Civil Engineering Infrastructures Journal, 51(1): 119 – 130, June 2018
Print ISSN: 2322-2093; Online ISSN: 2423-6691
DOI: 10.7508/ceij.2018.01.007

Evaluation of Hybrid Fiber Reinforced Concrete Exposed to Severe Environmental Conditions

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Received: 01 Aug. 2017; Revised: 20 Nov. 2017; Accepted: 28 Nov. 2017

ABSTRACT: Hybrid fiber reinforced concrete (HFRC) consisting of two or more different types of fibers has been widely investigated because of its superior mechanical properties. In the present study, the effect of the addition of steel (0.25%, 0.5%, 0.75% and 1% of concrete volume) and Polypropylene (0.2%, 0.4% and 0.6% of concrete volume) fibers on the surface scaling resistance of concrete, depth of penetration of water, and compressive strength of concrete is investigated. The permeability test is conducted for all the specimens to measure the depth of penetration of water under pressure. Moreover, scaling resistance of concrete subjected to freezing and thawing cycles in the presence of salt solution is assessed to simulate the durability of concrete under field exposure conditions. The results showed that the addition of fibers increases the permeability of concrete. However, it enhances the scaling resistance and compressive strength of concrete. The mixture containing 0.4% of Polypropylene (PP) fibers and 0.75% of steel fibers demonstrated the highest scaling resistance since the scaled materials in this mixture were almost half weight of the materials scaled from the control mixture after 84 cycles of freezing and thawing. Increasing the scaling resistance of concrete leads to a better long-term serviceability performance of HFRC compared to plain concrete, making these composites a great choice for application in environments exposed to cold weather.

Keywords: Hybrid Fiber Reinforced Concrete, Permeability, PP Fibers, Scaling Resistance, Steel Fibers.

INTRODUCTION

In the past few decades, fibers have been widely used and investigated as a reinforcement for concrete, to achieve a composite with desirable mechanical properties. The effectiveness of the addition of fibers greatly depends on geometry, length, aspect ratio, volume content, distribution, and most importantly the type of fibers (Kosmatka et al., 2003; Shadafza and Jalali, 2016). Previous studies indicate that steel fibers improve compressive, split-tensile, shear, and torsional strength of concrete (Rao et al., 2009; Thomas and Ramaswamy, 2007; Tan et al., 1993; Okay and Engin, 2012). Hybrid fiber reinforced concrete containing at least two different types of fibers produce a better mechanical performance compared to mono-fiber reinforced concrete providing

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that the fibers are chosen and combined appropriately (Rashid Dadash and Ramezanianpour, 2014). Hybridization of fibers can produce synergy in concrete by creating a uniform network of fibers: Smaller fibers can delay the initiation and propagation of micro-cracks while larger fibers can bridge across macro-cracks and lead to a higher ultimate strength. Combination of coarse monofilament and staple PP fibers in concrete contribute toward achieving a higher compressive, split tensile, and flexural strength compared to the mixture containing one type of PP fiber because of the complementary role of the fibers (Hsie et al., 2008).

Addition of steel and basalt fibers leads to the enhancement of flexural strength, toughness and fatigue properties in concrete (Balaguru et al., 1992; Penteado et al., 2005). Due to the cyclic and flexural nature of pavement loading, a few studies have been carried out to investigate the feasibility of utilizing fiber reinforced concrete in pavements (Mulheron et al., 2015; Mohod and Kadam, 2016; Taherkhani, 2016; Fang et al., 2017). Additionally, the fiber reinforced concrete pavement has been analyzed through nonlinear fracture mechanics, since the failure behavior of fiber reinforced concrete is different from that of conventional concrete (Belletti and Cerioni, 2008). Pozzolan materials are widely used as a part of concrete pavement to reduce the deterioration caused by freezing and thawing cycles especially in the presence of deicer materials (Nili and Zaheri, 2011; Yener and Hinisliolu, 2011).

