mixtures. Also, reinforced tension ties with shrinkage-compensated SHCC exhibited the best multiple cracking and tension-stiffening behavior among the three types of tension ties tested. The results show that shrinkage compensation using CSA-based EXA in SHCC with rich mixture is effective for resisting crack damage. Shrinkage-compensated SHCC may be used for civil infrastructure facilities that require high levels of durability and are exposed to extreme environments.

Keywords: strain-hardening cement composite (SHCC); shrinkage; tensile behavior; multiple cracks

1. Introduction

Reinforced concrete (RC) is an effective material for civil infrastructure construction due to its durability, economic advantages and superior compressive strength. However, the low tensile strength and quasi-brittle nature of cover concrete can lead to the development and localization of cracks in RC structures under mechanical or environmental loading. These cracks that appear on the surface of RC members reduce the load-bearing capacity and aesthetic quality of the structure and allow water or other chemical agents to create pathways to steel reinforcement. Localized surface cracks are major reasons for the deterioration of the structural performance and durability of RC structures. Such structural deterioration leads to serious economic and environmental problems due to the increase in maintenance costs and degradation of service life.

The economic impact of structural deterioration has led to extensive study of durability-related structural issues over the last several decades. Various alternatives, such as Supplementary Materials [1], surface coatings [2], mixture composition [3], and corrosion inhibitors [4], have been proposed to improve the durability of the concrete and RC structures. Recently, several researchers have focused on the development and application of a new type of short fiber-reinforced durable cement composite that exhibits tensile strain-hardening and multiple-cracking behaviors after the initial crack [5–7]. This innovative composite material is effective in improving the brittleness of ordinary cement composite. This is sometimes referred to as high performance fiber-reinforced cement composite (HPFRCC), engineered cementitious composite (ECC), or strain-hardening cement composite (SHCC). Ahmed and Mihashi [8] reviewed various durability properties, such as permeability, corrosion resistance, freeze-thaw resistance, and shrinkage crack resistance, of SHCC from published research results. They reported that the higher strain and crack-damage mitigation capacities of SHCC compared to ordinary concrete provide superior durability-related performance. Kobayashi and Kojima [9] investigated the chloride proofing and corrosion protection performance of cracked SHCC tension ties. They concluded that SHCC is superior to normal concrete in chloride diffusion resistance and rebar corrosion protection despite the existence of multiple cracks. The multiple-cracking characteristics of SHCC are now commonly known to enhance durability by retarding the ingress of moisture, gas, and other deteriorating substances [10].

Recently, SHCC, with superior durability and ductility, has been employed for critical members in new construction and for strengthening or repairing existing infrastructures [11]. In these practical applications, the high shrinkage characteristics of the SHCC, which has higher binder content without coarse aggregate compared to conventional concrete, can lead to cracks in SHCC members or joints and delamination between the SHCC layer and existing concrete substrate. To accelerate practical applications of SHCC, its shrinkage-compensating effect on the mechanical properties of SHCC and reinforced SHCC should be addressed. This study's literature review has identified that significant mitigation of the shrinkage in the SHCC could be achieved by controlling the mixture proportions [12,13] and using shrinkage-reducing agents [14] as well as expansive admixture (EXA) [15,16]. Also, Choi and Yun [16] investigated the effects of the replacement of calcium sulfoaluminate (CSA)-based EXA on the shrinkage and mechanical properties of SHCC. They showed that the replacement of ordinary cement by CSA-based EXA effectively reduces the shrinkage in SHCC that contains 1.5% polyethylene (PE) fibers and has a high binder content. Based on the shrinkage and mechanical performance, Choi and Yun [16] proposed 10% as the proper replacement level of CSA-based EXA for SHCC mixtures.

The present study investigates the feasibility of utilizing shrinkage-compensating SHCC to improve the durability of existing or new infrastructures and the effect of 10% replacement of cement with CSA-based EXA for the shrinkage compensation of SHCC on the mechanical properties. The study also examines the shrinkage-compensating effects of reinforced SHCC tension ties on the structural and cracking behaviors that are related to the durability of concrete structures.

2. Experimental Program

The experimental program was focused on investigating the shrinkage compensation effects on the mechanical performance of SHCC. To this end, the mechanical properties of two SHCC materials (conventional and shrinkage-compensating) and conventional concrete were evaluated. Also, the tension-stiffening and cracking responses of SHCC ties reinforced with a single mild steel bar were assessed.

2.1. Materials and Mix Proportions

Ordinary Portland cement produced in Korea, which corresponds to ASTM (American Society for Testing and Materials) type 1, was used in this study as the cementitious binder for two types of SHCC materials and normal concrete. For the production of control concrete with specified compressive strength of 30 MPa, both fine and coarse aggregate were used in saturated surface-dry (SSD) conditions. These conditions satisfy the requirements specified in Korean industrial standard (KS F 2526 and 2527) [17] for the crushed aggregate and sand used in structural concrete. Crushed gravel with a maximum size of 25 mm was used as coarse aggregate; its specific gravity and absorption were

2.60 and 0.85%, respectively. The fine aggregate was crushed sandstone with a nominal maximum aggregate size of 5 mm; the fineness modulus of the sand was 2.53, the unit weight was 2650 kg/m^3, and the water absorption rate was 0.98%. Cementitious binder, silica sand, polyethylene (PE) and steel fibers were used to mix the SHCC materials. The silica sand had a specific gravity of 2.16 and particle diameters ranging from 105 µm to 120 µm. The SHCC materials were reinforced with 0.75% PE fiber and 0.75% steel fiber as volume fractions. The PE fibers were 12 µm in diameter and 15 mm in length, with elastic modulus of 75 GPa and tensile strength of 2500 MPa. The hooked-end steel fibers were 32 mm in length, with an aspect ratio of 79, and tensile strength of 2300 MPa.

CSA-based EXA from Denka was used to compensate for shrinkage and reduce the internal tensile stress in the SHCC matrix. A chemical reaction mechanism can be found from the literature [18]. In the shrinkage-compensating SHCC matrix, 10% cement binder was replaced with CSA-based EXA, as proposed by Choi and Yun [16]. A small amount (0.02 wt.% of cement) of antifoaming agent was added to control the micro voids generated by the methyl cellulose. Table 1 lists the chemical contents of the cement and CSA-based EXA used in this study.

Table 1. Chemical contents of cement and calcium sulfoaluminate (CSA)-based expansive additive (EXA).

	Specific Gravity	Blaine Fineness (cm^2/g)	Chemical Composition (%)						
			SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Loss of Ignition
Cement	**45**	0	21.15	5.10	3.48	62.96	2.65	2.48	1.68
CSA-based EXA	30	10	1.48	13.10	0.60	50.75	0.50	32.27	0.8

To evaluate the tension stiffening and cracking behavior of reinforced SHCC ties, the SHCC ties were reinforced with a deformed steel bar with a nominal diameter of 16 mm. The yield strength and strain of the rebar were 513 MPa and 2704 µ, respectively.

