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Research Article

Effects of Shrinkage-Compensation on Mechanical Properties and Repair Performance of Strain-Hardening Cement Composite Materials

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This paper describes the effects of expansive admixture on the mechanical properties of strain-hardening cement-based composite (SHCC) mixtures. Also, this study investigates structural performance of reinforced concrete (RC) beam specimens repaired with SHCC and Ex-SHCC (SHCC with expansive admixture). In this study, SHCC and Ex-SHCC mixtures with two specified compressive strength values of 30 MPa and 60 MPa and the fiber volume fraction of 1.5% were investigated. The expansive admixture replacement ratio of 10% by cement weight was used in this study. The test results indicate that the compressive, tensile, and flexural strength values of the SHCC mixtures increased when expansive admixture was included in the mix; however, their toughness and ductility decreased. The study results also show that the application of both SHCC and Ex-SHCC mixtures to repair damaged RC beam specimens can lead to significant structural performance improvement by mitigating crack damage and increasing ductility.

1. Introduction

Wide surface cracks are known to accelerate the corrosion and further the degradation of steel reinforcing bar (rebar) by allowing moisture, oxygen, and carbon dioxide into the cement composite. Over the past several decades, researchers have investigated numerous applications of strain-hardening cement-based composite (SHCC) materials to try to improve the ductility and durability of reinforced concrete (RC) structures [1, 2]. The addition of synthetic fiber to cementitious composites that exhibit multiple cracking and strain-hardening behavior under uniaxial tensile loading can improve the toughness and ductility of these materials [3], which are referred to not only as SHCC materials, but also include engineered cementitious composite (ECC) materials and high-performance fiber-reinforced cement composite (HPFRCC) materials. To ensure good structural performance of fiber-reinforced cementitious composite (FRCC) materials, especially when they are applied to help repair damaged RC structures, a rich binder composite without coarse aggregate is required to reduce the fracture energy at the first-crack stage. However, mixtures with rich binders can lead to high levels of shrinkage and cracks.

In order to address this potential problem, some researchers have attempted to reduce the shrinkage of FRCC materials by incorporating shrinkage-reducing admixture (SRA) and expansive materials in the mix. For example, Maltese et al. [4] investigated the effects of both expansive and shrinkage-reducing admixtures to improve the dimensional stability of cement-based mortar and concluded that such admixtures are effective in reducing shrinkage. Cheung and Leung [5] examined the shrinkage properties of high-strength FRCC with various water-to-binder ratios. They found that the use of sulfoaluminate cement (SAC) to replace Portland cement can lead to

Table 1: Mix proportions of SHCC and Ex-SHCC mixtures.

Mixture ID	W/B (%)	Ex-Rep. ratio[1] (%)	Fiber volume (%)	Unit weight (kg/m^3)						
				Cement	Water	Sand	Ex[2]	PE[3]	MC[4]	SP[5]
SHCC30	45	0	1.5	1075	484	430	0	14	0.5	9.6
SHCC60	30	0	1.5	1281	384	513	0	14	0.5	13.3
Ex-SHCC30	45	10	1.5	968	484	430	107	14	0.5	9.6
Ex-SHCC60	30	10	1.5	1149	384	513	128	14	0.5	13.3

[1]Replacment ratio of expansive admixture; [2]expansive admixture; [3]polyethylene fiber; [4]methyl cellulose; [5]superplasticizer.

Table 2: Chemical components of cement and expansive admixture.

	Specific gravity	Blaine fineness (cm^2/g)	Chemical composition (%)						
			SiO	Al_2O	Fe_2O_3	CaO	MgO	SO_3	Loss of ignition
Cement	45	0	21.15	5.10	3.48	63.29	2.65	2.48	1.68
CSA-Ex	30	10	1.48	13.10	0.60	47.80	0.50	32.27	—

shrinkage reduction and that the combined use of SAC and SRA is even more effective in reducing shrinkage. Choi and Yun [6] investigated the effects of expansive admixture on the shrinkage and mechanical properties of HPFRCC materials. Their test results indicate that replacing cement with calcium sulfoaluminate- (CSA-) based expansive admixture is an effective method to mitigate shrinkage. Moreover, Choi and Yun [6] found that replacements of 10% CSA-K can considerably enhance the mechanical properties and reduce shrinkage of HPFRCC materials.

Yun et al. [7] tested the ability of one-way slabs with an SHCC layer to mitigate crack damage and improve the durability of RC slabs. Their test results showed that conventional RC slabs failed with only a few wide cracks. However, the RC slabs with an SHCC material layer at the bottom of the slabs significantly mitigated cracking and exhibited multiple fine cracks instead of wide cracks. Kobayashi and Rokugo [8] proposed the use of a HPFRCC layer to repair RC members damaged by chloride. They reported that rebar corrosion could be recovered for specimens that exhibited less than 10% corrosion by including a HPFRCC layer. Li et al. [9] investigated the structural performance of HPFRCC when used to repair damaged RC columns under 85% load capacity. Their test results showed that the RC columns that were repaired using HPFRCC improved the columns' load-carrying capacity and ductility better than conventional RC columns. The difference in shrinkage between the concrete and the SHCC can lead to bond failure. Thus, including expansive admixture in the SHCC material is effective because the shrinkage of SHCC is greater than that of conventional concrete.

Building on previous work found in the literature, this study investigated the effects of replacing cement with 10% CSA-based expansive admixture on the mechanical properties of SHCC materials with two different compressive strength values of 30 MPa and 60 MPa. Specifically, this study investigated RC beams that were repaired using SHCC material with and without CSA-based expansive admixture to evaluate the effects of expansive admixture on the structural performance of repaired RC beams.

