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Application of high performance polypropylene fibers in concrete lining of water tunnels

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Abstract

In this study, the application of high performance polypropylene fibers (HPP fibers) in concrete lining of water tunnels, was investigated experimentally. A comparison between the behavior of steel fiber reinforced concrete and HPP fiber reinforced concrete with ordinary concrete is drawn. Advantages and shortcomings of HPP fibers used for concrete lining of water tunnels are also presented.

The obtained results showed that the HPP fibers were not effective in compressive strength when compared to steel fibers, but the effects of HPP fibers on tensile strength, flexural strength, toughness and energy absorption of concrete were significant. Based on the results, the effects of HPP fibers on concrete characteristics such as the flexural toughness, concrete permeability and resistance to chloride penetration were higher than those of steel fibers. The results also showed that with application of HPP fibers, durability and serviceability of the concrete linings can be improved.

Keywords: fiber reinforced concrete, polypropylene fiber, steel fiber, concrete lining, durability.

1.Introduction

Today, concrete is one of the most widely used construction materials. Concrete enjoys several advantages over wood and steel and other construction materials such as flexibility in shaping, fire resistance, durability and ease of production and finally, more economy. However, along with these advantages, there are also shortcomings such as heavy weight, low tensile strength and brittle behaviour.

Research results have indicated that the ductility of concrete using fiber has been greatly increased. Additionally, an overall improvement in the application of fiber is the increase in tensile, flexural and shear strength. Concrete cracking can be delayed and controlled with the application of fibers in concrete. Compressive strength of concrete is increased by adding some kind of fibers to concrete mixtures [1,2]. Another advantage of adding fibers to concrete mixture is the improvement in cavitation resistance, ductility, toughness, resistance to abrasion and erosion [3,4]. Over the last decade, fiber-reinforced concrete (FRC) has been widely used in different structural and non-structural applications such as pavements, floors, overlays, industrial slabs, shotcrete and tunnel linings, where the major concern is toughness and first-crack strength in flexure[5]. Numerous research works have been done to quantify the enhanced properties of FRC materials and particularly to compare the effect of various types of fibers[5- 11]. On the contrary, there are a few researches on the application of fiber reinforced concrete in tunnel linings. This paper focuses on the application of fibers in water tunnel concrete linings.

Researches show that the incorporation of steel fibers in linings improves performance of structural and nonstructural concrete, including better crack resistance, ductility, and toughness, as well as an enhanced tensile strength, resistance to fatigue , impact and blast loading, and abrasion [12-14]. Also, other researches on fiber reinforced concrete lining indicated that fiber reinforcement can be used to reduce the amount of conventional steel reinforcement [14,15]. Other studies have shown that using fibers improves the durability of the tunnel lining and reduces permeability and crack width [13,16].

With the development of synthetic fiber, synthetic macro-fiber, fiber's diameter larger than 0.1 mm is considered as macro-fiber, has been used widely in civil engineering. Compared with steel fiber, the synthetic macro-fiber offers the advantages of light, even distribution and high corrosion resistance. Compared to synthetic fiber, synthetic macro-fiber not only provides resistance for early crack, but also obviously improves the impact resistance, flexural toughness and fracture properties. Synthetic macro-fiber, such as Barchip, is a new useful reinforcement material in concrete [17].

To examine the effect of high performance polypropylene(HPP) fibers on concrete characteristics, in this research, concrete mixtures with 0.4, 0.6 and 0.8 volume percent of HPP fibers and steel fibers were provided. Changes in compressive strength, tensile strength, flexural strength, toughness and energy absorption, water absorption of concrete and chloride ion penetration resistance were measured relative to the control samples. All tests were undertaken according to ASTM or BS standard test methods.