Recent studies on the effectiveness of utilizing fibers in improving the scaling resistance of concrete have demonstrated contrasting results. Some studies indicate that the addition of fibers has a positive effect on the scaling resistance of concrete (Pigeon et al., 1996; Berkowski and Kosior, 2015; Niu et al., 2013) while some studies reported their negative effect (Quanbing and Beirong, 2005) and some others reflected their ineffectiveness (Cantin and Pigeon, 1996). Such discrepancies may be the result of utilizing different types of fibers and aggregates, compaction techniques, and test methods. Similarly, previous studies have reported contradictory results with regard to the permeability of mono-fiber and hybrid fiber reinforced concrete. Some studies show the positive effect of the addition of fibers on permeability; i.e, decreasing the permeability (Zhang and Li, 2013; Singh, 2013). One the other hand, some other studies indicated their negative effect (Islam and Gupta, 2016; Miloud, 2005; Sun et al., 2001).

Since there is limited information about the permeability and durability of hybrid fiber reinforced concrete (HFRC) in addition to the various and divergent results of previous studies about these two parameters, more extensive experiments are needed in this regard. Besides, it is justifiable to investigate the long-term serviceability of fiber reinforced concrete, and study the feasibility of using such composites as the concrete exposed to severe environmental conditions. Consequently, deicer scaling resistance of concrete subjected to freezing and thawing cycles was assessed in order to simulate the field condition of the concrete pavement. Considering the indirect effect of permeability on the durability of concrete, it is important to assess the permeability of concrete as well.

MATERIALS AND METHODS

In the present study, steel fibers at contents of 0.25%, 0.5%, 0.75%, and 1% of concrete volume and PP fibers at contents of 0.2%, 0.4% and 0.6%, of concrete volume were used to prepare 13 different mixtures. A total of 92 specimens were cast: 39 specimens were evaluated under compressive test, 39 specimens were evaluated through permeability test and 14 specimens were subjected to freezing and thawing in order to assess the scaling resistance.

Local sand having a specific gravity of 2.66 gr/cm^3 and FM value of 2.58 and coarse aggregates with a maximum size of 12 mm were used. The grading curve for sand and coarse aggregate is presented in Figures 1 and 2, respectively. Type 2 Portland cement with specific gravity of 3.16 gr/cm^3 was used which conformed to ASTM C150. Polycarboxylate Ether based Superplasticizer was utilized in the experimental program. To maintain the workability (50 to 70 mm), slight modifications were made to the superplasticizer dosage when fibers were added. It should be noted that the slump test was used for controlling the workability of the specimens. Silica fume was also added to the mixture with a specific gravity of 2.13 gr/cm^3. Hooked end steel fibers with an aspect ratio of 62.5 and staple PP fibers were used as the reinforcement. Mechanical properties of steel and PP fibers are presented in Table 1. The sand, coarse aggregate, cement, and steel fibers were dry mixed for 1 min and, then, half of the water was added to the mixture and mixed for 2 min. Finally, the second half of water with the dissolved superplasticizer and the PP fibers were added and mixed for another 2 min. After pouring the concrete into the mold, the specimens were vibrated for 15 seconds for better compaction.

