Effect of Styrene Butadiene Latex Polymer Contents on the Bond Properties of Macro Polypropylene Fiber in Polymer-Modified Cement-Based Composites

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ABSTRACT: Because of its hydrophobicity, macro polypropylene (PP) fiber does not bond well in cement-based composites and can reduce the mechanical properties. This study evaluated the influence of styrene–butadiene latex polymer (0–25 wt %) on the bonding of macro PP fiber in these composites. Bond strength was determined using dog-bone test specimens compliant with JCI SF-8. The bond strength of macro PP fiber improved with increasing styrene–butadiene latex polymer (latex) content up to 15%. The elastic behavior of the precrack zone increased, and interface toughness increased because the debonded zone was strong after crack formation. For latex content above 20%, the latex retarded the hydration reaction due to the absorption of latex into cement particles. This resulted in bond strengths that were lower than those for composites prepared with up to 15% latex content. Microstructural analysis of the macro PP fiber revealed that the amount of scratches also increased with increasing latex content up to 15%. © 2012 Wiley Periodicals, Inc. J Appl Polym Sci 000: 000–000, 2012

Key words: bond behavior; cement-based composites; interface toughness; macro polypropylene (PP); fiber; styrene–butadiene latex polymer (latex)

INTRODUCTION

Cement-based composites are generally brittle and have low tensile strength, energy absorption capacity, and crack resistance.[1] For this reason, a reinforcing fiber is typically added to overcome these problems.[2–4] Cracks can develop during the degradation of cement-based composites, but the reinforcing fiber prevents brittle fracture and induces ductile fracture by controlling the energy absorption capacity through a bridging action.[1,5–7] The energy absorption capacity of fiber-reinforced cement composites is determined by the bonding mechanism between the fiber and the cement-based composite. These mechanisms include fiber bridging, debonding, pullout, and fiber fracture.[8–11] The energy absorption capacity of a cement-based composite is also influenced by the bonding mechanisms of the individual fibers.[12,13] Fiber bonding affects the entire energy absorption capacity at the interface during crack propagation.[1,2,14,15] Accordingly, the bonding between the fibers and the cement-based composite strongly influences crack propagation.[1,13] The bonding behavior of fiber-reinforced cement composites is highly influenced by the shape and surface properties of the fiber.[3,4,9,12,14] In general, there are two approaches to improve the bonding characteristics of the fiber.[2,13,15] The first is mechanical improvement using fibers having crimped, hooked, and twisted shapes.[4,5,9] The second is chemical treatment to improve the hydrophilicity of the fiber surface and thereby improve compatibility with the matrix.[2,12,15]

Because of its good mechanical and chemical properties, easy processing and low cost polypropylene (PP) is widely used in industry as a reinforcing fiber for cement-based composites, moldings, packaging films, and automotive components.[1] PP is a nonpolar material, and thus has poor affinity for polar macromolecules, such as nylon and polyester, and also for inorganic fillers.[1] Many of the difficulties in using PP in cement-based composites stem from the fiber's hydrophobicity.[1,2,15] Synthetic fibers such as macro PP fiber are being evaluated as a way to improve the corrosion resistance of structures such as dams and waterways.[9,10,13] Hydrophobic macro PP fiber reduces the durability of cement-based composites because of the presence of many voids located at the interface between the fiber and the matrix.[9,10] The bonding properties of macro PP fiber in cement-based composites must be improved for broader use in water-related applications.[9,10]

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TABLE I
Properties of Latex

Solids content (%)	Styrene content (%)	Butadiene content (%)	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

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

Styrene–butadiene latex polymer (latex) has been used in various cement-based composites requiring watertightness.[16–18] Latex is a milky semi-transparent liquid containing surfactant-coated organic polymer particles (0.5–5 μm in diameter). The surfactant stabilizes the particles, delays solidification, and increases the workability at a low water/cement ratio, while the latex particles form a film during hydration. A semi-continuous film forms on the surface of aggregate and thereby fills the air voids. As a result, the permeability is reduced, but both the bond and tensile strengths increase. The strength of cement-based composites depends strongly on the water/cement ratio; a higher ratio results in decreased strength and increased shrinkage. The water/cement ratio should be as low as possible to achieve high strength in a short time with minimum shrinkage. However, the workability is poorer at low water/cement ratios. The surfactants present in the latex may improve workability.[16–18]

This study examined the bonding performance of macro PP fiber in cement-based composites. The effect of latex content was the focus of the study.

