Technical Paper

ISSN 1997-1400 Int. J. Pavement Res. Technol. 4(5):274-280

Investigating Abrasion Resistance of Steel-Polypropylene Hybrid Fiber-Reinforced Concrete Using Statistical Experimental Design

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Abstract: This study investigated the abrasion resistance of steel-polypropylene hybrid fiber-reinforced concrete (SPHFRC). Of the steel fiber (S) types, S1, S2, and S3 were hooked-end, and S4 was crimped. The additional fiber type was polypropylene (P). The L_{16} orthogonal array and analysis of variance (ANOVA) method were applied in the analysis of the main and interaction effects on the mechanical properties of SPHFRC. The analytical results demonstrate that P fibers contributed most to compressive strength, and S2 fibers contributed most to the modulus of rupture (MOR). For abrasion resistance, P fibers contributed most of the abrasion resistance during the initial stage, while S2 fibers contributed the most during the final stage. The R^2 for accumulated abrasion resistance with compressive strength during the initial stage was 0.9925 and declined to 0.8300 as the abrasion increased. The R^2 for accumulated abrasion resistance with MOR during the initial stage was 0.6968 and increased to 0.9473 as the abrasion increased. For interaction effects, P×S1 and P×S2 reached a significant level of compressive strength; S1×S3 and S2×S3 reached a significant level of MOR; P×S1 and P×S2 reached a significant level of abrasion resistance during the initial stage; and S1×S3 and S2×S3 reached a significant level of abrasion resistance during the final stage.

***Key words**: Abrasion resistance; Analysis of variance; Steel-polypropylene hybrid fiber-reinforced concrete.*

Introduction

Fiber-reinforced concrete (FRC) is widely used in pavement for airport runways and highways due to its multiple advantages, including its high compressive strength [1], splitting tensile strength [2], modulus of rupture [3], impact resistance [4] and abrasion resistance [5]. Increasing the abrasion resistance of FRC is crucial to overcoming issues such as easily damaged pavement due to heavy loads from aircraft and vehicles. In particular, the top pavement layer has a high risk of damage, which can lead to increased repairs, traffic disruption, and an eventual waste of resources. Therefore, selecting an appropriate fiber additive has become a central in the durability of FRC pavement.

A number of studies have explored the abrasion resistance of FRC. Atis *et al*. [5] determined that steel fibers increase the abrasion resistance of concrete, and polypropylene fibers do not improve concrete abrasion resistance. Their study also demonstrates that a stronger relationship exists between abrasion and flexural tensile strength than between abrasion and compressive strength of concrete. Febrillet *et al*. [6] demonstrated that steel fibers and hot-press compaction increase the abrasion resistance of ultra-high-strength concrete. Sadegzadeh *et al*. [7] investigated the effects of adding glass, polypropylene, and steel fibers to concrete and found that all three fibers improve abrasion resistance significantly. Shi and Chung [8] indicated that the abrasion resistance of latex cement mortar reinforced with carbon fibers was better than that of silica fume cement mortar and latex cement mortar alone. Burak *et al*. [9] reported that steel fibers improve the abrasion resistance of self-compacting cement mortar and proposed an optimized ratio of steel fibers to superplasticizer to retain the workability of self-compacting cement mortar. Li *et al*. [10] noted that the addition of nano-particles and polypropylene fibers improve the abrasion resistance of concrete significantly. Notably, nano-particles have been shown to be superior to polypropylene fibers for abrasion resistance.

The performance of single fibers added to concrete may be limited. Therefore, current studies focus on various combinations of fibrous materials. Steel and polypropylene fibers have been widely utilized in recent fiber mixtures [11-15]. These studies focus mainly on such engineering properties as compressive strength, splitting tensile strength, and impact resistance. However, very few studies focus on the abrasion resistance of steel-polypropylene hybrid-reinforced concrete (SPHFRC). This study determines the abrasion resistance of concrete with four different steel fibers and one polypropylene fiber. The L_{16} orthogonal array [16] and analysis of variance (ANOVA) methods were applied to identify the interaction effects of steel and polypropylene fibers on concrete mechanical properties.

Experimental Program

Materials

Type I Portland Cement was used in all experiments. The maximum granular size of coarse aggregates was 2.54 cm. The fineness modulus of fine aggregates was 2.86. The weights of cement, water, coarse aggregates, and fine aggregates were 330 kg/m^3, 180 kg/m^3, 1,000 kg/m^3, and 850 kg/m^3, respectively. Steel and polypropylene fibers were added to the concrete; Table 1 lists the physical properties of these fibers and the content of five fibers. Table 2 shows the experiment with five factors designed by the L_{16}

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Note: Submitted September 17, 2010; Revised January 25, 2011; Accepted February 10, 2011.

Table 1. Physical Characteristics and Content Level of Fibers.