2. Experimental Design

2.1. Materials. Table 1 shows the composition of the SHCC and Ex-SHCC mixtures used in this study. Both mixture types were tested with specified compressive strength values of 30 MPa and 60 MPa. Polyethylene (PE) fiber of 1.5% volume fraction was added and mixed for each SHCC and Ex-SHCC mixtures. CSA-based expansive admixture with 10% replacement of the cement weight was used for the Ex-SHCC mixtures.

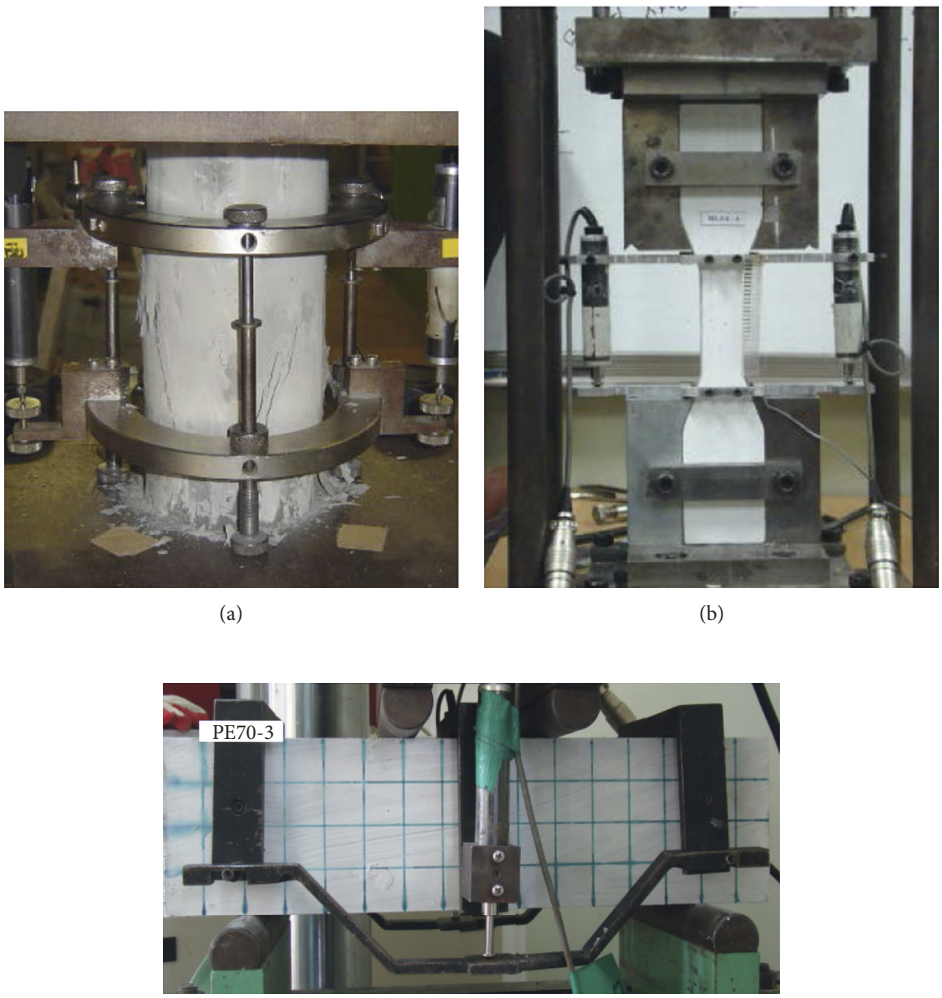
The cement used in this study was Type I Portland cement made in South Korea; this cement was made in a similar manner as recommended in American Society of Testing and Materials (ASTM) C150 [10] (i.e., specific gravity of 3.15 and fineness of 3300 cm^2/g). The CSA-based expansive admixture that was used in this study had a specific gravity of 2.9 and fineness of 3350 cm^2/g. Table 2 presents the chemical compositions and physical properties of the cement and CSA expansive admixture used in this study. Silica sand with a specific gravity of 2.61 and grain sizes ranging from 105 μm to 120 μm were used for the mixtures. The PE fibers were manufactured with an aspect ratio (length/diameter) of 12.0, elastic modulus of 75 GPa, and tensile strength of 2500 MPa, as shown in Table 3.

All mixtures were fabricated in the laboratory using a fan-type mixer. First, silica sand and cement were mixed for one minute. Then, water was added and the mixture was stirred for a few minutes to form the mortar mixture. Next, the PE fiber was added to the mixed mortar and mixed in for three minutes.

2.2. Test Methods for Mechanical Properties. To evaluate the actual mechanical properties of the SHCC and Ex-SHCC mixtures, cylindrical, dumbbell-shaped, and prismatic

Table 3: Mechanical properties of polyethylene fiber.

