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Research Article

Feasibility of Reduced Lap-Spliced Length in Polyethylene Fiber-Reinforced Strain-Hardening Cementitious Composite

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This research investigates the interfacial behavior between polyethylene (PE) fiber-reinforced strain-hardening cement composite (PE-SHCC) and reinforcing bars that are spliced in the tension region to determine feasibility of reduced lap-spliced length in PE-SHCC. Twenty test specimens were subjected to monotonic and cyclic tension loads. The variables include the replacement levels of an expansive admixture (0% and 10%), the compressive strength of the SHCC mixtures (40 MPa and 80 MPa), and the lap-spliced length in the tension region (40% and 60% of the splice length recommended by ACI 318). The PE-SHCC mixture contains polyethylene fiber to enhance the tensile strength, control the widths of the cracks, and increase the bond strength of the lap splice reinforcement and the calcium sulfo-aluminate- (CSA-) based expansive admixture to improve the tension-related performance in the lap splice zone. The results have led to the conclusion that SHCC mixtures can be used effectively to reduce the development length of lap splice reinforcement up to 60% of the splice length that is recommended by ACI 318. The addition of the calcium sulfo-aluminate-based expansive admixture in the SHCC mixtures improved the initial performance and mitigated the cracking behavior in the lap splice region.

1. Introduction

Many research studies have been carried out to investigate the force transfer from the reinforcement to the concrete in a splice zone in both tension and compression [1–7]. It has been established that the bond strength is governed by the mechanical properties of the concrete, concrete cover, the presence of confining reinforcement, reinforcement geometry, and so on. Ganesan et al. [6] reported that the confinement and bridging effect of hybrid fibers enhanced the bond strength of deformed reinforcing bars embedded in hybrid fiber-reinforced high-performance concrete (HFRHPC) composites when compared to plain high-performance concrete (HPC). They concluded from their test results that the anchorage length requirement for deformed bars can be reduced by the usage of HFRHPC.

Recently, Hosseini et al. [8] investigated the bond behavior of deformed steel reinforcement bars connected by a grouted spiral connection for linking precast member to member. The axial and flexural pullout test results indicated that the load transfer within the connected bars is dependent on the mechanical interlocking mechanism enhanced by the spiral confinement. The tensile resistance of spliced bars can be increased by better confinement in the spliced region.

Conventionally, the use of deformed reinforcement is an efficient way to improve the bond strength and ductility of concrete structures in order to mitigate bond failure as well as to enhance the energy absorption and dissipation in the splice zone in compression and tension. The bond strength between the concrete and spliced reinforcement increases as the length of the deformed reinforcement

Table 1: Design of the conventional concrete and SHCC mixtures.

Mixture ID	W/B	f'_c (MPa)	Fibers (%) PE	Unit weight (kg/m³) Cement	Water	Silica fume	EXA	S	G	AE	T
C30	0.50	30	—	350	175	—	—	770	981	—	—
C100	0.18	100		800	160	89	—	546	835	—	—
xxP40/00*	0.45	30	1.50	1,075	484	—	—	430	—	—	—
xxP40/10				968	489	—	108	430	—	—	—
xxP80/00	0.19	100	1.50	1409	319	245	—	163	—	33	7
xxP80/10				1268	319	245	141	163	—	33	7

*xxP40/00 (mixture ID example): xx = percent of spliced length; P = reinforced fiber type (P is polyethylene fiber); 40 = compressive strength of concrete (40 MPa); 00 = expansive admixture (EXA) replacement level (0%). The other specimen ID "C" is control concrete. W/B = water-to-binder ratio; PE = polyethylene fiber; EXA = expansive admixture; S = sand; G = gravel; AE = air-entraining agent; T = antifoaming agent.

Table 2: Mechanical properties of polyethylene (PE) fiber.

Fiber	Specific gravity	Length l (mm)	Diameter d (μm)	Aspect ratio l/d*	Tensile strength (MPa)	Young's modulus (GPa)
Polyethylene fiber	0.97	12	12	1000	2500	75

*l/d is length-to-diameter ratio.

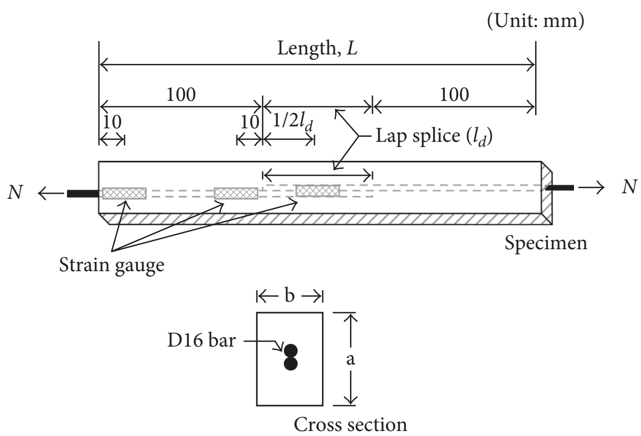


Figure 1: Schematic drawing for specimens.

increases, such that splitting failure converts to pullout failure [9].

