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Strength, Permeability, and Durability of Hybrid Fiber-Reinforced Concrete Containing Styrene Butadiene Latex

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ABSTRACT: Hybrid fiber-reinforced concrete (HFRC) is examined in this study. Two types of synthetic fibers were considered: polyvinyl alcohol fiber/macro synthetic fiber (PVA/MSF) and polypropylene fiber (PP)/MSF. Styrene butadiene latex was added at 0%, 5%, 10%, and 15% of the cement weight. Tests carried out for the study included compressive strength, flexural strength, chloride ion penetration, abrasion resistance, and impact resistance. The results demonstrated that higher latex contents improved the dispersibility of the fibers because of the increased workability of the HFRC and the improved adhesion. Formation of a latex film improved the strength, permeability resistance, abrasion resistance, and impact resistance. PVA/MSF HFRC had better properties than PP/MSF HFRC. This was attributed to stronger hydrogen bonding by the hydrophilic PVA fibers, which led to superior resistance to microcracking and crack propagation. © 2012 Wiley Periodicals, Inc. J. Appl. Polym. Sci. 129: 1499–1505, 2013

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INTRODUCTION

Concrete is a brittle material. Fiber-reinforced concrete (FRC), however, is less brittle and has better ductility because of the randomly distributed reinforcing fibers that help to arrest crack propagation.[1,2] The properties of FRC are influenced by the type of reinforcing fiber and its shape, volume fraction, dispersibility, and orientation.[1,2] Single-fiber FRC has traditionally been used, but having a single type of fiber prevents the FRC from reaching its optimal physical and mechanical properties and durability.[3,4] Therefore, blending two or more types of fibers ("hybrid fiber") has been investigated in an attempt to improve the concrete properties.[5,6] Hybrid fiber systems aim to provide a composite with superior properties by capitalizing on the merits of each fiber type.[7–9] Hybrid fiber-reinforced concrete (HFRC) uses fibers having different physical and mechanical properties to suppress cracking and improve the mechanical performance and durability.[10,11] If the volume fraction of the fibers is too high, however, fiber balling may take place, causing poor fluidity, making compaction difficult, and degrading the dispersibility of the fibers.[12,13] When the dispersibility of the fibers deteriorates, the quality of the concrete suffers, which can negatively affect the mechanical properties and structural integrity/durability of a concrete structure. Good dispersibility will help to ensure good fluidity, safeguard the quality of the HFRC, and improve its constructability.[14–16] One way to impart the required fluidity to the HFRC is to increase the water content per unit volume of concrete. This increases the possibility of cracking because of a decrease in the mechanical characteristics and shrinkage arising from an increase in the water/cement ratio.[12,13] An alternative method to increase the fluidity of the HFRC is to use a superplasticizer.[14,15] This additive provides fluidity to the HFRC without increasing the water/cement ratio, and leads to improved dispersibility of the hybrid fibers as well as improved constructability.[15,16] Adding styrene butadiene latex to improve the fluidity of the HFRC is another option. This method is particularly useful at low water/cement ratios.[17] It acts via interactions of the surfactant present in the latex with other components. The formation of a latex film improves the bond strength between materials, which reduces the permeability and improves the mechanical properties.[18,19] This approach further improves the workability without increasing the water/cement ratio, thereby reducing the possibility of cracking due to shrinkage of the concrete.[18,19] This study evaluated the effects of varying the amount of added latex on the various properties of HFRC. Two types of hybrid fibers were considered: polyvinyl alcohol fiber/macro synthetic fiber (PVA/MSF) and polypropylene fiber (PP)/MSF. Slump, compressive strength, flexural strength, chloride ion penetration, abrasion resistance, and impact resistance tests were carried out.

Table I. Properties of Latex

Solids content (%)	Water content (%)	Styrene content (%)	Butadiene content (%)	pH	Density (g/mm^3)	Surface tension (dyn/cm)	Particle size (Å)	Viscosity (cps)
49	51	34 ± 1.5	66 ± 1.5	11.0	1.02	30.57	1700	42

EXPERIMENTAL

Materials

Latex was obtained from Dow Chemical Company (Midland, MI); its properties are listed in Table I. 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 low water/cement ratios, whereas the latex particles form a film during cement hydration. A semi-continuous film forms on the surface of the aggregate and thereby fills the voids. As a result, the permeability is reduced, but both the bond and tensile strengths increase.