Fiber	Specific gravity (kg/m^3)	Length (mm)	Diameter (μm)	Aspect ratio (length/diameter)	Tensile strength (MPa)	Elastic modulus (MPa)
Polyethylene	0.97	15	12	1,250	2500	75



(a) (b) (c)

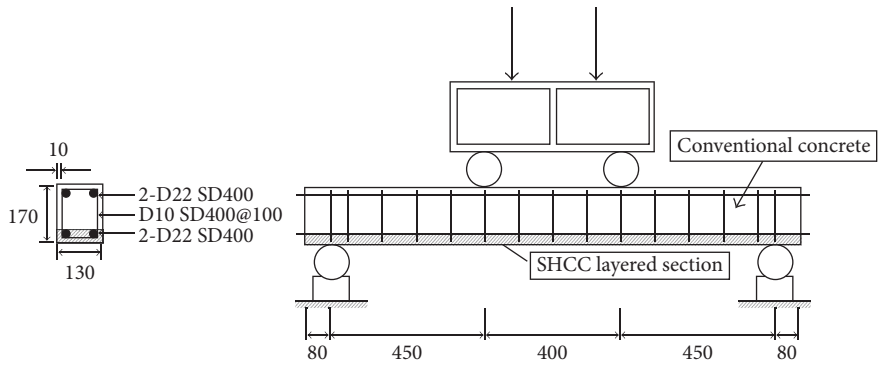
Figure 1: Test setups for mechanical properties. (a) Compression test. (b) Direct tensile test. (c) Flexural test.

specimens were prepared and tested for each mixture. Figure 1(a) shows the compression test setup that was used to evaluate the specimens' compressive behavior in accordance with ASTM C39 [11]. Three cylinders (ϕ100 mm × 200 mm) were tested on each day of curing using a universal testing machine with 2000 kN load capacity. The compressive strain was obtained from two linear variable displacement transducers (LVDTs) surrounding the cylindrical specimen.

Direct tensile tests were conducted as per Japan Society of Civil Engineers (JSCE) E-51 [12]; Figure 1(b) shows the test setup. Dumbbell-shaped specimens were fabricated, each with a cross section of 30 mm × 30 mm and length of 100 mm. Two LVDTs were installed to measure the tensile strain in the middle of each specimen.

Figure 1(c) shows the flexural test setup as per ASTM C1609 [13]. Prismatic specimens (100 mm × 100 mm × 400 mm) were fabricated to evaluate the flexural properties of the SHCC and Ex-SHCC Mixtures. The flexural tests were conducted under third-point loading, and a yoke with two LVDTs was used to measure the entire vertical deflection at the mid-span.

2.3. Configuration of Beam Specimens Repaired with SHCC and Ex-SHCC Mixtures. To evaluate the effects of SHCC/Ex-SHCC mixtures as repair material on RC beam specimens, small-scale RC beam specimens (1460 mm in length and rectangular cross section of 130 mm × 170 mm) were fabricated. Figure 2(a) illustrates the configuration and



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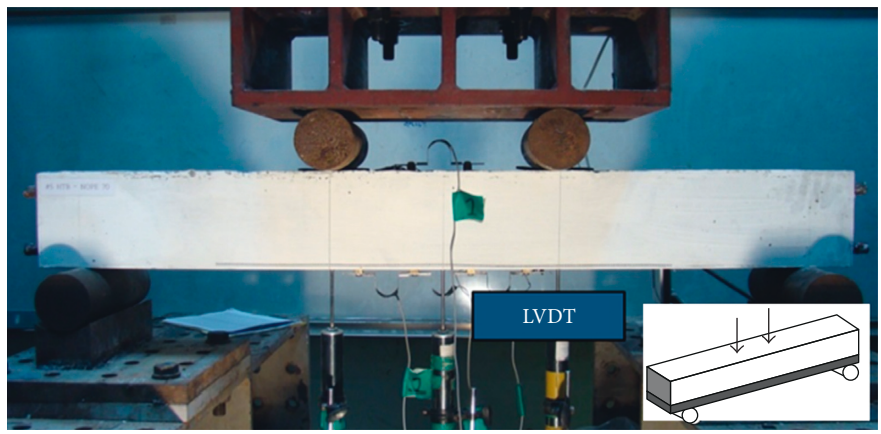


(b)

Figure 2: Details of specimen and test setup for structural performance tests. (a) Configuration and reinforcement details (mm). (b) Test setup for four-point bending.

Table 4: Summary of reinforced concrete beam specimens.

Specimens	Composite type	Width × depth × span length (mm × mm × mm)	Layer thickness (mm)
RC	Concrete	130 × 170 × 1300	0
RC-R (SHCC30)	Concrete + SHCC30		40
RC-R (Ex-SHCC30)	Concrete + Ex-SHCC30		

reinforcement details of the beam repair system employed for a layered RC beam section for structural performance testing.

For the conventional RC beam specimen (used as the control specimen), first the sand and coarse aggregate were mixed for one minute. Next, the cement was added and mixing was continued for another minute. Then, water was added to hydrate the cement for two to three minutes. This conventional concrete had an averaged compressive strength value of 33.7 (±2.1) MPa at 28 days. The yield strength and ultimate strength values of the steel rebar were 404.08 (±8.41) MPa and 624.44 (±22.15) MPa, respectively, with the nominal diameter of 22 mm (D22). To prevent the undesired shear failure of the RC beam, transverse reinforcement was included that consisted of 10 mm nominal diameter (D10) rebar at 100 mm spacing. SHCC30 and Ex-SHCC30 mixtures were layered with a total thickness of 40 mm at the bottom of two additional RC beam specimens. These SHCC and Ex-SHCC mixtures were cast onto the section after one day. Table 4 presents a summary of the RC beam specimens with the SHCC and Ex-SHCC mixtures added to the concrete for structural repair (designated as "R" for "repaired" in the specimen ID).