Table 2 provides the mix proportions of two SHCC materials and conventional concrete used in this study. To compensate for the shrinkage of SHCC in this experimental program, 10% cement binder was replaced with CSA-based EXA. Both normal and shrinkage-compensating SHCC materials were reinforced with a hybrid configuration of 0.75% PE and 0.75% hooked-end steel fibers.

Table 2. Mix proportions of concrete and strain-hardening cement composite (SHCC) materials.

Material	W/B (%)	Ex-Rep.[1] (%)	Fiber Volume (%)		Unit Weight (kg/m^3)					
			PE [2]	SF [3]	Cement	Water	Sand	EXA	Gravel [4]	MC [5]
Concrete	50	0	0	0	350	175	770	0	981	
SHCC30	45	0	0.75	0.75	1075	484	430	0	0	0.5
SC-SHCC30	45	10	0.75	0.75	967	489	430	107	0	0.5

[1] Replacement level of EXA; [2] polyethylene fiber; [3] hooked-end steel fiber; [4] coarse aggregate; [5] methyl cellulose. Note: SHCC30 is conventional SHCC and SC-SHCC30 is shrinkage-compensating SHCC.

2.2. Mixing Procedure

The concrete and two SHCC materials were mixed in the laboratory using a fan-type mixer. For both SHCC materials, all the binder and silica sand were mixed first for a few minutes until a homogeneous mixture was obtained. The water and chemical additives were then added to the dry mixture. Short fibers were added slowly in small amounts after the dry components were completely mixed with the liquid portions. Mixing was continued for one minute at low speed and for three minutes at high speed.

2.3. Specimen Fabrication and Test Procedure

To evaluate the shrinkage-compensating effects of SHCC with rich mixture on the mechanical and cracking behavior of the SHCC, test specimens were manufactured for shrinkage, compressive strength, flexural strength, tensile strength, and tensile and cracking behavior of ties with a single rebar. The length difference for each specimen was measured using a shrinkage gauge installed inside the specimen according to KS F 2424 [17]. All of the specimens were demolded 24 h after casting. The specimens were stored and tested in a standard environment at 20 °C ± 1 °C and 50% ± 1% relative humidity for shrinkage deformation measurement.

Three cylindrical specimens 100 mm in diameter and 200 mm in height for each SHCC mixture were fabricated for compressive testing according to KS F 2405 [17]. The mean value was reported as the compressive strength of each mixture. To evaluate the flexural performance of the SHCC materials, three prismatic specimens 100 mm wide, 100 mm high and 400 mm long were prepared for each mixture. Four-point loading flexural tests of the prisms were carried out in accordance with KS F 2408 [17]. The direct tensile response of each SHCC mixture was determined using dumbbell-shaped specimens according to the Japan Society of Civil Engineers recommendations [19].

For the axial tension tests on concrete and SHCC ties reinforced with 16 mm single rebar, six prismatic specimens with 100 × 100 mm in cross-section and 1500 mm in length were fabricated and set up, as presented in Figure 1. To protect the steel bar from fracturing within the gauge length, i.e., the region that measures 1200 mm along the length of the tie, 25 mm protruding bar was connected to each end of the rebar through a high-strength coupler at each end of the central portion of the tension tie. Spiral reinforcement was placed around both ends of the tension tie to resist the concentration of bond stress between the rebar and cement composite. Figure 1a shows the seven strain gauges mounted along the rebar in the central region of each specimen. Axial load was introduced to the specimen by pulling the rebar that protruded from both ends of the tension tie specimen. To measure the average axial displacement in the central portion of the tension tie, two dial gauges were placed, as illustrated in Figure 1b. A specimen for each mixture was tested separately under monotonic loading and cyclic loading. Also, a specimen for each mixture was cyclically loaded at the average axial strain levels of 1000 μ and 2000 μ, respectively.

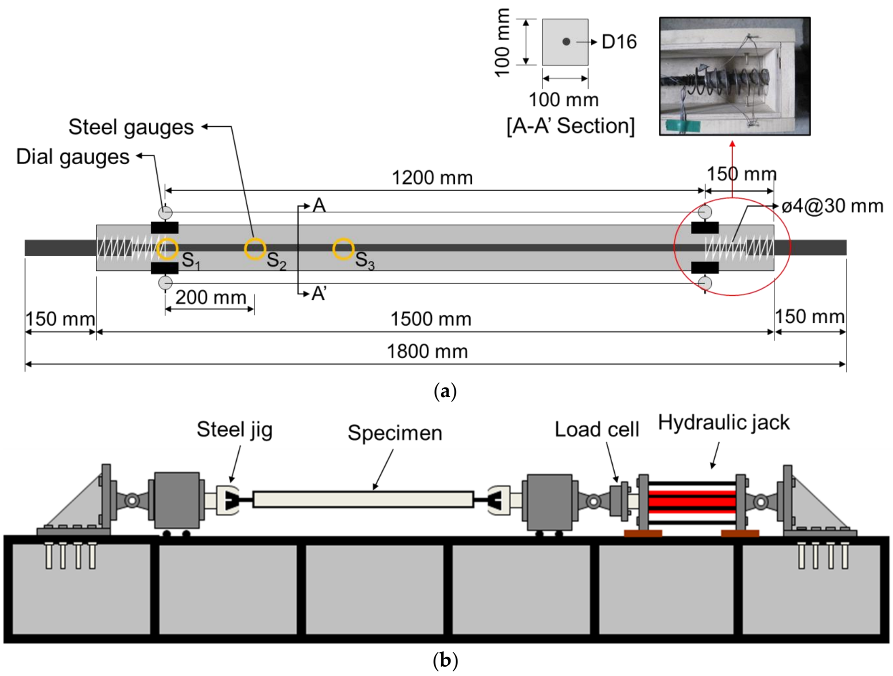


Figure 1. Specimen configuration and test setup on tension ties. (**a**) Configuration and dimensions; (**b**) Test set-up.

3. Results and Discussion

3.1. Shrinkage History of SHCC

Neville [20] reported that the ultimate shrinkage of normal concrete under normal drying conditions of 20 °C and 60% relative humidity ranges from 400 μ to 600 μ. According to Li and Li [21] and Yang et al. [22], the ultimate shrinkage strain of ordinary Portland cement-based ECC (another term for SHCC) ranges from 1200 μ to 1800 μ. Cheung and Leung [23] found that the ultimate shrinkage of normal cement and fly ash-based ECC increases from 812 μ to 1358 μ as the water-to-binder (w/b) ratio increases from 0.19 to 0.40. For ECC that has normal cement binder replaced by sulfoaluminate cement (SAC), the ultimate shrinkage values range from 530 μ to 650 μ with increases in the w/b ratio.