2.Materials and experimental work

2.1 *Materials*

In undertaken experiments, the cement used in concrete mixtures was Portland cement type II from Ardestan Cement Factory. Fine aggregates were natural siliceous sand, with a fineness modulus of 2.725, saturated surface dry specific gravity of 2.65 and water absorption of 0.7% and a maximum size of 4.75 mm. Crushed stone with a maximum nominal size of 12 mm with saturated surface dry specific gravity of 2.68 and water absorption of 0.42% was used as coarse aggregates. Fine and coarse aggregates gradation curve was entirely consistent with the requirements of ASTM: C-33. The polycarboxylated based high range water reducing admixture (HRWRA) was used for all mixtures. The characteristics of synthetic fibers, Figure 1, which were obtained from Elasto-Plastic Concrete Pty Ltd., are presented in Table 1. Mechanical properties of steel fibers are presented in Table 2. HPP fibers and steel fibers had an aspect ratio equal to 52.34 and 53.33, respectively.

Figure 1. Synthetic HHP Fiber (Barchip) [18]

Table 1 Properties of HPP fibers (Barchip)

Table 2 Properties of steel fibers

2.2 *Mix proportion*

Mix designs were calculated according to ACI 211.1[19]. Compositions of concrete mixes are given in Table 3. A total of seven concrete mixes was prepared. One ordinary concrete mix (OC), three fiber concrete mixes containing 0.4, 0.6 and 0.8 percent HPP-fiber by volume (HFRC-4, HFRC-6 and HFRC-8) and three fiber concrete mixes containing 0.4, 0.6 and 0.8 percent steel fiber by volume (SFRC-4, SFRC-6, SFRC-8) were provided. The amounts of cement, fine aggregates, coarse aggregates and super plasticizer (SP) were kept constant in all mixes.

Table 3. Concrete mix proportions.

3. Tests methods

All samples were made and cured as implied in ASTM: C-192. In order to evaluate the effects of fibers on compressive strength, splitting tensile strength and flexural strength, three samples from mixes with 0.4% , 0.6% and 0.8% fiber were made and applied for the tests. Compressive strength, splitting tensile strength and flexural toughness were performed according to BS 1881 part 116 [20], ASTM: C-496 and ASTM: C-78, respectively, at age of 28 days. The amount of energy absorption of concrete sample was also measured along with toughness strength test by installing 4 LVDTs on test beams. Two LVDTs were installed on supports and two other LVDTs were installed on both sides of the beam.

To measure the concrete permeability, a test method outlined by Corps of Engineers Standards was employed [21]. This test should be conducted on cylindrical specimens with 50 mm diameter using triaxial (or Hassler) cell. However, the nearly equal size of fibers and test molds could lead to wrong results. Therefore, 150x150 mm cube specimens were made and the specimens of 50mm diameter were brought out. Then this test was performed on the cored specimens.

Colourimetric method was used for chloride ion penetration depth measurement. Measuring the depth of chloride ion penetration into concrete was performed by spraying a 0.1-N $AgNO_3$ solution on premorse concrete surface.

4. Results and discussion

4.1. *Workability*

The effect of fibers on reducing the workability of the concrete mixes was measured by slump test. It is clear from Table 3 that adding steel fibers or HPP fibers into the concrete mixes has reduced the slump of mixes. The comparison between the control sample (OC) and the mixes of 0.8% volume of fiber (HFRC-8 and SFRC-8) shows that the slump has dropped from 120 mm to 80 and 82 mm, respectively. With the increase in fibers content, the slump was reduced more due to more interlock between aggregates and fibers. It can be seen from Table 3 that the test results for the concrete samples containing Barchip fibers with 48 mm length and steel fibers with 32 mm length were similar at the same fiber percentage content. This is due to the flexibility and adaptability of the Barchip fibers among concrete aggregates.

4.2. *Water absorption percentage*

The results of water absorption percentage of all mixes at the age of 28 days are presented in Table 4. Based on the results, in all fiber concrete specimens, the water absorption percentage has been reduced about 50%. It can be seen that steel fibers were slightly more effective in reducing water absorption percentage as compared to Barchip fibers. To take into account the durability issues, this test was repeated for samples that were kept for 4 months in 100% NaCl solution and results are given in Table 4. All samples kept in chloride solution showed lower water absorption when compared to ordinary samples. It can be due to concrete pores blockage due to penetration of chloride ions. By comparing samples containing different percentages of steel fibers, it can be seen that by increasing the amount of steel fibers in concrete mix, the water absorption was increased. This increase in permeability could be due to inhomogeneous texture provided by steel fibers in concrete mixtures.

