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An Analysis of the Shear Strength and Rupture Modulus of Polyolefin-Fiber Reinforced Concrete at Different Temperatures

Moslem Yousefvand*[1], Yaser Sharifi[2], Saeed Yousefvand[3]

[1] Department of Structural Engineering, Vali Asr University, Rafsanjan, Iran.
[2] Department of Civil Engineering, Vali Asr University, Rafsanjan, Iran.
[3] Department of Structural Engineering, Malayer University, Malayer, Iran.

*Correspondence should be addressed to Moslem Yousefvand, Department of Structural Engineering, Malayer University, Malayer, Iran. Tel: +98217451500; Fax: +982177563254; Email: M.yousefvand.vru@gmail.com

ABSTRACT

Structural engineers are generally aware of the intrinsic safety properties of concrete exposed to fire (non-flammability at high temperatures). However, the tendency of concrete for spalling at high temperatures is a significant defect, and recently many researchers have conducted studies on this issue. One of the primary objectives of this study is to assess the shear strength and modulus of rupture of concrete reinforced with different percentages of modified polyolefin synthetic fibers at different temperatures and to compare the results with the preliminary design. The other objective of the present study is to compare the behaviors of synthetic fiber concrete under the effect of the furnace temperature and direct fire. After adding fibers (1.5 volumetric percentage), a 29% increase in the tensile strength and a 56% increase in the modulus of rupture (the stress corresponding to the development of the first crack) were observed. Considering the fiber concrete results in the experimental temperature condition, it can put on an acceptable strength performance. However, at temperatures equal to or greater than 400 $^{\circ}C$, the fibers lose their role in compensating the low tensile strength of concrete due to oxidation, causing porosity in the concrete and reducing its strength.

Keywords: fiber-reinforced concrete, tensile strength, rupture modulus, high temperature

1. INTRODUCTION

Structural engineers are aware of the intrinsic safety properties of concrete exposed to fire (non-flammability at high temperatures). However, the tendency of concrete for spalling at high temperatures is an important defect, and recently many researchers have conducted studies on this issue. Fibers are classified into the groups of natural and synthetic fibers. Examples of fibers commonly used in FRC (fiber-reinforced concrete) include steel, glass, carbon, polymer fibers, and cellulose fibers. In general, the reinforcing fibers cannot replace rebars in structural members because they deliver a different function in concrete. The most important role of fibers in FRC is to control cracking and change the concrete behavior when cracks develop in the concrete grout. Researchers have proven that the addition of polymer fibers to concrete improves its flexibility and toughness. Flexural toughness is the measure of the energy absorbed by a substance under the effect of plastic deformations. Substances with low toughness generally experience brittle fractures. Adequate toughness is substantially important for a safe structural system. Adding fibers considerably improves ductility and flexural toughness. An adequate bond between the fibers and the cement matrix is essential for improving the flexural toughness [1-3]. Celik et al. [4] studied the behavior of concrete reinforced with synthetic fibers at high temperatures. The results of their experiments indicated that adding different types of synthetic fibers improves the mechanical characteristics of concrete, such as its compressive strength and flexural strength under the effect of temperature. Microstructural analyses also adequately confirmed the bond between the cement matrix and fibers. Yurdakul et al. [5] assessed the mechanical properties and durability of concrete reinforced with metakaolin-based polypropylene fibers under the effect of high temperatures. They realized that the specimens containing the fibers had more flexural strength than the primary specimens at high temperatures. The ultrasonic testing, microstructural analysis, and visual examinations confirmed this finding. Sukontasukkul et al. [6] studied the performance of polymer-fiber reinforced concrete. They found out that in the fiber-reinforced concrete specimens, the flexural toughness and ductility of the specimens grew drastically following the cracking. Felipe et al. [7] studied the behavior of polypropylene fiber-reinforced concrete under the effect of furnace temperature and compared it to fire temperature. They reported that adding fibers to concrete prevents the collapse and delamination of concrete up to a temperature of 600 $^{\circ}C$. They also concluded that adding fibers does not contribute to the prevention of a decrease in the concrete weight. Researchers [8-9] also analyzed the properties of concrete reinforced with polypropylene and steel fibers when exposed to fire heat. They stated that steel fibers are more effective than polymer fibers in controlling fire-induced cracks. In fact, polymer fibers melt in concrete and increase the steam exhaust pressure. First, they increase the concrete strength, but it loses its positive effect on concrete with an increase in temperature over time, causing extensive porosity in concrete and reducing concrete strength. Li et al. [10] assessed ultra-high performance concrete reinforced with hybrid fibers (steel and polymer) for the prevention of collapse with high efficiency at furnace temperature. The results of their structural analysis indicated that the hybrid fiber-reinforced concrete specimen showed more coherence than the steel fiber-reinforced concrete specimen at high furnace temperatures. Mazin et al. [11] examined the effects of fire heat on polypropylene fiber reinforced reactive powder concrete beams. They concluded that the beams containing 0.25 volumetric percentage had doubled toughness in relation to time as compared to the fiber-free sample, while the beams containing 0.75 and 1.25 volumetric percentages fully maintained their toughness when exposed to the fire heat and did not undergo complete rupture. Eidan et al. [12] assessed the residual mechanical properties of polypropylene fiber-reinforced concrete after heating it in a furnace. One of their primary goals was to determine the critical temperature (400 $^{\circ}C$). At temperatures higher than the aforementioned temperature, the effects of adding fibers were considerably evident on concrete. They also realized that the fibers did not positively affect the modulus of elasticity at temperatures higher than 600 $^{\circ}C$. They reported that in fiber-reinforced concrete, polypropylene fibers with a length of 12mm outperformed the 6-mm fibers when exposed to heat. Abaeian et al. [13] explored the effect of high temperature on the mechanical behavior of high-strength concrete reinforced with macro polypropylene (HPP) fiber. According to their findings, adding this fiber has no drastic effect on the compressive strength of high-strength concrete at normal temperatures. However, these fibers drastically affect this type of concrete at high temperatures by preventing its collapse and preserving its coherence. Ding et al. [14] analyzed the pore pressure of self-consolidating concrete reinforced with different fibers exposed to fire and analyzed the effect of fibers on the change in the concrete pore pressure. They proposed an empirical formula to determine the maximum relative pore pressure in fiber-reinforced concrete exposed to fire. They realized that polypropylene fibers could be among the fundamental factors for reducing the concrete pore pressure at high temperatures. Moreover, these fibers could contribute to the preservation of concrete consolidation at high temperatures.