MATERIALS AND METHODS

Materials

The properties of the latex (Dow Chemical Company, Midland, Michigan, USA) are given in Table I. 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. PH-200 maleic anhydride-grafted polypropylene (mPP) was obtained from the Gum-ho Company (Republic of Korea). The shape of the macro PP fiber is straight and has a smooth surface. Also, the properties of macro PP fiber made of non-corrosive PP macro monofilaments are shown in Table V.

Mix proportions

The mix ratios of the latex-modified cement-based composites (LMCC) are shown in Table VI. Latex was added at 0–25% of the binder (cement + mineral admixtures) weight. FA, BFS, and mPP were added to the cement at weight replacement ratios of 30, 30, and 3%, respectively.

TABLE III
Physical and Chemical Properties of FA

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 BFS

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 PP Fiber

Properties	Macro PP fiber
Elastic modulus (MPa)	4.7×10^3
Density (g/mm^3)	0.91
Fiber length (mm)	30
Fiber diameter (mm)	1
Tensile strength (MPa)	470
Surface	Hydrophobic

Flexural strength test

Flexural tests were conducted in accordance with the KSL ISO R 679 standard.[19] The test specimens measured 40 mm × 40 mm × 160 mm and were cured in water at (23 ± 2)°C. Each test was performed on six specimens that had been cured for 28 days.

Bond behavior

Pullout tests were conducted in accordance with the Japan Concrete Institute (JCI) SF-8 standard for fiber-reinforced concrete. The pullout test specimens were prepared as described in the JCI SF-8 standard.[20] The pullout tests were performed using a 50-kN universal testing machine at a displacement rate of 0.5 mm/min in the displacement-controlled mode. Figure 1 shows the preparation of the specimens. The pullout strength of the macro PP fiber was calculated as follows:

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

where $\tau_{\max}$ 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 critical to enhancing the ductility of reinforcing fibers in cement-based composites. Reinforcing fibers inhibit crack propagation by transferring a constant tensile stress after crack formation, thereby preventing brittle failure. The interface toughness is also an important factor that determines the behavior of the 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. The pullout toughness defined in this way correlates with the fracture energy of the fiber-reinforced cement-based composite. Increased interface toughness in a cement-based composite effectively increases the fracture toughness of the composite. In this study, the interface toughness was determined by integrating the area under the pullout–displacement curve. The displacement required to measure the interface energy in the JCI SF 8 standard is 2.5 mm. The results of the pullout performance tests, including the pullout strength and the interface toughness, are presented as the mean values for six specimens.

RESULTS AND DISCUSSION

Flexural strength

The flexural strength test results are shown in Figure 2. The flexural strength increased with increased latex content. The flexural strength decreased the latex content at 20%. The latex filled the pores within the cement-based composite, improved adhesion between the various materials, and created a film around the aggregate. At higher latex contents (≥20%), the hydration reaction was delayed because of the adsorption of latex particles onto the cement particles. The retardation of the hydration reaction was more significant than the improvement in adhesion caused by the film formation, and thus the strength decreased.

TABLE VI
Mix Proportions of LMCC with Latex Contents

No. of mix	W/B (%)	Cement (kg/m^3)	Water (kg/m^3)	Fine aggregate (kg/m^3)	FA (kg/m^3)	BFS (kg/m^3)	mPP (kg/m^3)	Latex (weight of binder, wt %)
No. 1	47	424.2	285	1363	181.8	0	18.2	0
No. 2								5
No. 3								10
No. 4								15
No. 5								20
No. 6								25
No. 7					0	181.8		0
No. 8								5
No. 9								10
No. 10								15
No. 11								20
No. 12								25

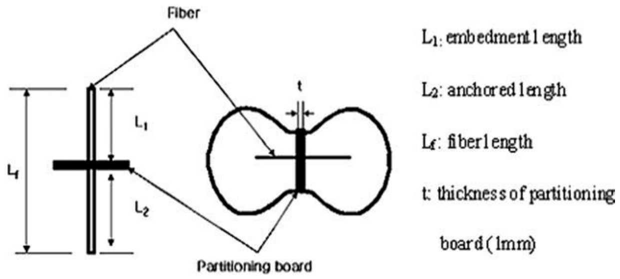

Figure 1 Arrangement of the partitioning board and fibers, and setting in the mold.

