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Effect of Styrene-Butadiene Latex on the Bond Performance of Macro Synthetic Fiber in Micro Jute/Macro Synthetic Hybrid Fiber-Reinforced Latex-Modified Cement-Based Composites

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ABSTRACT: This study evaluated the effect of latex content on the pullout behavior of macro synthetic fiber in hybrid fiber-reinforced latex-modified cement-based composites (HFLMCCs). A bond-strength test which utilized dog-bone-shaped test specimens was used to determine the pullout behavior. Micro jute fiber was incorporated at 9.00 kg/m^3 and macro synthetic fiber at 0.45 kg/m^3. Latex was added at 0, 5, 10, 15, 20, and 25% of the binder weight (wt %). Pullout tests showed that latex increased the area of the debonded zone of the pullout load–displacement curve. Bond strength increased with latex content up to 15% in HFLMCCs and decreased when the latex content reached 20%. The interface toughness increased until the latex content reached 20% and decreased when the latex content was 25%. These results were confirmed by microstructural analysis of the macro synthetic fiber surface, which showed that the number of scratches increased due to friction. © 2012 Wiley Periodicals, Inc. J. Appl. Polym. Sci. 000: 000–000, 2012

KEYWORDS: bond behavior; hybrid fiber-reinforced SB latex-modified cement-based composites; macro synthetic fiber; micro jute fiber

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INTRODUCTION

A hybrid fiber-reinforced cement-based composite (HFRCC) reinforced with two different types of fiber exhibits properties that a single-fiber-reinforced cement-based composite does not.[1,2] When a fiber-reinforced cement-based composite is blended with fibers that are physically and mechanically different, durability and mechanical performance improve due to controlled cracking attributable to the properties of each fiber.[3–5] Crack control in HFRCC is affected by the bond behavior of the reinforcing fiber.[6–8] Reinforcing fiber suppresses crack propagation in cement-based composites by fiber bridging, debonding, pullout, and fracture.[6,7,9] For HFRCCs, stress increases because microfibers control the formation and propagation of microcracks, and the flexural performance of cement-based composites increases because macrofibers control the formation and propagation of macrocracks.[1,6,10] However, when hybrid fiber is used in a cement-based composite, the performance of the HFRCC can be reduced because of fiber balling caused by low workability.[6] As a hydrophobic fiber, macro synthetic fiber has the disadvantages of low-bond strength and poor fiber dispersion.[6,11] For water-related structures, in particular, pores can form between the fiber and cement-based composite, reducing the durability of the structure.[11] Recently, styrene–butadiene latex polymer (latex) has been applied to structures requiring watertightness.[12,13] In particular, latex improves the workability and increases the adhesion among materials by forming a film.[12–14] This study evaluated the effect of latex on the bond properties of macro synthetic fiber in HFRCC.

EXPERIMENTAL

Materials

The properties of latex (Dow Chemical Company, USA) are listed in Table I. Latex is a semitransparent, milky liquid containing organic polymer particles such as colloidal microparticles (0.5–5.0 μm diameter). The particles, coated by surfactant, float in the solute, and the surfactant provides spaces in which a single polymer cell forms by the chain mechanism between monomers. The surfactant delays solidification, stabilizing the particles, and increasing the workability at a low water/cement ratio, while the latex particles form a film during hydration. The air voids are filled in such a way that a semicontinuous film attaches to the aggregate surface. As a result, the permeability is degraded, and both the bond and tensile strength increase. The compressive strength of cement-based composites depends on the water/

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

Table II. Physical and Chemical Properties of Cement

				Setting time		Compressive strength (MPa)		
Physical properties	Fineness (cm^2/g)	Density (g/mm^3)	Stability (%)	Initial (min)	Final (min)	3 days	7 days	28 days
	3,200	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 on ignition.

cement ratio; a higher water/cement ratio results in decreased strength and increased shrinkage. The water/cement ratio should be low in order to achieve high strength in a short time with minimum shrinkage. However, this approach decreases the workability. The surface activation mechanism of latex may compensate for the degraded workability resulting from a low water/cement ratio.[12–14] The physical and chemical characteristics of ASTM Type 1 cement, fly ash (FA), and blast-furnace slag (BFS) are shown in Tables II–IV, respectively. The properties of macro synthetic fiber made of polypropylene macro monofilaments are shown in Table V. Micro jute fibers are hydrophilic and widely used in cement-based composites. The properties and shape of the micro jute fibers are presented in Table V and Figure 1.