Several investigations have been carried out to study the effect of fiber as an alternative method for improving the bond strength between concrete and reinforcement. The lap splice length of the reinforcement in a fiber-reinforced strain-hardening cement composite (SHCC), which has strain-hardening behavior and a capacity to control macrocracks in direct tension, can be lesser (shorter) than that of reinforcement used in conventional concrete. The reduction in the length of the reinforcement used for joints between precast concrete members would lead to construction efficiency as well as time and cost savings. Hamad and Itani [10] converted a concrete structure from brittle failure character to ductile failure character by adding steel fibers to the concrete mixture. The fibers play a role similar to that of confinement reinforcement in a splice region, with bridging effects to the cracks that delay the propagation of cracks. Research findings indicate that the brittle failure that occurs after reaching the maximum tensile load can be controlled by using fibers in the splice region in tension [6, 7, 11]. Yazici and Arel [7] concluded that pullout loading is increased by 7% to 16% when the amount of steel fiber and the aspect ratio in the steel fiber concrete mixtures are increased in comparison to concrete mixtures without steel fiber. The pullout loads of the deformed steel reinforcement are affected by the mechanical properties of the concrete mix, concrete cover, amount of steel fibers, and the aspect ratio of the steel fibers. A study carried out by Haddad [12] similarly showed that the bond strength of concrete with steel fibers added by 2% volume was increased by 23% of the bond strength of plain concrete.

Fischer and Li [13] investigated the tensile characteristics of a polyvinyl alcohol (PVA) fiber in an engineered cementitious composite (ECC) mixture to compensate for the brittle nature of concrete. In the Fischer study, tension members reinforced with PVA fibers showed superior tensile performance after forming initial cracks. However, the initial cracks at the hardening stage in the rich mix design of the ECC mixture led to lower tensile stress than for a conventional cement mixture.

Similarly, SHCCs reinforced with fiber also show superior tensile performance, which includes the control of crack propagation, but considerable shrinkage was observed due to the rich mix design [14]. This study investigated the effects of the expansive admixture, compressive strength, and the reduced lap splicing length associated with the bond performance in the splice region. It is likely that the initial shrinkage cracks adversely affect the tensile strength, lap splice length, and bond behavior in the splice region. Therefore, shrinkage cracking needs to be considered in SHCC mix design. To compensate for the excessive shrinkage of the SHCC mixtures, the cement was replaced with an expansive admixture [15].

Table 3: Details of test specimens.

[1]b × a (mm)	[2]Splice length (mm)	Specimen ID	40% of spliced length		Specimen ID	60% of spliced length	
			L (mm)	[3]40% of l_d (mm)		L (mm)	[4]60% of l_d
80 × 100	440	C40	640	—	—	—	—
	240	C80	440	—	—	—	—
	440	40P40/00	380	180	60P40/00	460	260
	440	40P40/10	380	180	60P40/10	460	260
	240	40P80/00	300	100	60P80/00	340	140
	240	40P80/10	300	100	60P80/10	340	140

[1]See Figure 1 for cross section; [2]splice lengths were calculated using ACI 318-11 equation; [3]40% of splice length (SHCC specimens); [4]60% of splice length (SHCC specimens).

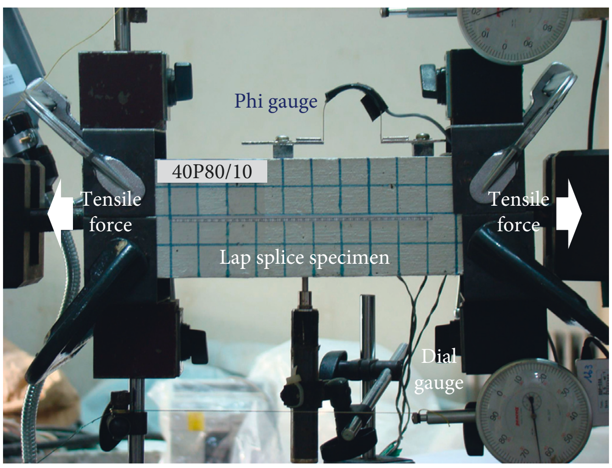


Figure 2: Test setup of spliced specimens in the direct tension.

2. Experimental Program

2.1. Preparation. Twenty test specimens were fabricated in order to examine the bond performance in tension in terms of the following parameters. The variables include the replacement levels of an expansive admixture (0% and 10%), the compressive strength of the SHCC mixtures (40 MPa and 80 MPa), and the length of the lap splice in the tension region (40% and 60% of the splice length recommended by ACI 318). In order to reduce the excessive shrinkage of the SHCC mixtures, 10% of the cement was replaced with a CSA-based expansion admixture [15].

Table 1 presents the design of the concrete and SHCC mixtures used in this study. For example, the designation P30/10 indicates that the compressive strength of SHCC mixture is 30 MPa and includes 10% expansive admixture.