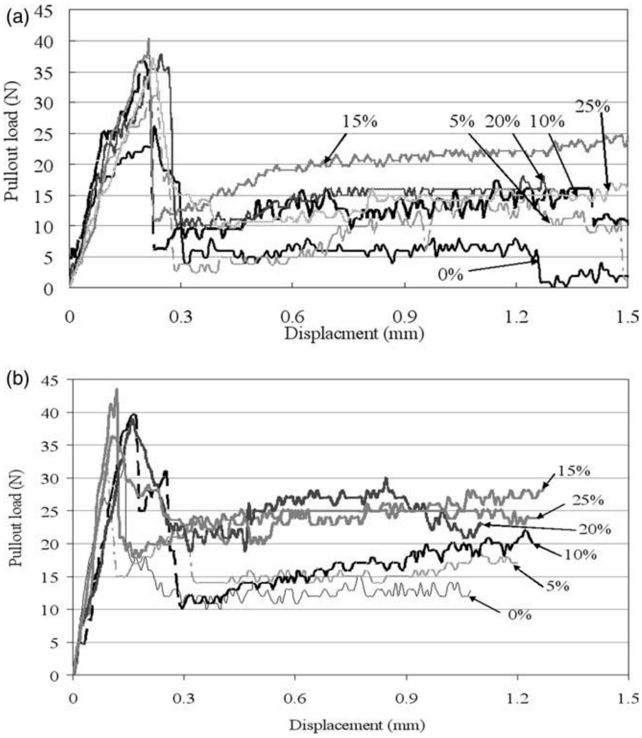

Figure 3 Pullout behavior of macro PP fiber in LMCC: (a) FA and (b) BFS.

Pullout behavior

The relationship between the pullout load of the macro PP fiber and displacement as a function of latex content is shown in Figure 3. The bonding behavior of the reinforcing fiber can be discussed in terms of the load–displacement behavior before cracking (precrack zone) and after cracking (debonded zone). Before the onset of cracking, the load–displacement curve showed elastic behavior. Pullout occurred when the fiber and the cement-based composite became debonded. Frictional forces resist separation when a reinforcing fiber becomes debonded in a cement-based composite. This study observed nearly elastic behavior before the onset of cracking and separation of the fiber from the cement-based composite after cracking. Adding latex fills the pores inside a cement-based composite and creates a latex film around the aggregate, thereby increasing both the tensile strength of the cement-based composite and the bond strength between the fiber and the cement-based composite. Increasing the latex content in both FA LMCC and BFS LMCC increased the tensile stress at crack formation. However, latex content more than 20% delayed the hydration reaction because of adsorption of latex particles onto the cement particles. For this reason, the tensile strength of the cement-based composites and the tensile stress at crack formation decreased, reducing the elasticity of the precrack zone. Bonding in the debonded zone, where the cement-based composite had separated from the fiber after cracking, improved with increasing latex content. For the FA LMCC, the load decreased rapidly after cracking and increased slightly in the debonded zone, ultimately leading to separation. Also, the displacement was relatively large compared to that of the BFS LMCC. For the BFS LMCC, the load decreased to a lower value than that of the FA LMCC after cracking, maintained a constant value, and decreased further. Also, the displacement was relatively small compared to that of the FA LMCC. The flexural strength of the BFS LMCC was greater than that of the FA LMCC; hence, separation of the fiber from the matrix (debonding) occurred more slowly for the BFS LMCC. The load increased with increasing latex