Table 4. Water absorption percentage results

4.3 *Compressive strength*

The 28-day compressive strength of all mixes is presented in Table 5. Similar to the previous section, this test was repeated for samples kept for 4 months in 100% NaCl solution and results are given in Table 5.

By comparing the results of HFRC samples with those of control samples, it was understood that Barchip fibers had no significant effect on compressive strength. By adding 0.8% Barchip fibers into concrete mix, compressive strength increased by a maximum of 3.3% compared to control sample. Contrary to Barchip fibers, steel fibers increased compressive strength, so that by the increase in volume percentage of steel fibers, the compressive strength increased as a result. By adding 0.8% steel fibers into the concrete, compressive strength was increased nearly 17% higher than that of control sample. For all samples kept for 4 months in 100% NaCl solution, compressive strength was increased. This is due to the hydration process progresses in this period of time. For samples kept in NaCl solution, Barchip fibers had the same effect on compressive strength that they had on compressive strength at the age of 28 days. Comparison of samples containing steel fibers before keeping in chlorine solution and after that shows that steel fibers lost their positive effects on compressive strength. For example, by adding 0.8% volume of steel fibers into the concrete mix (SFRC-8), compressive strength was increased to about 16.8% higher than that of the control sample but with using the same amount of steel fibers and keeping it in NaCl solution for 4 months, compressive strength was increased to about %12 higher than that of control sample. This was probably due to the development of iron rusts around the steel fibers and the formation of discontinuity between fibers and concrete.

Table 5. Compressive strength results

4.4. *Splitting tensile strength and Rupture modulus*

This test was undertaken based on ASTM: C-496. Cylindrical specimens with 150 mm in diameter and 300 mm in height were used. The splitting tensile strength results of all concrete samples are given in Table 6. Results show that adding fibers into concrete mixes had a small effect on splitting tensile strength. Based on the results, by using 0.8% fiber volume, tensile strength reached to a maximum of 10% more than that of control sample, approximately. Splitting test delivers accurate information until the occurrence of the first crack; but fibers actually act after cracking. Hence, this test is not suggested for assessing tensile strength of fiber reinforced concretes. Flexural strength test was employed and rupture modulus was calculated according to ASTM: C-78. The results of this test are given in Table 6. The obtained results showed that the fibers have significant effects on after-cracking concrete tensile strength. Indeed, an increase in fibers volume percentage increased flexural strength. This result is certified by previous researchers [22-25]. Among the different fibers volume percentages, the effect of using 0.8% fibers content on the flexural strength was more significant for both kinds of fibers (HHP and steel fibers). By using 0.8% steel fibers and HPP fibers into concrete, an increase of 33.8% and 17.5% of rapture modulus was observed, respectively.

Table 6. Tensile strength and modulus of rapture results

4.5. *Flexural strength and toughness*

Flexural toughness, first-crack strength and values of toughness indices, residual strength factors were obtained using 350 by 100 by 100 mm specimens. Toughness indices and residual strength factors of HFRC and SFRC specimens are calculated and presented in Table 7. To calculate the toughness indices and residual strength factors from the load-deflection curves, the area under the load-deflection curve up to first-crack deflection, deflection of 3.0 times the first-crack deflection, deflection of 5.5 times the first-crack deflection and deflection of 10.5 times the first-crack deflection were measured. The dissipated energy, during the flexural failure of concrete specimen, equivalent to the area under the load-deflection curve is regarded as toughness. Toughness indices are equal to the numbers obtained by dividing the area up to a specific deflection by the area up to first-crack deflection (I_5, I_{10} and I_{20}).Residual Strength factors, which are derived directly from toughness indices, characterize the level of strength retained after first crack ($R_{5,10} = 20(I_{10}-I_5)$, $R_{10,20}=10(I_{20}-I_{10})$).

