JOURNAL OF Applied Polymer SCIENCE

Bond Properties of Structural Polypropylene Fiber in Hybrid Nonstructural Polypropylene and Structural Polypropylene Fiber-Reinforced Latex-Modified Cement-Based Composites

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ABSTRACT: This study investigated the effect of styrene–butadiene latex (latex) content on the pullout behavior of structural polypropylene fibers (SPF) in hybrid fiber-reinforced latex-modified cement-based composite made with a blend of SPF and nonstructural polypropylene fiber. Bond tests were performed in accordance with JCI SF-8. NSPF was incorporated at 9.10 kg/m^3 and SPF at 0.45 kg/m^3. Latex was added at 0–20% of the binder weight. The experimental results demonstrated that latex improved the pullout properties of the load–displacement curve in the debonded zone. Also, the bond strength and interface toughness increased with latex content up to 15% but decreased when the latex content reached 20%. Microstructure analysis showed increased scratching on the SPF surface. © 2012 Wiley Periodicals, Inc. J. Appl. Polym. Sci. 000: 000–000, 2012

KEYWORDS: bond behavior; hybrid fiber-reinforced latex-modified cement-based composite; structural polypropylene fiber; nonstructural polypropylene fiber; styrene–butadiene latex (latex)

Received 23 December 2011; accepted 7 March 2012; published online
DOI: 10.1002/app.37668

INTRODUCTION

Reinforcing fiber inhibits crack growth in cement-based composites through a series of effects, such as fiber bridging, debonding, pullout, and fracture.[1] Cracks develop in cement-based composites when micro cracks form and increase in number; stress increases throughout crack formation.[1] Then, the sizes of the cracks change, and macro cracks form, reducing flexural stress and increasing deformation.[1] Hybrid fiber-reinforced cement composites (HFRCC) made with a blend of two or more types of fibers exhibit improved flexural capability.[1,2] This is because micro fibers in one part of the matrix control the formation and growth of micro cracks, while macro fibers in other parts control the formation and growth of macro cracks.[3–5] Additionally, HFRCCs are expected to exhibit superior properties that are not displayed by single-fiber-reinforced cement composites.[6–8] HFRCCs can be tailored for specific functionality, such as effective control of cracking in cement composites, by using fibers with different mechanical and physical properties.[9,10]

In this study, the bond performance of structural polypropylene fibers (SPF) in HFRCC made with a blend of nonstructural polypropylene fiber (NSPF) and SPF was evaluated. Styrene–butadiene latex (latex) was added to improve the bonding of SPF. Blended SPF and NSPF fiber reinforcements may reduce the workability of cement-based composites due to increased fiber balling, leading to degradation of the performance characteristics of HFRCCs.[6,10] Polypropylene (PP) fiber has the disadvantages of weak bonding and poor dispersibility in a cement-based composite because of its intrinsic hydrophobicity.[6,10] Recently, latex-modified cement-based composites (LMCC) have been used for structures that require watertightness.[11,12] Latex improves the performance of HFRCCs by increasing workability, fiber dispersion, and bonding between materials because of the formation of a latex film.[11–13] Thus, infiltration of latex can also improve the dispersion and bonding properties of PP fiber. This study evaluated the effects of latex content on the bonding characteristic of SPF in HFRCC made with a blend of SPF and NSPF.

Table I. Properties of Latex

Solids contents (%)	Styrene contents (%)	Butadiene contents (%)	pH	Density (g/mm^3)	Surface tension (dyne/cm)	Particle size (A)	Viscosity (cps)
46.5	34 ± 1.5	66 ± 1.5	11.0	1.02	30.57	1700	42