Maluk et al. [15] studied the effect of adding polypropylene fibers on the heat-induced spalling tendency of concrete. They reported that these fibers drastically reduce concrete spalling at high temperatures. They also indicated that the tendency for spalling at higher temperature decreases in concrete with an increase in fiber length. Park Jung et al. [16] analyzed the positive effects of adding synthetic fibers on the residual mechanical properties of ultra-high performance concrete after exposure to ISO 834 standard fire. SEM (scanning electron microscope) images were used to assess the condition of concrete specimens containing synthetic and steel fibers following exposure to fire and to analyze the porosity variations of the cement matrix. They concluded that steel fibers could not prevent concrete spalling and crushing at high temperatures. However, the polymer fibers improved flexural toughness at high temperatures as compared to the initial specimens. Abid et al. [17] assessed short-term strain and long-term strain in steel fiber reinforced reactive powder concrete and concluded that short-term strain and long-term strain grow by increasing stress and temperature. The ascending trend in thermal strain up to 150 $^{\circ}C$ was slow. However, a sudden increase was observed at higher temperatures, and the growing trend was controlled and enhanced by adding steel fibers. Wang et al. [18] studied the effect of adding polypropylene (PP) fibers on rubber concrete based on its mechanical performance, durability, and microstructure. Specimens were prepared with two rubber volumes of 10 and 15%, which were combined with 0.5 volumetric percentage of fiber. Their results indicated that compressive strength can increase to 40MPa with PP fibers and rubber grains. Moreover, the ultrasonic wave speed properly reflected the good quality of the concrete specimens. The failure of morphology and ESEM imaging indicated the positive effect of the rubber grains and PP fibers on post-cracking propagation. The stable uses can be restored by combining macro glass fibers and recycled rubber. Folino et al. [19] analyzed the failure and mechanical properties of fiber-reinforced concrete beams on the actual scale. Afterward, the experimental results of the four- point bending test on different concrete beams containing metal fibers were presented and discussed. It was indicated that fibers improve the structural coherence in behavior after the exertion of maximum load, thereby improving the shear and flexural strengths of the beams and the fiber-reinforced concrete specimens. Jose et al. [20] analyzed the mechanical behavior and rupture in models of fiber-reinforced concrete exposed to heat. The destruction of the pores structure due to the damage caused by heat was analyzed through X-ray radiography. Besides, the mechanical properties and rupture of the specimens were analyzed at the room temperature and