Table 2 presents the mechanical properties of the polyethylene (PE) fibers used in the mixtures. SHCC mixtures are affected significantly by shrinkage and also show strain-hardening effects and broadly dispersed cracks in the tension zone. In order to determine the mechanical properties of the SHCC mixtures used in this study, test specimens were fabricated specially for shrinkage, compressive strength, and tensile strength. A prismatic specimen 100 mm × 100 mm × 400 mm was used to test for shrinkage. After placing the mixture, a shrinkage gauge was installed in the middle of the specimen, and then the specimen was cured in an environmental chamber at 20°C ± 1°C and 50% ± 1% relative humidity. Three cylindrical specimens 100 mm × 200 mm for each SHCC mixture were fabricated for compressive strength testing according to KS F2405. The direct tensile strength of each SHCC mixture was determined using dumbbell-shaped specimens according to JSCE-E-53110. A specimen for each mixture was tested separately under monotonic loading and cyclic loading.

Figure 1 presents a schematic illustration of a test specimen that includes details for the three strain gauges that were attached at the splice region and both ends of the steel reinforcement. In addition, a crack gauge was installed at the end of the splice region to measure the crack width, also shown in Figure 1. The overall deformation of the specimen and strain of the reinforcement were measured using dial gauges attached at both ends of the specimen. Table 3 presents detailed information for the specimens associated with the spliced length in this study.

The reinforcement used for the splice region is D16 reinforcement with a nominal diameter of 16 mm. The yield stress (f_y), strain at yielding (ε_y), and the elastic modulus (E_s) of the reinforcement are 528 MPa, 2750 μm, and 193 GPa, respectively.

2.2. Experimental Procedure. Twenty SHCC specimens were fabricated to examine the tensile performance in the lap splice zones; the tensile performance was based on the mechanical characteristics of the reinforcing fibers and mixing conditions. The splice lengths for the concrete specimens (C40 and C80) were computed using the equation found in ACI 318. Monotonic and cyclic direct tension loads were applied using a universal testing machine with a capacity of 50 kN as shown in Figure 2.

For the cyclic tensile tests, the number of cracks and the crack widths were measured at maximum stress so that the dispersion and mitigation of the cracks that developed in the spliced zone could be examined. The cyclic loads, which were controlled using two displacement gauges installed at the ends of the specimens, were repeatedly applied at 500 μ, 1000 μ, and 2000 μ.

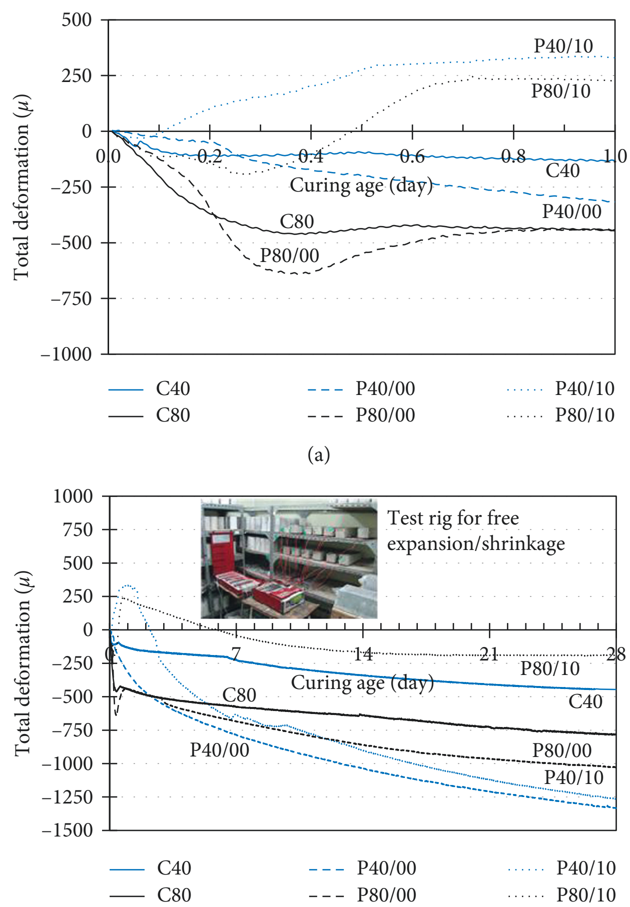
3. Experimental Results

3.1. Mechanical Properties of the SHCC Mixtures. Table 4 presents the experimental results for the mechanical

Table 4: Material properties of concrete and SHCC mixtures.

Mixture type	Strain 1 day after casting (μ)	Compressive strength (MPa)	Young's modulus (GPa)	Tensile strength (MPa)	Tensile strain capacity* (%)
C40	−134	32.9	22.5	—	—
C80	−443	84.7	35.4	—	—
P40/00	−316	39.4	13.4	5.88	2.78
P40/10	330	39.5	13.4	6.61	1.12
P80/00	−446	81.7	27.4	7.83	0.93
P80/10	229	86.7	25.9	6.65	1.11

Note. The compressive and tensile strength results are the averages for three and five specimens, respectively. *Tensile strain at the peak tensile stress.