MATERIALS AND METHODS

Materials

The properties of the latex (Dow Chemical Company, Midland, MI) are listed in Table I. Latex is a semitransparent, milky liquid containing organic polymer particles, such as colloidal microparticles (0.5–5 μm diameter). The particles, coated with a surfactant, float in the solute, and the surfactant provides spaces in which a single polymer cell is formed by a chain mechanism between monomers. The surfactant delays solidification, stabilizing the particles, and increases the workability at low water/cement ratios, while the latex particles form a film membrane during hydration. Air voids are filled in such a way that a semi-continuous plastic film is attached to the surface aggregate. As a result, the permeability is degraded, and both the bond strength and tensile strength are increased. The compressive strength of cement-based composites depends on the water–cement ratio; a higher water–cement ratio results in decreased strength and increased shrinkage. The water–cement ratio should be low to achieve high strength in a short time with minimum shrinkage. However, this approach reduces the workability. The latex polymer surface activation mechanism may compensate for the degraded workability due to the low water–cement ratio.[11–13]

The physical and chemical characteristics of ASTM Type 1 cement and fly ash (FA) are shown in Tables II and III, respectively. The properties of SPF made of PP macro monofilaments are shown in Table IV. The properties of NSPFs, hydrophobic materials that are widely used in cement-based composite reinforcements, are given in Table IV.

Mix Proportions

The mix ratio of hybrid fiber-reinforced latex-modified cement-based composite (HFRLMCC) is shown in Table V. For HFRLMCC, 0.45 kg/m^3 of SPF and 9.10 kg/m^3 of NSPF were used. Latex was added at 0, 5, 10, 15, and 20% of the binder (cement + FA) weight (wt %). The plain mix did not contain FA. For those mixes containing FA, it was added to the cement at a weight replacement ratio of 30%. SPF (0.45 kg/m^3) and NSPF (9.10 kg/m^3) were added to the mixes to improve flexural strength. For pullout tests, NSPF fiber was added at 9.10 kg/m^3, and a single SPF was embedded in the test specimens according to the Japan Concrete Institute (JCI) SF-8 standard.

Flexural Test

Flexural tests were conducted in accordance with the KS L ISO 679 standard.[14] The test mortar prism specimens measured 40 × 40 × 160 mm^3 and were cured in water at 23 ± 2°C. Each test was performed on six specimens after 28 days of curing.

Pullout Test

Pullout tests, conducted according to the JCI SF-8 standard for fiber-reinforced concrete, were used to evaluate the pullout performance at different latex contents.[15] The pullout test specimens were prepared as described in the JCI SF-8 standard. The pullout tests were performed using a 50 kN universal testing machine at a displacement rate of 0.5 mm/min in displacement-controlled mode. The specimen preparation for the pullout test is illustrated in Figure 1. The pullout strength of the SPF was calculated using eq. (1):

$$\tau_{max} = \frac{P_{max}}{\pi DL} \tag{1}$$

where t_{max} is the maximum pullout strength, P_{max} is the maximum pullout load, D is the diameter of the fiber, and L is the embedded fiber length.

Interface toughness is a critical factor for enhancing the ductility of reinforcing fibers in cement-based composites. Reinforcing fibers inhibit crack propagation by transferring a constant tensile stress after a crack occurs, thereby preventing brittle failure of the cement-based composite. Interface toughness is also a critical factor that determines the behavior of cement-based composites after a crack occurs. Interface toughness is usually defined as the mechanical energy consumed during fiber pullout and can be determined by integrating the area under the pullout curve. Interface toughness correlates with the fracture energy of fiber-reinforced cement-based composites, indicating that increased interface toughness in cement based-composites effectively enhances the fracture toughness of the composite material. In this study, interface toughness was determined by integrating the area under the pullout–displacement curve. The displacement required to measure the interface toughness according to the JCI SF-8 standard is 2.5 mm. Since, most of the displacements measured in this study exceeded 2.5 mm at maximum load, the interface toughness was measured using displacements of 5.0 mm.[8] The results of the pullout performance tests,

Table II. Physical and Chemical Properties of Cement

	Fineness (cm^2/g)	Density (g/mm^3)	Stability (%)	Setting time: Initial (min)	Setting time: Final (min)	Compressive strength (MPa): 3 days	Compressive strength (MPa): 7 days	Compressive strength (MPa): 28 days
Physical properties	3200	3.15	0.02	220	400	20	30	38
Chemical properties	L.O.I[a] (%)			MgO (%)		SO$_3$ (%)		
	1.5			3.0		2.0		

[a]Loss of ignition.