The physical and chemical characteristics of ASTM Type 1 cement are shown in Table II. The coarse aggregate had a maximum grain size of 25 mm, and the fine aggregate had a density of 2.62 g/mm^3. Crimped MSF (30 mm long and 1 mm diameter), PVA fiber (6 mm × 0.015 mm), and PP fiber (6 mm × 0.1 mm) were used as the reinforcing fibers. The aspect ratio of the fiber (fiber length/diameter) has a major effect on FRC. As the aspect ratio of the fiber increases, the tensile performance is substantially improved. However, if the aspect ratio is too high, fiber balling can occur and the tensile performance can deteriorate. Hence, there is an optimal aspect ratio for the reinforcing fiber. The crimped MSF, PVA fiber, and PP fiber used in this research were from Nycontech Company (Seoul, Republic of Korea) and had aspect ratios of 30, 60, and 400, respectively. Their shapes and other characteristics are shown in Figure 1 and Table III.

Mix Proportions

Two types of hybrid fibers were used in this study to evaluate the permeability and durability of the HFRC. The HFRC mixes were made using crimped MSF (0.5 vol %) + PVA fiber (0.2 vol %) and with crimped MSF (0.5 vol %) + PP fiber (0.2 vol %). The latex used in this research was a dispersion of 49% solid polymer particles with the balance as water and surfactants. The "total latex addition" noted in Table IV refers to the amount of latex used, i.e., the combined solid and liquid contents. The addition of latex solid polymer particles at 0%, 5%, 10%, and 15% (wt %) increased the amount of cement (488 kg) by 24.4, 48.8, and 73.2 kg, respectively. Also, the amount of water contained at 5%, 10%, and 15% (wt %) added latex levels reduced the mixing water to 25.4, 50.8, and 76.2 kg, respectively. The total amount of water (total water = added water + water from the latex) remained constant for every mix, i.e., 171 kg. Hence, the water/cement ratio was the same for every mix, i.e., 171/488 = 0.35. The various HFRC mix proportions are listed in Table IV.

Slump Test

The slump test was carried out according to the ASTM C143 standard to assess the effect of added latex on the workability.

Compressive Strength Test

Compressive strength tests were performed according to the ASTM C39 standard. Specimens (100 mm × 200 mm) were cured in air for 1 day and then cured in water at 23°C ± 2°C. Each test was performed after 28 days of curing.

Flexural Strength Test

Flexural strength tests were conducted in accordance with the ASTM C78 standard. The dimensions of the test specimen were 100 (width) × 100 (depth) × 400 mm (length), and the test span was 300 mm. Specimens were cured in water at 23°C ± 2°C. Each test was performed after 28 days of curing.

Chloride Ion Penetration Test

Chloride ion penetration tests were conducted in accordance with the ASTM C1202 standard. Specimens (150 mm × 50 mm) were tested after curing for 28 days. The test setup is shown in Figure 2.

Abrasion Test

Abrasion testing was done in accordance with the ASTM C944 standard. Specimens (150 mm × 60 mm) were tested after curing for 28 days. The test setup is shown in Figure 3.

Impact Test

Impact testing was conducted in accordance with the specifications of the ACI Committee 544.[20] Specimens (150 mm × 60 mm) were cured in water at 23°C ± 2°C. Each test was

Table II. Properties of Cement

Physical properties	Fineness (cm^2/g)	Density (g/mm^3)	Stability (%)	Setting time		Compressive strength (MPa)		
				Initial (min)	Final (min)	3 days	7 days	28 days
	3200	3.15	0.02	220	400	20	30	38
	L.O.I[a] (%)			MgO (%)			SO_3 (%)	
Chemical properties	1.5			3.0			2.0	

[a]Loss on ignition.