(a)

(b)

Figure 3: Free expansion-shrinkage strain of concrete and PE-SHCC prisms. (a) Free strain history during 1 day. (b) Free strain history during 28 days.

properties, which include shrinkage, compressive strength, elastic modulus, and tensile strength and strain for each SHCC mixture.

Figures 3(a) and 3(b) show the shrinkage that was monitored over 1 day and 28 days, respectively, after casting the SHCC mixtures. The shrinkage for each mixture was measured in an environmental chamber at a temperature of 20°C ± 1°C and at 60% ± 1% relative humidity. The amounts of the free length change for the polyethylene fiber-reinforced SHCC (i.e., PE-SHCC) specimens during 1 day are higher than that for the plain concrete specimens. The shrinkage was turned into expansion with respect to the presence of the expansive admixture. In particular, the levels of early age shrinkage within 1 day for specimens C80 and P80/00 are higher than for the other specimens, which is due to the relatively large amount of cement and the presence of 17% silica fume.

The C40 and C80 specimens shrank rapidly over half day after placement, and then the shrinkage increased gradually. The PE-SHCC specimens, however, tended to shrink

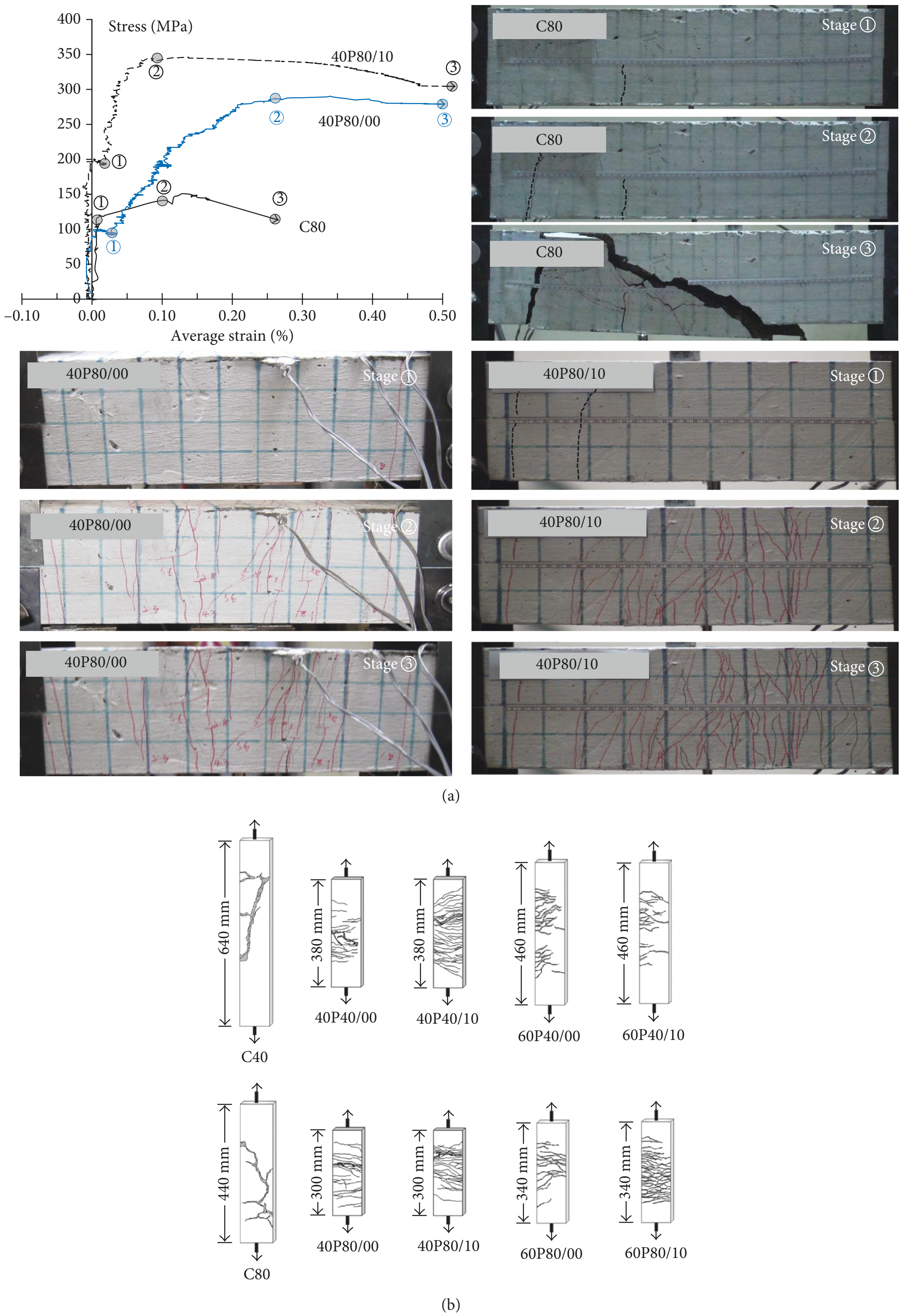


Figure 4: Typical cracking patterns of spliced specimens. (a) Typical crack propagation. (b) Cracking patterns at failure.