Figure 2 shows the measured ultimate shrinkage of concrete and SHCC materials under standard conditions up to 90 days. In this study, the measured shrinkage history of each mixture indicates that the ultimate shrinkage strain of SHCC30 mixture is very close to that of normal cement-based ECC reported in the literatures [21–23]. In the early stages, the drying shrinkage of the conventional SHCC30 mixture increased gradually, whereas during the first two days after casting, the SC-SHCC mixture, which contains 10% CSA-based EXA, exhibited a significant expansion of approximately 471 μ. Then, the SC-SHCC mixture started to shrink and showed a similar shrinkage pattern to that of the SHCC during early stages.

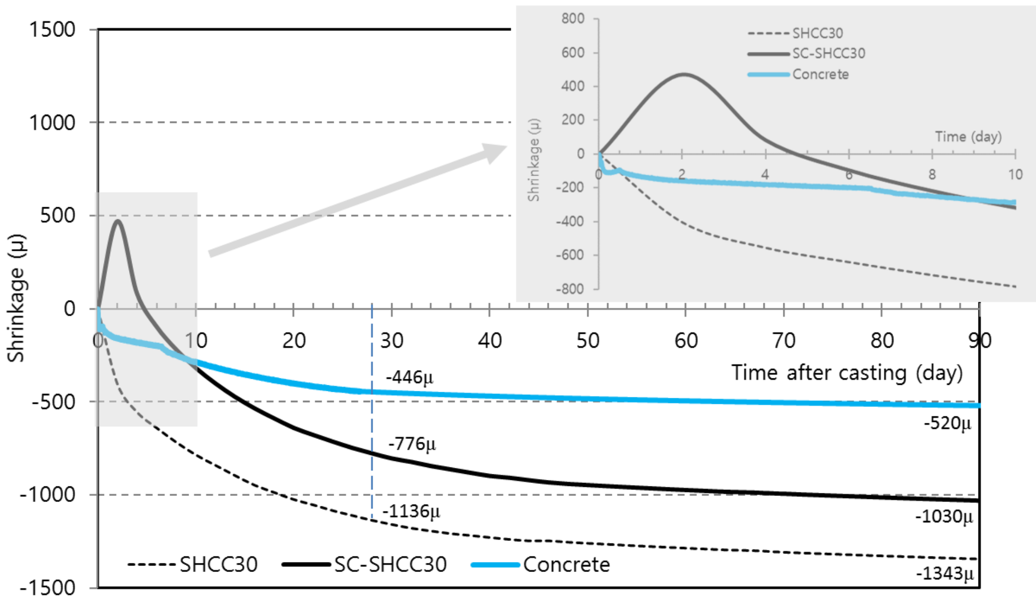


Figure 2. Shrinkage history of concrete and SHCC materials in a standard environment.

The total shrinkage strains after 90 days of concrete, SHCC30, and SC-SHCC30 mixtures were 520 μ, 1343 μ and 1030 μ, respectively. Figure 2 provides a comparison of the SHCC and SC-SHCC mixes and shows that, when ordinary cement is replaced partially with CSA-based EXA in the SHCC mixture used in this study, the shrinkage at 28 and 90 days after casting under standard conditions decreases by approximately 31.7% and 23.3%, respectively. This shrinkage compensation provided by the CSA-based EXA included in SC-SHCC mixture is due to the volume change that is caused by the formation of ettringite, monosulfate, and calcium hydroxide and that occurs when the main components, i.e., SO_3, CaO, and Al_2O_3, of CSA-based EXA hydrate [16,18].

Mechanical Properties of SHCCs

Table 3 presents the test results for the compressive strength, flexural strength, and direct tensile strength values for the concrete and SHCC materials at the curing age of 28 days. In this study, 10% cement binder in the SHCC material with rich mixture was replaced with CSA-based EXA to compensate for shrinkage strain. The EXA in the SHCC matrix may affect the mechanical properties of the SHCC material. Therefore, the mechanical properties of SHCC material with EXA should be evaluated to determine whether SHCC material with EXA can be used as a durable and ductile material for structural members of civil infrastructure facilities. Table 3 indicates that shrinkage compensation in the SHCC material (SC-SHCC30) with EXA improves the compressive, flexural, and tensile strength of PE fiber-reinforced and steel fiber-reinforced SHCC compared to the conventional SHCC (SHCC30). The replacement of an appropriate amount of EXA would be expected to lead to a significant volume increase of the SHCC matrix due to the presence of ettringite, monosulfate, and calcium hydroxide. Specially, the ettringite may fill the capillary pores and lead to the strength increase in the SHCC matrix [16]. However, Meddah et al. [23] reported that CSA-based EXA reduced the compressive strength of high-performance concrete due to the weak interfacial transition zone and micro cracks between hardened paste and ettringite. Cheung and Leung [15] showed that for high-strength ECC with w/b ratios of 0.19 and 0.21, CSA-based cement does not cause a reduction in compressive strength. In short, the effect of CSA-based EXA on the compressive strength is inconclusive. In compression, the SHCC30 and SC-SHCC30 mixtures showed lower elastic modulus values than the concrete due to the lack of coarse aggregate in the SHCC mixtures.

Table 3. Mechanical properties of concrete and SHCC materials, ( ) : standard deviation.

Material	Compression		Flexure		Tension	
	Strength (MPa)	Elastic Modulus (GPa)	Strength (MPa)	Displacement at Strength (mm)	Strength (MPa)	Strain at Strength (%)
Concrete	32.9(±1.80)	22.5(±1.85)	3.7(±0.36)	0.07(±0.02)	-	-
SHCC30	40.7(±3.21)	16.0(±2.64)	8.6(±2.09)	1.20(±0.36)	4.21(±0.82)	0.74(±0.05)
SC-SHCC30	44.3(±2.51)	16.0(±1.73)	11.6(±2.26)	1.13(±0.15)	5.29(±0.22)	037(±0.06)

Figure 3 presents a comparison of the average flexural stress versus central deflection curves of SHCC prismatic specimens in the presence and absence of EXA. Table 3 and Figure 3 both show the positive effects of replacing 10% cement binder with CSA-based EXA on the flexural strength of PE- and steel fiber-reinforced SHCC materials. Figure 3 shows that shrinkage-compensated SHCC with EXA has greater flexural strength and less ductility compared to conventional SHCC due to the improvement of the interfacial adhesion that is caused by the formation of crystalline ettringite at the interface between fibers and surrounding cement matrix [24]. Corinaldesi et al. [25] also reported the effectiveness of CaO-based EXA on the improvement of flexural strength.

Figure 4 presents the averaged direct tensile stress versus strain relationships and cracking procedures at the initial stage (designated as '(1)' throughout the figure) and the tensile strength (designated as '(2)') of representative dumbbell-shaped specimen for the SHCC30 and SC-SHCC30 mixtures. SHCC mixtures are similar to their flexural behavior in terms of strength and ductility. The cracking strength of the conventional SHCC is shown to be less than that of shrinkage-compensated SHCC. Table 3 shows that the averaged tensile strength value of each of the five dumbbell-shaped specimens for SC-SHCC30 mixture is 5.29 MPa, which is approximately 26% higher than that of the SHCC30 specimen. However, the SC-SHCC30 specimen shows less average tensile strain capacity compared to the SHCC30 specimen.