Table 7. Toughness indices and residual strength results

It can be seen from Table 7 that adding HPP or steel fibers to concrete mix increased the first crack load and therefore flexural strength. It can be seen from Table 7 that Barchip fibers had positive effects on flexural strength comparable to the effects of steel fibers. The effect of two kinds of fibers on flexural strength of concrete is compared in Figure 2. As figure shows, the ratio of flexural strength of HFRC samples to SFRC samples (HFRC/SFRC) for all of the three fibers volume percentages was greater than 0.86. It means that HPP fibers had a comparable effect on flexural strength of ordinary concrete with steel fibers. Generally, adding fibers to concrete mixes led to ductile failure of concrete specimens. This is because fibers bridge at cracked sections and prevent sudden failure. The role of fibers in cracked section has been shown in Figure 3. At the cracked section, fibers handle the load and restore the load into the concrete section. In Table 7, from the comparison of I_5, I_{10} and I_{20} for samples with the same fibers volume percentage shows that Barchip fibers behaved more efficiently in toughness and energy absorption than steel fibers. This can be seen in Figures 5 to 7, as well. As Figures show, the area under toughness diagram for HFRC samples are meaningfully larger than SFRC samples after the first crack. Failure mode of ordinary concrete (OC) and fiber reinforced concrete (HFRC) are compared in Figure 4. It is clear from Figure 4 that the failure of fiber reinforced concrete sample was ductile while ordinary concrete was brittle.

Figure 2. The ratio of HFRC/ SFRC flexural strength

Figure 3. Fibers bridging at crack section

Figure 4. OC and HFRC failure type A) HFRC (ductile) B) OC(brittle)

Fig.5. Comparison of HFRC-4 and SFRC-4 toughness and energy absorption

Figure 6. Comparison of HFRC-6 and SFRC-6 toughness and energy absorption

Figure 7. Comparison of HFRC-8 and SFRC-8 toughness and energy absorption

4.6. *Chloride ion penetration depth*

The amount of chloride penetration depth into concrete is one of the issues associated with concrete lining durability. Chloride ions can be present in water passing the tunnel, concrete cement and aggregate and etc. Chloride ions that have penetrated into concrete may cause reinforcement corrosion. To measure the resistance of fiber reinforced concrete to chloride ion penetration, three samples for each mix were kept in 100% NaCl solution for 4 months. After 4 months, all samples were brought out of the solution and cut for test. 0.1 N $AgNo_3$ was sprayed on concrete surface. Spraying the 0.1 N $AgNO_3$ solution on a freshly broken concrete surface led to the formation of white and black regions with well-distinguished boundaries. Results are shown in Table 8. Results, for all fibers volume percentage, show that adding fibers to concrete mix reduced the chloride penetration depth. The penetration depth reduced by 30% in HFRC samples and almost 15% in SFRC samples compared to control samples. Probably blockage of cement pores by fibers lead to reduction of chloride ion penetration depth in fiber reinforced concrete samples. It can be understood from the results that HPP fibers are more efficient than steel fibers as chloride penetration depth in HFRC samples is less than SFRC samples with the same fiber volume percentage. This superiority of concrete specimens containing high performance polypropylene fibers might be due to the following reasons. Developing iron rusts around the steel fibers somehow creates discontinuity between steel fibers and cement paste and therefore, chloride ions penetrate more conveniently into the concrete. The second reason is that Barchip fibers were longer than steel fibers. Thus, one Barchip fiber could block more pores than one steel fiber. Therefore, at the same fiber volume percentage, HPP fibers blocked more pores and caused less chloride penetration depth.

Table 8. Chloride ion penetration depth results

5. Conclusions

The experimental study on the high performance polypropylene (HPP) fiber reinforced concrete and steel fiber reinforced concrete with various volume percentages of fibers revealed the following conclusions:

1) Adding HPP fibers to concrete mix reduced the workability due to aggregate and fibers interlock. Barchip fibers with 48 mm in length and aspect ratio of 52.34 had the same effects on the slump of fresh concrete as steel fibers with 32 mm in length and aspect ratio of 52.33.
2) The results of water absorption test showed that adding fibers to concrete mix could decrease the water absorption of concrete by 50 percent. In this test, steel fibers were slightly more efficient than Barchip fibers. Water absorption percentage results for samples kept in chloride solution for 4 months showed that steel fibers lost their positive effects on the reduction of water absorption slightly. Developing iron rusts around the fibers created discontinuity between steel fibers and cement paste; therefore, water could penetrate into the concrete more conveniently.
3) The compressive strength results showed that HPP fibers had no significant effects on compressive strength as by adding 0.8% volume fibers to the concrete mix, 3.3% increase in compressive strength was observed. But in general, steel fibers increased compressive strength, so that by applying 0.8% steel fibers 16.8% increase in compressive strength was resulted. Compressive strength of samples kept in chloride solution, showed less increase in compressive strength in compare with those not kept in chloride solution.
4) Application of 0.8% steel fibers and HPP fibers increased the splitting tensile strength of concrete specimens by 10%.
5) Rupture modulus based on ASTM: C-78 requirements was calculated. The obtained results indicated that the use of 0.8% HPP fibers results in 17.5% increase in modulus of rapture, while the use of 0.8% steel fibers led to 33.8% increase in modulus of rapture.
6) Results of measuring toughness and energy-absorption characteristics of fiber reinforced concrete mixes, showed that FRC specimens acquire a great ductile behavior and energy absorption capacity, compared to ordinary concrete samples. In

the same fiber volume percentage, HFRC samples behaved remarkably more ductile and absorbed more energy compared to SFRC specimens.

7) Adding fibers to the concrete mix reduced chloride ion penetration depth. HPP fibers, in this regard, were more effective than steel fibers. The reason could be due to development of iron rusts around the steel fibers which created discontinuity between steel fibers and cement paste and therefore, opened the way for chloride ions to penetrate more conveniently into the concrete.

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<u>Caption of figures:</u>

Figure 1. Synthetic HHP Fiber (Barchip) [18]

Figure 2. The ratio of HFRC/ SFRC flexural strength

Figure 3. Fibers bridging at crack section

Figure 4. OC and HFRC failure type A) HFRC (ductile) B) OC(brittle)

Figure 5. Comparison of HFRC-4 and SFRC-4 toughness and energy absorption

Figure 6. Comparison of HFRC-6 and SFRC-6 toughness and energy absorption

Figure 7. Comparison of HFRC-8 and SFRC-8 toughness and energy absorption

Table 1 Properties of HPP fibers (Barchip)

Base resin	Polyelifen
Length (mm)	48
Tensile Strength (MPa)	550
Surface Texture	Continuously embossed
No. fibers per Kg	>35000
Specific Gravity	0.90-0.92
Young Modulus (GPa)	10
Melting Point (°C)	150- 165
Ignition Point (°C)	Over 450

Table 2 Properties of steel fibers

Average fiber length (mm)	32
Average fiber diameter (mm)	0.6
Tensile strength (MPa)	>1100
Specific gravity	7.85

Table 3. Concrete mix proportions.

Specimen	Water Kg/m^3	Cement Kg/m^3	Fine aggregate Kg/m^3	Coarse aggregate Kg/m^3	SP Kg/m^3	HPP fiber %	Steel fiber %	Slump mm
OC	208.25	350	1066	848	4	0	0	120
HFRC-8	208.25	350	1066	848	4	0.8	0	80
HFRC-6	208.25	350	1066	848	4	0.6	0	99
HFRC-4	208.25	350	1066	848	4	0.4	0	105
SFRC-8	208.25	350	1066	848	4	0	0.8	82
SFRC-6	208.25	350	1066	848	4	0	0.6	100
SFRC-4	208.25	350	1066	848	4	0	0.4	105

Table 4. Water absorption percentage results

Specimen name	Water absorption %	Compared to control specimen	Water absorption (After being held in chloride solution) %	Compared to control specimen
OC	2.481	1	0.558	1
HFRC-8	1.419	0.572	0.36	0.645
HFRC-6	1.749	0.705	0.443	0.794
HFRC-4	1.366	0.55	0.381	0.683
SFRC-8	1.19	0.48	0.318	0.57
SFRC-6	1.15	0.463	0.281	0.504
SFRC-4	1.12	0.451	0.242	0.433