2.4. Test Setup for Repaired RC Beam Specimens. All of the repaired RC beam specimens ("RC-R") were tested using a 500 kN load capacity hydraulic actuator that was fixed to a reaction steel frame. Each beam was simply supported on rollers while the load-transfer frame was used to apply two-point loads. The specimens each had a net span of 1300 mm and shear span of 450 mm. To measure the vertical deflection of the beams, an LVDT was installed at the center of the bottom of the slab, as shown in Figure 2(b). The tensile crack

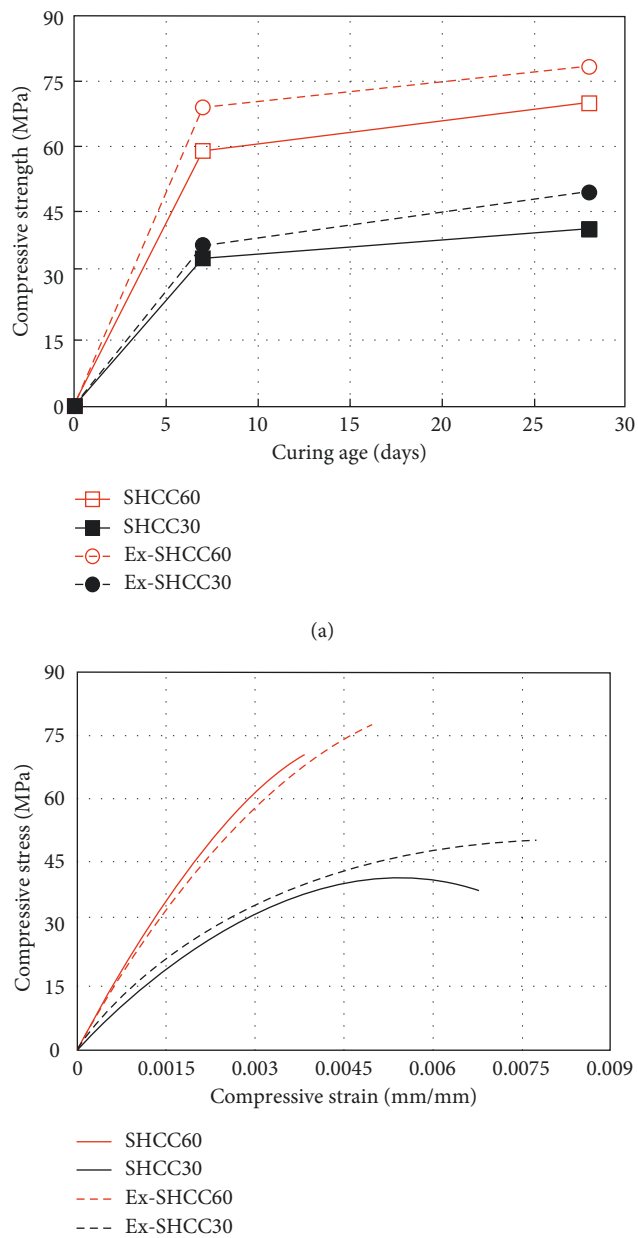


Figure 3: Effects of expansive admixture on compressive properties of SHCC and Ex-SHCC mixtures. (a) Effects of curing age on compressive strength. (b) Compressive response of SHCC and Ex-SHCC mixtures.

formation in terms of number and width of the cracks was observed using a 60x microscope over the 800 mm length at the center of the specimen.

3. Test Results and Discussion

3.1. Compressive Strength of Cement Composite. Figure 3(a) presents the effects of curing duration on the compressive strength of the SHCC and Ex-SHCC mixtures. The compressive strength progression for all the mixtures indicates a rapid increase up to seven days of curing and then a steady moderate increase up to 28 days of curing. The Ex-SHCC mixtures show greater compressive strength than those without expansive admixture at all curing times. Figure 3(b) shows the effects of the inclusion (and exclusion) of expansive admixture on typical strain-stress relationships (curves) of the mixtures under compressive loading. The inclusion of the expansive admixture does not have a significant effect on the initial behavior and modulus of elasticity for both the normal- and high-strength SHCC mixtures. On the other hand, both Figures 3(a) and 3(b) show that the compressive strength and strain values increase at the peak stress with the inclusion of expansive admixture.

3.2. Direct Tensile Behavior of SHCC and Ex-SHCC Mixtures. Figure 4 shows the direct tensile responses of

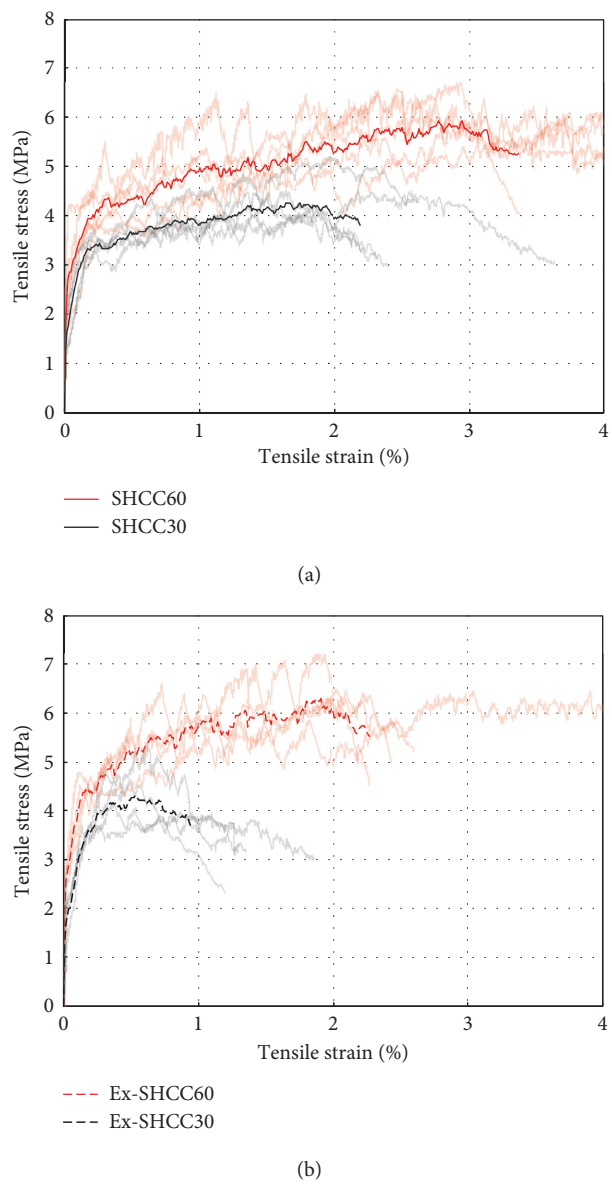


Figure 4: Effects of expansive admixture on tensile responses of SHCC and Ex-SHCC mixtures. (a) SHCC mixtures. (b) Ex-SHCC mixtures.