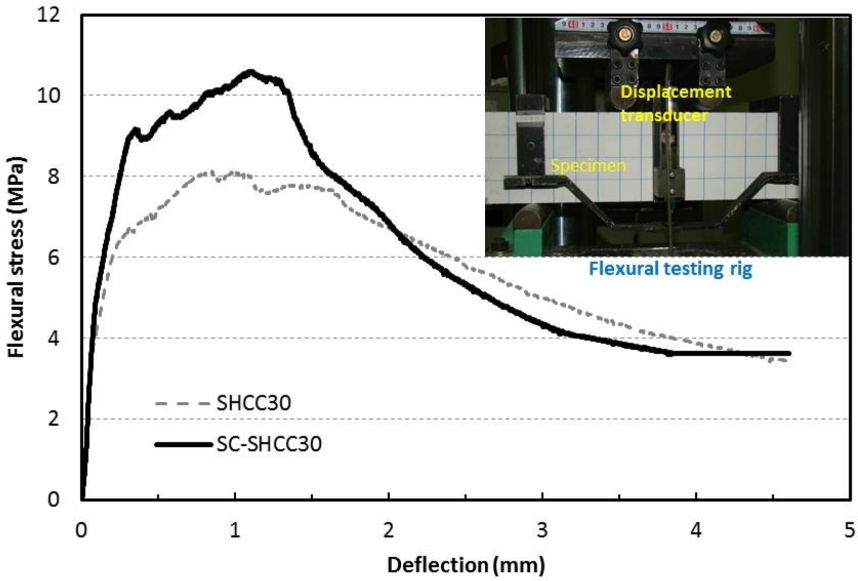


Figure 3. Flexural responses of SHCC prismatic specimens.

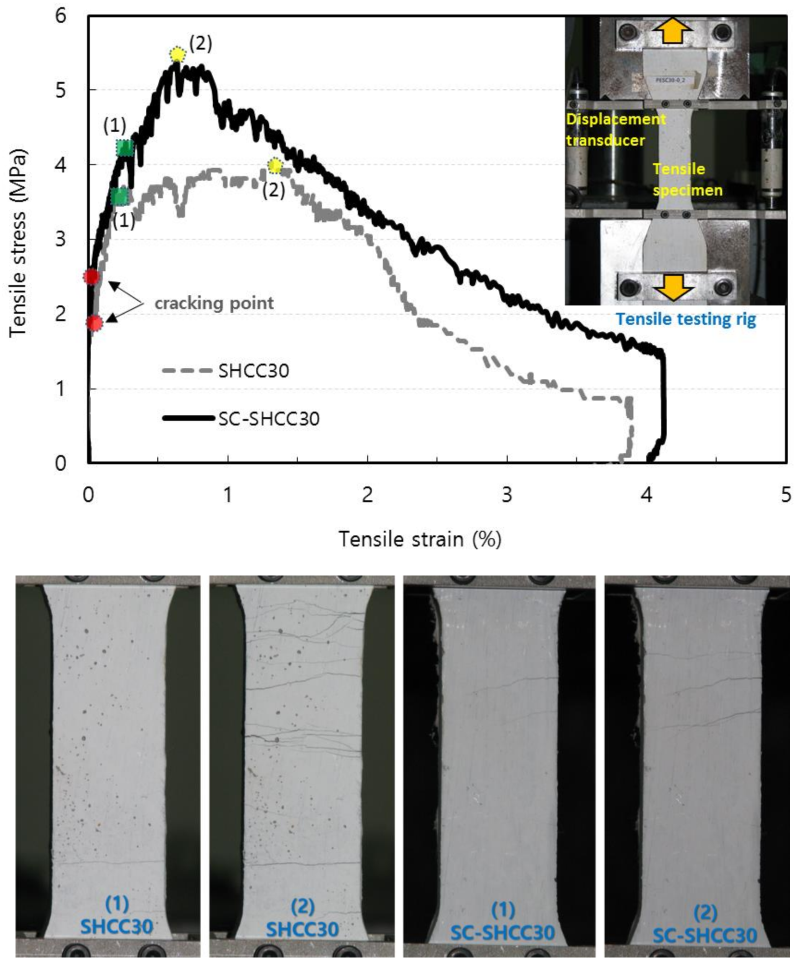
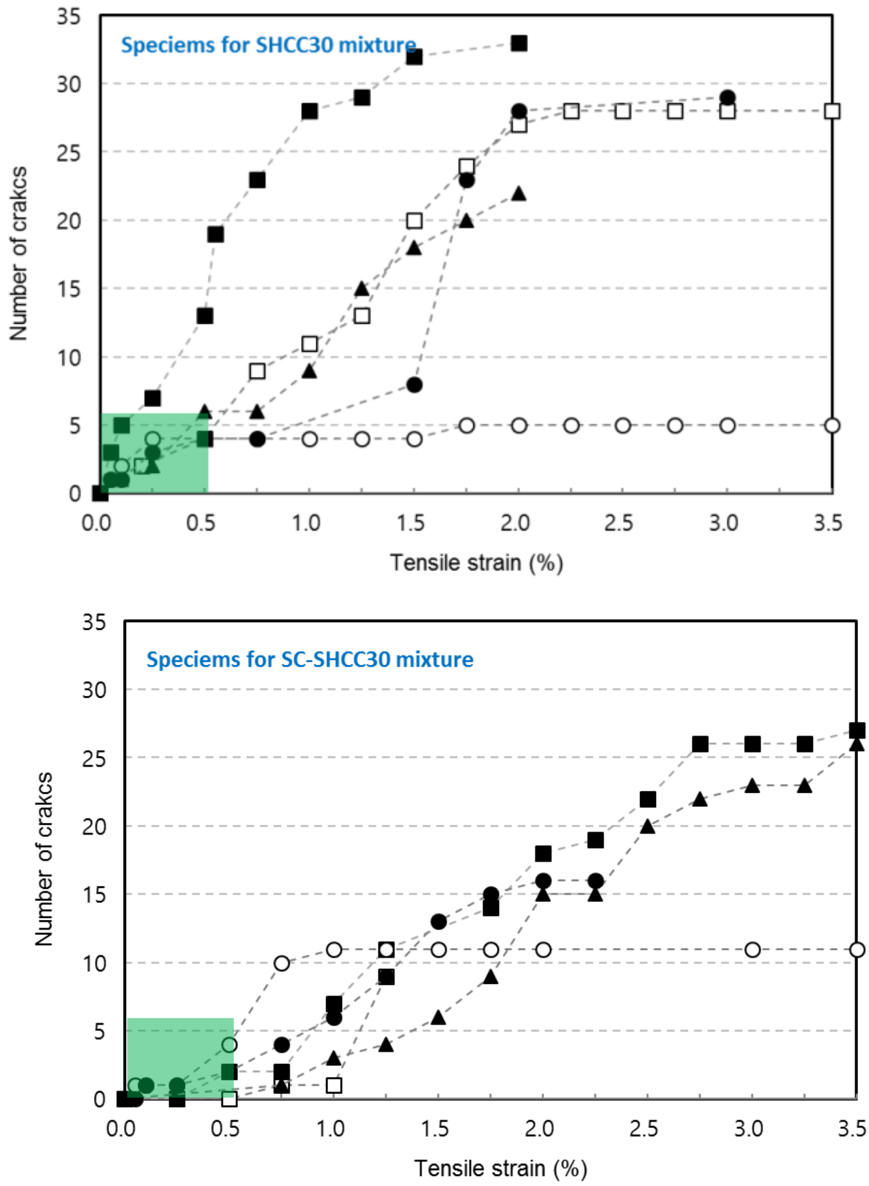