Mix Proportions

The mix ratios of hybrid fiber-reinforced latex modified cement based composites (HFLMCCs) are shown in Table VI. For the HFLMCC, 0.45 kg/m^3 of macro synthetic fiber and 9.00 kg/m^3 of micro jute fiber were used. Latex was added at 0, 5, 10, 15, 20, and 25% of the binder weight. FA and BFS were added to the cement at a weight replacement ratio of 30%. Macro synthetic fiber and micro jute fiber were used in test specimens to evaluate flexural strength. For bond tests, micro jute fiber was added to test specimens at 9.00 kg/m^3, while a single macro synthetic fiber was embedded in the test specimens according to the Japan Concrete Institute (JCI) SF-8 standard.

Flexural Strength Test

Flexural tests were conducted in accordance with the KS L ISO 679 standard.[15] The mortar prism specimens measured 40 × 40 × 160 mm^3 and were cured in water at 23°C ± 2°C. Each test was performed using six specimens that had been cured for 28 days.

Pullout Test

Pullout tests were conducted in accordance with the JCI SF-8 standard for fiber-reinforced concrete to evaluate pullout performance as a function of latex content.[16] 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. Specimen preparation for the pullout tests is illustrated in Figure 2. The pullout strength of the macro synthetic fiber was calculated using the following eq. (1):

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

where τ_{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 cement-based composites. 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

Table III. Physical and Chemical Properties of Fly Ash

Density (g/mm^3)		Fineness (cm^2/g)			L.O.I. (%)		
2.14		3400			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

Table IV. Physical and Chemical Properties of Blast Furnace Slag

Density (g/mm^3)		Fineness (cm^2/g)			L.O.I. (%)		
2.8		4000–6000			3.0		
Chemical compositions (%)							
SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	MnO	TiO	S
33.1	13.9	0.29	42.4	6.1	0.4	0.96	0.66

Table V. Properties of Macro Synthetic and Micro Jute Fiber

Property	Macro synthetic fiber	Micro jute fiber
Elastic modulus (GPa)	4.7	61
Density (g/mm^3)	0.91	1.26
Fiber length (mm)	30	3
Fiber diameter (mm)	1	0.015
Tensile strength (MPa)	470	510
Surface	Hydrophobic	Hydrophilic

Figure 1. Photo of micro jute fiber. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

can be determined by integrating the area under the pullout curve. The interface toughness is correlated to the fracture energy of HFRCCs, indicating that increased interface toughness in cement-based composites effectively enhances the fracture toughness of the composite materials. In this study, the interface toughness was determined by integrating the area under the pullout–displacement curve. The displacement required to measure the interface toughness in the JCI SF-8 standard is 2.5 mm. The results of the pullout performance tests, including the pullout strength and interface toughness, are presented as mean values of six specimens.

RESULTS AND DISSCUSION

Flexural Strength

The flexural strength as a function of latex content is shown in Figure 3. The flexural strength remained nearly constant up to 15% latex addition. However, at over 20% content, the flexural strength decreased. This is because latex filled the pores inside the cement composite. Latex forms a film around the aggregate and improves flexural strength. However, when the latex content is above 20%, the latex film in the cement paste becomes too thick, limiting the transfer of ions and preventing further cement hydration.[17,18] Latex also inhibits the formation of C_4AH_{13}.[17,18] Thus, the flexural strength decreased at the highest latex contents. Also, the flexural strength of the BFS HFLMCC was higher than that of the FA HFLMCC.