Table III. Physical and Chemical Properties of Fly Ash

Density (g/mm^3)			Fineness (cm^2/g)			L.O.I (%)	
2.14			3,400			3.28	
Chemical compositions (%)							
SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	TiO_2
58.12	23.56	7.69	2.59	1.12	0.31	1.42	1.05

including the pullout strength and interface toughness, are reported as the mean values of six specimens.

RESULTS AND DISCUSSION

Flexural Strength

The flexural strength at different latex contents is shown in Figure 2. Flexural strength increased with increasing latex content up to 10% but decreased when the latex content was 15% or greater. This was because latex filled the voids within the cement-based composite, forming a latex film around the aggregate. Thus, bonding strength among the materials and flexural strength increased. When latex was added at 15% or more; however, the latex film in the cement paste was too thick, limiting the transfer of ions, and preventing further cement hydration.[16,17] Latex also inhibits the formation of C_4AH_{13}.[16,17] Thus, the flexural strength of the HFRLMCC decreased at the higher latex contents. The results for flexural strength were similar for the plain HFRLMCC (i.e., without FA) and FA HFRLMCC.

Pullout Load Versus Displacement

The relationship between pullout load and displacement of SPF with latex content is shown in Figure 3. The behaviors noted above were similar for the plain and FA HFRLMCC materials. The bonding behavior in cement-based composites can be divided into the precrack zone and the debonded zone. Elastic behavior was observed in the precrack zone. In the debonded zone, the behavior varied depending on frictional forces and the growth rate of cracks at the interface between the reinforcing fiber and cement-based composites. The results of this study showed linear elastic behavior in the precrack zone, followed by deformation-resistant behavior in the debonded zone after crack generation and load reduction. Strain-hardening behavior was also observed for the plain and FA HFRCC without latex; however, the value of the highest load caused by strain hardening was less than that in the precrack zone. This study further showed that, when the latex content was 5% or higher, the value of the load caused by strain hardening was higher than the maximum pullout load that was detected when cracks occurred at the interface. The maximum pullout load in the debonded zone was highest when the latex content was 15% and decreased at 20% latex. Also, displacement increased with latex content up to 15%, and decreased when the latex content reached 20%. These results demonstrate that latex improves bonding because latex film enhances the bond strength among the component materials. Also, latex promotes the dispersion of NSPF, which has inherently poor dispersibility in hydrophobic cement-based composites. HFRLMCCs improve the dispersion of NSPF and prevent fiber balling that may occur because of the addition of high volume fractions of hydrophobic fiber. Increased dispersion was confirmed by the separation of the SPF and the cement-based composite in the debonded zone, indicating strain hardening behavior during pullout of NSPF due to mechanisms such as fiber bridging, debonding, pullout, and fiber fracture. Pullout resistance increased with latex content due to increased dispersion of NSPF. Furthermore, the maximum pullout load decreased slightly in the debonded zone when the latex content reached 20%, because displacement resistance increased due to improved dispersion of NSPF.

Table IV. Properties of Structural PP and Nonstructural PP Fibers

Property	Structural PP fiber	Nonstructural PP fiber
Elastic modulus (GPa)	4.7	4
Density (g/mm^3)	0.91	0.91
Fiber length (mm)	30	12
Fiber diameter (mm)	1	0.1
Tensile strength (MPa)	470	600
Surface	Hydrophobic	Hydrophobic

Table V. Mix Proportions of HFRLMCC with Latex Contents

No. of mix	W/B[a] (%)	Unit weight (kg/m^3)						Latex (Weight of binder, wt %)
		Cement	Water	Fine aggregate	FA[b]	SPF	NSPF	
No.1								0
No.2								5
No.3		606			0			10
No.4						0.45	9.1	15
No.5	47		285	1363				20
No.6								0
No.7								5
No.8		424.2			181.8			10
No.9								15
No.10								20

[a]Binder, [b]Fly ash.