Table 5. Compressive strength results

Specimen	Compressive Strength (MPa)	Compared to the control sample	Compressive Strength (held in NaCl solution) (MPa)	Compared to the control sample (held in Nacl solution)
OC	33.66	1	39.55	1
HFRC-8	34.77	1.033	40.59	1.026
HFRC-6	34.62	1.029	39.97	1.01
HFRC-4	34.585	1.027	40.44	1.02
SFRC-8	39.31	1.168	44.22	1.12
SFRC-6	37.69	1.12	46.388	1.173
SFRC-4	37.39	1.11	45.48	1.15

Table 6. Tensile strength and modulus of rapture results

Specimen	Splitting tensile Strength (MPa)	Compared to control specimen	Modulus of rupture (MPa)	Compared to control specimen
OC	2.563	1	4.33	1
HFRC-8	2.82	1.10	5.086	1.175
HFRC-6	2.81	1.096	4.487	1.036
HFRC-4	2.69	1.05	4.364	1.008
SFRC-8	2.81	1.096	5.794	1.338
SFRC-6	2.77	1.08	5.231	1.21
SFRC-4	2.74	1.069	4.679	1.081

Table 7. Toughness indices and residual strength results

Specimen	First crack load (kN)	I_5	I_{10}	I_{20}	$R_{5,10}$	$R_{20,10}$
OC	14.443	1	1	1	0	0
HFRC-8	16.953	1.93	2.96	5.22	20.6	22.6
HFRC-6	14.956	1.57	2.46	3.98	17.8	15.2
HFRC-4	14.547	1.53	2.096	2.91	11.32	8.14
SFRC-8	19.313	1.98	2.95	4.11	19.4	11.6
SFRC-6	17.436	1.9	2.53	3.46	12.6	9.3
SFRC-4	15.597	1.47	2.05	2.79	11.6	7.4

Table 8. Chloride ion penetration depth results

Specimen	Chloride ion penetration depth (mm)	Compared to the control specimen
OC	45.81	1
HFRC-8	31.56	0.69
HFRC-6	33	0.72
HFRC-4	32.19	0.7
SFRC-8	38.28	0.836
SFRC-6	39.5	0.86
SFRC-4	38.12	0.83

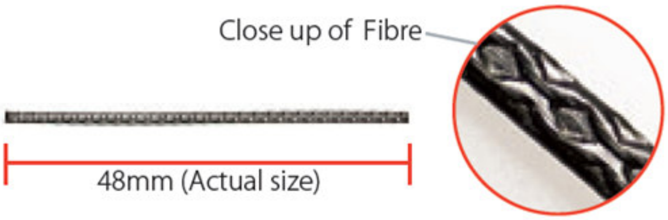

Figure 1. Synthetic HHP Fiber (Barchip) [18]