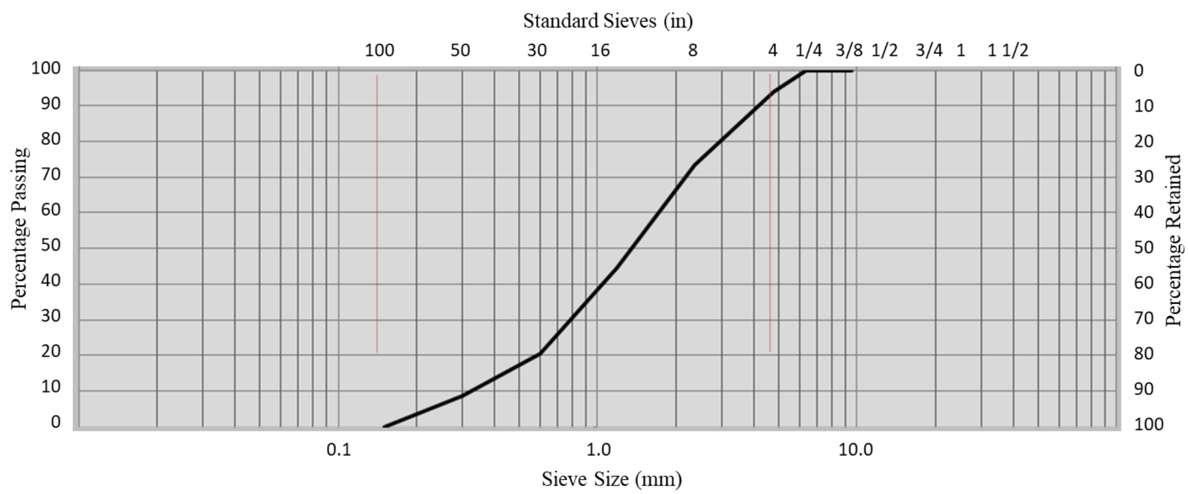

Fig. 1. Grading curve for sand

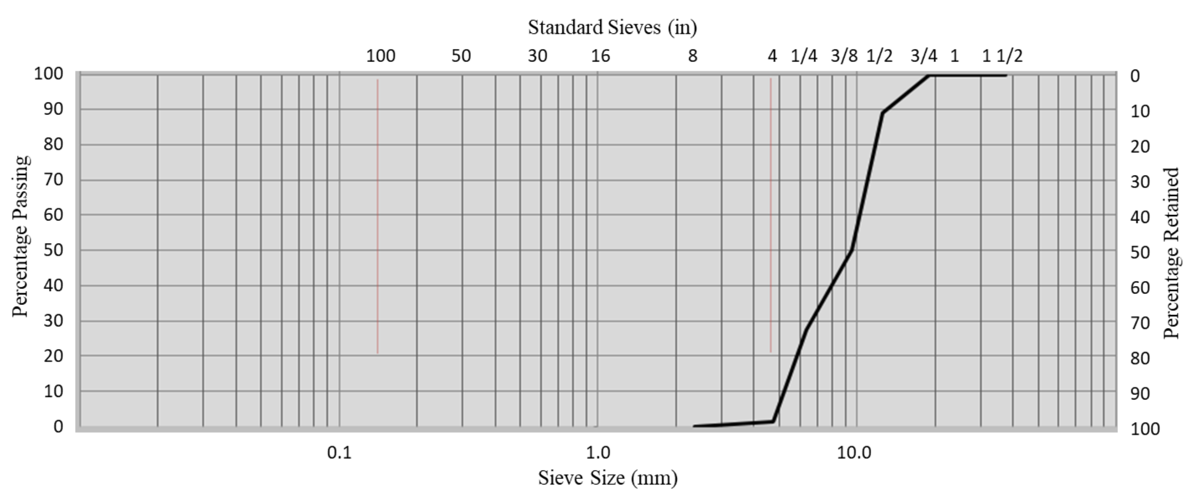

Fig. 2. Grading curve for coarse aggregate

Table 1. Fiber properties

Fiber Type	Specific Gravity (gr/cm^3)	Yielding Strength (MPa)	Length (mm)	Diameter (mm)	Aspect Ratio
Steel fibers	7.85	809	50	0.8	62.5
PP fibers	0.91	345	12	0.035	342.9

Mixture proportion used for all the test specimens is presented in Table 2. As shown in the table, it has a water/binder ratio of 0.4 (silica fume comprised 4.8% of the binder). Table 3 presents 13 different mixtures formed through the combination of steel and PP fibers. All mixtures were evaluated under compressive strength and permeability test (3 similar specimen were cast for each mixture) while 7 mixtures were subjected to freezing and thawing cycles in the presence of deicer in order to investigate their scaling resistance (2 similar specimens were cast for each mixture).

The compressive strength test was carried out based on the requirements of BS EN 12390-3:2009. Accordingly, cubic specimens with dimensions of 150 mm*150 mm*150 mm were cast and cured for 28 days before testing. The compressive strength of all specimens was determined by means of a compression testing machine with a loading capacity of 2000 kN.

Permeability test was performed on cubic specimens of dimensions 150 mm*150 mm*150 mm in accordance with BS EN 12390-8 in order to determine the depth of penetration of water under pressure in hardened concrete. For this purpose, the specimens were placed in test cells and sealed carefully. Afterward, test cells containing specimens were placed in the apparatus in such a manner that water pressure could be applied on the test surface as presented in Figure 3. Before performing the main test, the testing of the seal was done for any leakage. According to the requirements of BS EN 12390-8, water pressure of 500 kPa was applied for 72 hours, and the pressure was measured continuously during the test process. After performing the test, specimens were split in half perpendicularly to the surface that the pressure was applied and the water front was marked and reported as the depth of penetration of water in concrete.