300 $^{\circ}C$. Finally, a relationship was established between the intra-matrix damage to the concrete grout and the corresponding mechanical behavior, revealing that the propagation of the intra-matrix damage and its effect on mechanical behavior varied by the pore size. Moreover, the fibers in concrete change the structure of the pores. Chen et al. [21] studied the use of recycled aggregate concrete. One of the main concerns about using such concrete types in buildings is their spalling and collapse during fires. In this study, this weakness was considerably overcome by adding fibers to the concrete mix. The results of their experiment revealed that adding steel fibers postpones the onset of cracking in concrete and reduces the crack width. Hence, it considerably increases the failure of energy and toughness of the specimens following their exposure to high temperatures.Mai et al. [22] reported that the polypropylene fibers in fiber-reinforced concrete are oxidized when exposed to furnace heat and drastically lose their flexibility. Lau et al. [23] reported a decrease in the compressive strength of fiber-reinforced concrete exposed to furnace heat. In this study, the shear strength and modulus of rupture of polyolefin-fiber reinforced concrete are studied at different temperatures based on the results of previous studies.

2. MATERIALS AND METHODS

Concrete aggregates account for approximately 60 to 80% of concrete volume, and many of the physical, chemical and mechanical properties of concrete are directly linked to the characteristics of the aggregates. Aggregates are almost cheap and do not have complex reactions with water. Hence, aggregates are usually used as neutral fillers in concrete. Some of the properties of aggregates that are important in concrete include porosity, gradation, moisture absorption, shape and surface texture, crushing strength, modulus of elasticity, and type of the harmful substances. Table 1 shows some of the important characteristics of these aggregates. The gradation diagram Figure1 is also presented in the following. In this research, Kerman type 2 cement is used. The chemical and physical properties of this cement type are listed in Table 2 These properties comply with the ASTM C150-07 standard [24]. According to the national concrete standard, drinkable water can be used in concrete. However, previous records indicate that drinkable water does not suit concrete and it should not be used. Water is used in three forms in concrete: for washing the aggregates, as one of the constituents of concrete, and for concrete curing. The drinkable water in Rafsanjan City, Kerman Province, was used in this study. The use of superplasticizers in concrete reduces cement consumption and simplifies the compaction and mixture of concrete. Superplasticizers have more powerful effects than plasticizers. These substances preserve concrete coherence and increase its efficiency without reducing its strength. Moreover, these substances are capable of reducing concrete water demand by 25 to 35% and preventing bleeding. The future development of concrete is determined by its additives, especially the concrete superplasticizers. In this research, a PCE-based (polycarboxylate ether) superplasticizer, which is capable of preserving efficiency for a long time and is made by Alborz Chemicals Company, is used. The physical and the chemical properties of this superplasticizer are listed in Table 3. Polyolefin fibers (Figure 2) with the technical specifications listed in Table 4 are used in this study.

Table 1. The aggregates physical properties (sand and gravel)

	Sand	Gravel
Particle density SSD	2.48	2.56
Water absorption capacity (%)	3.3	2.4
Shape	Round with sharp corners	Halved