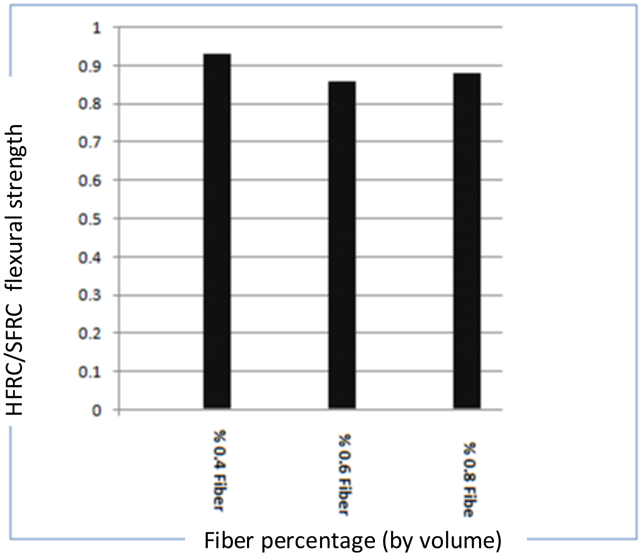

Figure 2. The ratio of HFRC/ SFRC flexural strength

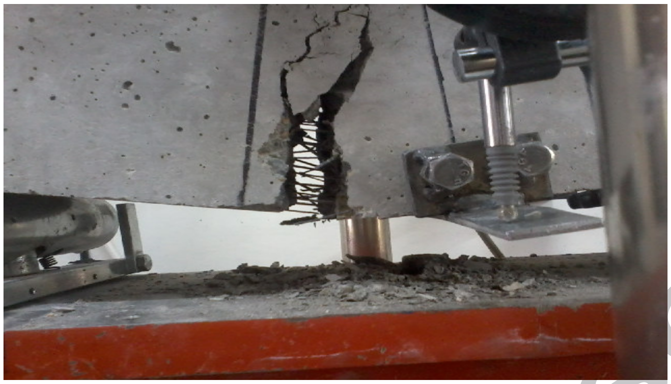

Figure 3. Fibers bridging at crack section

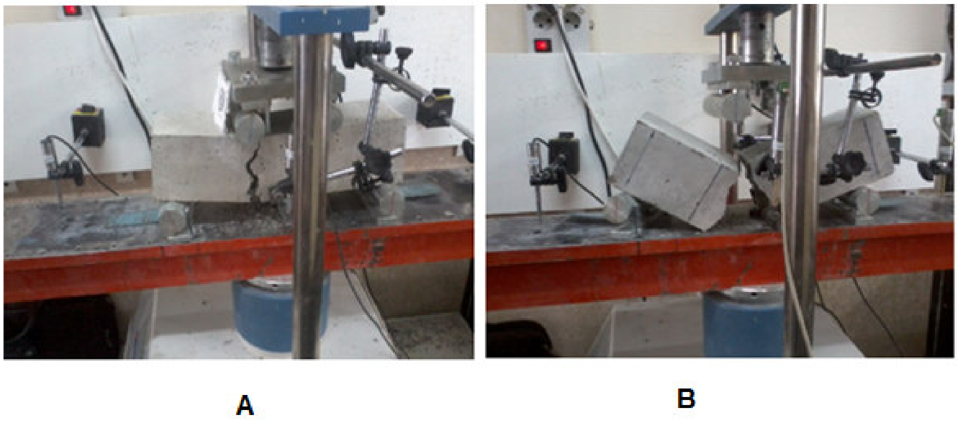

Figure 4. OC and HFRC failure type A) HFRC (ductile) B) OC(brittle)