Table 2. Mixture design

Cement kg/m^3	Water kg/m^3	Coarse Aggregate kg/m^3	Sand kg/m^3	Silica Fume kg/m^3	Superplasticizer[a] kg/m^3
400	170	650	1175	20	2.5

[a] Slight modifications were made to the superplasticizer dosage when fibers were added to maintain the workability.

Table 3. Specimen labeling

Steel Fiber Content (%)	PP Fiber Content (%)	Mixture
0	0	A1
0	0.4	A2
0.25	0	A3
0.5	0	A4
1	0	A5
0.25	0.2	A6
0.5	0.2	A7
0.25	0.4	A8
0.5	0.4	A9
0.75	0.4	A10
1	0.4	A11
0.75	0.6	A12
1	0.6	A13

Fig. 3. Apparatus for measuring water depth of penetration

There are a few methods for evaluation of the concrete durability, namely ASTM C666, ASTM C672, ASTM C1262, BS EN 1340:2003 (Annex D), and DD CEN/TS 12390-9:2006. BS EN 1340:2003, DD CEN/TS 12390-9:2006 and ASTM C672 determine the scaling resistance of concrete. It should be noted that the conditions applied to concrete based on these codes correspond to the field conditions of the concrete used in service where only the surface is subjected to scaling. Furthermore, the extensive application of deicer materials for pavement, which is inevitable in cold weather, makes these methods appropriate choices for simulating the field conditions of pavement concrete. Scaling resistance of cubic specimens with dimensions of 150 mm*150 mm*150 mm was assessed after the specimens were cast and cured for 28 days. The test was inspired by the requirements of BS EN 1340:2003 (Annex D). As depicted in Figure 4, all the specimens were prepared according to the requirements of the test method. For this purpose, the surface of all specimens, except the test surface, were sealed and covered by rubber sheets and plastic strips. The rubber sheets were extended 20 mm above the test surface to hold the freezing medium. Before starting the test, 3% NaCl solution was poured on the test surface to a depth of 5 mm. Figure 5 presents placing all the specimens in the apparatus, which performs the freezing and thawing cycles automatically. Duration of each cycle was 24 hours and the temperature ranged from -20 to 24 °C while the temperature exceeded 0 °C for 7 hours in each cycle. The temperature of the freezing medium was monitored continuously by means of 12 thermal sensors placed on the specimens.

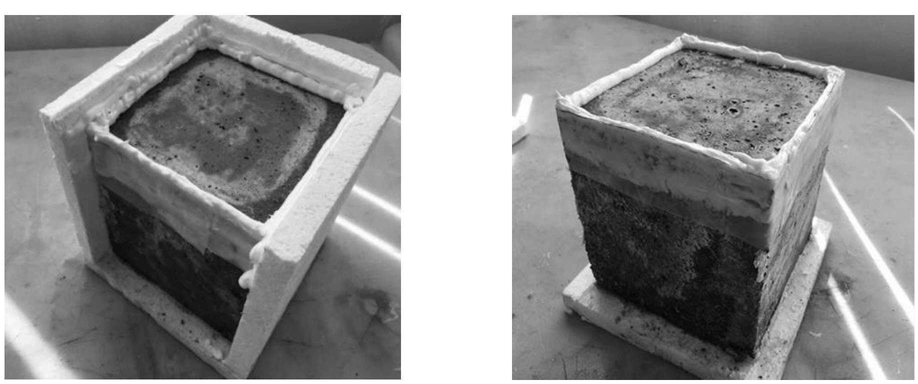

Fig. 4. Preparing specimens for freeze-thaw cycles

Based on the requirements of BS EN 1340:2003, the scaling resistance of the specimens is assessed after 28 cycles. In this experimental program, the mass of the scaled materials was so inconsiderable that almost made it impossible to weigh and compare the scaled materials from different mixtures. Consequently, the scaling resistance of all specimens was evaluated after 84 cycles (84 days). Finally, the scaled materials for each specimen was weighed and divided by the area of the surface test representing the scaling resistance of specimen.