Fiber Type	Steel-Fiber Type 1 (S1)	Steel-Fiber Type 2 (S2)	Steel-Fiber Type 3 (S3)	Steel-Fiber Type 4 (S4)	Polypropylene-Fiber (P)
Fiber Geometry	hooked-end	hooked-end	hooked-end	crimped	fibrillated
Fiber Length (mm）	30	40	50	50	19
Diameter (mm)	0.75	0.5	0.75	1.14	-
Aspect Ratio	40	80	67	44	-
Number / kg	9000	15000	5400	3100	above 7 million
Tensile Strength (MPa)	1100	1100	1100	966-1242	350
Modulus (Youngs）(GPa)	200	200	200	200	3.2
Specific Gravity	7.8	7.8	7.8	7.8	0.91
Content of Level 1 (kg/m^3)	0	0	0	0	0
Content of Level 2 (kg/m^3)	20	20	20	20	0.9

Table 2. Orthogonal Array for $L_{16}(2^{15})$ with Factor Assignment for the Experiments.

	P	S1	P×S1	S2	P×S2	S1×S2	S3×S4	S3	P×S3	S1×S3	S2×S4	S2×S3	S1×S4	P×S4	S4
Mix.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
M01	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
M02	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2
M03	1	1	1	2	2	2	2	1	1	1	1	2	2	2	2
M04	1	1	1	2	2	2	2	2	2	2	2	1	1	1	1
M05	1	2	2	1	1	2	2	1	1	2	2	1	1	2	2
M06	1	2	2	1	1	2	2	2	2	1	1	2	2	1	1
M07	1	2	2	2	2	1	1	1	1	2	2	2	2	1	1
M08	1	2	2	2	2	1	1	2	2	1	1	1	1	2	2
M09	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2
M10	2	1	2	1	2	1	2	2	1	2	1	2	1	2	1
M11	2	1	2	2	1	2	1	1	2	1	2	2	1	2	1
M12	2	1	2	2	1	2	1	2	1	2	1	1	2	1	2
M13	2	2	1	1	2	2	1	1	2	2	1	1	2	2	1
M14	2	2	1	1	2	2	1	2	1	1	2	2	1	1	2
M15	2	2	1	2	1	1	2	1	2	2	1	2	1	1	2
M16	2	2	1	2	1	1	2	2	1	1	2	1	2	2	1

orthogonal array. The five control factors were contents of S1, S2, S3, S4 and P fibers, and the interaction factors were P×S1, P×S2, S1×S2, S3×S4, P×S3, S1×S3, S2×S4, S2×S3, S1×S4, and P×S4. The ANOVA method was applied in this study. If the p-value of the factor is smaller than 0.05, the factor reaches a significant level.

Mixing and Curing

The mixing process started with dry mixing coarse and fine aggregates for 1 minute. Cement was then added to the mixture, which was mixed for 1 minute. Water was added, and the mixture was blended for 2 minutes. Fibers were sprinkled over the slurry concrete, which was then mixed for 3 minutes to distribute fibers evenly within the concrete mixture. This mixed SPHFRC was poured into 150 mm×300 mm cylindrical molds for compression tests; 150 mm× 150 mm×530 mm rectangular molds were filled for MOR tests; and 200 mm×200 mm×50 mm rectangular molds were filled for abrasion resistance tests. All molds were removed after 24 hours, and specimens were cured in a water cabinet at 23±1°C. All tests were performed after samples had cured for 28 days. In this study, each test result represents the average data from 9 replicated tests.

Test Methods

Compressive Strength

The American Society for Testing Material (ASTM) C39 method was utilized to determine the compressive strength of cylindrical specimens [17]. The cylindrical specimens were loaded into a universal hydraulic testing machine under a load control at a rate of 0.3 MPa/s until the specimen failed.

Modulus of Rupture

The ASTM C293 test approach was used to determine the MOR of rectangular specimens [18]. The load was increased at a rate of 0.9–1.2 MPa/min; maximum load was measured when the specimen failed.

Abrasion Resistance

The ASTM C944 rotating cutter approach was used to assess abrasion resistance [19]. First, a specimen was weighed with an accuracy of ±0.01 g. The specimen was then placed on the seat of the abrasion tester, and a 197 N load was applied to the specimen surface. A grinding wheel rotating at 200 r/min was used to abrade the specimen surface. Each abrasion stage lasted 2 minutes. Dust on the specimen surface was removed, and the abraded specimen was weighed. Each specimen was abraded for 8 minutes total; weight loss was determined every 2 minutes to assess abrasion resistance.

Table 3. Strength Test Results on Hybrid Fiber Reinforced Concrete.