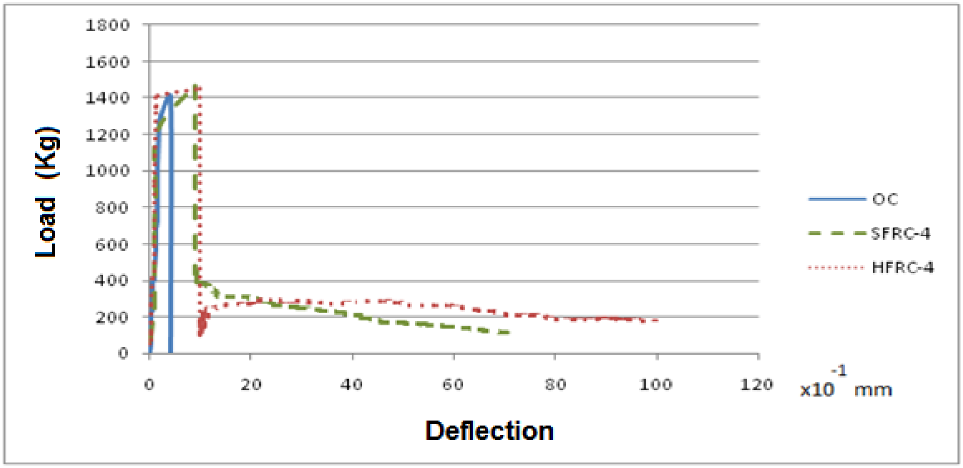

Figure 5. Comparison of HFRC-4 and SFRC-4 toughness and energy absorption

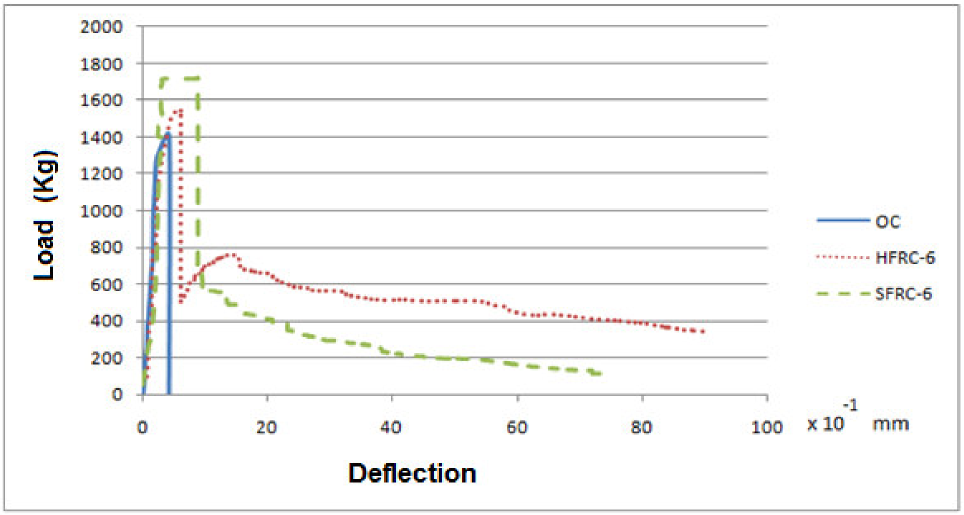

Figure 6. Comparison of HFRC-6 and SFRC-6 toughness and energy absorption

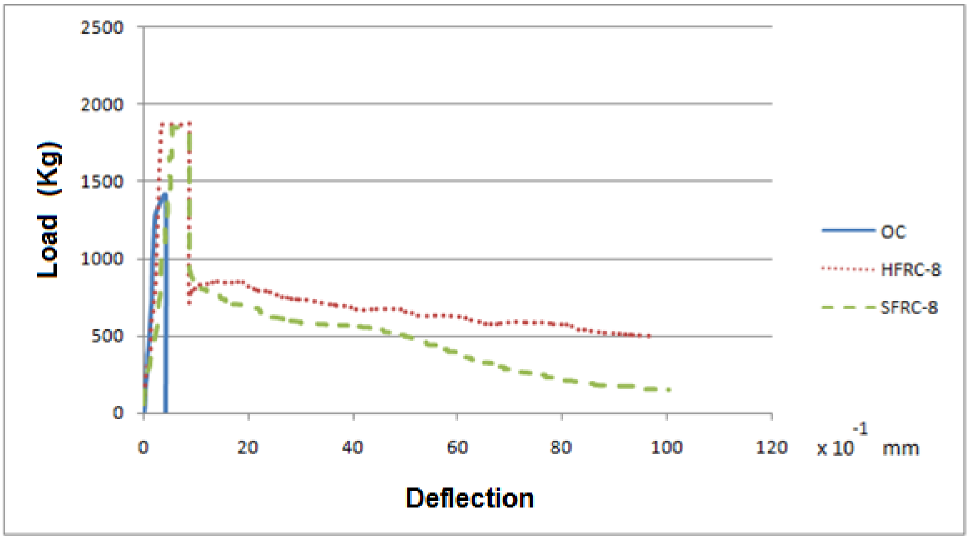

Figure 7. Comparison of HFRC-8 and SFRC-8 toughness and energy absorption

Application of high performance polypropylene fibers in concrete lining of water tunnels

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Research Highlights

1) Adding high performance polypropylene fibers to concrete mix reduced the workability.
2) Adding fibers to concrete mix decreased the water absorption of concrete by 50 percent.
3) HPP fibers had no significant effects on compressive strength.
4) Specimens containing HPP fibers behaved remarkably more ductile and absorbed more energy compared to specimens containing steel fibers.
5) Adding HPP fibers to the concrete mix reduced chloride ion penetration depth.