Journal of Applied Polymer Science

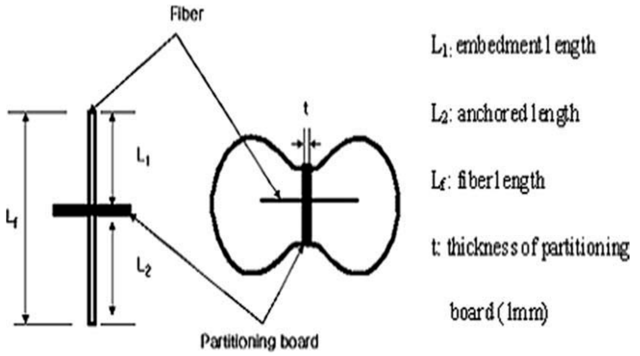

Figure 1. Arrangement of the partitioning board and fibers, and setting in the mold.

Bond Strength and Interface Toughness

Bond strength at different latex contents is shown in Figure 4. For the plain HFRLMCC, the bond strength was 1.95, 2.47, 3.20, 3.31, and 2.96 MPa at latex contents of 0, 5, 10, 15, and 20%, respectively. For the FA HFRLMCC, the bond strength was 1.98, 2.87, 3.02, 3.34, and 2.86 MPa at latex contents of 0, 5, 10, 15, and 20%, respectively. The addition of latex enhanced the dispersion of NSPF and improved the bonding among materials because of the formation of latex films. However, latex also has some disadvantages, e.g., latex films adsorbed onto cement particles delay the hydration of cement-based composites and decrease hardness. The present study also demonstrated that latex contents above 20% delayed the hydration reaction of HFRLMCCs, decreasing bond strength. Additionally, the maximum bond strengths of all the composites occurred in the debonded zone, except for composites with 0% latex. Without latex, load decreased because cracks occurred at the interface between the cement-based composite and the SPF in the precrack zone. In particular, the maximum bond strengths in the debonded zone were less than those in the precrack zone. The maximum bond strengths occurred in the debonded zone because strain-hardening behavior, which suppressed separation between the cement-based composite and SPF in the debonded zone, occurred due to bonding mechanism(s) involving fiber bridging, pullout, debonding, and fracture. There was a combined effect between the latex content and the dispersion of the NSPF, which enhanced the bond strength with latex content up to 15%. However, when latex content was 20%, the bond strength decreased because the latex film in the cement paste was too thick, limiting the transfer of ions and preventing further cement hydration.[16,17] These results were the same for the plain and FA HFRLMCC.

Figure 4 shows the interface toughness at different latex contents. For plain HFRLMCC, the bond strength was 67.71, 107.88, 236.68, 252.47, and 220.66 N-mm at latex contents of 0, 5, 10, 15, and 20%, respectively. For the FA HFRLMCC, the bond strength was 71.12, 150.96, 250.54, 268.41, and 237.77 N-mm at latex contents of 0, 5, 10, 15, and 20%, respectively.

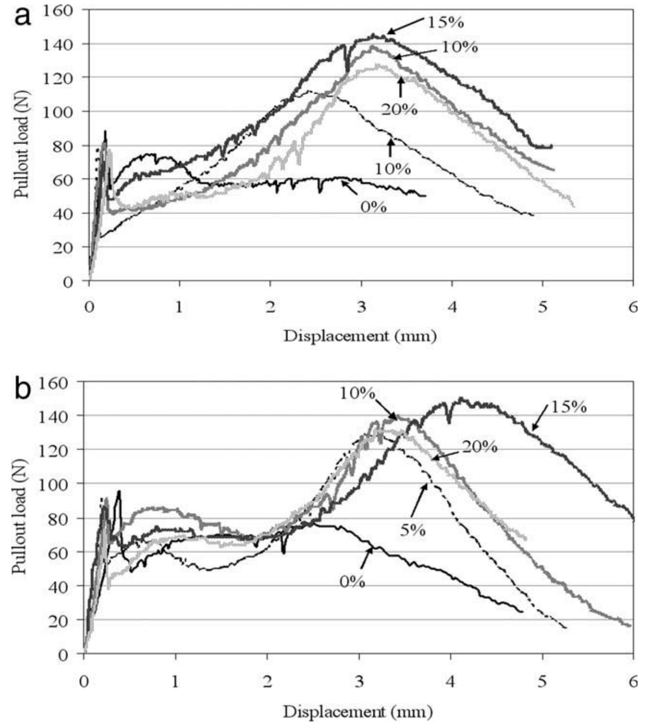

Figure 3. Pullout behavior of SPF in HFRLMCC with latex contents (wt %): (a) Plain and (b) FA.