Mix	Fiber Content (kg/m^3)					Compressive Strength (MPa)	Modulus of Rupture (MPa)
	P	S1	S2	S3	S4		
M01	0	0	0	0	0	28.03	4.65
M02	0	0	0	20	20	29.82	6.37
M03	0	0	20	0	20	30.34	6.86
M04	0	0	20	20	0	30.64	7.68
M05	0	20	0	0	20	30.33	6.73
M06	0	20	0	20	0	30.72	7.33
M07	0	20	20	0	0	31.54	7.25
M08	0	20	20	20	20	32.94	10.90
M09	0.9	0	0	0	20	30.58	5.77
M10	0.9	0	0	20	0	31.03	6.09
M11	0.9	0	20	0	0	31.95	6.28
M12	0.9	0	20	20	20	33.99	8.92
M13	0.9	20	0	0	0	32.21	5.86
M14	0.9	20	0	20	20	33.96	9.04
M15	0.9	20	20	0	20	35.73	8.74
M16	0.9	20	20	20	0	36.27	10.41

Table 4. The ANOVA Table for Compressive Strength and Modulus of Rupture (MOR).

Factor	ANOVA of Compressive Strength				ANOVA of MOR			
	SS	dof	p	rho	SS	dof	p	rho
P	28.49	1	0.0000	38.81	0.69	1	0.0035	1.43
S1	18.71	1	0.0000	25.47	11.63	1	0.0000	25.44
PxS1	0.96	1	0.0026	1.24	0.01	1	-	-
S2	17.45	1	0.0000	23.75	14.42	1	0.0000	31.56
PxS2	0.81	1	0.0043	1.03	0.00	1	-	-
S1xS2	0.20	1	-	-	0.14	1	-	-
S3xS4	0.09	1	-	-	0.01	1	-	-
S3	4.67	1	0.0000	6.30	13.37	1	0.0000	29.24
PxS3	0.05	1	-	-	0.07	1	-	-
S1xS3	0.02	1	-	-	0.81	1	0.0022	1.69
S2xS4	0.00	1	-	-	0.00	1	-	-
S2xS3	0.00	1	-	-	0.55	1	0.0066	1.11
S1xS4	0.05	1	-	-	0.11	1	-	-
PxS4	0.01	1	-	-	0.00	1	-	-
S4	1.76	1	0.0004	2.33	3.76	1	0.0000	8.17
Error	0.42	8		1.07	0.33	8		1.36
Total	73.27			100	45.57			100

rho: contribution ratio

Results and Discussion

Compressive Strength

Table 3 shows the compressive strength and the MOR of SPHFRC. The compressive strength and MOR varied with fiber type and content. Table 4 shows the ANOVA for compressive strength, indicating that factors P, S1, S2, S3, S4, P×S1 and P×S2 reached a significant level ($p < 0.05$) of compressive strength. The contribution ratio to compressive strength of different factors was P > S1 > S2 > S3 > S4 > P×S1 > P×S2. The polypropylene fibers improved compressive strength more than steel fibers did. This finding is in agreement with results obtained by Qian and Stroeven [15]. The polypropylene fibers were much finer than steel fibers and more evenly distributed in the concrete. When a force was loaded onto the specimens, the polypropylene fibers transferred stresses concentrated at the tips of cracks, thereby increasing compressive strength. For steel fibers, the hook-ended fibers improved compressive strength more than crimped fibers. This finding is in agreement with results acquired by Soroushian and Bayasi [20]. Furthermore, the contribution of the hook-ended steel fibers to compressive strength was S1 > S2 > S3, indicating that the contribution to compressive strength was approximately inversely proportional to fiber length [15].

Fig. 1(a) shows the interaction effects on compressive strength between P and S1, as well as P and S2. When 0.9 kg/m^3 of P was added and steel fibers reached 20 kg/m^3, polypropylene fibers and steel fibers generated complimentary effects.

Modulus of Rupture

Table 4 shows the analysis of variance for MOR, indicating that S1, S2, S3, S4, P, S1×S3, and S2×S3 reached a significant level ($p < 0.05$) of MOR. The contribution ratio to MOR of different factors was S2 > S3 > S1 > S4 > S1×S3 > P > S2×S3. The hooked-end steel fibers' contribution to the MOR was proportional to the aspect ratio of fibers. Fibers with a large aspect ratio typically provide increased embedment depth into the failure surface and had increased