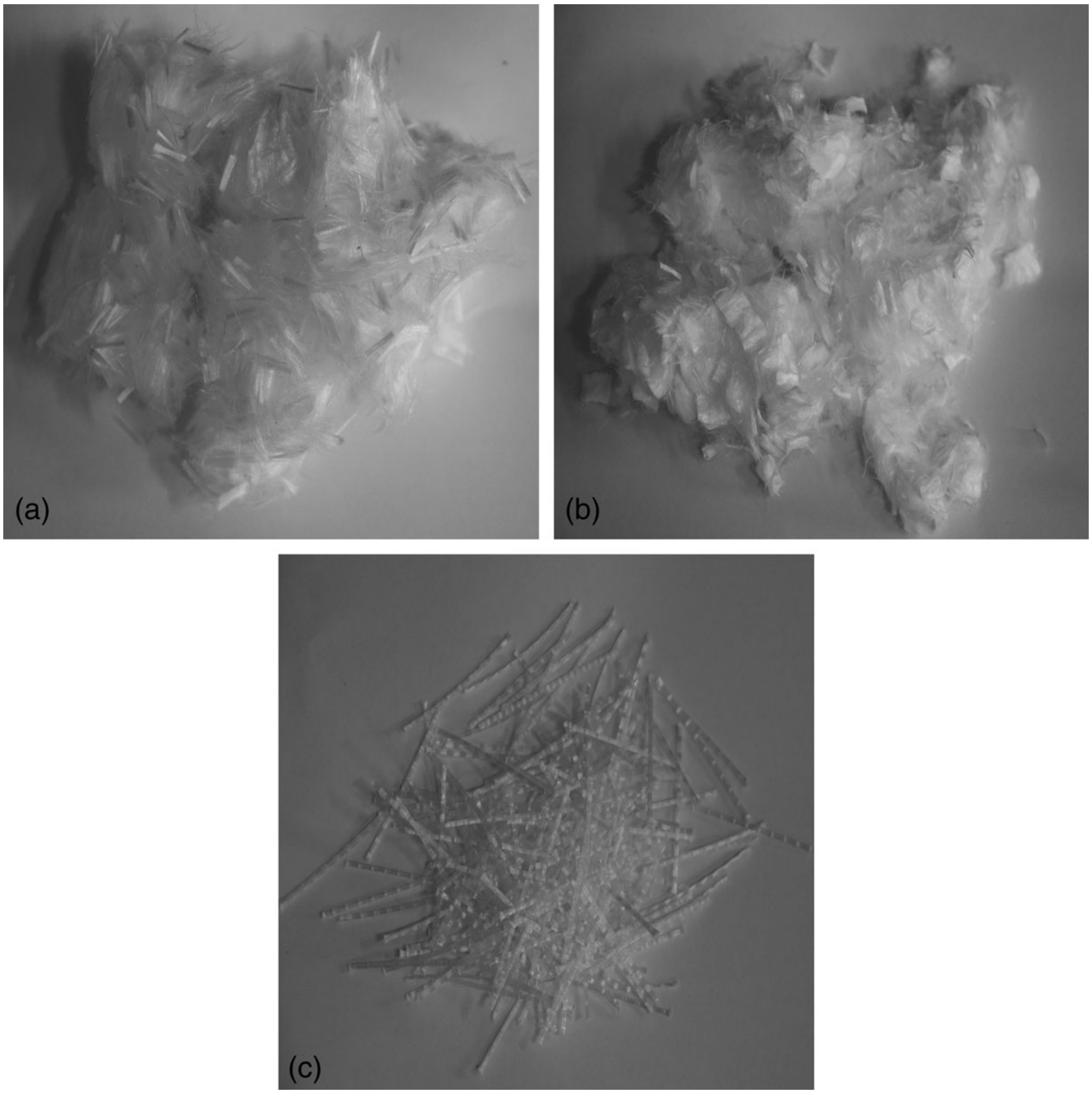

Figure 1. Shape of reinforcing fibers; (a) PP fiber (b) PVA Fiber (c) Macro synthetic fiber.

performed after curing for 28 days. The test setup is shown in Figure 4.