Pullout Behavior

The relationship between the pullout load and displacement vs. latex content is shown in Figure 4. The pullout behaviors of FA and BFS HFLMCCs were similar. The bond behavior of cement-based composites can be divided into two zones: behavior before cracking and after cracking. Before cracking, elastic behavior was observed, i.e., displacement increased as load increased. Pullout occurred when the fiber and cement-based composite separated, or debonded, after cracking. When a reinforcing fiber debonds in a cement-based composite, friction resists the separation. Elastic behavior was observed before cracking, and the elastic zone was affected by the latex content. Formation of the first crack was affected by the tensile strength and tensile stress of the HFLMCC. Increased latex content in HFLMCCs increased tensile strength, and greater tensile stress affected the load at which the first crack occurred. The load at

Table VI. Mix Proportions of HFLMCC with Latex Contents

		Unit weight (kg/m^3)							
No. of mix	W/B[a] (%)	Cement	Water	Fine aggregate	FA	BFS	Macro synthetic fiber	Jute fiber	Latex (weight of binder, wt %)
No. 1									0
No. 2									5
No. 3		424.2			181.8	0			10
No. 4									15
No. 5									20
No. 6	47		285	1363			0.45	9	25
No. 7									0
No. 8									5
No. 9		424.2			0	181.8			10
No. 10									15
No. 11									20
No. 12									25

[a]Binder (cement + FA or cement + BFS).

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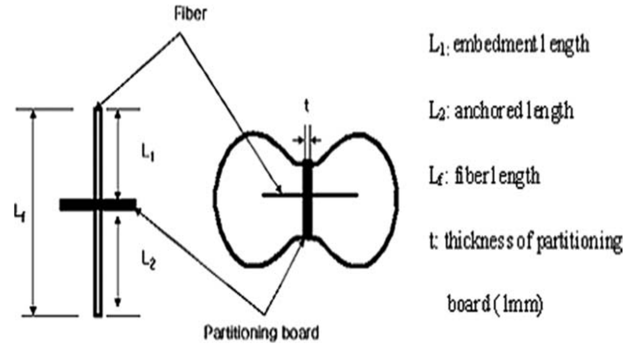

Figure 2. Arrangement of the partitioning board and fibers, and setting in the mold.

first crack increased until the latex content reached 15%. In the debonded zone, after cracking, the pullout load initially decreased for all latex contents. Following this decrease, the load then increased steadily increased with increasing latex content to 20%; the load was lower at 25% than at 20%. As a hydrophilic material containing hydroxyl groups, micro jute fiber reduces workability by adsorbing the mixing water in cement-based composites. Thus, there is concern that HFRCCs will reduce the workability of the material. Fiber balling can occur in HFRCCs due to low workability, reducing the bond performance of the HFRCCs. Latex is a semitransparent, milky liquid containing organic polymer particles. The particles, coated by surfactant, float in the solute, and the surfactant provides spaces in which a single polymer cell forms by the chain mechanism between monomers. The surfactant delays solidification, stabilizing the particles and increasing the workability at a low water/cement ratio. [12–14] Therefore, latex addition increased the dispersion of micro jute fiber by increasing the workability. Well-dispersed micro jute fiber is better than nondispersed micro jute fiber for suppressing the pullout of macro synthetic fibers. Therefore, the bond performance of macro synthetic fiber increased with latex content up to 20%. However, the pullout control of macro synthetic fibers decreased at a latex content at 25% .