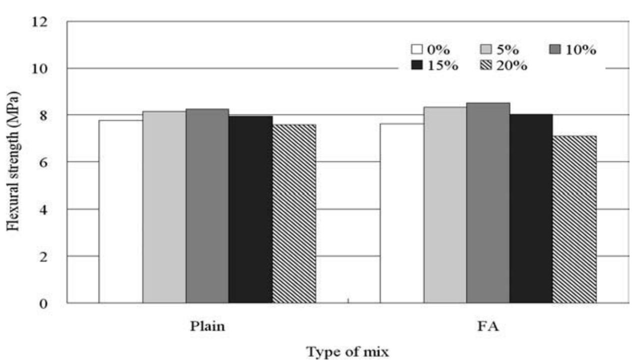

Figure 2. Flexural strength of HFRLMCC with latex contents (wt %).

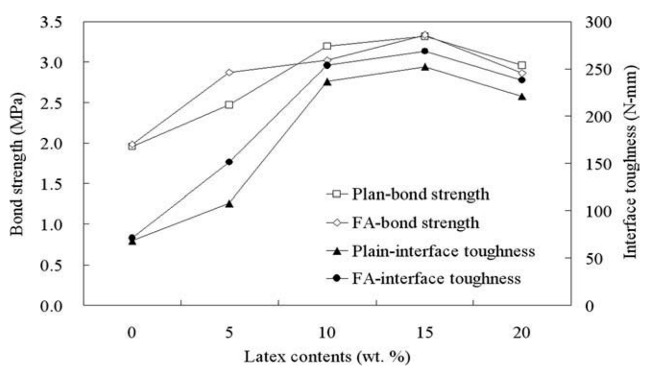

Figure 4. Bond strength and interface toughness of SPF in HFRLMCC with latex contents (wt %).

Table VI. Relative Bond Performance of SPF in HFRLMCC with Latex Contents

Type of mix	Latex contents (wt %)	Flexural strength (f_T, MPa)	Bond strength (τ_{max}, MPa)	Relative bond strength ($\tau_{max}/\sqrt{f_T}$)	Interface toughness (IT_{max}, N-mm)	Relative interface toughness ($IT_{max}/\sqrt{f_T}$)
Plain	0	7.8	1.95	0.70	67.71	24.28
	5	8.1	2.47	0.86	107.88	37.80
	10	8.3	3.31	1.11	236.68	82.38
	15	8.0	3.20	1.17	252.47	89.49
	20	7.6	2.96	1.07	220.66	80.16
FA	0	7.6	1.98	0.72	71.12	25.78
	5	8.3	2.87	0.99	150.96	52.26
	10	8.5	3.34	1.03	253.54	86.88
	15	8.0	3.02	1.18	268.41	94.79
	20	7.1	2.86	1.07	237.77	89.23