the SHCC and Ex-SHCC mixtures as obtained from five or four dumbbell-shaped specimens, respectively. The SHCC30 specimens show the first-crack strength and tensile strength averaged values of 1.22 (±0.18) MPa and 4.49 (±0.42) MPa, respectively. The average tensile strain at peak stress is 1.86% (±0.20%). The Ex-SHCC30 specimens (SHCC30 with 10% replacement of CSA-based expansive admixture), however, show the first-crack strength, tensile strength, and strain values at averaged tensile strength values of 1.20 (±0.10) MPa, 4.54 (±0.51) MPa, and 0.58% (±0.18%) MPa, respectively. Thus, including CSA-based expansive admixture in SHCC mixtures can lead to an increase in the first-crack and tensile strength values.

Similar results also can be observed for the tensile responses of the SHCC and Ex-SHCC mixtures with the specified compressive strength of 60 MPa. The first-crack strength values of the SHCC60 and Ex-SHCC60 mixtures are 1.77 (±0.46) MPa and 2.57 (±0.35) MPa, respectively. The tensile strength values are 6.27 (±0.38) MPa and 6.60 (±0.36) MPa, respectively. However, the SHCC mixtures with expansive admixture tend to have less tensile strain capacity compared to those without expansive admixture. The strain capacity values at the tensile strength of the SHCC60 and Ex-SHCC60 mixtures are 3.49% (±0.89%) and 2.29% (±0.44%), respectively.

Figure 5 shows typical crack patterns on the dumbbell-shaped specimens after the direct tensile tests. All of the specimens exhibit multiple cracking characteristics and fiber bridge action. The strain capacity of the mixtures correlates with the number of fine cracks in the specimens. Figures 4 and 5 both indicate that the inclusion of expansive admixture in SHCC mixtures leads to less strain capacity and dispersed cracking.

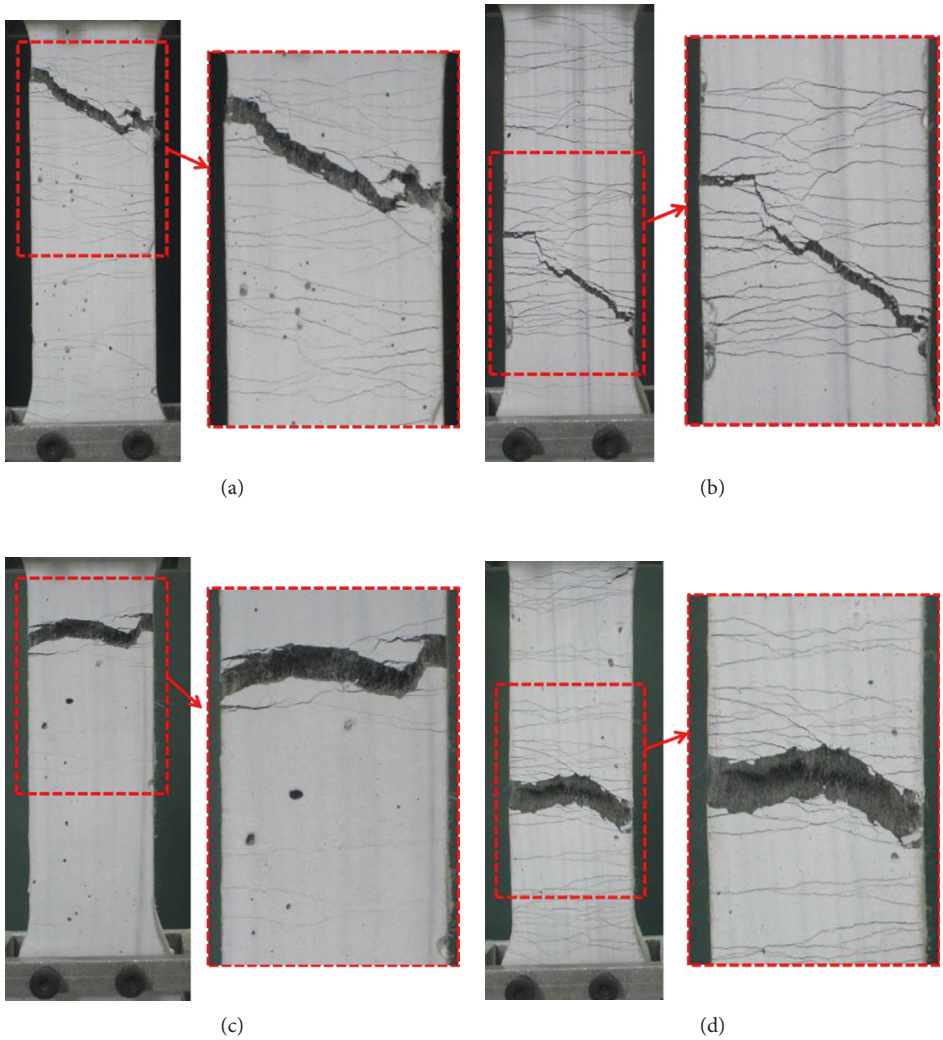


Figure 5: Typical crack patterns after direct tensile tests for each mixture type. (a) SHCC30 mixture. (b) SHCC60 mixture. (c) Ex-SHCC30 mixture. (d) Ex-SHCC60 mixture.