RESULTS AND DISCUSSION

Slump

The degree of slumping varied with the level of added latex (Figure 5). In the absence of latex, the slump was 45–65 mm. The slump value of the HFRC containing hybrid PP/MSF was greater than that containing PVA/MSF. PVA fiber is a hydrophilic material, and it absorbed the mixing water. This resulted in a lower slump for the mix than when PP fiber, a hydrophobic material, was used. This behavior was true at all the latex levels. While the slump values for the 5% latex contents were not significantly higher than those for the 0% contents, the 10% contents had significantly higher slump values than the 5% contents. This was because superplasticizer was added at 0.65 wt % of the cement to ensure some fluidity for the cases lacking latex, and no superplasticizer was used in the cases where latex was added. Therefore, the slump value of a mix with no added

Table III. Properties of Fiber

Properties	PVA fiber	Macro synthetic fiber	PP fiber
Elastic modulus (GPa)	45	10	4
Density (g/mm^3)	1.26	0.91	0.91
Fiber length (mm)	6	30	6
Fiber diameter (mm)	0.015	1	0.1
Aspect ratio	400	30	60
Tensile strength (MPa)	1600	550	600

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Table IV. Mix Proportions of HFRC

			Unit weight (kg/m^3)											
												Latex		
No. of mix	W/C[a] (%)	S/a (%)	Cement	Total water[b]	Water	Fine aggregate	Coarse aggregate	Admixture	PP fiber	PVA fiber	Macro synthetic fiber	Total	Solid	Water
1	0.35	38.28	488	171	171	620	1015	3.22	0	2.52	4.5	0	0	0
2					171			3.22	1.8	0	4.5	0	0	0
3					145.6			0	0	2.52	4.5	49.8	24.4	25.4
4					145.6			0	1.8	0	4.5	49.8	24.4	25.4
5					120.2			0	0	2.52	4.5	99.6	48.8	50.8
6					120.2			0	1.8	0	4.5	99.6	48.8	50.8
7					94.8			0	0	2.52	4.5	149.4	73.2	76.2
8					94.8			0	1.8	0	4.5	149.4	73.2	76.2

[a] Total water/cement.
[b] Water + water from the latex.

latex was, because of the presence of the superplasticizer, almost identical to the mix containing 5% added latex. However, the slump values were much higher when the latex level was 10% or more compared with those mixes containing superplasticizer.

Compressive Strength

The compressive strength decreased with increasing latex content (Figure 6). This behavior was true for all HFRC samples. The addition of latex is known to improve the tensile strength rather than the compressive strength. Latex addition improved the tensile strength because the formation of the latex film improved the bond strength between materials and filled the voids. However, when the latex was used, the latex film that formed around the cement paste prevented the formation of C_4AH_{13} by restricting the movement of ions,[21,22] which reduced the compressive strength by delaying the hydration reaction.[21,22] A sufficiently long curing period can provide a compressive strength that is similar to that of a mix made without latex.[21,22] Therefore, to maintain the compressive strength, a sufficiently long-curing period is necessary.[21,22]

Flexural Strength

The flexural strength results are shown in Figure 7. The addition of latex improves the tensile and flexural strengths of concrete, rather than the compressive strength. This is because the latex film enhances the bond strength between materials when concrete is subjected to flexural or tensile loading. In this study, the flexural strength increased in all types of HFRC samples with increasing latex content. The flexural strength for the 5% latex composition was not higher than the value obtained when no latex was present. However, the flexural strength was much

Figure 2. Chloride ion penetration test setup. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Figure 3. Abrasion resistance test setup. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

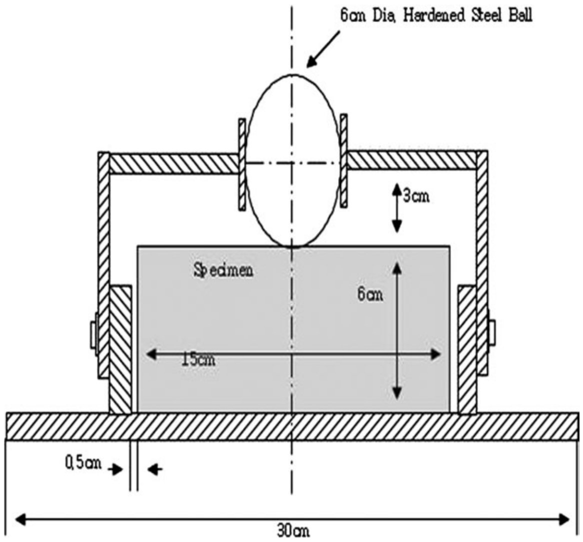

Figure 4. Impact resistance test setup.