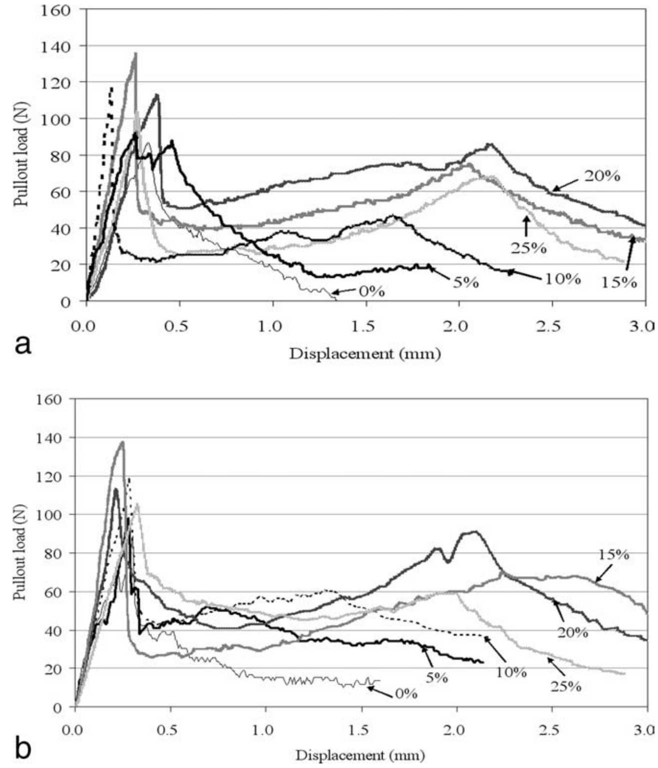

Figure 4. Pullout behavior of macro synthetic fiber in HFLMCC with latex contents: (a) FA and (b) BFS.

Bond Strength

Bond strength vs. latex content is shown in Figure 5. For the FA HFLMCC, the bond strength was 1.847, 1.969, 2.586, 2.943, 2.482, and 2.218 MPa at latex contents of 0, 5, 10, 15, 20, and 25%, respectively. For the BFS HFLMCC, the bond strength was 1.923, 2.098, 2.811, 3.025, 2.525, and 2.290 MPa at latex contents of 0, 5, 10, 15, 20, and 25%, respectively. As a hydrophilic material containing hydroxyl groups, micro jute fiber reduces workability by adsorbing the mixing water in cement-based composites. Thus, there is concern that HFRCC will reduce the workability of the material. Fiber balling can occur in HFRCCs due to low workability, reducing the bond performance of the HFRCC. Latex increases the workability of HFRCC, improves fiber dispersion, and improves bond performance. Latex forms a film that improves bond strength among substances and increases the tensile strength of micro jute fiber in cement-based composites up to 15% latex contents. Therefore, the first crack load and the bond strength increased. Above 20% latex content,

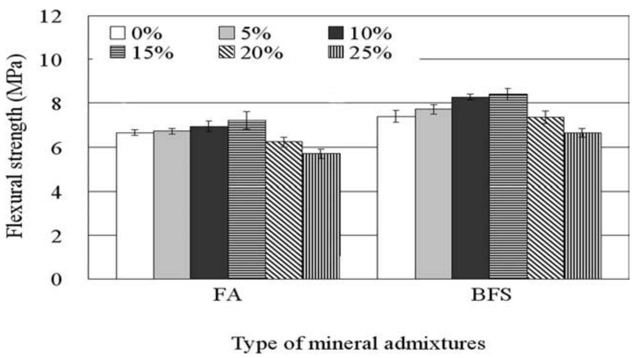

Figure 3. Flexural strength of HFLMCC with latex contents.

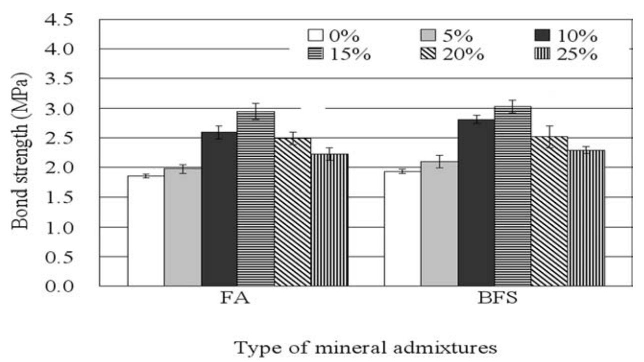

Figure 5. Bond strength of macro synthetic fiber in HFLMCC with latex contents.