3.3. Flexural Behavior of SHCC Mixtures. In Figure 6, the dark lines (red and black) show the test results for each specimen and the light lines show the averaged test results at each deflection. Figure 6(a) presents the flexural stress-deflection curves for the SHCC mixtures without expansive admixture. The averaged deflections at peak stress for the SHCC30 and SHCC60 mixtures are 2.32 (±0.25) mm and 3.44 (±0.35) mm, respectively. The higher compressive strength values led to higher flexural strength values and deflections at the peak stress. Similar properties can be observed from the test results and flexural responses of the Ex-SHCC mixtures, as shown in Figure 6(b). The Ex-SHCC30 and Ex-SHCC60 mixtures have average flexural strength values of 11.13 (±1.17) MPa and 14.38 (±0.54) MPa, respectively. The average modulus of rupture values and the deflection at peak stress of the Ex-SHCC60 mixture are about 1.3 and 1.5 times more, respectively, than those of the Ex-SHCC30 mixture.

Figures 6(a) and 6(b) clearly show that the flexural strength of the mixtures increases when expansive admixture is included in the mix. However, the toughness and ductility of the Ex-SHCC mixtures are shown to decrease after the peak stress. Table 5 presents the tensile and flexural properties of the SHCC and Ex-SHCC mixtures.

3.4. Failure Mode and Responses of RC Beams Repaired with SHCC and Ex-SHCC Mixtures. Figure 7 shows the cracking patterns of the beam specimens at each yield load. All of the RC beam specimens exhibited similar failure modes during testing. First, flexural cracks developed at the bottom of the beam and then shear cracks developed with increasing applied loads. Flexural shear cracks were observed for all the specimens. Also, shear bond face cracks occurred for the repaired beam specimens that contained the SHCC30 and Ex-SHCC30 mixtures, as shown in Figures 7(b) and 7(c).

Figure 8 shows the effects of the SHCC and Ex-SHCC layer on the structural performance of the repaired RC beam specimens. As expected, the RC beams with the SHCC and Ex-SHCC layers improved the ductility better than the conventional (control) RC beam. For example,

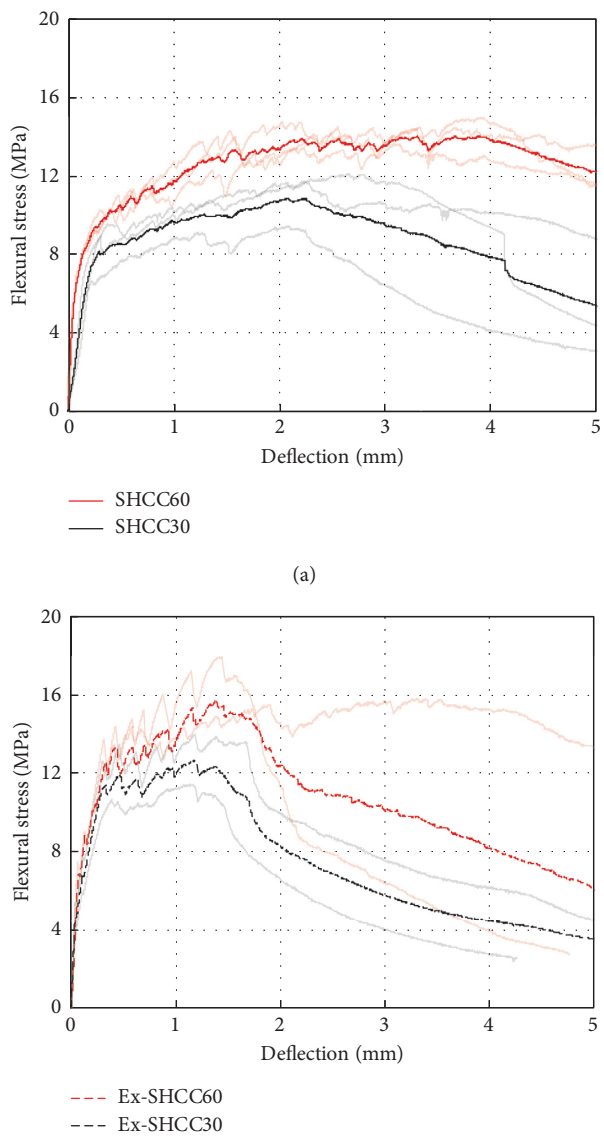
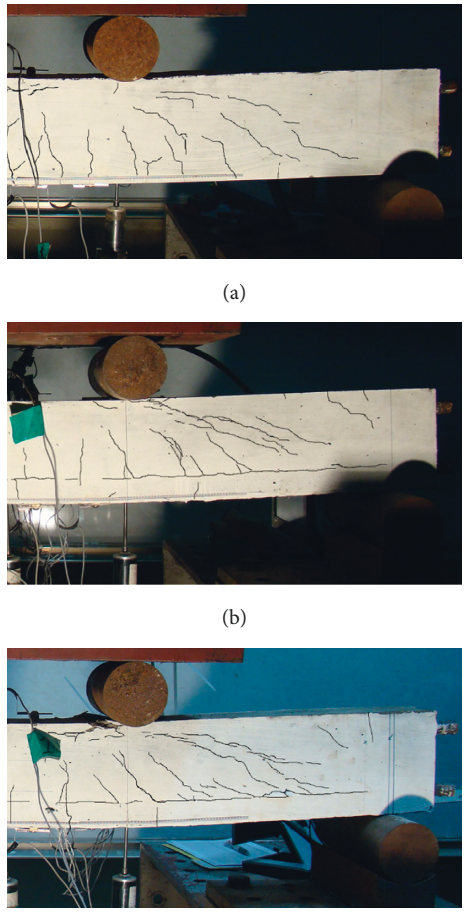