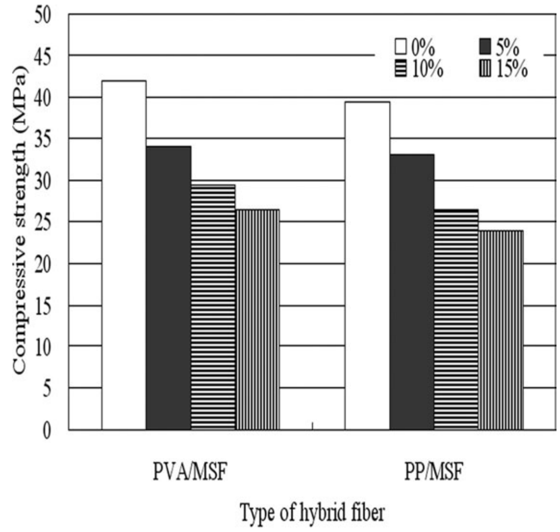

Figure 6. Compressive strength test results with various latex contents.

greater for the 10% composition. Fiber dispersion is a key factor influencing the performance of HFRC. Fiber dispersibility is affected by the fluidity of the HFRC. Considering the two cases where no latex was added and with 5% latex, the difference between their slump values was not great. Although latex served to slightly increase the flexural strength, there was little improvement in the dispersion of the hybrid fibers, as indicated by the slump values. On the contrary, for the 10% and 15% latex compositions, the dispersion and especially the flexural strength of the hybrid fibers improved because the latex strengthened the mechanism of fiber reinforcement (in terms of fiber bridging, fiber debonding, fiber fracture, and fiber pull-out). The greater flexural strength of PVA/MSF HFRC compared with the PP/MSF analog is attributed to the hydrophilic PVA fiber being more effective at arresting the occurrence/growth of cracks because of its greater bonding performance within concrete compared with the hydrophobic PP fiber.

Chloride Ion Penetration

The chloride ion penetration resistance of the HFRC samples as a function of latex content is shown in Figure 8. The chloride ion penetration test is an indirect method of evaluating the permeability of concrete. This study found that the chloride penetration rate decreased with increasing amount of latex. This finding is attributed to the latex filling the voids within the HFRC and forming a thick film, which led to a reduction in the penetration rate. However, there was little difference in the chloride penetration rate between the mixes made with 0% and 5% latex. This was similar to the behavior in fluidity or slump, as described above. At a latex content of 10% or higher, a thick latex film was formed, thus leading to an improvement in permeability and fluidity, which in turn improved the dispersion of the hybrid fibers. The hybrid fibers may also reduce the number of micro-voids and thereby improve penetration resistance. The HFRC containing the hydrophilic PVA fiber had a lower

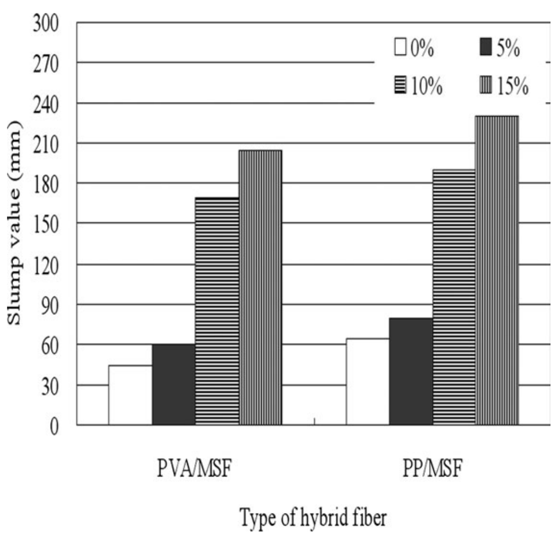

Figure 5. Slump test results with various latex contents.