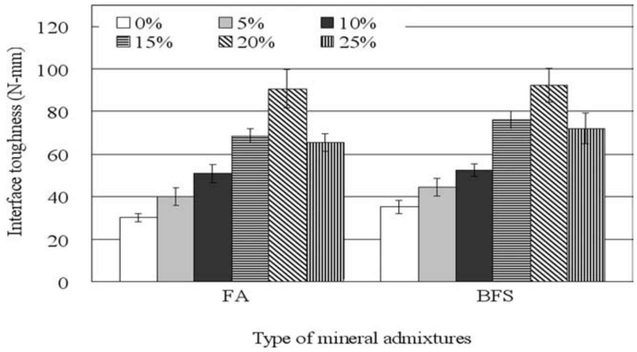

Figure 6. Interfacial toughness of macro synthetic fiber in HFLMCC with latex contents.

fiber dispersion improved but bond strength decreased. This strength reduction was caused by delay of the hydration reaction caused by the latex film in the cement paste. At the higher latex contents, the film becomes too thick, limits the transfer of ions, and restricts the formation of C_4AH_{13}.[17,18] At a given latex contents, the bond strength of the BFS HFLMCC was higher that of the FA HFLMCC because the flexural strength of the former was higher than that of the latter.

Interface Toughness

Interface toughness vs. latex content is shown in Figure 6. For the FA HFLMCC, the interface toughness was 30.197, 39.996, 50.830, 68.733, 90.681, and 65.480 N-mm at latex contents of 0, 5, 10, 15, 20, and 25%, respectively. For the BFS HFLMCC, the interface toughness was 35.267, 44.470, 52.419, 75.921, 92.492, and 72.073 N-mm at latex contents of 0, 5, 10, 15, 20, and 25%, respectively. Interface toughness is affected by behavior in the debonded zone, after the first crack occurs. Therefore, an improvement in the debonded zone corresponds to improved interface toughness. In this study, micro jute fiber was added at 9.00 kg/m^3. Accordingly, the pullout of macro synthetic fibers can be controlled by fiber bonding mechanisms that include fiber bridging, fiber debonding, fiber pullout, and fiber fracture in the debonded zone. However, fiber balling reduces interface toughness. In this study, latex improved fiber dispersion by increasing the initial workability. Interface toughness increased as the latex content increased to 20% but was lower at 25%. This is because the micro jute fibers were well-dispersed at latex contents up to 20%, serving to improve fiber bonding with respect to pullout of the macro synthetic fibers and improving the interface toughness. However, at a latex content of 25%, fiber dispersion improved, but interface toughness decreased because of a delayed hydration reaction caused by the latex film in the cement paste. At this highest latex contents, the film was so thick that it limited the transfer of ions and restricted the formation of C_4AH_{13}.[17,18] This weakened the interface between the macro synthetic fiber and the HFLMCC and between the micro jute fiber and the HFLMCC. Thus, additional cracks formed at the interface. Therefore, the pullout process at 25% latex content was faster than at 20% latex content.

Relative Bond Performance

To investigate bonding properties other than strength, the relative bond characteristic was calculated according to eq. (2)[19]:

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

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

The calculated relative bond performances are given in Table VII. The bond strength and interface toughness were affected by the latex content independent of flexural strength. The relative bond strength increased up to 15% latex, and the relative interface toughness increased up to 20% latex. These trends in relative bond characteristics are the same as those for bond strength and interface toughness. Therefore, regardless of the strength of HFLMCCs, addition of latex was effective at increasing the bond performance of macro synthetic fiber.

Table VII. Relative Bond Performance of Macro Synthetic Fiber in HFLMCC with Latex Contents

Type of mix	Latex contents (%)	Flexural strength (f_T, MPa)	Bond strength ($\tau_{\max}$, MPa)	Relative bond strength ($\tau_{\max}/\sqrt{f_T}$)	Interface toughness ($IT_{\max}$, N mm)	Relative interface toughness ($IT_{\max}/\sqrt{f_T}$)
FA	0	6.65	1.85	0.72	30.20	11.71
	5	6.73	1.97	0.76	40.00	15.41
	10	6.94	2.59	0.98	50.83	19.29
	15	7.21	2.94	1.10	68.73	25.60
	20	6.24	2.48	1.00	90.68	36.30
	25	5.69	2.22	0.93	65.48	27.45
BFS	0	7.40	1.92	0.71	35.27	12.97
	5	7.72	2.10	0.76	44.47	16.00
	10	8.28	2.81	0.98	52.42	18.91
	15	8.42	3.03	1.04	75.92	27.98
	20	7.36	2.51	0.92	92.49	34.09
	25	6.64	2.29	0.89	72.07	27.09