Figure 6: Effects of expansive admixture on flexural responses of SHCC and Ex-SHCC mixtures. (a) SHCC mixtures. (b) Ex-SHCC mixtures.

Table 5: Tensile and flexural properties of SHCC and Ex-SHCC mixtures.

Mixture ID	First-crack strength (MPa)	Tensile strength (MPa)	Strain at tensile strength (%)	Flexural strength (MPa)	Deflection at flexural strength (mm)
SHCC30	1.22 (±0.18)	4.49 (±0.42)	1.86 (±0.20)	11.13 (±1.17)	2.32 (±0.25)
SHCC60	1.77 (±0.46)	6.27 (±0.38)	3.49 (±0.89)	12.71 (±1.27)	1.16 (±0.02)
Ex-SHCC30	1.20 (±0.10)	4.54 (±0.51)	0.52 (±0.18)	14.38 (±0.54)	3.44 (±0.35)
Ex-SHCC60	2.57 (±0.35)	6.60 (±0.36)	2.29 (±0.44)	16.21 (±1.77)	1.78 (±0.36)

the stiffness value of the RC-R(SHCC30) beam specimen decreased more than that of the conventional RC beam specimen. The measured maximum loads of the RC, RC-R (SHCC30), and RC-R(Ex-SHCC30) beam specimens were 170, 165, and 185 kN, respectively. The results obtained for the three beam specimens indicate that the specimens that were repaired using the SHCC and Ex-SHCC mixtures exhibited small differences in flexural strength. However, the ductility of the beams significantly improved by including SHCC and Ex-SHCC layer, as evidenced by the mitigation of critical crack damage shown in Figure 8(a).



(a)

(b)

(c)

Figure 7: Failure modes and cracking patterns of RC beam specimens. (a) RC beam specimen. (b) RC-R (SHCC30) beam specimen. (c) RC-R (Ex-SHCC30) beam specimen.

3.5. Cracking Behavior of Beam Specimens Repaired with SHCC and Ex-SHCC Mixtures. The crack growth of the conventional RC beam and the RC beams that were repaired using SHCC and Ex-SHCC mixtures was observed using a microscope over the central 800 mm of the specimens. The crack growth was measured up to the yield load for each 20 kN load increment. The initial cracks developed before 20 kN loading for all the beam specimens. Figure 9(a) shows the effects of the SHCC and Ex-SHCC mixture layer on the crack widths of the specimens. As aforementioned, the SHCC and Ex-SHCC mixture specimens exhibited multiple fine cracks. The control RC beam specimen maintained the same number of cracks after 40 kN. In the case of the beam specimens that were repaired using the SHCC and Ex-SHCC mixtures, however, the number of cracks increased up to failure of the specimen. The beam specimen repaired with SHCC mixture had a wider distribution of more cracks than the specimen that was repaired using Ex-SHCC mixture.

Figure 9(b) shows the crack width according to each load increment from 20 kN to 140 kN. The crack width of the RC-B (control) specimen steadily increased with an increase in vertical loading. Such wide cracks can lead to decreased durability and increased corrosion of steel rebar. On the other hand, the RC beams that were repaired with the SHCC and Ex-SHCC mixtures maintained their crack widths. Therefore, these results indicate that the application of SHCC and Ex-SHCC mixtures to the tensile zone of RC flexural members may prevent the intrusion of aggressive substances into the steel reinforcement.

4. Conclusions

The effects of CSA-based expansive admixture on the mechanical properties of SHCC mixtures were investigated in this study through experimental research. This study examined the application of SHCC and Ex-SHCC mixtures in the tensile zone of RC beams as a repair mechanism to mitigate crack damage and increase ductility. Based on the test results, the conclusions can be summarized as follows:

(1) The compressive, tensile, and flexural strength levels of SHCC mixtures tend to increase when using CSA-based expansive admixture as the cementitious composite with 10% replacement of the cement weight. However, the strain capacity, ductility, and toughness of Ex-SHCC mixtures tend to decrease compared to SHCC mixtures.