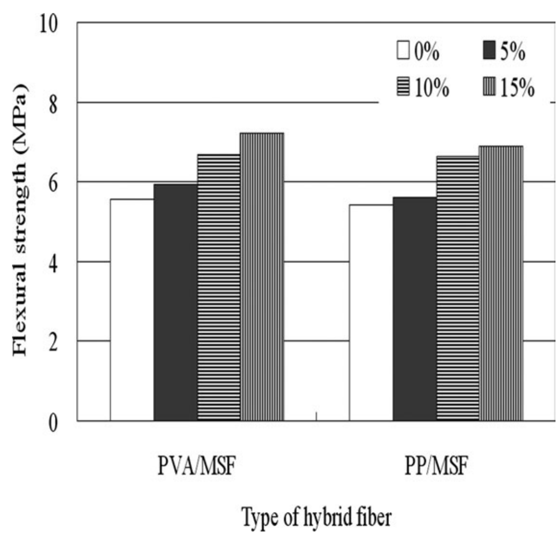

Figure 7. Flexural strength test results with various latex contents.

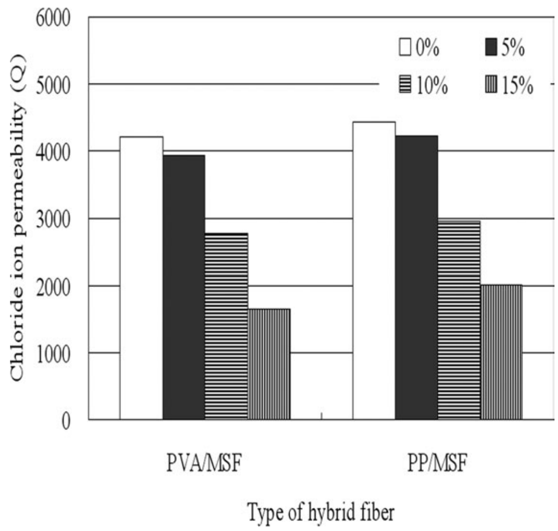

Figure 8. Chloride ion penetration test results with various latex contents.

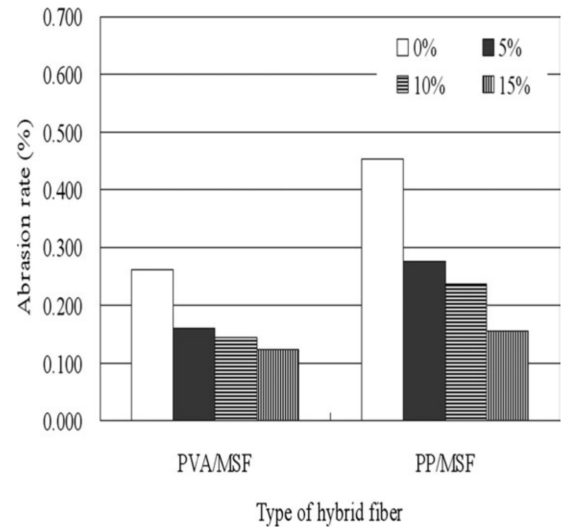

Figure 9. Abrasion resistance test results with various latex contents.

penetration rate than the HFRC incorporating the hydrophobic PP fiber. This was attributed to stronger hydrogen-bonding between the hydrophilic PVA fiber and the matrix, which reduced the amount of micro-voids between the fiber and the matrix.

Abrasion Testing

The degree of abrasion depended on the amount of added latex (Figure 9). The abrasion resistance improved with increasing latex content; this was attributed to the latex filling the voids within the HFRC and forming a thick latex film. The mix containing 5% latex had better abrasion resistance than the mix made without latex. Abrasion mostly occurs at the surface of a test specimen during abrasion testing of concrete. Hence, strengthening of the surface of a test specimen will improve its abrasion resistance. The added latex protected and strengthened the concrete surface by forming a latex film on the surface and thereby improved the abrasion resistance.

For PVA/MSF and PP/MSF, the former showed greater improvement in the abrasion resistance than the latter. Using the hydrophilic PVA fiber instead of the hydrophobic PP fiber led to better mechanical properties through improved bonding characteristics within the concrete.