Figure 4. Tensile response (**top**) and cracking patterns (**bottom**) of SHCC dumbbell-shaped specimens.

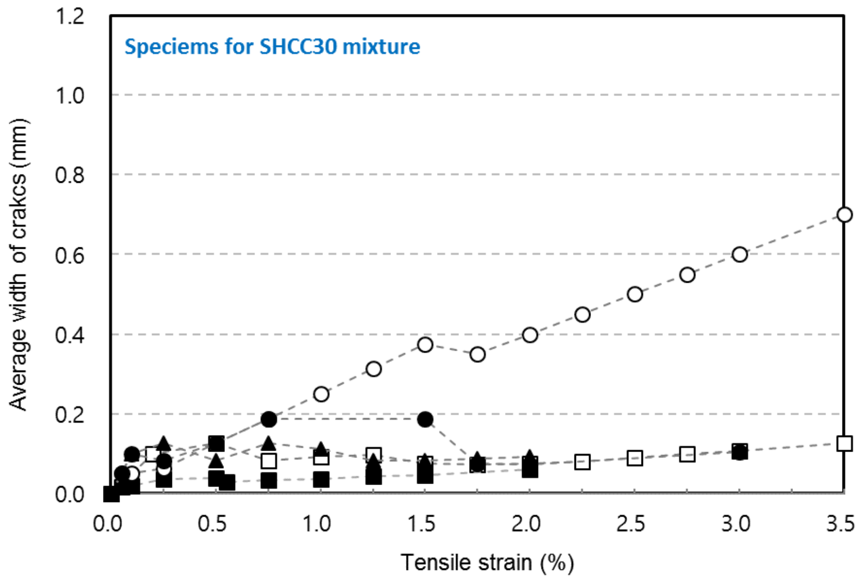
Figure 5a,b shows the number of cracks and average crack widths of the five dumbbell-shaped specimens for each SHCC mix, respectively. For the SHCC30 specimens, cracks occurred gradually from the initial loading stage whereas cracks in the SC-SHCC30 specimens started to increase after the tensile strain reached 0.5%. Although the average crack of the SC-SHCC30 specimen is wider than that of the SHCC30 specimen in the early loading stage, after the tensile strain of 1.0% is reached, the average crack widths for both SHCC mix specimens show slightly less than 0.2 mm.

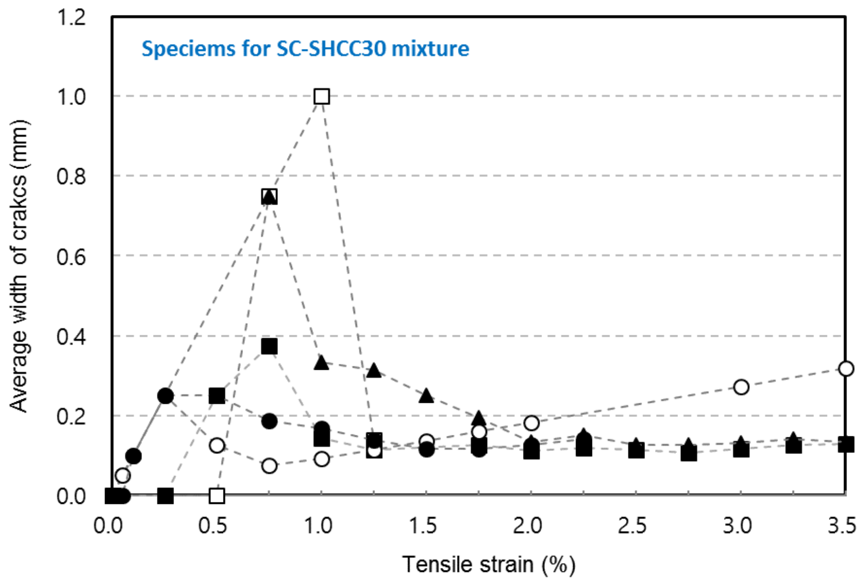
In sum, the results of the direct tensile tests indicate that the replacement of CSA-based EXA in SHCC mixtures leads to higher tensile cracking strength, higher tensile strength, and less tensile strain capacity. This result can be explained by the fact that, because the crystalline ettringite produced by CSA-based EXA fills the capillary pores and increase the SHCC volume, it compensates for the shrinkage and increases the bond strength between the fibers and cement matrix. Ultimately, this phenomenon results in the improvement of cracking behavior in the early loading stages and the enhancement of tensile strength.



(**a**)

Figure 5. *Cont.*





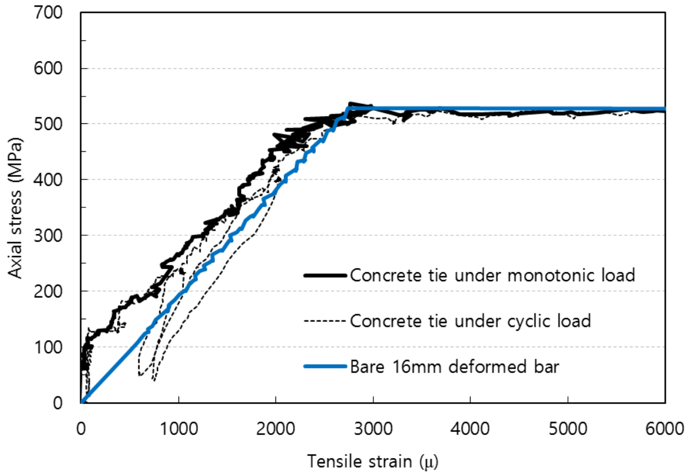
(**b**)

Figure 5. Cracking characteristics of SHCC dumbbell-shaped specimens in direct tension. (**a**) Crack number of dumbbell-shaped specimens in direct tension; (**b**) Average crack width of dumbbell-shaped specimens in direct tension.