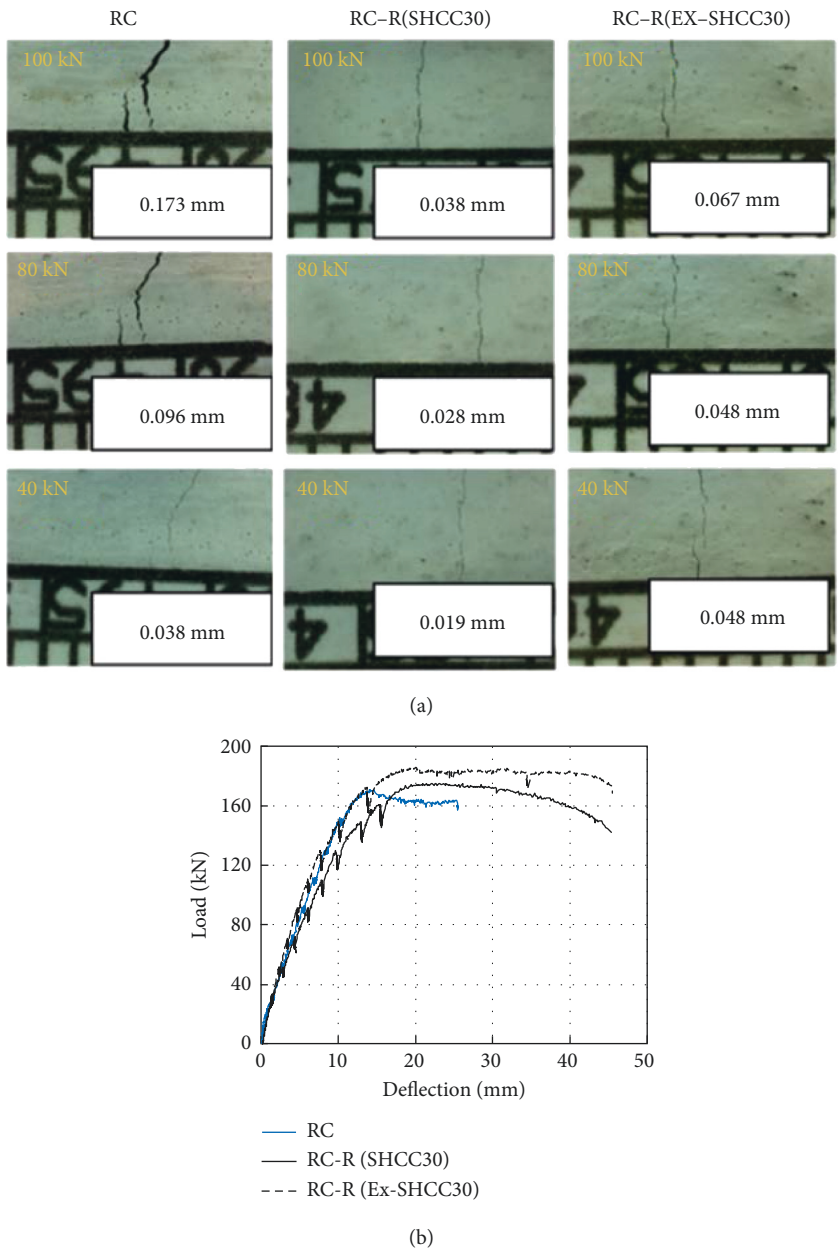


Figure 8: Observed behavior of repaired beam specimens versus control specimen. (a) Variation in crack widths. (b) Responses of beam specimens.

(2) The beam specimens that were repaired using both the SHCC and Ex-SHCC mixtures exhibited significant improvement in crack damage mitigation and ductility compared to the conventional RC beam control specimen. The application of SHCC and Ex-SHCC mixtures in a layered system thus should be used to prevent the corrosion of the steel rebar in RC flexural members.

(3) The stiffness of the beams that were repaired using the SHCC mixtures decreased due to the slippage at the interface between the concrete and the SHCC layer. On the other hand, the stiffness of the beam that was repaired using the Ex-SHCC mixture showed similar performance as the control RC beam specimen. It is concluded that the shrinkage of SHCC mixtures that contain rich cementitious material can lead to bond-face slippage. The use of expansive admixture in SHCC mixtures can help reduce shrinkage and improve the integrity of a layered beam repair system.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

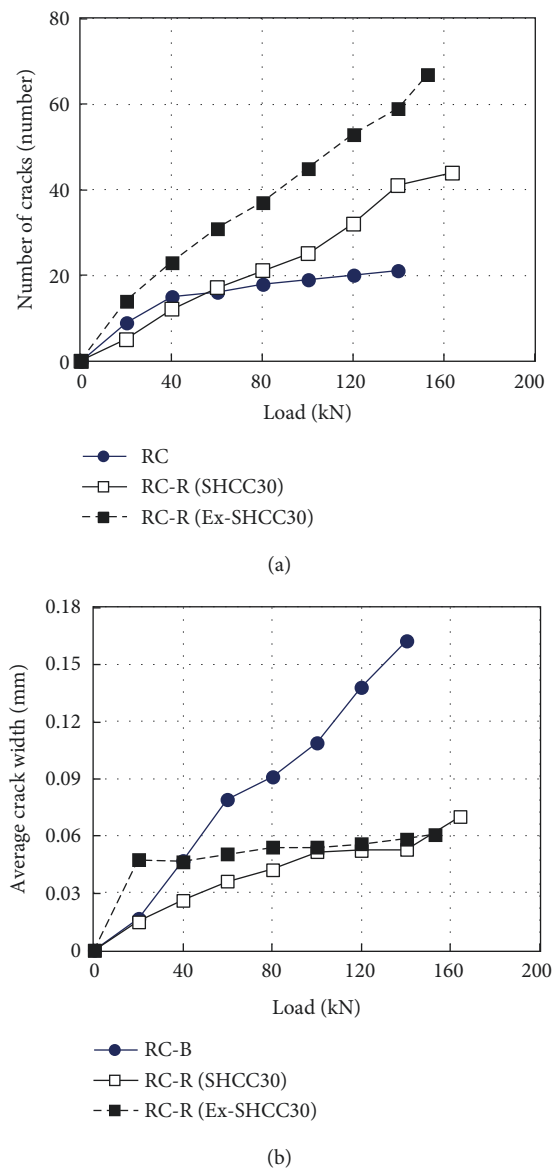


Figure 9: Cracking behavior of beam specimens. (a) Number of cracks. (b) Average crack width.

Acknowledgments

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