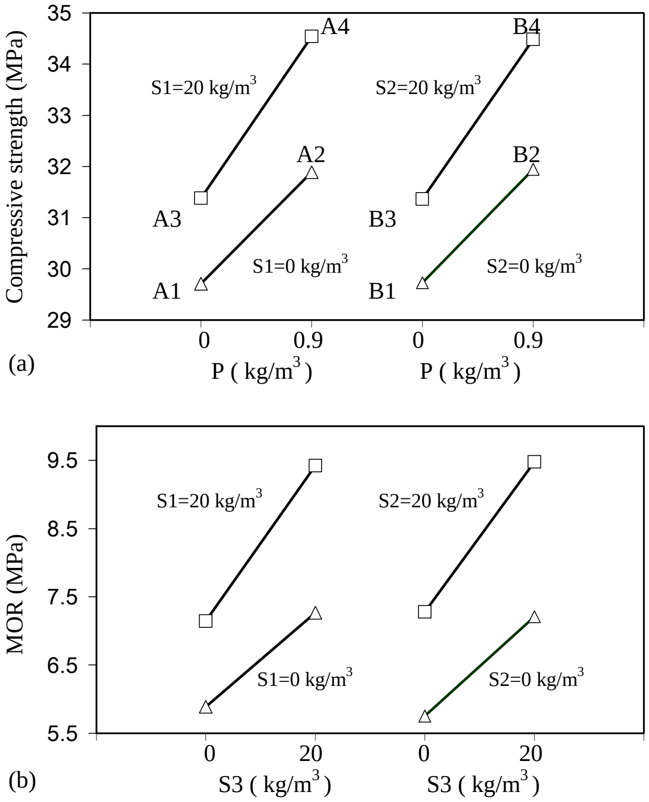

Fig. 1. Graphs of Interaction Effects (a) Response of Interaction on Compressive Strength between P and S1, P and S2. (b) Response of Interaction on MOR between S1and S3, S2 and S3. *Note:*
A1= (M01+M02+M03+M04)/4; A2= (M09+M10+M11+M12)/4;
A3= (M05+M06+ M07+M08)/4; A4= (M13+M14+M15+M16)/4;
B1= (M01+M02+M05+M06)/4; B2= (M09+M10+M13+M14)/4;
B3= (M03+M04+ M07+M08)/4; B4= (M11+M12+M15+M16)/4;
M01-M16 are the numbers of specimens from Table 2.

resistance to stresses when concrete specimens failed under flexural loading, resulting in a high MOR.

Fig. 1(b) shows the interaction effects on MOR between S1 and S3, as well as between S2 and S3. Adding 20 kg/m^3 of steel fiber generated complimentary effects among the fibers. When a load was placed on a specimen, hybrid fibers withstood the tensile stress of the tensile zone below the neutral axis. As short fibers failed, the long fibers could retain bridging and distribute the stress of large cracks until fibers could no longer sustain the stress. Therefore, the interaction effects of fibers further improved the MOR.

Table 5. Abrasion Loss Rate of Concrete Mixture.

Mix.	Abrasion Loss Rate (1/100000)				
	0-2 Min	2-4 Min	4-6 Min	6-8 Min	Sum
M01	41.30	31.56	25.92	22.72	121.50
M02	38.00	27.58	21.25	18.40	105.24
M03	36.26	26.51	20.28	17.75	100.79
M04	35.93	25.12	18.24	15.61	94.90
M05	36.36	27.58	21.27	18.36	103.57
M06	35.93	25.59	19.24	15.92	96.68
M07	34.36	26.02	19.36	16.67	96.41
M08	30.99	19.54	10.99	8.95	70.48
M09	36.56	27.46	22.81	20.18	107.00
M10	35.63	26.97	21.77	19.04	103.41
M11	33.59	25.39	21.00	18.58	98.57
M12	30.09	19.72	15.03	12.67	77.50
M13	33.29	26.97	22.29	19.49	102.04
M14	29.39	20.99	15.63	13.28	79.28
M15	27.45	20.42	15.75	13.62	77.24
M16	25.82	18.13	12.61	10.49	67.05

Abrasion Resistance

Table 5 shows the abrasion loss rate of SPHFRC. Table 6 shows the ANOVA results for abrasion resistance during 0–2 minutes, indicating that P, S1, S2, S3, S4, P×S1, and P×S2 reached a significant level ($p < 0.05$). The contribution ratio to the abrasion resistance of different factors was P > S1 > S2 > S3 > S4 > P×S1 > P×S2. The polypropylene fibers contributed the most to abrasion resistance because of their low specific weight, which allowed the

Table 6. The ANOVA Table for Abrasion Resistance during Different Stages.