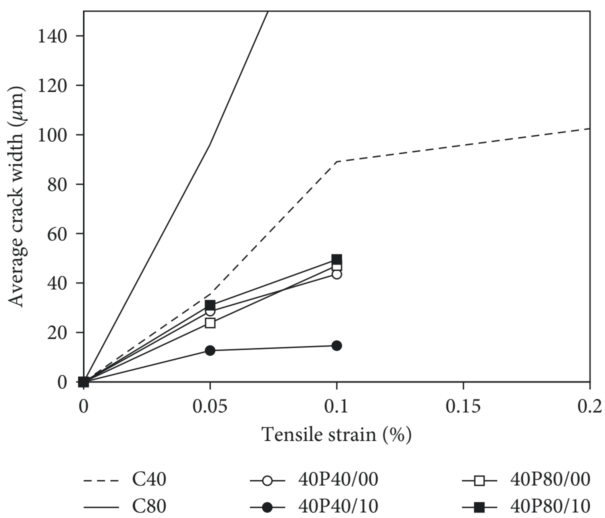


Figure 5: Average crack widths in lap splice for the specimens with 40% l_d.

radically after 1 day. This tendency can be observed especially for specimens P40 and P80 in Figure 3.

The SHCC mixtures containing the expansive admixture exhibited greater compressive strength than those without the expansive admixture. Among those mixtures, the high-strength PE-SHCC mixture had a relatively high increasing rate of compressive strength with the presence of the expansive admixture.

All of the tensile specimens of the PE-SHCC mixture exhibited over 1% strain at maximum loading, and microcracks were distributed throughout the specimens. With respect to the presence of the expansive admixture, the tensile strength of the normal-strength PE-SHCC mixture increased, but the strain capacity decreased at the maximum stress level. Conversely, the tensile strength of the high-strength PE-SHCC mixture decreased with the addition of the expansive admixture, and the mixture showed relatively ductile behavior.

Ductile behavior was also observed in the high-strength mixtures, similar to the PE-SHCC mixture, without any significant change in tensile strength. The expansion of the high-strength PE-SHCC mixtures that contained the expansive admixture adverse effect on ductility caused low tensile strength.

3.2. Cracking Pattern and Failure Character. Figure 4(a) shows the crack propagation patterns for each load stage of the specimens with the high-strength PE-SHCC mixture. For the specimen C80, the first crack was presented at the end of spliced reinforcement, and the maximum load was reached without forming any new cracks. Finally, the splitting cracks were developed rapidly at failure. Several hairline cracks form along the spliced region in the specimens 40P80/0 and 40P80/10 after presenting initial cracks because of the increment of tensile strength. The strength and deformation capacity along the spliced region tends to be increased significantly.

In particular, forming initial cracks was delayed in the specimen containing 10% of an expansive admixture (40P80/10), and the cracks were distributed widely as similar as that for the dumbbell-shaped specimen in the PE-SHCC mixture. This phenomenon was remarkable in the high-strength specimen with design compressive strength of 80 MPa containing the relatively large amount of cement.

Figure 4(b) shows typical crack patterns at failure of the specimens for this study. The crack widths were measured using a microscope with 60 magnifications. The average crack widths were computed by measuring all the cracks at each level of deformation.

Figure 5 presents the average crack widths that correspond to the tensile strain of the reinforcement in the splice zones of the concrete and SHCC mixtures. The average crack widths of the SHCC specimens are 50% smaller than those of the concrete specimens. For the specimens that contained SHCC, the crack widths of the specimens with normal strength are wider than those of the specimens with high strength, whereas for the control specimens, the crack width of the high-strength concrete specimen (C80) is wider than that of the specimen with conventional concrete strength (C40). Table 5 indicates that the tensile strength and strain levels of the high-strength specimens are lower than those of the normal-strength specimens, which results in fewer instances of crack formation and development.

Figure 5 also shows that large splitting cracks, which are due to the bond failure in a splice region, were observed for the high-strength specimens. However, many vertical microcracks subsequently transformed to splitting cracks in the normal-strength specimens.

The polyethylene fiber is shown to perform well to control microcracking as well as low strength and large deformations. The cracks of the PE-SHCC specimens were fewer in number and less wide due to the presence of the expansive admixture.

3.3. Tensile Performance in Lap Splice Zone. Figure 6 presents the tensile stress-strain relationship in the lap splice zone when the specimens were subjected to monotonic and cyclic loading. The figure also includes the material properties of the reinforcement (D16). The experimental results are summarized in Table 5 and include (1) tensile strength, (2) tensile strain, (3) average crack width at 0.2% tensile strain, and (4) average bond strength (u) determined by summing the forces parallel to the reinforcement axis, assuming that the bond stress levels are distributed uniformly over this length [3], as follows:

$$u_{\text{avg}} = \frac{f_s \cdot d_b}{4 \cdot L_s}, \quad (1)$$

where d_b is the nominal diameter of the reinforcement, L_s is the splice length, and f_s is the stress of the spliced reinforcement at failure.