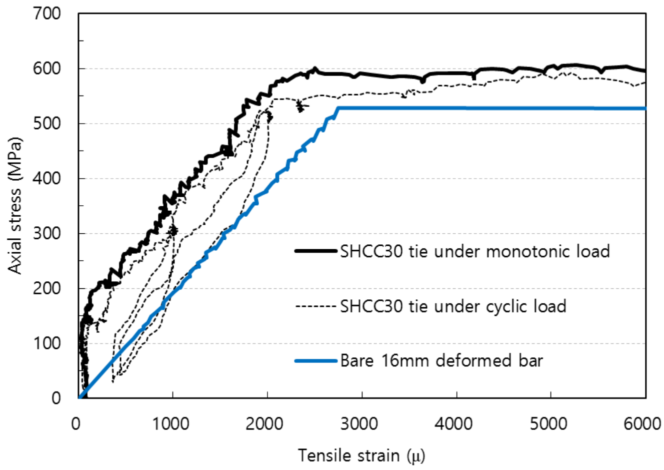
3.2. Tensile and Cracking Behaviors of Reinforced SHCC Tension Ties

To investigate the effects of shrinkage compensation and loading method on the tensile behavior and cracking patterns of RC and SHCC tension ties, two concrete and four SHCC tension ties were prepared and tested to failure. The axial stress of each of the tie specimens was calculated by dividing the applied tensile force by the nominal area of 16 mm rebar. The average tensile strain in the tie specimens was obtained by dividing the average displacement measured by two dial gauges by the gauge length.

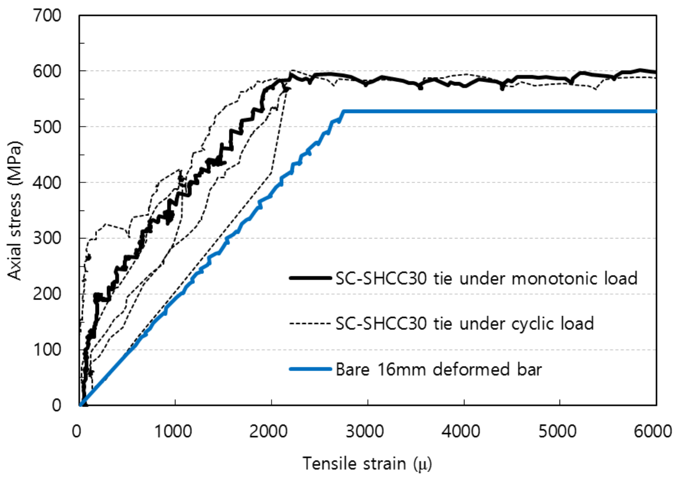
Figure 6 presents the tensile stress and average tensile strain relationships of RC and SHCC tension ties up to 6000 μ. The figure also included also the tensile stress versus strain curves of bare rebar. For all the tie specimens, the tensile response is linear in the initial loading stage prior to the cracking of the cement matrix. Figure 6 also shows that the tensile stiffness of all the tie specimens before the formation of transverse cracks is much greater than that of bare rebar.



(**a**)



(**b**)



(**c**)

Figure 6. Axial stress versus strain curves of tension ties under monotonic and cyclic load. (**a**) Concrete tension ties; (**b**) SHCC30 tension ties; (**c**) SC-SHCC30 tension ties.

The average cracking strength values for the concrete, SHCC30, and SC-SHCC30 ties under monotonic and cyclic loadings are approximately 115, 135, and 243 MPa, respectively. The shrinkage compensation in the SHCC matrix caused by the CSA-based EXA prevented shrinkage cracks and led to an increase in the cracking strength of the reinforced SHCC tension ties, as shown in SHCC dumbbell-shaped specimens. Figure 6a shows that, beyond the cracking strength, the concrete ties experienced a gradual reduction in the tensile stiffness; this phenomenon is remarkable for a specimen under cyclic loading. Figure 6a shows that, as the tensile strain increases, the tensile response of the RC ties becomes like that of bare rebar. The tensile behaviors of the reinforced SHCC ties with or without EXA are almost identical in that, as the axial displacement increases after the initial crack, the tension-stiffening effect does not decrease up to yielding, as shown in Figure 6b,c. Figure 6 shows that, after the initial crack, the reinforced SHCC ties exhibit improved tension stiffening performance compared to the conventional concrete ties in monotonic and cyclic tension. This outcome may be due to the contribution of PE microfibers in bridging the micro cracks and of the steel macro fibers in resisting the tensile stresses across the macro cracks [26,27].

Figure 7 shows the local strain behavior of the rebar in the SHCC and SC-SHCC ties under monotonic loading. The tensile strain behavior of the SHCC30 tie at the first crack stage is not as obvious as that of the SC-SHCC30 tie due to the shrinkage-induced cracks that already had appeared. Fischer and Li [28] also reported this phenomenon for reinforced ECC ties. The test results suggest that the utilization of EXA in SHCC matrix with rich mixture may help control shrinkage-induced cracks and improve the tension-stiffening effect at the initial loading stage prior to cracking.

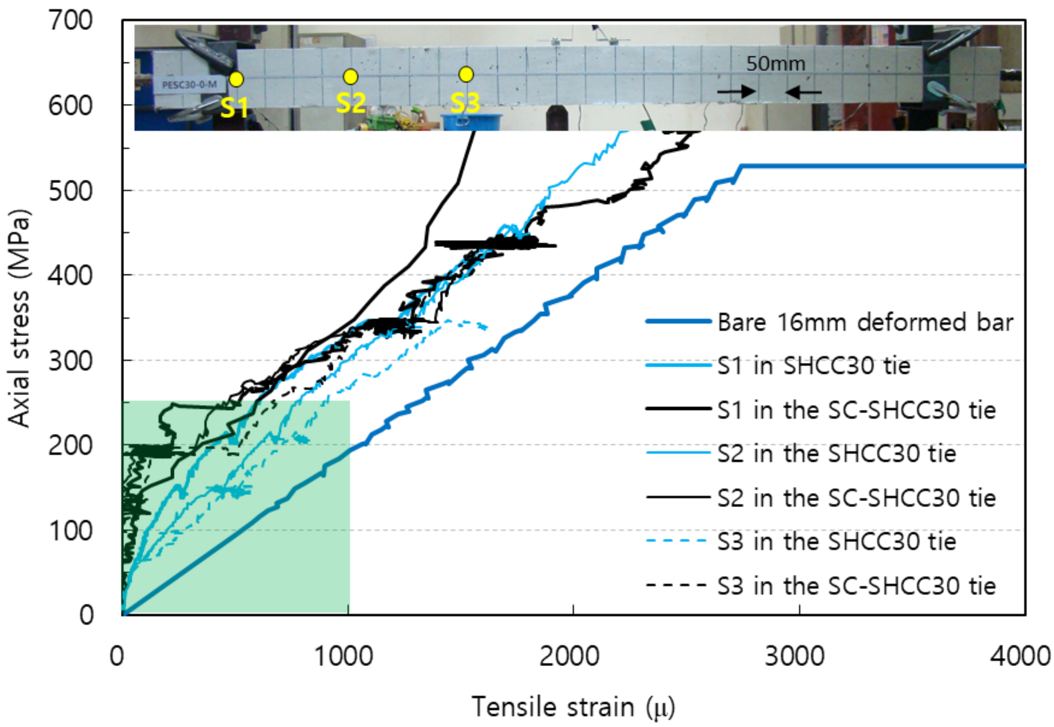


Figure 7. Axial stress versus local strain curves of rebar in ties under monotonic load.