	0-2 min				2-4 min				4-6 min				6-8 min			
Factor	SS	dof	p	rho	SS	dof	p	Rho	SS	dof	P	rho	SS	dof	p	rho
P	120.51	1	0.0000	34.45	34.44	1	0.0000	16.01	5.84	1	0.0001	2.39	3.09	1	0.0012	1.46
S1	71.24	1	0.0000	28.21	39.26	1	0.0000	18.26	53.15	1	0.0000	22.09	49.62	1	0.0000	23.83
P×S1	2.30	1	0.0011	0.88	0.06	1	-	-	0.02	1	-	-	0.06	1	-	-
S2	51.33	1	0.0000	25.28	71.61	1	0.0000	33.32	85.24	1	0.0000	35.45	68.25	1	0.0000	32.80
P×S2	0.94	1	0.0131	0.33	0.81	1	0.0055	0.35	0.03	1	-	-	0.00	1	-	-
S1×S2	0.03	1	-	-	0.00	1	-	-	0.39	1	-	-	0.16	1	-	-
S3×S4	0.07	1	-	-	0.00	1	-	-	0.02	1	-	-	0.00	1	-	-
S3	18.90	1	0.0000	7.46	49.93	1	0.0000	23.23	71.87	1	0.0000	29.88	68.11	1	0.0000	32.73
P×S3	0.40	1	-	-	0.02	1	-	-	0.01	1	-	-	0.00	1	-	-
S1×S3	0.10	1	-	-	1.69	1	0.0007	0.76	2.64	1	0.0011	1.05	2.25	1	0.0004	1.05
S2×S4	0.05	1	-	-	0.06	1	-	-	0.05	1	-	-	0.12	1	-	-
S2×S3	0.00	1	-	-	0.72	1	0.0073	0.31	1.63	1	0.0045	0.63	1.44	1	0.0018	0.66
S1×S4	0.01	1	-	-	0.01	1	-	-	0.33	1	-	-	0.12	1	-	-
P×S4	0.07	1	-	-	0.20	1	-	-	0.02	1	-	-	0.01	1	-	-
S4	7.27	1	0.0000	2.84	15.90	1	0.0000	7.38	18.96	1	0.0000	7.85	14.68	1	0.0000	7.03
Error	0.74	8		0.55	0.36	7		0.36	0.85	8		0.67	0.48	8		0.44
Total	273.23				214.72			100.00	240.18				129.64			100

rho: contribution ratio

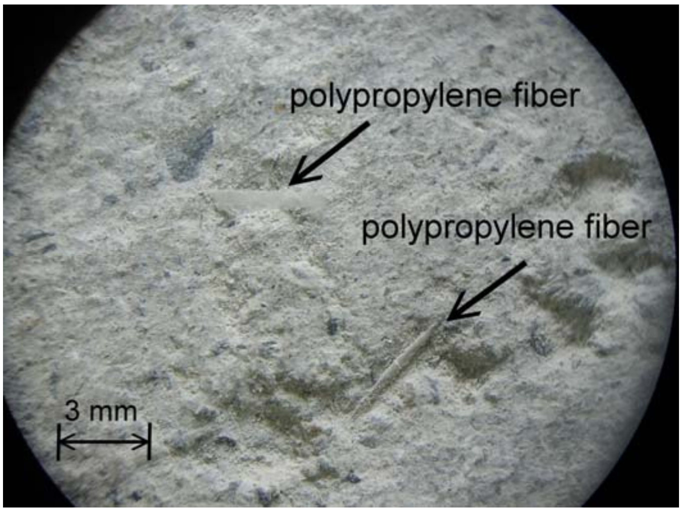

Fig. 2. Specimen Surface of SPHFRC during Initial Stage.

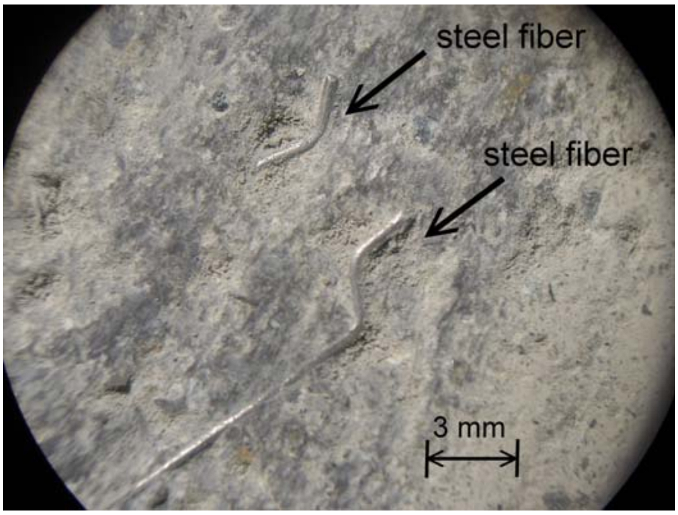

Fig. 3. Specimen Surface of SPHFRC during Final Stage.

fibers to scatter evenly across the entire surface of specimens, resulting in enhanced initial abrasion resistance. Fig. 2 shows the polypropylene fibers on the abrasion surface of a specimen. Moreover, the contribution of steel fibers for abrasion resistance was inversely proportional to fiber length, indicating that short fibers performed better than long fibers during the initial stage of abrasion resistance.