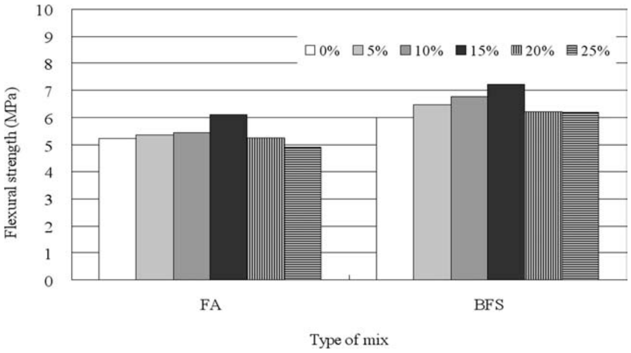

Figure 2 Flexural strength of LMCC.

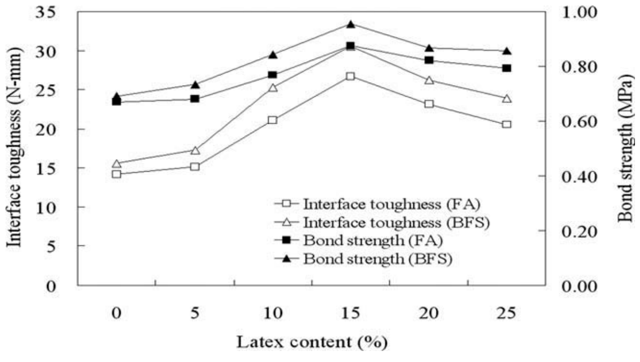

Figure 4 Bond strength and interface toughness of macro PP fiber in LMCC.

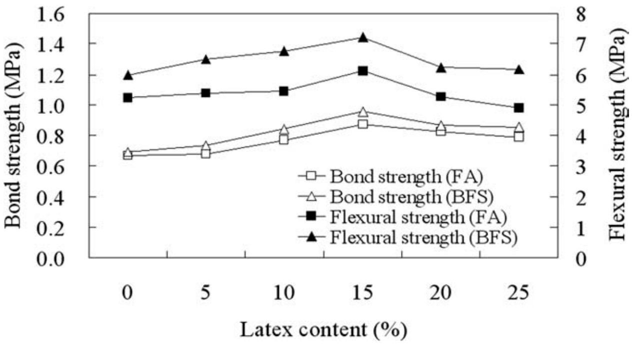

Figure 5 Relationship between flexural strength and bond strength of macro PP fiber with latex contents.

content until 15% substitution for FA and BFS, because the latex film increased the friction and hindered fiber pullout. Pullout progressed more rapidly for specimens containing more than 20% latex compared to those containing 15% latex.

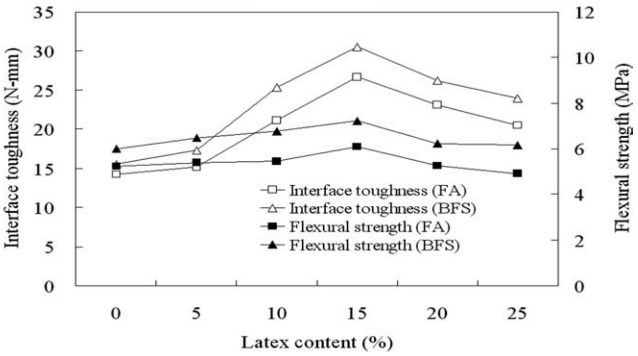

Figure 6 Relationship between flexural strength and interface toughness of macro PP fiber with latex contents.

Bond strength and interface toughness

The bond strength as a function of latex content is shown in Figure 4. For the FA LMCC, bond strengths were 0.67, 0.68, 0.77, 0.87, 0.82, and 0.79