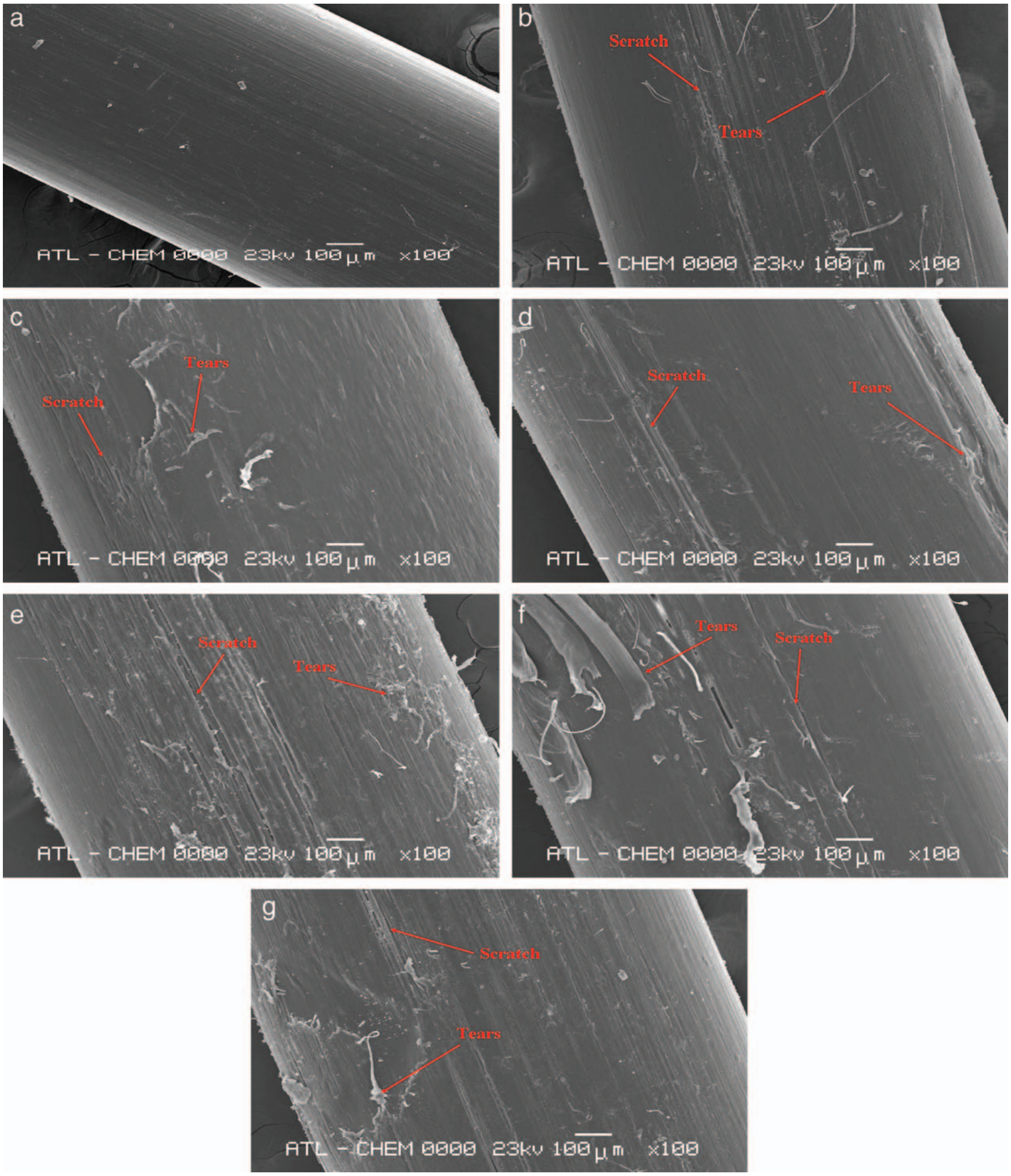

Figure 7. SEM investigation of macro synthetic fiber surface in FA HFLMCC with latex contents: (a) Control, (b) 0%, (c) 5%, (d) 10%, (e) 15%, (f) 20%, and (g) 25%. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Microstructural Analysis