During 2–4 minutes, P, S1, S2, S3, S4, S1×S3, P×S2 and S2×S3 reached a significant level ($p < 0.05$), as shown in Table 6. The contribution ratio to abrasion resistance of different factors during 2–4 minutes was S2 > S3 > S1 > P > S4 > S1×S3 > P×S2 > S2×S3. During this stage, the contribution of steel fibers to abrasion resistance was proportional to the aspect ratio of steel fibers, indicating that steel fibers with large aspect ratios performed better than steel fibers with small aspect ratios.

During 4–6 minutes, P, S1, S2, S3, S4, S1×S3 and S2×S3 reached a significant level ($p < 0.05$), as shown in Table 6. The contribution ratio to abrasion resistance of different factors during 4–6 minutes was S2 > S3 > S1 > S4 > P > S1×S3 > S2×S3. The contribution ratio of different factors during 6–8 minutes was identical to that during 4–6 minutes (Table 6). During the final stage, the

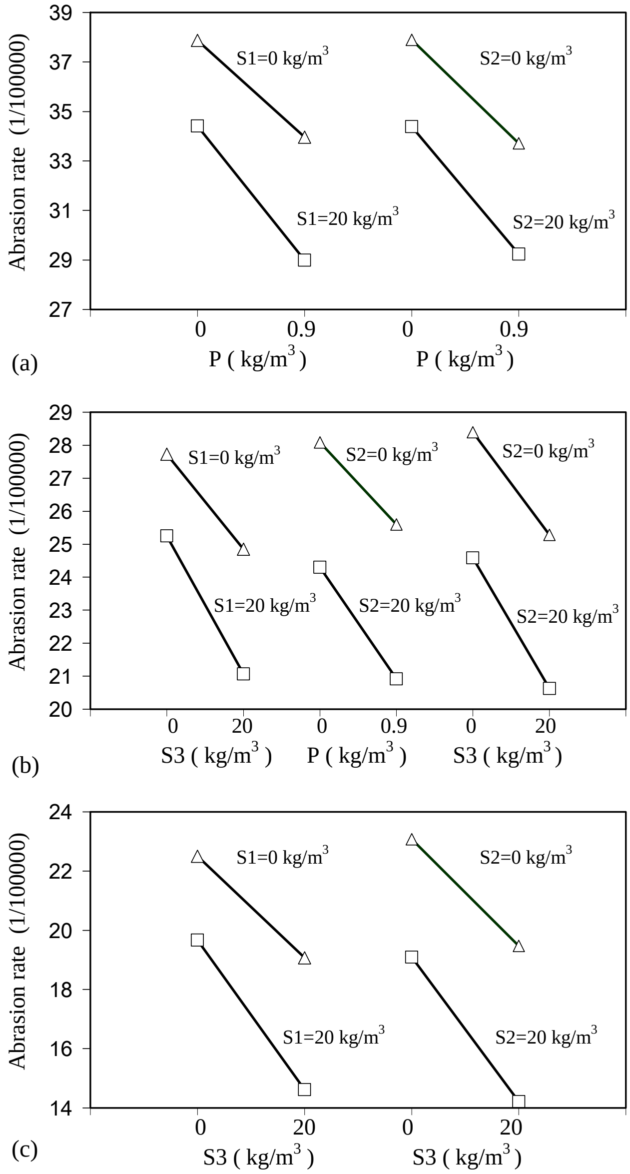

Fig. 4. Graphs of Interaction Effects on Abrasion Resistance. (a) Response of Interaction on Abrasion Resistance during 0-2 min between S1and P, S2 and P. (b) Response of Interaction on Abrasion Resistance during 2-4 min between S1and S3, S2 and P, S2 and S3. (c) Response of Interaction on Abrasion Resistance during 4-6 min between S1and S3, S2 and S3.

Note: Abrasion rate = w_i / w_0; w_i = abrasion loss weight of the specimen; w_0= original weight of the specimen.

contribution ratio of polypropylene fibers to abrasion resistance declined, while that of steel fibers increased. Fig. 3 shows steel fibers exposed on a specimen surface, and the polypropylene fibers were worn off from the surface. In terms of abrasion resistance, the hybrid fiber-reinforced concrete performed better than single fiber-reinforced concrete. The polypropylene fibers performed better during the initial stage. The steel fibers with large aspect ratios performed better during the final stage.

Fig. 4 shows the interaction effects between S1 and P and between S2 and P on abrasion resistance during 0–2 minutes, the

Table 7. Relationship between Abrasion Resistance and Mechanical Properties during Different Stages.