Similar initial cracking strength levels were obtained for all the specimens. The tensile strength of the SHCC specimens for Class B in the ACI 318 specifications exceeded the 50% yield strength of the reinforcement (264 MPa). This

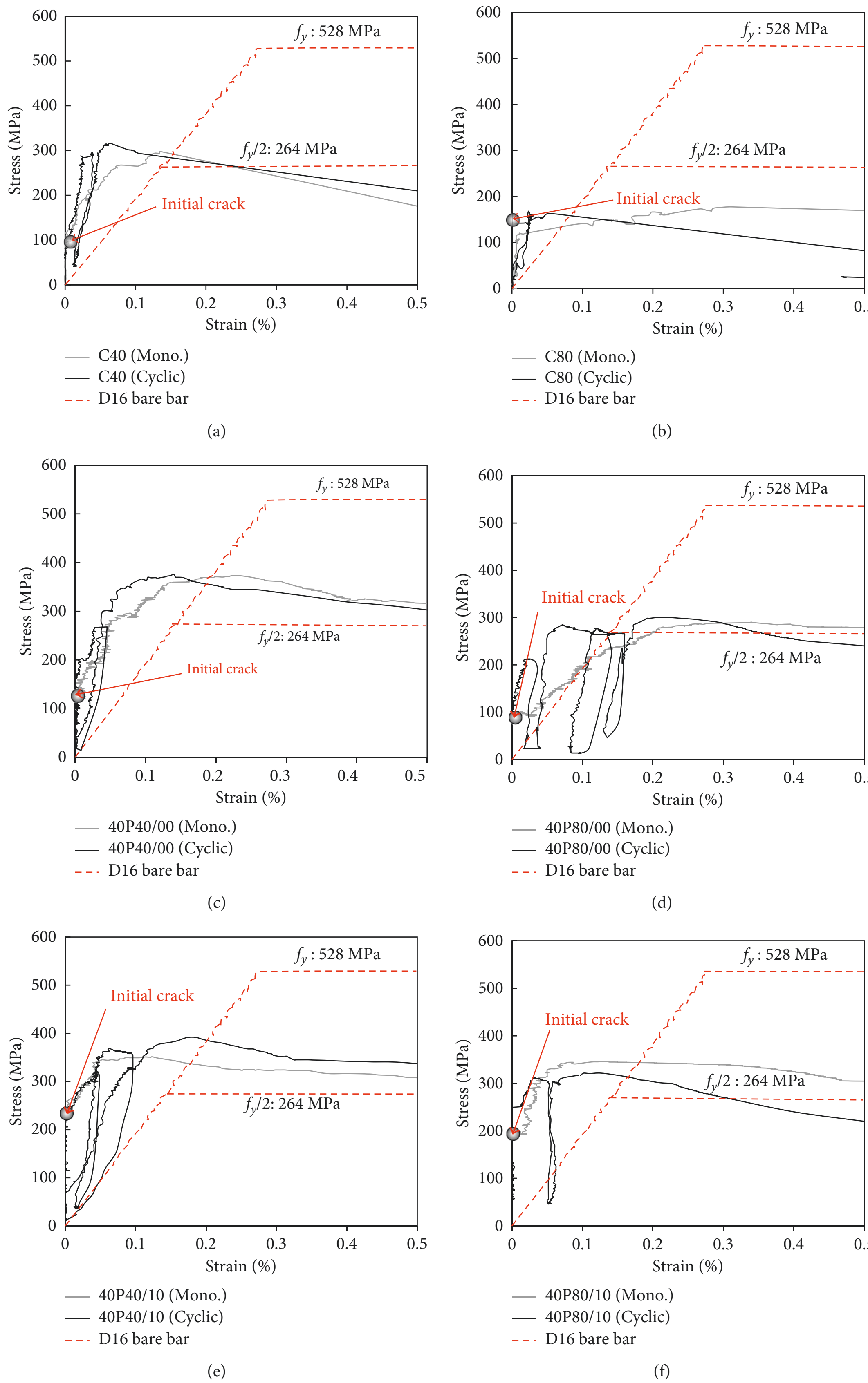


Figure 6: Continued.