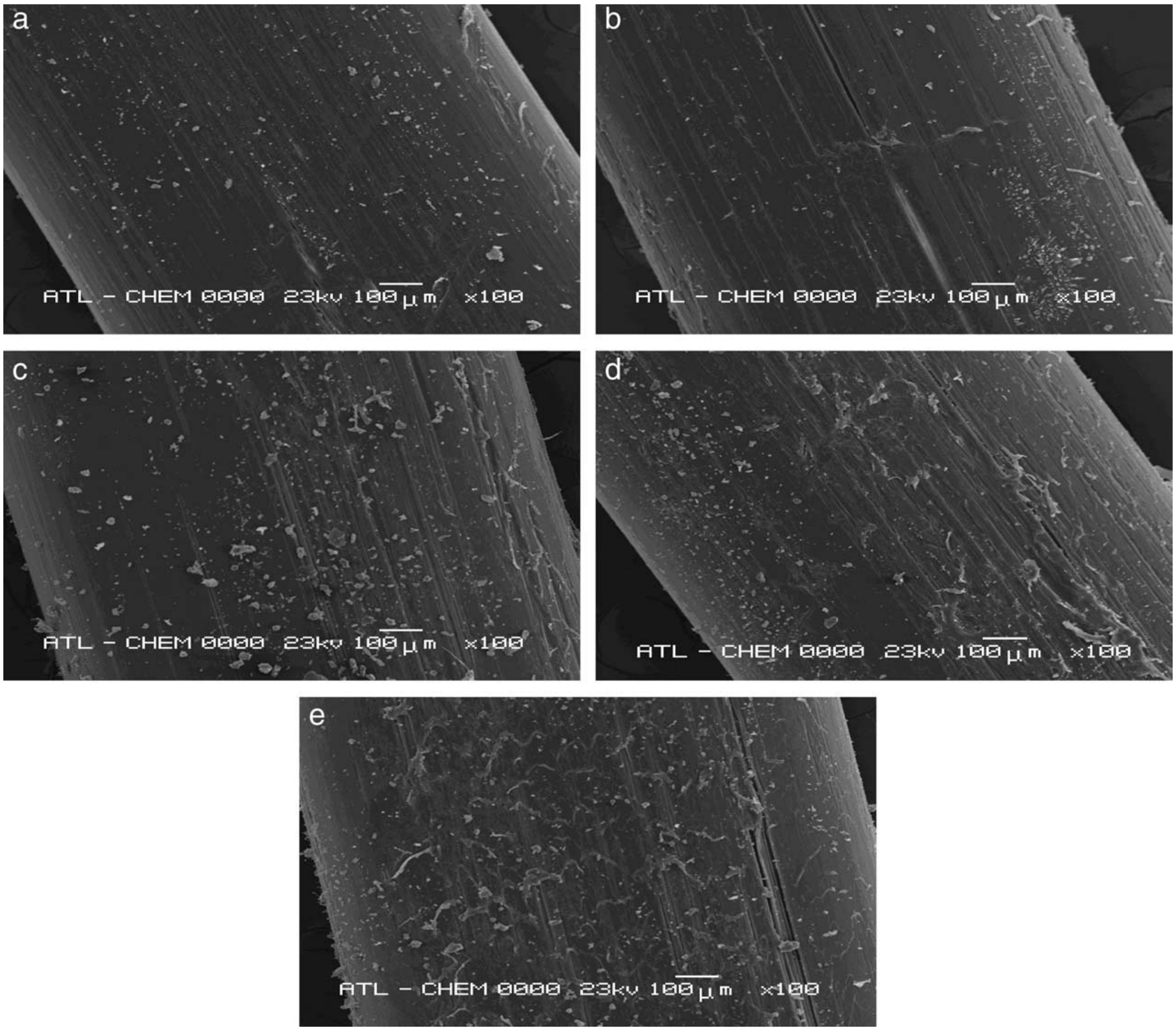

Figure 5. SEM investigation of SPF surface in plain HFRLMCC with latex contents (wt %): (a) 0%, (b) 5%, (c) 10%, (d) 15%, and (e) 20%.