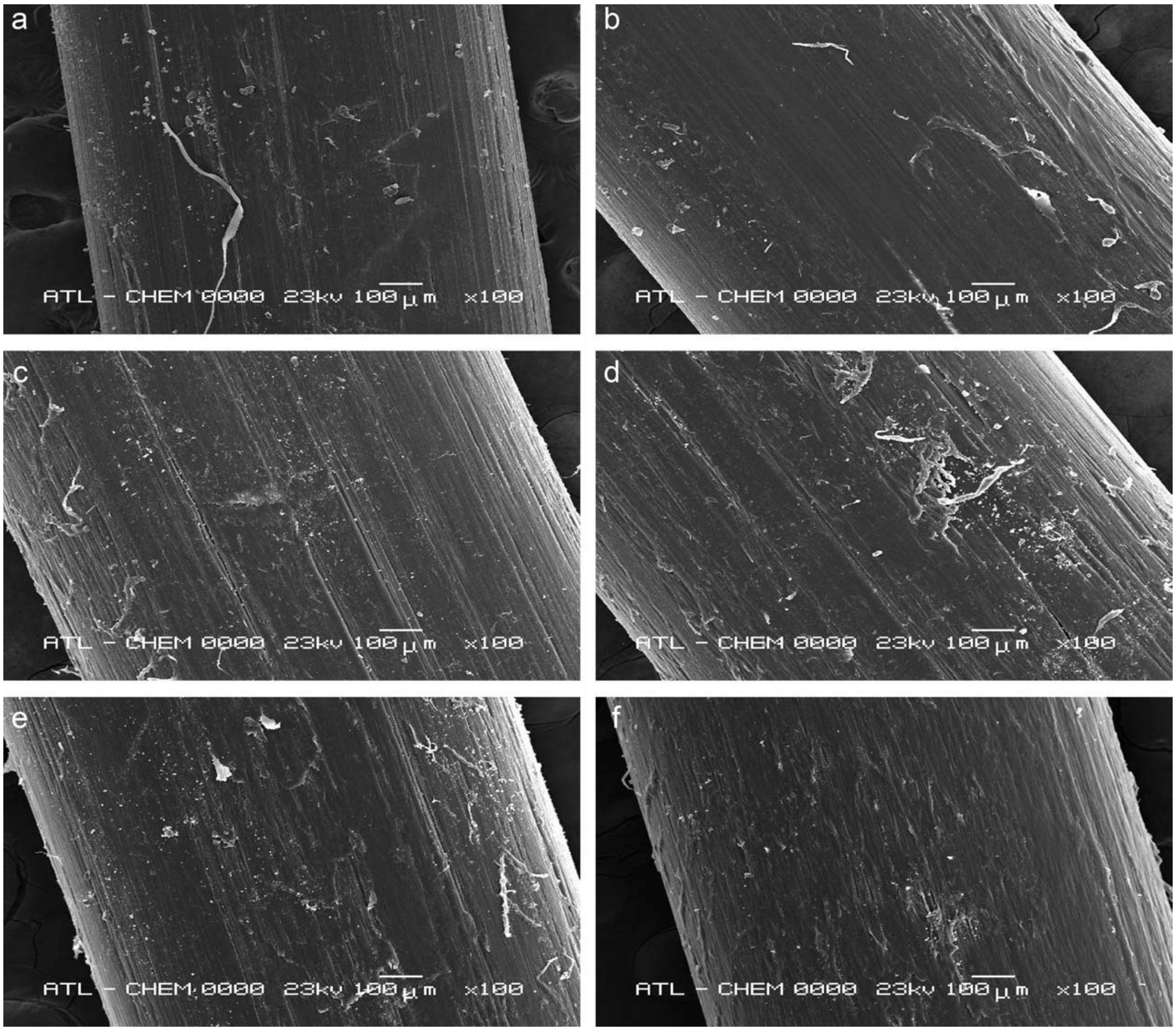

Figure 7 SEM investigation of macro PP fiber surface in FA LMCC with latex contents: (a) 0%, (b) 5%, (c) 10%, (d) 15%, (e) 20%, and (f) 25%.