RESULTS AND DISCUSSIONS

Based on the results presented in Table 4, it is observed that the addition of fibers leads to the improvement of compressive strength. The main reason for this improvement is the formation of a network of fibers that delays the propagation of cracks in concrete. PP fibers act as bridges across the micro-cracks while steel fibers postpone the propagation of macro-cracks. Comparing the compressive strength of mixtures A3 and A4 (containing 0.25% and 0.5% of steel fibers) with mixture A2 (containing 0.4% of PP fibers) shows that steel fibers are more effective in the enhancement of compressive strength because of their higher modulus of elasticity and greater length. Incorporation of fibers in hybrid form (mixtures A9 and A6) results in a higher compressive strength compared to the individual addition of steel fibers (mixtures A4 and A5) because of the synergy caused by hybridization of fibers. Figure 6 compares the compressive strength of mixtures containing steel fibers and hybrid fibers. Although the mixtures containing steel fibers benefit from a higher compressive strength compared to the mixtures with PP fibers, hybrid fiber mixtures demonstrate a higher compressive strength at the same total fiber volume content compared to steel fiber mixtures.

Fig. 5. Apparatus for simulating freeze-thaw cycles

Table 4. Compressive strength of specimens

Mixture	PP Fiber Content (%)	Steel Fiber Content (%)	Compressive Strength (MPa)
A1	0	0	39.5
A2	0.4	0	42.8
A3	0	0.25	42.6
A4	0	0.5	44.5
A5	0	1	46
A6	0.2	0.25	45.7
A7	0.2	0.5	45.7
A8	0.4	0.25	44.2
A9	0.4	0.5	48.6
A10	0.4	0.75	45.8
A11	0.4	1	46.2
A12	0.6	0.75	43.3
A13	0.6	1	42.4

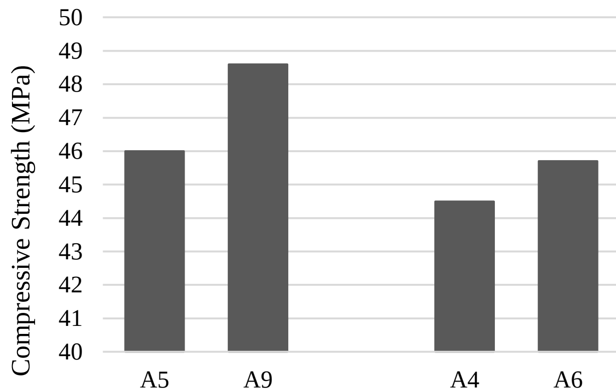

Fig. 6. Comparison between compressive strength of steel fiber and hybrid fiber specimens

Once the permeability test is performed and the specimens are split in half, the depth of penetration of water in concrete is measured as presented in Figure 7. The result of the permeability test for all the specimens is summarized in Table 5. The results show that the addition of fibers increases the permeability of the specimens, and this continues by the increase in fiber content. The depth of penetration of water in mixture A12 containing 0.6% of PP fibers and 0.75% of steel fibers was 7 times more than that of the control mixture.

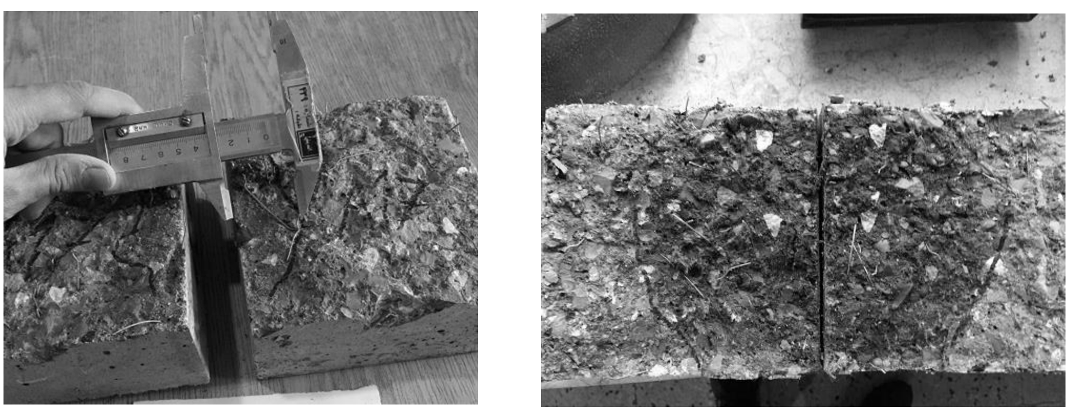

Fig. 7. Measuring depth of penetration

Table 5. Depth of water penetration

Mixture	PP Fiber Content (%)	Steel Fiber Content (%)	Permeability (mm)
A1	0	0	15
A2	0.4	0	50
A3	0	0.25	25
A4	0	0.5	30
A5	0	1	75
A6	0.2	0.25	50
A7	0.2	0.5	60
A8	0.4	0.25	85
A9	0.4	0.5	90
A10	0.4	0.75	90
A11	0.4	1	90
A12	0.6	0.75	110
A13	0.6	1	115