Journal of Applied Polymer Science

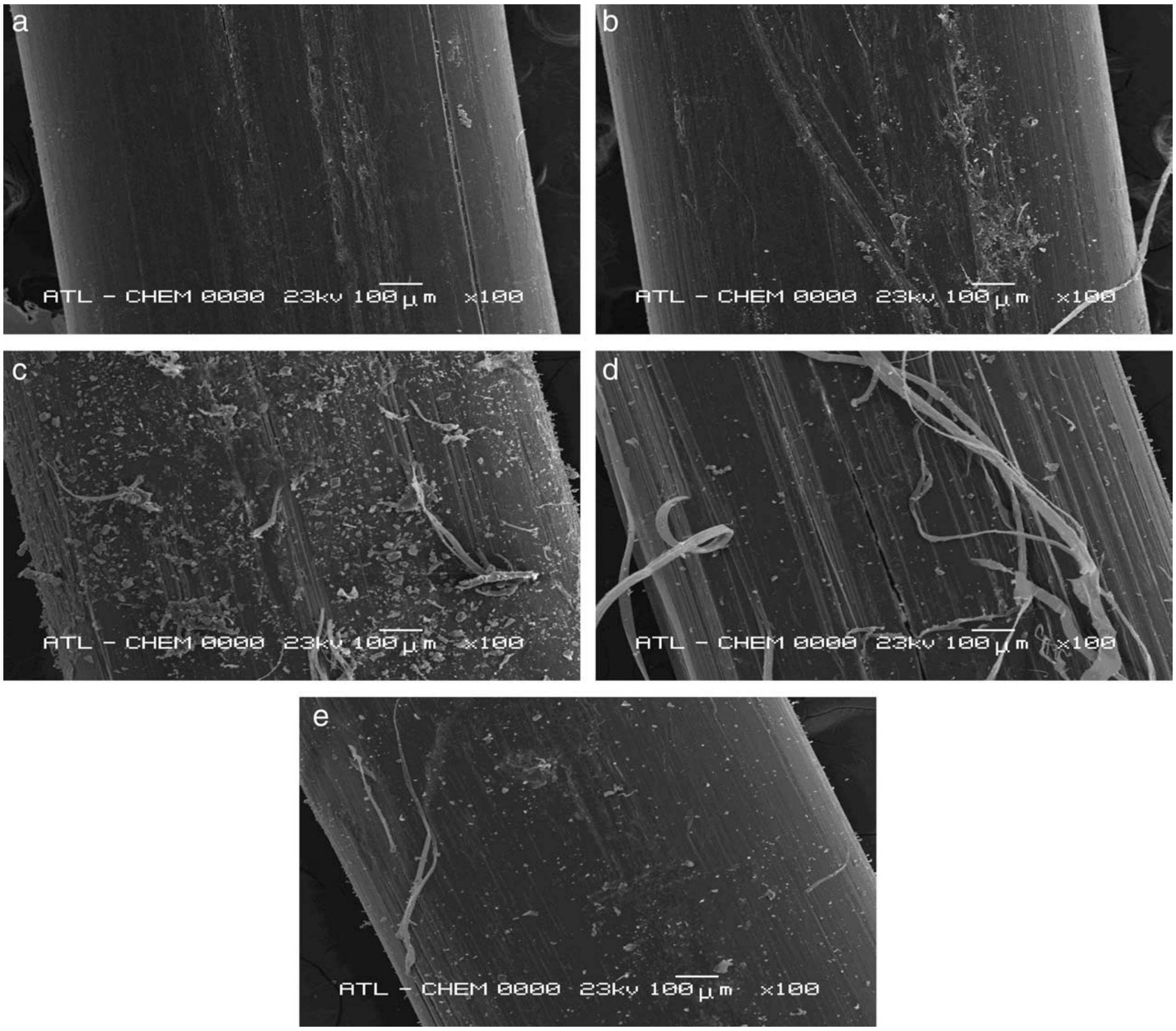

Figure 6. SEM investigation of SPF surface in FA HFRLMCC with latex contents (wt %): (a) 0%, (b) 5%, (c) 10%, (d) 15%, and (e) 20%.

Interface toughness is affected by the debonded zone after cracking, indicating that interface toughness can be improved by improving the debonded zone. The pullout of SPF in the debonded zone can be controlled by the bonding mechanism discussed above for NSPF. However, attempts to improve interface toughness may be hindered if fiber balling occurs. This study showed that the addition of latex improved the dispersion of fibers by improving the initial workability; increased latex content resulted in further improvement of interface toughness. However, when the latex content reached 20%, interface toughness decreased. Interface toughness improved with latex content up to 15% because fiber dispersion was enhanced by NSPF bonding during SPF pullout. However, when the latex content reached 20%, the interface toughness of SPF and HFRLMCC or NSPF and HFRLMCC decreased because of adsorption of latex on cement particles, which delayed the hydration reaction and facilitated pullout at the interface.