Scanning electron microscopy (SEM) was used to observe the microstructure of macro synthetic fibers surfaces after the pullout test. Figure 7 shows SEM images of a fiber surface after the pullout test as a function of latex content in HFLMCCs containing FA. Figure 7(a) is the surface of a control macro synthetic fiber that was not subjected to a pullout test. It has a clean surface free of scratches and tears in the fiber surface. Figure 7(b) shows a small amount of scratches and marks of tear. Figure 7(c) shows that scratching expanded to the entire surface of the fiber, and the amount of tears increased. Figure 7(d) shows that the area of the fiber surface subject to tearing expanded, and the severity of tearing increased. Figure 7(e) shows still more scratching and tearing; tearing is very severe in Figure 7(f). Figure 7(g) shows a slight reduction in tearing along with a reduction in the depth of the scratches.

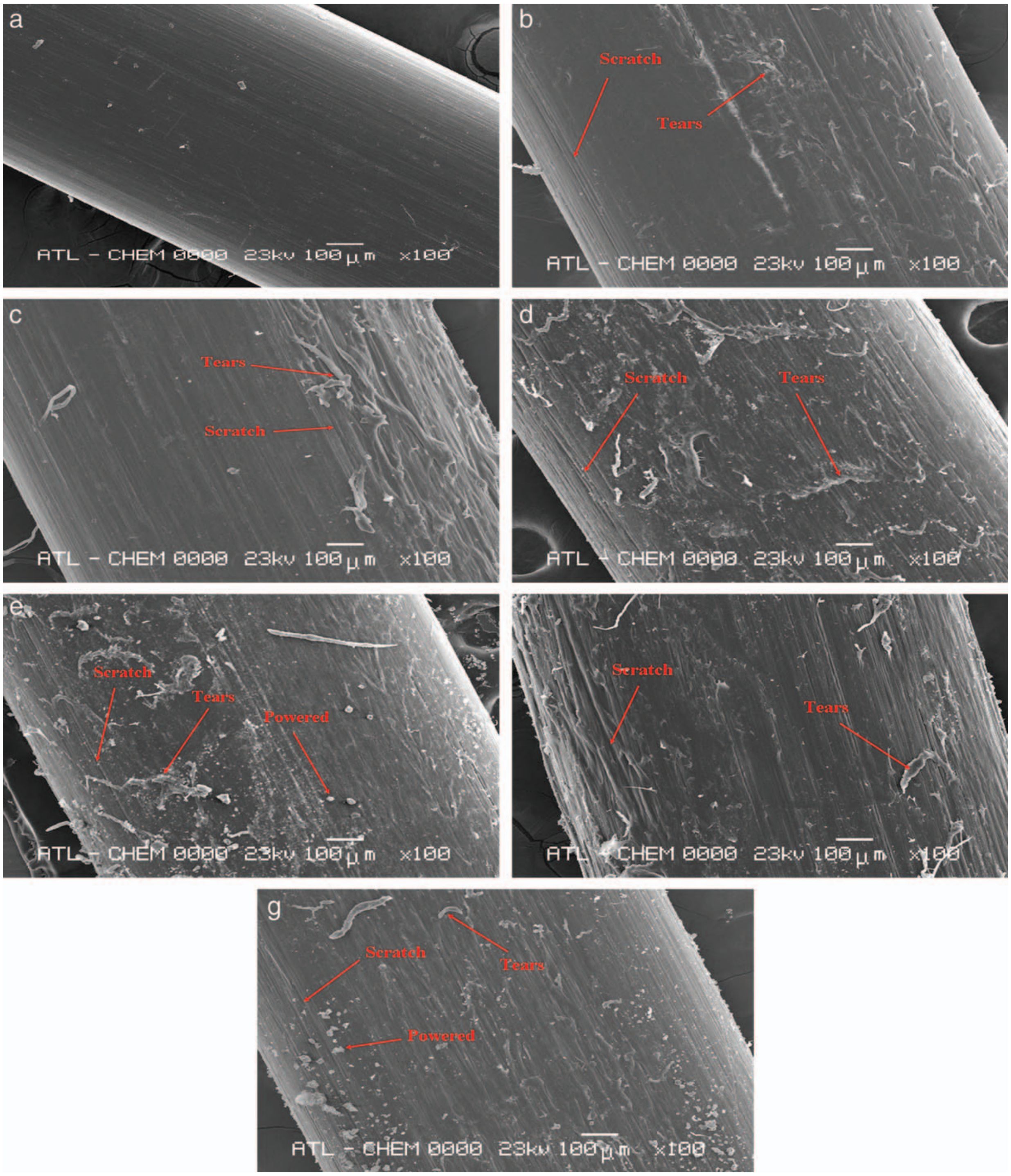

Figure 8. SEM investigation of macro synthetic fiber surface in BFS HFLMCC with latex contents: (a) Control, (b) 0%, (c) 5%, (d) 10%, (e) 15%, (f) 20%, and (g) 25%. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Figure 8 is a series of SEM images of a fiber surface after the pullout test with changing latex content in HFLMCCs incorporating BFS. Figure 8(a) is the surface of macro synthetic fiber that was not subjected to a pullout test and shows a clean surface without scratches or tears of the fiber surface. Figure 8(b) shows some scratches and tears on the fiber surface. Figure 8(c) shows deeper scratches and the amount of tears increased. Figure 8(d) shows that the scratches and tearing extended over the entire surface. The scratching and tearing is more extensive in Figure 8(e), with some powdered HFLMCC present on the fiber surface. Figure 8(f) shows that scratches are deeper, and there is much more tearing. Figure 8(g) shows reduced scratch depth despite widespread scratching over the entire fiber surface; tearing is also less than that in Figure 8(f). Scratching and tearing of the fiber in HFLMCCs occurred during pullout of the macro synthetic fibers. The pullout resistance of the fiber from friction forces and increased as the friction force increases. Enhanced pullout resistance increases interface toughness. The trend in scratch and tear development with increasing latex content thus matches that for interface toughness.