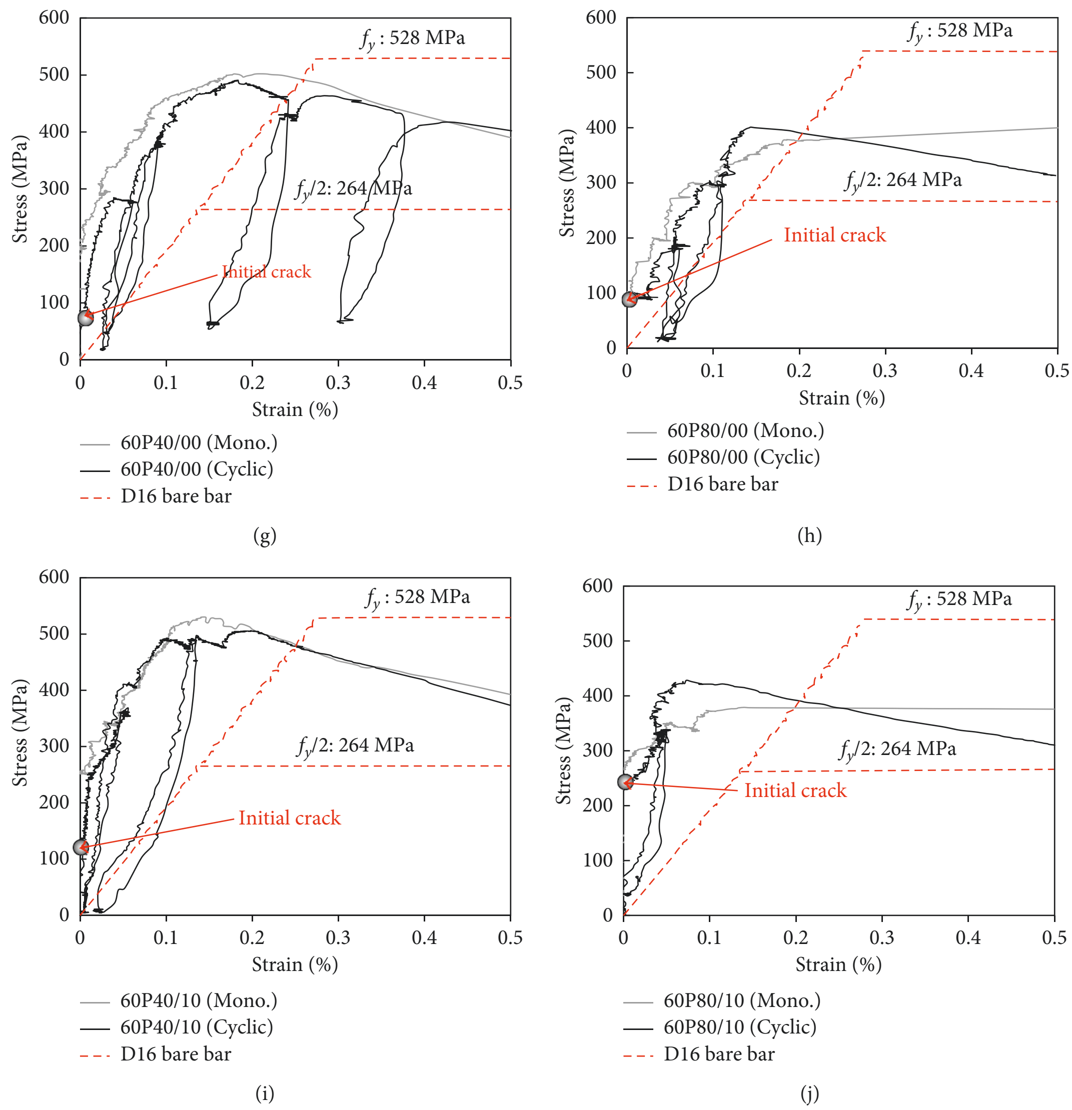


Figure 6: Tensile responses of lap splice specimens. (a) C40. (b) C80. (c) 40P40/00. (d) 40P80/00. (e) 40P40/10. (f) 40P80/10. (g) 60P40/00. (h) 60P80/00. (i) 60P40/10. (j) 60P80/10.

result indicates that 60% of the lap splice length required by the ACI code equation can be used safely.

The tensile strength in the lap splice region for the high-strength SHCC specimens was 10% lower than for the normal-strength SHCC specimens. Azizinamini [16] reported that the bond strength between a concrete surface and the reinforcement does not increase, even if the lap splice length increases with compressive concrete strength above 70 MPa. Therefore, the high-strength SHCC specimens used in this study (80 MPa) have a similar result in which the concrete and SHCC mixtures did not contribute significantly to the tensile strength in the splice region. In addition, Kaklauskas et al. [17] reported that the cracking resistance can be reduced by the shrinkage-induced stresses in the concrete due to the restraining action of bar reinforcement. In this study, the early age shrinkage within 24 hours of the high-strength SHCC specimens was greater than that of the normal-strength SHCC specimens. This outcome led to shrinkage cracking in the cement matrix, which then affected the cracking resistance in the splice region.

Substituting the expansive admixture in the PE-SHCC mixture increased the tensile strength and initial stiffness under monotonic loads and cyclic loads. In particular, the stiffness of the high-strength SHCC specimens substantially increased more than for the normal-strength SHCC specimens. This outcome is due to the characteristic nature of expansive admixture in high-strength SHCC specimens, whereby initial cracking is controlled and stress is redistributed [15].

Figure 7 presents the role of cement composites as part of the tensile strength development in the splice region for each specimen subjected to axial tensile force. The tensile strength of the cement composites was computed by subtracting the

Table 5: Experimental test results.