Relative Bond Characteristics

The effect of latex content on the bond characteristics of HFRLMCC and SPF was evaluated. The relative bond characteristic was determined using eq. (2),[18]

$$b_R = \frac{b_{\max}}{\sqrt{f_T}} \tag{2}$$

where b_R is the relative bond characteristic (relative bond strength: τ_R; relative interface toughness: IT_R), $b_{\max}$ is the maximum bond characteristic (bond strength: $\tau_{\max}$; interface toughness: $IT_{\max}$), and f_T represents flexural strength.

The relative bond characteristics are presented in Table VI. Bond strength and interface toughness increased with latex content, regardless of flexural strength. The relative bond strength and interface toughness increased with latex content up to 15% in the HFRLMCC. These results were similar to those for bond strength and interface toughness, indicating that increased latex improves the bond characteristics of HFRLMCC and SPF.

Microstructure Analysis

This study examined the microstructure of SPF by observing the fiber surface after pullout tests. Figures 5 and 6 show scanning electron microscopy (SEM) images of the SPF surfaces after the pullout test for the plain and FA HFRLMCC. The images show that the amount of scratches on the surfaces of SPF increased with latex content up to 15% but decreased slightly at 20%. Figure 5(a) shows little scratching on the fiber surface, implying almost no generation of frictional forces, in the case of 0% added latex. In contrast, Figure 5(b), which pertains to the case in which 5% latex was added, shows partial scratching of the fiber surface. Figure 5(c) shows that the scratches are deeper. Figure 5(d) shows the commencement of fiber tearing. Figure 5(e) shows a slight reduction in tearing along with a reduction in the amount of scratches. Figure 6(a) shows only slight scratching on the fiber. Figure 6(b) shows some scratches on the fiber surface. Figure 6(c) shows that the scratches on the fiber surface have started to spread over the fiber surface; some fiber tearing is also evident. Figure 6(d) shows that scratching and tearing due to frictional forces cover the entire fiber surface. Figure 6(e) shows some scratches and tears on the fiber. These SEM results for the SPF are consistent with the bond performance results. Latex (up to 16%) improves the bond behavior of SPF in HFRLMCC by strengthening the interface; it also provides pullout resistance by enhancing the dispersion of NSPF. Thus, the number of surface scratches increased because the effects of latex resist the pullout of SPF. In contrast, when latex content reached 20%, the delayed hydration reaction decreased the interface toughness between SPF and the HFRLMCC or between NSPF and the HFRLMCC; thus, there were fewer surface scratches.

CONCLUSIONS

This study evaluated the effect of latex content on the pullout behavior of SPF in HFRLMCC containing a blend of SPF and NSPF. A bond test was performed using a dog-bone specimen in accordance with JCI SF-8. Microstructure analysis of SPF surfaces offered insight into the pullout mechanism. The results are summarized as follows:

1. The bond strength of SPF in HFRLMCC containing a blend of SPF and NSPF increased with latex content up to 15% but decreased when the latex content reached 20%. The formation of latex films and the addition of reinforcing fibers improved the tensile strength of the cement-based composite. However, when the latex content reached 20%, the latex film adsorbed onto the cement particles delayed hydration and decreased the bond strength and flexural strength.
2. The interface toughness of SPF increased with latex content up to 15%. The addition of latex increased the bond strength between materials because of the formation of latex films and enhanced the dispersion of NSPF. However, interface toughness decreased when latex content was 20% because extensive adsorption of latex on cement particles delayed the hydration reaction.
3. Analysis of the relative bond strength, excluding the strength-increasing effect, showed that latex improved the bond performance of HFRLMCC made with a blend of SPF and NSPF. The bond strength of SPF increased due to enhanced dispersion of NSPF and increased bonding among the component materials.
4. Microstructure analysis of the SPF surface showed that the amount of scratches and tears on SPF increased with latex content up to 15%.

ACKNOWLEDGMENTS

This study was supported by the CAER (Center for Aquatic Ecosystem Restoration) of Eco-STAR project from MOE (Ministry of Environment, Republic of Korea).

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