Stage	0-2 Min	2-4 Min	4-6 Min	6-8 Min
Compressive Strength	$y = 0.0363x_1^2 - 4.1998x_1 + 130.66$	$y = 0.0576x_1^2 - 5.3118x_1 + 135.23$	$y = 0.0818x_1^2 - 6.7651x_1 + 151.08$	$y = 0.075x_1^2 - 6.189x_1 + 137.09$
R^2	0.9925	0.8517	0.6594	0.6293
MOR	$y = 0.1419x_2^2 - 4.1876x_2 + 56.683$	$y = 0.0965x_2^2 - 3.5824x_2 + 45.738$	$y = 0.0404x_2^2 - 2.9238x_2 + 38.341$	$y = 0.0461x_2^2 - 2.8548x_2 + 34.891$
R^2	0.6968	0.9065	0.9924	0.9928

x_1 is compressive strength; x_2 is modulus of rupture; y is abrasion loss rate; R^2 is the coefficient of determination

Table 8. Relationship between Accumulated Abrasion Resistance and Mechanical Properties during Different Stages.

Stage	022 Min	0-4 Min	0-6 Min	0-8 Min
Compressive Strength	$y = 0.0363x_1^2 - 4.1998x_1 + 130.66$	$y = 0.0939x_1^2 - 9.5115x_1 + 265.89$	$y = 0.1757x_1^2 - 16.277x_1 + 416.97$	$y = 0.2508x_1^2 - 22.466x_1 + 554.06$
R^2	0.9925	0.9526	0.8806	0.8300
MOR	$y = 0.1419x_2^2 - 4.1876x_2 + 56.683$	$y = 0.2384x_2^2 - 7.7701x_2 + 102.42$	$y = 0.2788x_2^2 - 10.694x_2 + 140.76$	$y = 0.3249x_2^2 - 13.549x_2 + 175.65$
R^2	0.6968	0.8188	0.9107	0.9473

x_1 is compressive strength; x_2 is modulus of rupture; y is accumulated abrasion loss rate; R^2 is the coefficient of determination

interaction effects between S1 and S3, S2 and P, and S2 and S3 on abrasion resistance during 2–4 minutes, and the interaction effects between S1 and S3 and between S2 and S3 on abrasion resistance during 4–6 minutes. The hooked-end steel fibers (S1 and S2) and the polypropylene fibers have a significant interaction effect on abrasion resistance during 0–2 minutes, but the crimped steel fibers (S4) and the polypropylene fibers do not have a significant interaction effect on abrasion resistance during 0–2 minutes. During 4–6 minutes, the polypropylene fibers had no interaction effects with steel fibers on abrasion resistance.

Relationship between Abrasion Resistance and the Mechanical Properties of SPHFRC

Table 7 shows the relationship between abrasion resistance and compressive strength and the relationship between abrasion resistance and MOR. During 0–2 minutes, the R^2 for compressive strength and MOR were 0.9925 and 0.6968, respectively. This suggests that abrasion resistance strongly correlates with compressive strength during the initial stage of abrasion resistance.

During 2–4 minutes, the R^2 for compressive strength and MOR were 0.8517, and 0.9065, respectively. During 4–6 minutes, the R^2 for compressive strength and MOR were 0.6594, and 0.9924, respectively. During 6–8 minutes, the R^2 for compressive strength and MOR were 0.6293, and 0.9928, respectively. These analytical results suggest that the relationship between abrasion resistance and compressive strength is strong during the initial stage of abrasion but weakens during the final stages. However, the relationship between abrasion resistance and the MOR is weak during the initial stage of abrasion and strengthens during the final stage.

Table 8 shows the relationship between accumulated abrasion resistance and compressive strength and the relationship between accumulated abrasion resistance and MOR. The R^2 for compressive strength at 2 minutes was 0.9925 but decreased to 0.8300 at 8 minutes. The R^2 for MOR at 2 minutes was 0.6968 and increased gradually to 0.9473 at 8 minutes. A stronger relationship exists between accumulated abrasion resistance and the MOR than between accumulated abrasion resistance and compressive strength, which is in agreement with results obtained by Atis *et al*. [5].

Conclusions

1. Based on ANOVA results, the contribution ratio to compressive strength of different factors was P > S1 > S2 > S3 > S4 > P×S1 > P×S2, indicating that polypropylene fibers increase compressive strength more than steel fibers. The contribution of different factors to MOR of different factors was S2 > S3 > S1 > S4 > S1×S3 > P > S2×S3, demonstrating that hooked-end steel fibers with large aspect ratios to MOR perform better than those with small aspect ratios to MOR.
2. The contribution ratio to abrasion resistance of different factors during the initial stage was P > S1 > S2 > S3 > S4 > P×S1 > P×S2. The contribution ratio to abrasion resistance of different factors during the final stage was S2 > S3 > S1 > S4 > P > S1×S3 > S2×S3, indicating that steel fibers are more important than polypropylene fibers in regards to abrasion resistance during the final stage.
3. For the interaction effects, P×S1 and P×S2 had a significant effect on compressive strength, and S1×S3 and S2×S3 had a significant effect on the MOR. During the initial stage of abrasion resistance, P×S1 and P×S2 had significant effects, while S1×S3 and S2×S3 had significant effects during the final stage.
4. As abrasion duration increased, the relationship between accumulated abrasion rate and compressive strength weakened, and the relationship between accumulated abrasion rate and the MOR strengthened.