CONCLUSIONS

This study evaluated the effect of latex content on the pullout behavior of macro synthetic fiber in HFLMCCs blended with macro synthetic fiber and micro jute fiber. Bond strength was measured using dog-bone test specimens compliant with JCI SF-8. The pullout behavior mechanism of macro synthetic fibers in HFLMCCs was evaluated via microstructural analysis of macro synthetic fiber surfaces after the pullout test. The conclusions are as follows:

1. The bond strength of macro synthetic fiber in HFLMCC blended with both macro synthetic fiber and micro jute fiber increased up to 15% latex content and then decreased at higher contents. Formation of a latex film increased the bond strength of HFLMCCs, as well as the load at which the first crack occurred during the pullout test of the macro synthetic fiber. However, at above 20% latex content, the hydration reaction was delayed because of thickening of the latex film in the cement paste. As a result, both flexural strength and bond strength decreased.
2. The interface toughness of macro synthetic fiber increased with latex content up to 20% but was lower at 25%. This was because interface toughness is affected by the debonded zone, and increased latex content improved the dispersion of micro jute fiber and controlled the pullout behavior of macro synthetic fiber by micro jute fiber bridging, debonding, fracture, and the pullout effect. At a latex content of 25%, the effect of the retardation of the hydration reaction was more important than the dispersion effect, reducing interface toughness.
3. The trend in relative bond performance was similar to those for bond strength and interface toughness with changing latex content. Latex addition improves bond performance of macro synthetic fiber independent of the increase in the strength of HFLMCCs.
4. The surface microstructure of a macro synthetic fiber was examined after a pullout test. Scratches and tearing were generated by friction at the interface of HFLMCCs during pullout of the macro synthetic fiber. The trend in severity of these defects changed with latex level and matched the trend for interface toughness. Latex improved the bond performance by increasing friction during pullout of macro synthetic fibers.

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