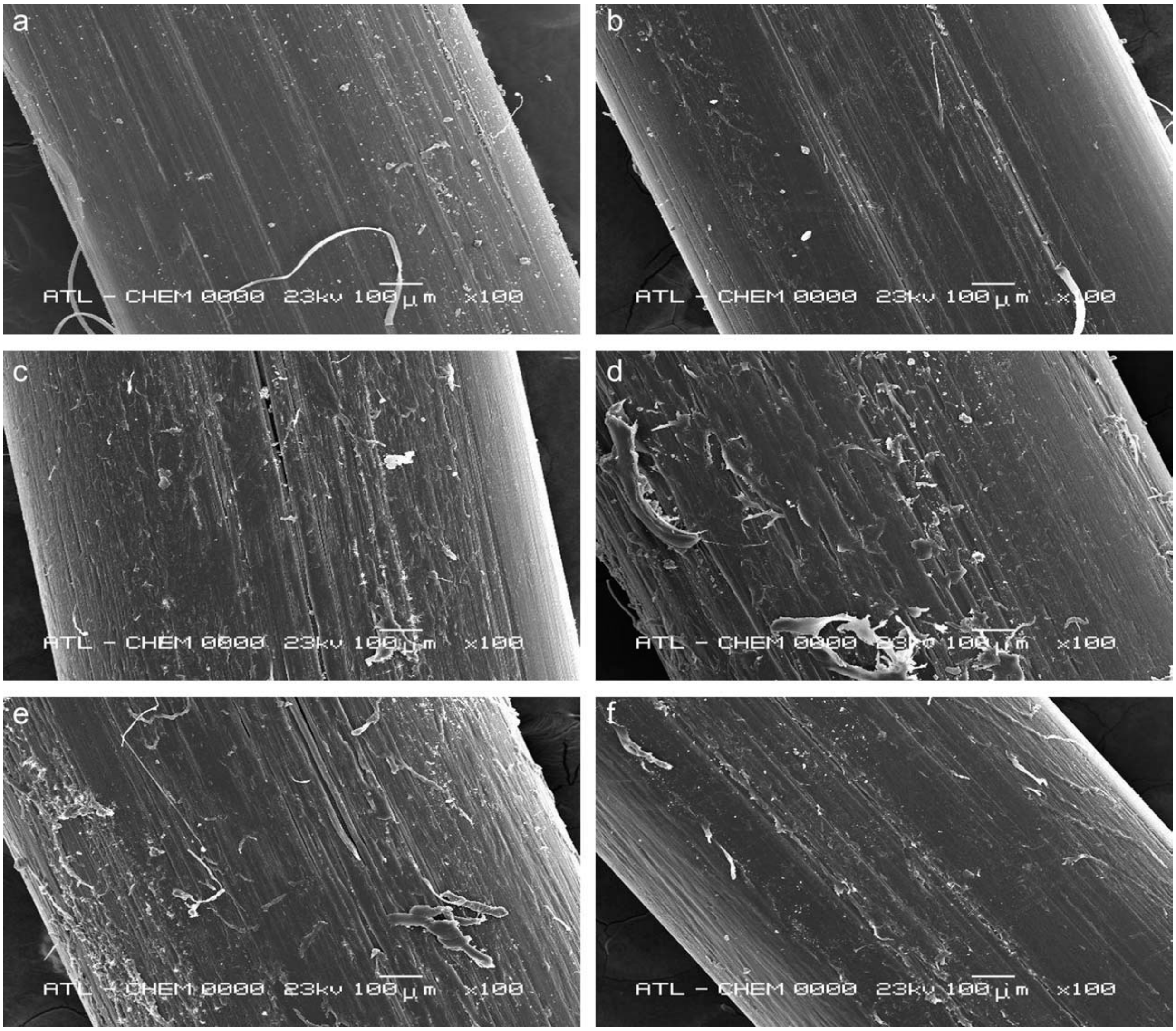

Figure 8 SEM investigation of macro PP fiber surface in BFS LMCC with latex contents: (a) 0%, (b) 5%, (c) 10%, (d) 15%, (e) 20%, and (f) 25%.

MPa for latex contents of 0, 5, 10, 15, 20, and 25%, respectively. For the BFS LMCC, bond strengths were 0.69, 0.73, 0.84, 0.96, 0.87, and 0.86 MPa, respectively. As the latex content increased, the latex film thickness also increased, and adhesion improved between the components. This reduced crack formation at the interface between the macro PP fiber and the cement-based composite as well as the tensile strength of the cement-based composite. For specimens containing more than 20% latex, the hydration reaction and strength development were also delayed. This decreased the bond strength because the interface was weaker. Also, the macro PP fiber in the BFS LMCC had higher bond strength than the macro PP fiber in the FA LMCC, and the BFS LMCC had higher flexural strength than the FA LMCC.