The main reason for the increase in permeability of concrete is the weak zone with a high porosity between fibers and the paste that acts as channels conveying water in concrete. Furthermore, PP fibers can act as bridges between the pores in concrete, and transfer the moisture through the specimen. As can be seen from Figure 8, the addition of steel fibers increases the permeability of concrete, and this situation is aggravated as the fiber content rises. As illustrated in Figure 9, comparing mixture A2, containing 0.4% of PP fibers and mixture A8 containing 0.4% of PP fibers and 0.25% of steel fibers shows that increasing the steel fiber content also increases the penetration depth in the presence of PP fibers. However, comparing mixtures A9, A10, and A11 (containing 0.4% of PP fibers and 0.5, 0.75 and 1% of steel fibers) reveals that after reaching a specific volume content, increasing the fiber content does not have a significant effect on the permeability of concrete.

As shown in Figure 10, similar to the steel fiber reinforced specimens, the addition of PP fibers increases the permeability of concrete. Based on the results of this study, the addition of 0.2% and 0.4% of PP fibers to concrete in the presence of 0.25% of steel fibers (mixtures A6 and A8) increases the permeability up to 2 and 3.5 times compared to the mixture with 0.25% of steel fibers (mixture A3).

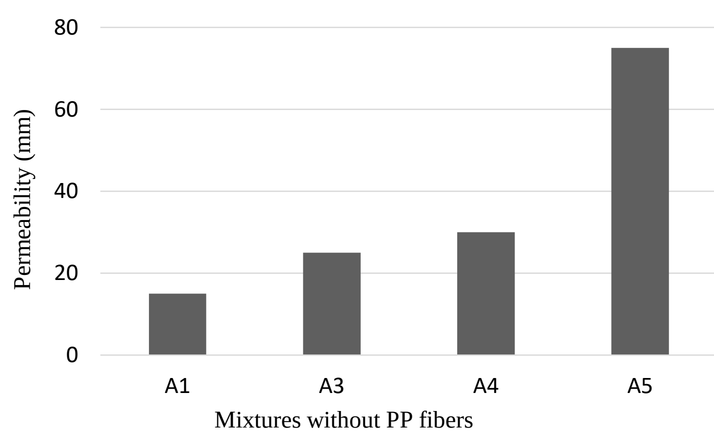

Fig. 8. Effect of steel fibers on the depth of penetration

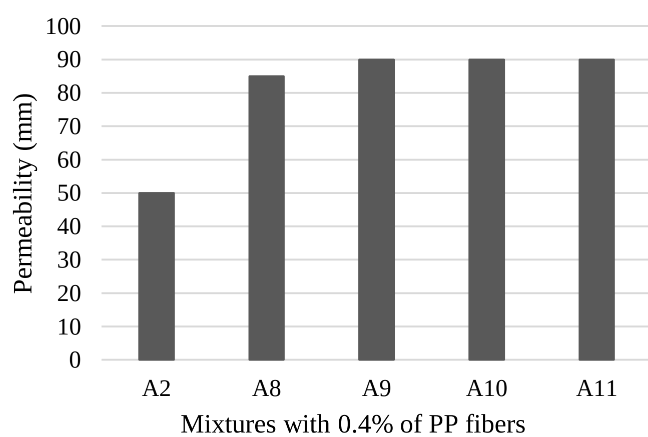

Fig. 9. Effect of increasing steel fibers in the hybrid mixtures on the depth of penetration