References

1. Song, P.S. and Hwang, S. (2004). Mechanical Properties of High-Strength Steel Fiber-Reinforced Concrete, *Construction*

Building Material, 18(9), pp. 669–673.
2. Choia, Y. and Yuan, R.L. (2005). Experimental Relationship between Splitting Tensile Strength and Compressive strength of GFRC and PFRC, *Cement and Concrete Research*, 35(8), pp. 1587-1591.
3. Hsie, M.H., Tua, C.J., and Song, P.S. (2008). Mechanical Properties of Polypropylene Hybrid Fiber-Reinforced Concrete, *Materials Science & Engineering A*, 494 (1), pp. 153–157.
4. Song, P.S., Wu, J.C., Hwang, S., and Sheu, B.C. (2005). Statistical Analysis of Impact and Strength Reliability of Steel-Polypropylene Hybrid Fiber-Reinforced Concrete, *Construction Building Material*, 19(1), pp. 1-9.
5. Atis, C. D., Karahan, O., Ari, K., Sola, Ö. C., and Bilim, C. (2009). Relation between Strength Properties (Flexural and Compressive) and Abrasion Resistance of Fiber (Steel and Polypropylene)-Reinforced Fly Ash Concrete, *Journal of Materials in Civil Engineering*, 21(8), pp. 402-406.
6. Febrillet, N., Akihiro, K., Yukihiro, I., and Kouji, I. (2000). Strength and Abrasion Resistance of Ultra-High Strength Steel Fiber Reinforced Concrete, *Transportation Japan Concrete Institute*, 22, pp. 243–252.
7. Sadegzadeh, M., Kettle, R.J., and Vassou, V. (2001). Influence of Glass, Polypropylene and Steel Fibers on Physical Properties of Concrete, *Proceedings of the 1st International Conference on Concrete and Development C and D,* Ministry of Housing and Urban Development, pp. 483–492, Tehran, Iran.
8. Shi, Z.Q. and Chung, D.D.L. (1997). Improving the Abrasion Resistance of Mortar by Adding Latex and Carbon Fibers, *Cement and Concrete Research*, 27(8), pp. 1149-1153.
9. Burak, F.L., Selcuk, T., and Yigit, A. (2007). Effects of Steel Fiber Reinforcement on Surface Wear Resistance of Self-Compacting Repair Mortars, *Cement and Concrete Composites*, 29(5) pp. 391–396.
10. Li, H., Zhang, M.H., and Ou, J.P. (2006). Abrasion Resistance of Concrete Containing Nano-Particles for Pavement, *Wear*, 260(11-12), pp. 1262–1266.
11. Yao, W., Li, J., and Wu, K. (2003). Mechanical Properties of Hybrid Fiber-Reinforced Concrete at Low Fiber Volume Fraction, *Cement and Concrete Research*, 33(1), pp. 27-30.
12. Banthia, N. and Nandakumar, N. (2003). Crack Growth Resistance of Hybrid Fiber Reinforced Cement Composites, *Cement and Concrete Composites*, 25(1), pp. 3-9.
13. Sun, W., Chen, H., Luo, X., and Qian H. (2001). The Effect of Hybrid Fibers and Expansive Agent on the Shrinkage and Permeability of High-Performance Concrete, *Cement and Concrete Research*, 31(4), pp. 595-601.
14. Qian, C.X. and Stroeven, P. (2000). Fracture Properties of Concrete Reinforced with Steel-Polypropylene Hybrid Fibers, *Cement and Concrete Composites*, 22(5), pp. 343-351.
15. Qian, C.X. and Stroeven, P. (2000). Development of Hybrid Polypropylene-Steel Fiber-Reinforced Concrete, *Cement and Concrete Research*, 30(1), pp. 63-69.
16. Alberto, G.D. and Phillips, D.T. (1995). *Principles of Experimental Design and Analysis*, Chapman & Hall, New York, USA.
17. ASTM-C39 M-05 (2005). *Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens*, ASTM International, pp. 1-7, West Conshohocken, Pennsylvania, USA.
18. ASTM-C293 M-08 (2008). *Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Center-Point Loading)*, ASTM International, pp. 1-3, West Conshohocken, Pennsylvania, USA.
19. ASTM-C944 M-05 (2005). *Standard Test Method for Abrasion Resistance of Concrete or Mortar Surfaces by the Rotating-Cutter Method*, ASTM International, pp. 1-4, West Conshohocken, Pennsylvania, USA.
20. Soroushian, P. and Bayasi, Z. (1991). Fiber-Type Effects on the Performance of Steel Fiber Reinforced Concrete, *ACI Material Journal*, 88(2), pp. 129-134.