Figure 8 presents a comparison of the representative crack patterns in the gauge length of the RC and SHCC tension ties. The first transverse crack is shown to appear near the center of the gauge length for all the tie specimens. However, as the tensile load increases, the cracking processes in the ties show significantly different trends according to the loading method and matrix type. For the RC ties, the initial crack widens and additional cracks appear up to yield whereas the SHCC ties exhibit multiple cracking characteristics until the localization of several multiple cracks. Table 4 provides the cracking properties of all the tie specimens at yield. The SC-SHCC30 ties show greater cracking strength than the SHCC30 ties. The yield strength of the concrete tie is approximately equal to that of bare rebar, whereas the SHCC ties show on average 13% higher yield strength and tension stiffening even after the rebar yielded due to the fibers bridging the cracks. Figure 8 shows that the multiple cracking behavior is especially noticeable for the SC-SHCC30 tie, regardless of loading method. Table 4 presents the cracking characteristics of the concrete and SHCC tension ties.

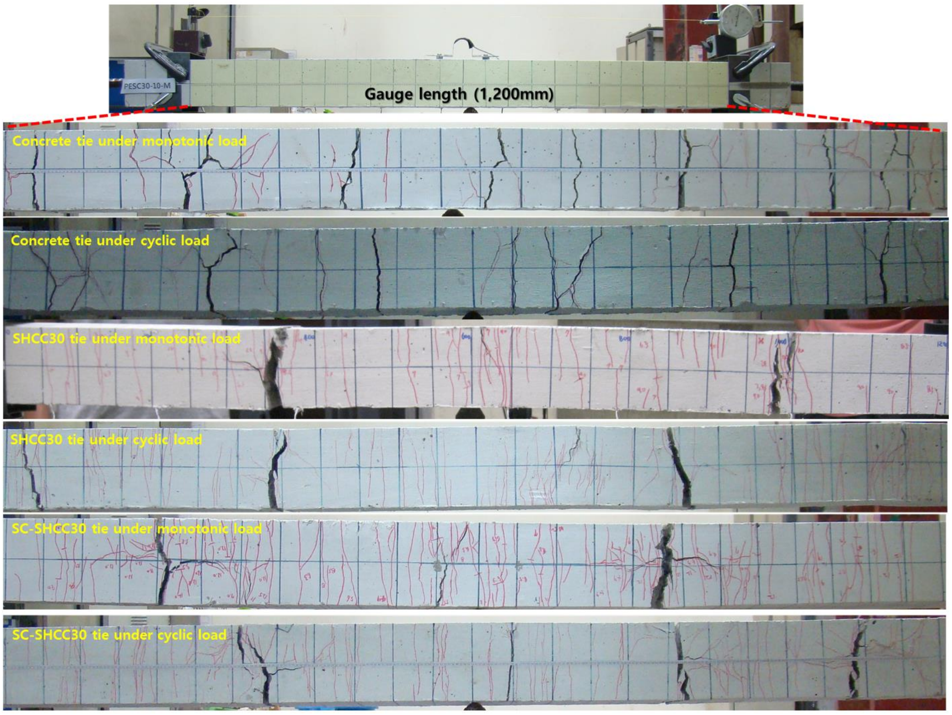


Figure 8. Failure modes of concrete and SHCC material tension ties.

Table 4. Cracking behavior of concrete and SHCC tension ties.

Material	Loading Method	Cracking Strength (MPa)	Yield Strength (MPa)	No. of Transverse Cracks at Yielding	Average Crack Spacing at Yielding [1] (mm)
Concrete	Monotonic	106.1	527.6	9	133.3
	Cyclic	123.8	514.8	9	133.3
SHCC30	Monotonic	132.9	600.5	45	26.6
	Cyclic	136.6	544.3	38	31.5
SC-SHCC30	Monotonic	191.6	592.8	47	25.5
	Cyclic	295.3	584.1	41	29.3

[1] Average crack spacing at yielding = length of central region of specimen (1200 mm)/No. of transverse cracks at yielding.

4. Conclusions

To investigate the effects of shrinkage compensation on the mechanical and cracking behavior of SHCC with rich mixture, tests were carried out in this study to examine shrinkage, compressive strength, flexural strength, and the direct tensile strength of conventional and shrinkage-compensating SHCC materials for durable infrastructures. Also, the tensile and cracking behaviors of RC, conventional SHCC (SHCC30), and shrinkage-compensating SHCC (SC-SHCC30) ties under monotonic and cyclic loading was examined. Based on this study, the following conclusions can be drawn;

(1) For the SC-SHCC30 mixture, shrinkage strain at 28 days was approximately 32% less than that of the SHCC30 mixture. The replacement of a part of the Portland cement binder by CSA-based EXA appears to be an effective alternative for compensating for the shrinkage of PE and steel fiber-reinforced SHCC materials with rich mixture under drying conditions.

(2) A comparison of the SHCC30 and SC-SHCC30 mixtures shows an effective increase in compressive strength, flexural strength, and direct tensile strength by 9%, 35%, and 26%,

respectively. The replacement of CSA-based EXA in SHCC materials with rich mixture can significantly enhance the mechanical performance, specifically the flexural and direct tensile strength, of SHCC.

(3) The dispersion of fine cracks in the SC-SHCC30 dumbbell-shaped specimens and the performance of ties reinforced with rebar in direct tension were improved. Specifically, the occurrence of initial cracks at the early-loading stage was delayed because the EXA reduced both the shrinkage strain and the tensile stress induced in the SHCC matrix during early-age curing.

(4) For the SHCC reinforced tie specimens in monotonic and cyclic tension, the addition of CSA-based EXA increased cracking strength and improved the tension-stiffening effect at early loading. The tension-stiffening effect showed little difference between the SHCC30 and SC-SHCC30 ties, but multiple cracking was significant in the SC-SHCC30 tie and in ties under monotonic tension.

(5) Ultimately, the use of conventional SHCC material, which is susceptible to shrinkage cracking, and shrinkage compensation obtained by replacing cement binder with CSA-based EXA may significantly improve the durability and mechanical properties of SHCC by mitigating early-age shrinkage strain and enhancing multiple cracking characteristics.

Author Contributions: H.-D.Y. and W.-S.P. contributed to the project idea development and experimental design, and S.-W.K., S.-J.J. and J.-H. K performed the experiment and data analysis. H.-D.Y. and W.-S.P. reviewed the final manuscript and contributed to the results, discussion, and conclusions.