Impact Testing

The impact resistance also depended on the amount of added latex (Figure 10). The number of impacts required for both initial cracking and fracturing tended to increase with increasing latex content. Little difference in this property was found for the 0% and 5% latex cases, but there was a clear improvement when 10% latex was incorporated. The number of impacts required for initial cracking and final fracturing was affected by the type of hybrid fiber. The degree of dispersion of a fiber influenced the impact resistance of the HFRC; specimens made from mixes containing 10% latex and having higher fluidity (and better fiber dispersion) had better impact resistance than

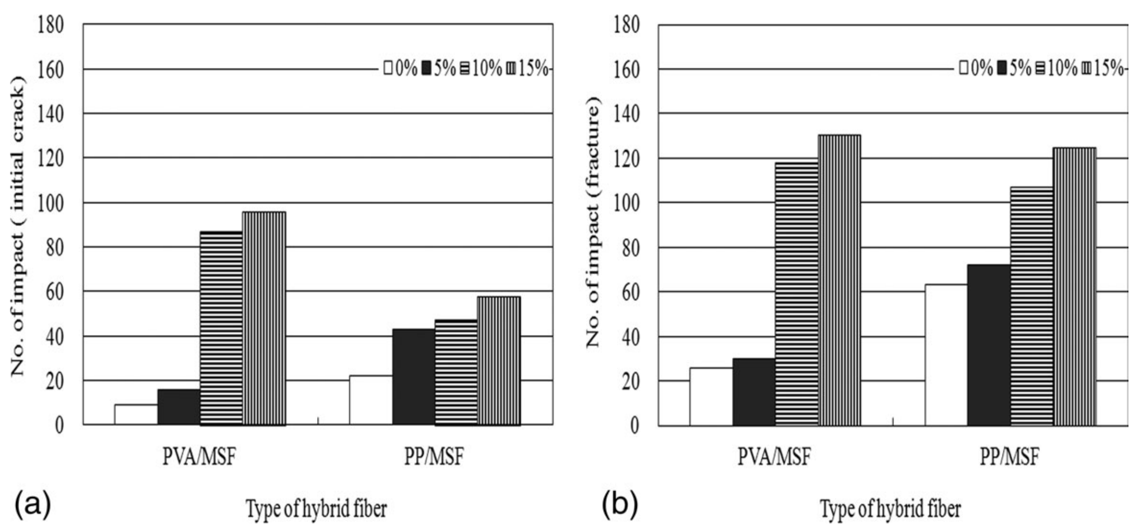

Figure 10. Impact resistance test results with various latex contents; (a) initial crack (b) fracture.

those formed from mixes containing 5% latex, which had poorer fluidity. Greater fluidity improved the dispersion of the hybrid fiber, which in turn improved the impact resistance by suppressing the occurrence and growth of cracks, and increased the fracture toughness under impact load. HFRC samples made with PVA/MSF had better impact resistance than those made with PP/MSF. The hydrophilic PVA fiber bonded better to the concrete matrix than did the hydrophobic PP fiber, thereby improving the impact resistance.

CONCLUSIONS

This study evaluated the effect of varying the amount of admixed styrene butadiene latex on HFRC performance. Two types of hybrid fibers—PVA/MSF and PP/MSF—were used, whereas the amount of added latex was varied (0%, 5%, 10%, and 15%). Superplasticizer (0.65%) was added to the latex-free mix. Slump, compressive strength, flexural strength, chloride ion penetration, abrasion resistance, and impact resistance were measured. The findings are summarized below.

1. The slump values tended to increase with the latex content for mixes containing either PVA/MSF or PP/MSF. This finding was attributed to the surfactant present in the latex improving the fluidity of the HFRC. Additionally, mixes containing PP/MSF had greater slump values (higher fluidity) that those containing PVA/MSF.
2. Increasing the amount of admixed latex led to improved dispersibility of the hybrid fiber because of increased fluidity. It also improved the bond strength because of the formation of a latex film, which increased the flexural strength but had little effect on compressive strength. The HFRC samples containing hydrophilic PVA fiber had higher flexural strength because of better dispersibility and greater bond strength than the HFRC samples containing hydrophobic PP fiber.
3. Resistance to chloride ion penetration, abrasion resistance, and impact resistance improved with increasing latex content. This finding was attributed to the latex, which improved the bonding performance between materials while concurrently improving the dispersion of the hybrid fiber.
4. The hydrophilic PVA fiber was more dispersible and provided higher bond strength in HFRC than the hydrophobic PP fiber. Consequently, the HFRC samples containing PVA fiber had better resistance to chloride ion penetration, abrasion resistance, and impact resistance.

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