The change in interface toughness with latex content is shown in Figure 4. The interface toughness of the FA LMCC having latex contents of 0, 5, 10, 15, 20, and 25% was 14.20, 15.16, 21.11, 26.71, 23.12, and 20.53 N mm, respectively. For the BFS LMCC with latex contents of 0, 5, 10, 15, 20, and 25%, the interface toughness was 15.53, 17.31, 25.32, 30.50, 26.24, and 23.94 N mm, respectively. The interface toughness was greater for the BFS LMCC than for the FA LMCC at the same latex content. Similar behavior was observed for flexural strength. Interface toughness is influenced by the debonded zone at the interface between the macro PP fiber and the cement-based composite after cracking. In this study, the interface toughness increased with latex content up to 15% because the bond strength between the fibers and the cement-based composite increased due to more extensive latex film formation. Rapid debonding did not occur as a consequence. However, for specimens containing more than 20% latex, film formation delayed the hydration reaction and reduced the friction at the interface. The flexural and bond strengths were greater for the BFS LMCC than for the FA LMCC; higher friction during pullout of the macro PP fibers reduced the load slightly after cracking.

Relationship between flexural and bond performance

Figure 5 shows the relationship between flexural and bond strengths. Figure 6 shows the relationship between flexural strength and interface toughness. Flexural strength, bond strength, and interface toughness showed similar trends with changing latex content: they all increased until 15% latex and decreased thereafter. Latex content of 15% is most effective at improving the pullout behavior of macro PP fiber in the cement-based composites. The BFS LMCC had superior flexural strength, bond strength, and interface toughness compared with the FA LMCC at the same latex content. BFS is thus more effective than FA at increasing flexural and bond performance.

Microstructural analysis

Scanning electron microscopy (SEM) was used to study the surface microstructure of macro PP fibers after pullout. Figures 7 and 8 show SEM images of the surface of a macro PP fiber after pullout from the LMCC. As the latex content increased, more scratches were observed on the fiber surfaces. But, the scratches on the fiber surfaces decreased the specimens containing more than 20%. This was consistent with the trends for interface toughness and bond strength: higher latex content improved the bonding between the macro PP fiber and the cement-based composite. Additionally, the BFS LMCC became scratched more easily than the FA LMCC. This result is consistent with the trends for flexural strength, bond strength, and interface toughness.

CONCLUSIONS

This study evaluated the bonding of macro PP fiber in cement-based composites with latex content. The pullout behavior of macro PP fiber was evaluated through pullout test and microstructural analysis of fiber surfaces. The results were as follows:

1. Up to a latex content of 15%, the elasticity of the pullout behavior of macro PP fiber increased in the precrack zone and the debonded zone. This is because latex filled the pores and created a film, thereby improving the bonding between the components. For specimens containing more than 20% latex, adsorption of latex particles onto the cement particles delayed the hydration reaction and reduced the elasticity of the precrack zone and the debonded zone.
2. The test results showed that both bond strength and interface toughness increased until 15% latex content. This is because the latex filled the pores and created a film that improved bond strength between the components as well as increased the friction during pullout. For specimens containing more than 20% latex, the bond strength and interface toughness decreased because of a delay in the hydration reaction.
3. The relationship between bond strength and flexural strength was similar to that between flexural strength and interface toughness for macro PP fiber. Latex addition improved the bond strength between the components by forming a film. This also improved bonding and thereby increased the flexural strength.
4. Microstructural analysis of the surface of macro PP fibers following the pullout test showed scratches on the fiber surfaces. These scratches were attributed to friction during pullout. The number of scratches increased with increasing latex content up to 15% due to increasing friction during pullout. The bond strength and interface toughness also increased with increasing latex content up to 15%. This confirmed that latex improved the bonding of macro PP fiber in the cement-based composites.

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