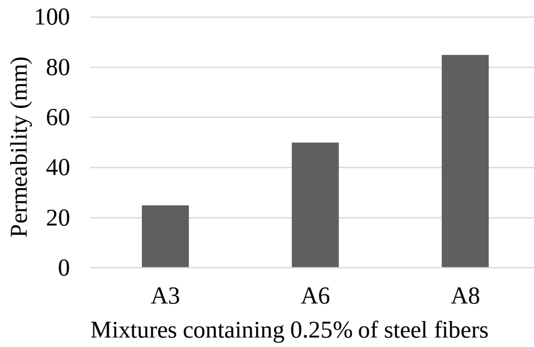

Fig. 10. Effect of increasing PP fibers in the hybrid mixtures on the depth of penetration

Comparing mixture A2 (containing 0.4% of PP fibers) and mixture A4 (containing 0.5% of steel fibers) shows that the addition of PP fibers has a greater effect on the permeability of concrete. Figure 11 compares the permeability of two steel fiber reinforced specimens with two hybrid fiber reinforced specimens. Based on this comparison it can be concluded that the permeability of steel fiber reinforced concrete is lower than that of the hybrid fiber reinforced concrete. Furthermore, a comparison between mixture A5 and A9 (where 0.5% of PP fibers out of 1% is replaced with 0.4% of steel fibers) and also comparing mixtures A4 and A6 shows that the substitution of a portion of steel fibers with PP fibers increases the permeability of concrete.

It is worth mentioning that since the applied water pressure in this research does not exist in practice, this parameter should be considered alongside other variables such as the durability of concrete in order to evaluate the long-term serviceability of concrete.

In this study, 7 mixtures (14 specimens) were chosen from all the designed mixtures to investigate the effects of fiber type and fiber content on the scaling resistance of concrete. After performing the test for 84 days, surface scaling deterioration was determined by dividing the mass of scaled materials in kg by the area of the surface test in m^2. It is worth mentioning that as the surface scaling increases, the ratio of scaled material to the surface test area rises, suggesting the lower scaling resistance of the specimen. Surface scaling deterioration of all specimens in kg/m^2 is presented in Table 6. Based on the result of the present study, it can be concluded that the addition of fibers improves the scaling resistance and reduces the surface scaling deterioration of concrete since the mass of scaled materials after freezing and thawing cycles was declined by the addition of fibers.

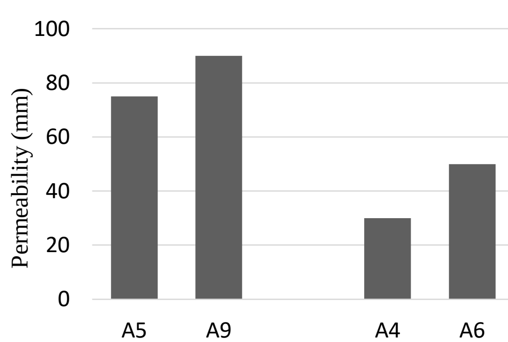

Fig. 11. Comparison of depth of penetration of steel and hybrid fiber specimens

Table 6. Surface scaling deterioration of the specimens

Mixture	PP Fiber Content (%)	Steel Fiber Content (%)	Surface Scaling Deterioration (Kg/m^2)
A1	0	0	0.523
A2	0.4	0	0.514
A4	0	0.5	0.403
A7	0.2	0.5	0.355
A10	0.4	0.75	0.278
A12	0.6	0.75	0.365
A13	0.6	1	0.367

As illustrated in Figure 12, mixture A10 containing 0.4% of PP fibers and 0.75% of steel fibers has the highest scaling resistance (lowest surface scaling deterioration). The mass of scaled materials from the surface of this specimen after 84 cycles was almost half of the scaled materials from the control mixture. The results show the lower scaling deterioration of mixture A10 compared to mixtures A12 and A13 containing higher total fiber content. Based on the results of the current study, the volume content of fibers in mixture A10 can be considered as the optimum volume content of fiber for enhancement of the concrete scaling resistance. Although there is an increasing trend in the scaling resistance of specimens by the addition of fibers, some specimens do not significantly benefit from this. Comparing the surface scaling deterioration of mixture A2 (containing 0.4% of PP fibers) and control mixture and also the comparison between mixture A13 (containing 0.6% of PP fibers and 1% of steel fibers) and mixture A12 (containing 0.6% of PP fibers and 0.75% of steel fibers) indicate that the addition of PP fibers less than 0.4% and the addition of steel fibers higher than 0.75% does not provide noteworthy results. In other words, increasing the volume content of PP fibers from 0.4% to 0.6% and steel fibers from 0.75% to 1% increases the mass of scaled materials, probably due to the less effective compaction process of mixtures with higher fiber content.