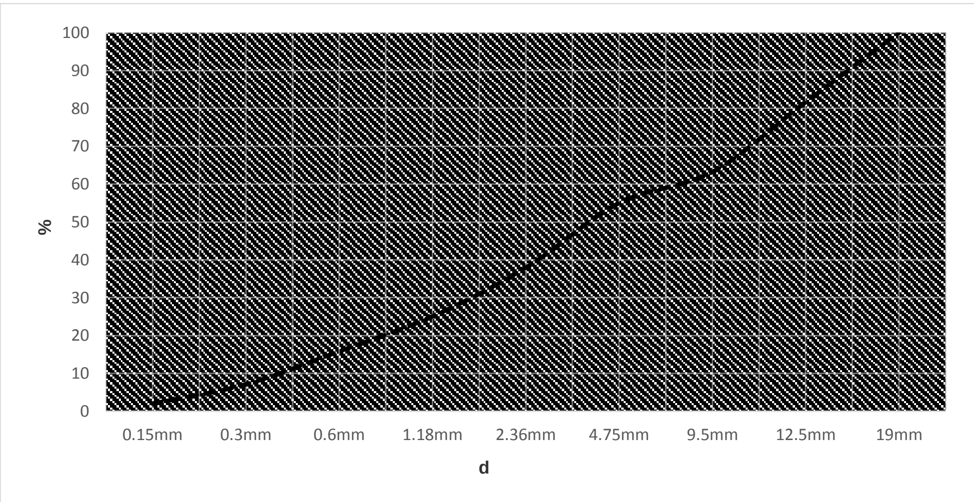

Figure 1. Gradation curve of aggregates mixture

Table 2. Chemical specifications of Kerman type 2 Portland cement

Component	Loss on Ignition	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Cl	Free CaO	C_3S	C_2S	C_3A	C_4AF
Result (%)	1.19	21.50	4.95	3.97	63.52	1.75	2.20	-	1.4	50	24	6.4	12.1

Table 3. Technical specifications of the carboxylate superplasticizer

particulars	values
Superplasticizer	carboxylate
Appearance	Light
Density	1.09 g/cm^3
pH value	6-8
Specific gravity	1.1

Figure 2. Polyolefin fibers

Table 4. Polyolefin fibers specifications

Ingredients	Modified polyolefin
Shape	Interlocked grains
Length	18mm
Tensile strength	800MPa
Bulk density	0.91- 0.94
Water absorption	Zero

2.1. CNCRETE MIX

After optimizing the aggregates mix and determining the mix ratios based on the national mixing method, the concrete specimens were built in accordance with the standard. In the present project, mix designs in all concrete tests are listed in Table 5 and Table 6. After mixing the main ingredients of concrete without any additive, the main ingredients were mixed for 2 minutes in a mixer. Afterward, the fibers and subsequently the superplasticizer were added to the mix and sampling was performed when the materials were fully mixed.

Table 5. Naming the mix designs

Mix Design Name	Description
CN , N (Normal)	Control
CP, P (polyolefin)	Polyolefin-fiber reinforced concrete

Table 6. Mix design

Mix design	Fiber volumetric percent	Superplasticizer (cement weight percent) (kg/m³)	Cement (kg/m³)	Gravel (kg/m³)	Sand (kg/m³)	Water (kg/m³)
CN	-	0.6	410	850	940	200
CP 0.5%	0.5	0.6	410	850	940	200
CP 1%	1	0.6	410	850	940	200
CP 1.5%	1.5	0.6	410	850	940	200

3. DISCUSSION AND RESULTS

3.1. TENSILE AND FLEXURAL TESTS

The tensile strength tests (split-half tests) were conducted in accordance with the ASTM C496/C496M-04 standard [25] (10x20 test cylinders) and flexural strength tests were performed in accordance with ASTM C78-08 [26] (45x15x15cm specimens with 30-cm spans) using different volumetric percentages at furnace temperature (Figure 3 and Figure 4). Prior to the tests, all the specimens were submerged and cured for 28 days in laboratory conditions. The results of the specimens exposed to heat at the 400 and 600 °C are listed separately in Tables 7 and 8. The diagram of each test and visual reports of the failure types of the specimens are also presented.