Specimen ID	Initial cracking		Tensile strength (MPa)	Tensile strain (%)	Average crack width at 0.1% tensile strain (μm)	Average bond strength by (1) (MPa)
	Strength (MPa)	Strain (%)				
C40	95	0.008	316	0.06	89	2.69
C80	149	0.002	168	0.06	214	2.72
40P40/00	125	0.003	375	0.83	43	7.67
40P40/10	235	0.002	391	1.78	14	8.10
40P80/00	89	0.005	316	2.13	47	11.80
40P80/10	196	0.002	321	0.50	49	10.76
60P40/00	73	0.005	491	0.18	43	8.24
60P40/10	124	0.001	506	0.20	25	7.76
60P80/00	89	0.003	401	0.14	34	11.54
60P80/10	240	0.002	428	0.07	29	13.76

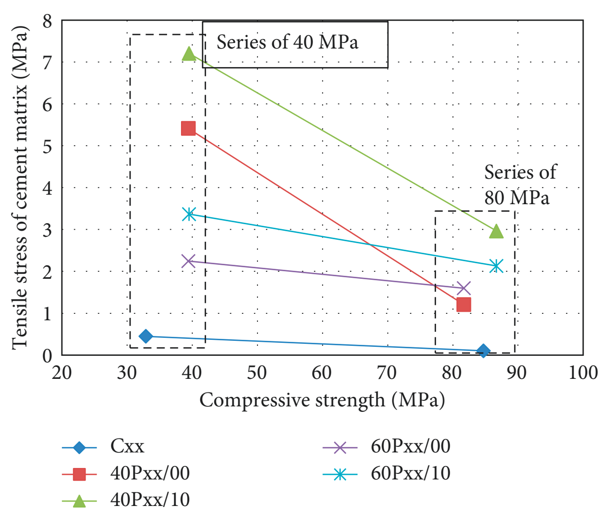


Figure 7: Tensile stress of cement matrix in lap splice specimens.

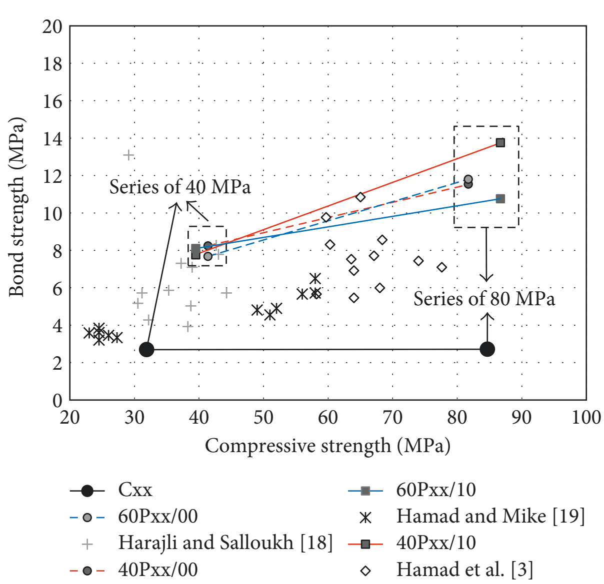


Figure 8: Bond strength of lap splice reinforcement [3, 18, 19].

tensile strength of the reinforcement (D16) from the tensile strength of each specimen.

The concrete specimens shown in Figure 7 are seen to contribute slightly only to the tensile strength of the reinforcement. For the SHCC specimens, however, the tensile strength levels of the SHCC mixtures in the splice region are over three times that of the concrete. The tensile stress levels of the cement matrix in the normal-strength SHCC mixtures are 30% higher than in the high-strength SHCC mixtures. Substituting the expansive admixture increased the tensile stress of the SHCC in the splice region. Furthermore, the use of cement composite enhanced the tensile strength of the specimens, which then led to improvement in terms of strength and deformation. The reduced spliced length, as opposed to the length recommended by the ACI specifications, was able to ensure the required tensile strength.

3.4. Bond Stress. Figure 8 presents a comparison between the bond strength and compressive strength of each specimen. The bond strength in the splice region increases as the compressive strength increases [1].

This study found that the bond strength slightly increases when an expansive admixture is substituted into the mix. Replacement with expansive admixture induces the reduction of shrinkage cracking and redistributes the tensile stress in the specimen, which serves to improve the compressive strength as well as the bond performance in the splice zone.

4. Conclusions

In order to evaluate the feasibility of the reduced lap-spliced length in the PE-SHCC mixture, direct tensile tests were performed for SHCC mixtures with lap-spliced lengths that were 40% and 60% shorter than those recommended in the ACI provisions. The following results have been obtained.

Initial cracking, stress, stiffness, and maximum strength levels increased due to the substitution of the expansive admixture into the SHCC mixtures. The tensile performance in the lap splice region of the high-strength SHCC mixtures was worse than that of the normal-strength SHCC mixtures. The PE-SHCC mixture effectively controlled macrocracks so that the stress was distributed and numerous microcracks developed throughout the specimens. This behavior was evident in the specimens that contained the expansive admixture, which is used to control initial cracks. Moreover, the direct tensile test results show that the tensile strength values of all the SHCC specimens were above the allowable stress level for Class B splices and also show steady strength reduction and ductile behavior after reaching maximum strength.

Conflicts of Interest

The authors declare that there are no conflicts of interests regarding the publication of this paper.

Acknowledgments

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