As shown in Figure 12, mixture A4 that contains 0.5% of steel fibers demonstrate a higher scaling resistance compared to mixture A2 having 0.4% of PP fibers. Hence, it can be concluded that steel fiber reinforced specimens has higher scaling resistance compared to PP fiber reinforced specimens. The addition of fibers especially in hybrid form has a positive effect on the scaling resistance of concrete, and may reduce the materials scaled from the surface of specimens subjected to freezing and thawing cycles in the presence of deicer up to 90%.

Similar to the study conducted by Berkowski and Kosior (2015), it was shown that the addition of steel fibers increases the scaling resistance of concrete, significantly. Similarly, it was demonstrated that the effectiveness of soft PP fibers is negligible.

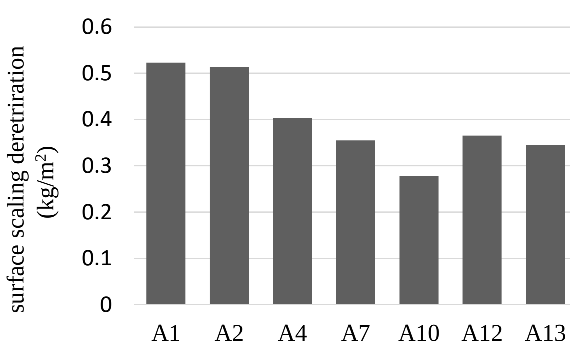

Fig. 12. Trend of changing the surface scaling deterioration

The scaling resistance of specimens is higher in the current study, probably, due to the presence of silica fume. Furthermore, an optimum percentage of hybrid fibers for enhancement of scaling resistance was proposed in the present study, while most of the previous studies are based on mono-fiber mixtures. The results obtained by Quanbing and Beirong (2005) show that the addition of steel fibers reduces the scaling resistance of concrete, while the current study and a few previous research achieved contradictory results.

Considering the superior scaling resistance of hybrid fiber reinforced concrete compared to the conventional concrete, utilizing these composites should be considered for situations in which the concrete is exposed to severe environmental conditions such as concrete pavement in cold regions. Using fibers in hybrid form as the primary reinforcement has several beneficial effects for concrete pavements such as increasing the scaling resistance (enhancing the long-term serviceability of pavement) and reducing the thickness of the pavement. However, the addition of fibers to the concrete subjected to cold weather condition in the presence of steel reinforcing bars needs further considerations since the permeability of hybrid fiber reinforced concrete is higher than that of conventional concrete, which may result in the corrosion of steel bars.

CONCLUSIONS

The present study was conducted to address different and contradictory results of previous studies about the permeability and durability of hybrid fiber reinforced concrete (HFRC). For this purpose, an experimental program was carried out to investigate deicer scaling resistance, permeability and compressive strength of concrete. Based on the result of the present study, following conclusions can be drawn:

- Incorporation of fibers increases the permeability of the specimens, which even continues by the increase in fiber content. The depth of penetration of water in mixture A12 containing 0.6% of PP fibers and 0.75% of steel fibers was 7 times more than that of the control mixture. Moreover, the addition of fibers especially in hybrid form leads to the enhancement of compressive strength increasing the compressive strength up to 23% compared to conventional concrete.
- Addition of fibers up to a specific limit has a positive effect on the scaling resistance of concrete and reduces the materials scaled from the surface of specimens subjected to freezing and thawing cycles in the presence of deicer by 90%. Thus, it makes the hybrid fiber reinforced concrete an appropriate material to be used as the concrete exposed to cold weather conditions. However, increasing the volume content of PP fibers from 0.4% to 0.6% and steel fibers from 0.75% to 1% results in a corresponding increase in the mass of scaled materials. Based on the results of the current study, incorporating 0.4% of PP fibers and 0.75% of steel fibers is the optimum volume usage of fibers for improving long-term serviceability of concrete.
- Considering the superior scaling resistance of hybrid fiber reinforced concrete compared to the conventional concrete, utilizing these composites should be considered in pavement concrete in cold regions.

ACKNOWLEDGMENTS

This research was financially supported by Payhan Concrete Company and Ferdowsi University of Mashhad.

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