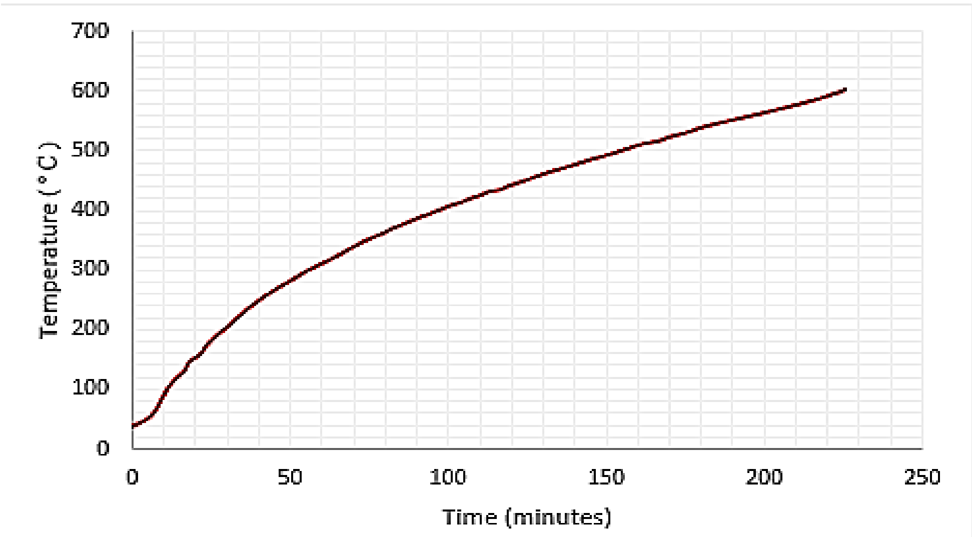

Figure 3. Temperature-furnace time diagram

Figure 4. The furnace and specimens

Table 7. The results of the tensile strength test at different temperatures

Mix design	Tensile strength (Mpa)		
	25 ° C	400 ° C	600 ° C
CN(Normal)	3.8	3.7	2.1
CP 0.5%	4.1	4.1	2
CP 1%	4.6	4.5	1.7
CP 1.5%	4.9	5	1.2

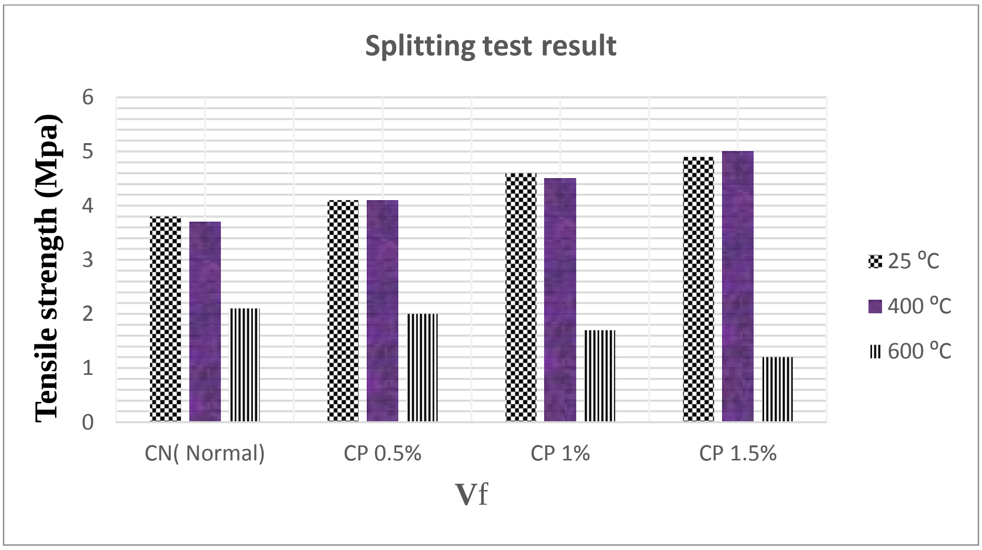

Figure 5. Results of the Brazilian tensile test

Figure 6. Images of the tensile strength test

Table 8. Results of the flexural strength test at different temperatures

Mix design	Flexural strength (Mpa)		
	25 ° C	400 ° C	600 ° C
CN(Normal)	3.7	2.3	1.6
CP 0.5%	4.4	3.5	1.4
CP 1%	5.1	4.1	1.3
CP 1.5%	5.8	4.2	1.2