Funding: This research was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea Government (MSIT) (No. 2018R1A4A1025953).

Conflicts of Interest: The authors declare that there is no conflict of interests regarding the publication of this article.

References

1. Gruber, K.A.; Ramlochan, T.; Boddy, A.; Hooton, R.D.; Thomas MD, A. Increasing concrete durability with high-reactivity metakaolin. *Cem. Concr. Compos.* **2001**, *23*, 479–484. [CrossRef]
2. Almusallam, A.A.; Khan, F.M.; Dulaijan, S.U.; Al-Amoudi OS, B. Effectiveness of surface coatings in improving concrete durability. *Cem. Concr. Compos.* **2003**, *25*, 473–481. [CrossRef]
3. Alexander, M.G.; Magee, B.J. Durability performance of concrete containing condensed silica fume. *Cem. Concr. Res.* **1999**, *29*, 917–922. [CrossRef]
4. Söylev, T.A.; Richardson, M.G. Corrosion inhibitors for steel in concrete: State-of-the-art report. *Constr. Build. Mater.* **2008**, *22*, 609–622. [CrossRef]
5. Naaman, A.E. Characterization of high performance fiber reinforced cement composites-HPFRCC. In: Naaman AE, Reinhardt HW, co-editors. Proceeding of second international symposium on high performance fiber reinforced cementitious composites; 1996; Ann Arbor; MI in RILEM PROCEEDING, 31; E&FN Spon. 1–24.
6. Li, V.C. On engineered cementitious composites (ECC). *J. Adv. Concr. Technol.* **2003**, *1*, 215–230. [CrossRef]
7. Yun, H.D. Flexural behavior and crack-damage mitigation of plain concrete beam with a strain-hardening cement composite (SHCC) layer at tensile region. *Compos. Part B Eng.* **2013**, *45*, 377–387. [CrossRef]
8. Ahmed SF, U.; Mihashi, H. A review on durability properties of strain hardening fibre reinforced cementitious composites (SHFRCC). *Cem. Concr. Compos.* **2007**, *29*, 365–376. [CrossRef]
9. Kobayashi, K.; Kojima, Y. Effect of fine crack width and water cement ratio of SHCC on chloride ingress and rebar corrosion. *Cem. Concr. Compos.* **2017**, *80*, 235–244. [CrossRef]
10. Van Zijl, G.P.; Wittmann, F.H.; Oh, B.H.; Kabele, P.; Toledo Filho, R.D.; Fairbairn, E.M.; Slowik, V.; Ogawa, A.; Hoshiro, H.; Mechtcherine, V.; Altmann, F.; Lepech, M.D. Durability of strain-hardening cement-based composites (SHCC). *Mater. Struct.* **2012**, *45*, 1447–1463. [CrossRef]
11. Choi, W.C.; Yun, H.D.; Cho, C.G.; Feo, L. Attempts to apply high performance fiber-reinforced cement composite (HPFRCC) to infrastructures in South Korea. *Compos. Struct.* **2014**, *109*, 211–223. [CrossRef]
12. Şahmaran, M.; Lachemi, M.; Hossain, K.M.; Li, V.C. Internal curing of engineered cementitious composites for prevention of early age autogenous shrinkage cracking. *Cem. Concr. Res.* **2009**, *39*, 893–901. [CrossRef]

13. Zhang, J.; Gong, C.; Guo, Z.; Zhang, M. Engineered cementitious composite with characteristic of low drying shrinkage. *Cem. Concr. Res.* **2009**, *39*, 303–312. [CrossRef]
14. Wang, J.Y.; Banthia, N.; Zhang, M.H. Effect of shrinkage reducing admixture on flexural behaviors of fiber reinforced cementitious composites. *Cem. Concr. Compos.* **2012**, *34*, 443–450. [CrossRef]
15. Cheung, A.K.; Leung, C.K. Shrinkage reduction of high strength fiber reinforced cementitious composites (HSFRCC) with various water-to-binder ratios. *Cem. Concr. Compos.* **2011**, *33*, 661–667. [CrossRef]
16. Choi, W.C.; Yun, H.D. Effect of expansive admixtures on the shrinkage and mechanical properties of high-performance fiber-reinforced cement composites. *Sci. World J.* **2013**, *2013*, 418734. [CrossRef] [PubMed]
17. Korea Agency for Technology and Standards. *Korean Industrial Standards*; Korea Agency for Technology and Standards: Seoul, Korea, 2017. Available online: https://kssn.net/en/ (accessed on 8 March 2019).
18. Nagataki, S.; Gomi, H. Expansive admixtures (mainly ettringite). *Cem. Concr. Compos.* **1998**, *20*, 163–170. [CrossRef]
19. Japan Society of Civil Engineers. Recommendation for design and construction of high performance fiber reinforced cement composites with multiple fine cracks (HPFRCC). *Concr. Eng. Ser.* **2008**, *82*, 104.
20. Neville, A.M. *Properties of Concrete*; Longman: London, UK, 1995; Volume 4.
21. Li, M.; Li, V.C. Behavior of ECC/Concrete Layered Repair System Under Drying Shrinkage Conditions. *Restor. Build. Monum.* **2006**, *12*, 143–160.
22. Yang, E.H.; Yang, Y.; Li, V.C. Use of high volumes of fly ash to improve ECC mechanical properties and material greenness. *ACI Mater. J.* **2007**, *104*, 620–628.
23. Meddah, M.S.; Suzuki, M.; Sato, R. Influence of a combination of expansive and shrinkage-reducing admixture on autogenous deformation and self-stress of silica fume high-performance concrete. *Constr. Build. Mater.* **2011**, *25*, 239–250. [CrossRef]
24. Maltese, C.; Pistolesi, C.; Lolli, A.; Bravo, A.; Cerulli, T.; Salvioni, D. Combined effect of expansive and shrinkage reducing admixtures to obtain stable and durable mortars. *Cem. Concr. Res.* **2005**, *35*, 2244–2251. [CrossRef]
25. Corinaldesi, V.; Nardinocchi, A.; Donnini, J. The influence of expansive agent on the performance of fibre reinforced cement-based composites. *Constr. Build. Mater.* **2015**, *91*, 171–179. [CrossRef]
26. Moreno, D.M.; Trono, W.; Jen, G.; Ostertag, C.; Billington, S.L. Tension stiffening in reinforced high performance fiber reinforced cement-based composites. *Cem. Concr. Compos.* **2014**, *50*, 36–46. [CrossRef]
27. Ganesan, N.; Indira, P.V.; Sabeena, M.V. Tension Stiffening and Cracking of Hybrid Fiber-Reinforced Concrete. *ACI Mater. J.* **2013**, *110*, 715–721.
28. Fischer, G.; Li, V.C. Influence of matrix ductility on tension-stiffening behavior of steel reinforced engineered cementitious composites (ECC). *Struct. J.* **2002**, *99*, 104–111.