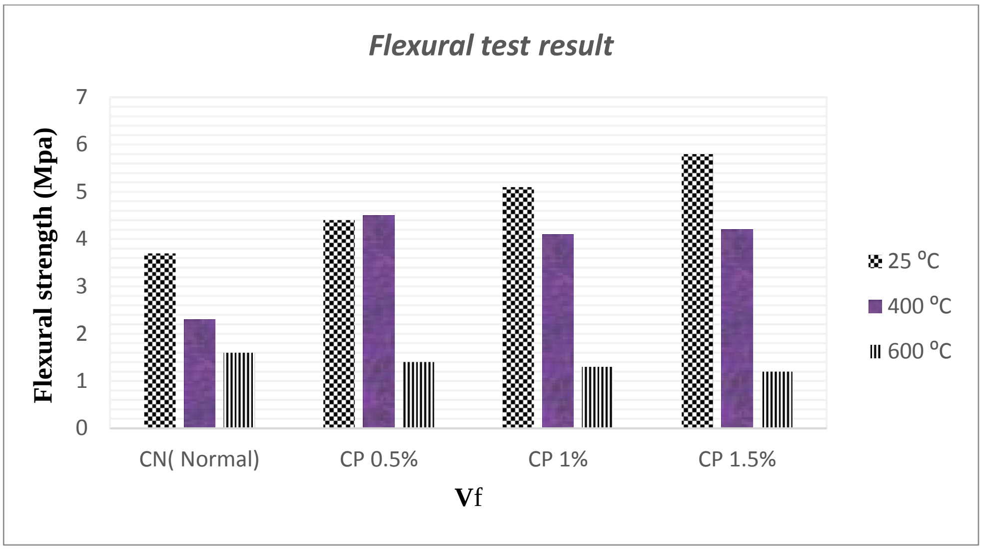

Figure 7. Results of the flexural strength test (four-point test)

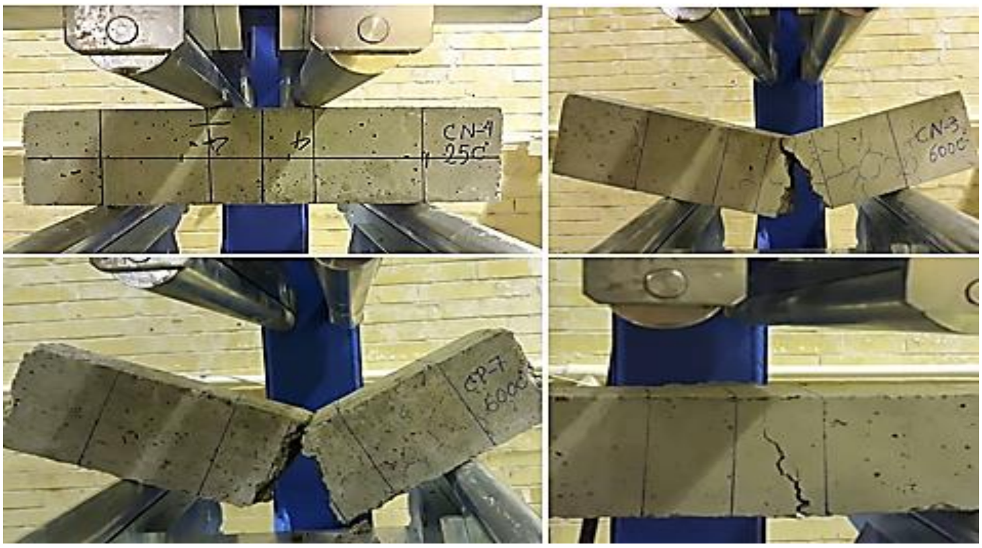

Figure 8. Images of the flexural strength test

It could be concluded that the fibers play their role in improving tensile and flexural strength prior to the 400 $^{\circ}C$ temperature. Thereafter, the fibers gradually lose their role as the furnace temperature rises, reducing concrete strength. The specimens in the control design showed a lower decrease in strength than the fiber-reinforced specimens at 600 $^{\circ}C$. A drastic decrease in strength was observed over time, with an increase in the volume of fibers at the mentioned temperature. Considering the results of similar studies, it could be concluded that the addition of fibers has no drastic effect on the compressive strength of high-strength concrete at the normal temperature. However, the addition of fibers to this type of concrete has a drastic effect at high temperatures on the prevention of collapse and preservation of concrete coherence [13]. Adding 1.5 volumetric percent of fibers to concrete resulted in a 56% increase in its flexural strength (the stress corresponding to the emergence of the first crack) at the 25 $^{\circ}C$ temperature, which could be attributed to the bond established between the concrete nanocracks. Adding fibers to concrete beams can contribute to the improvement in the modulus of rupture and change the concrete failure type from the brittle failure to the ductile failure [19]. Since adding fibers destroys the continuity of pores and the bonds between the flow channels in concrete [27], oxidation of fibers and loss of its modulus in the fibers at a high temperature not only destroy these bonds but also increase the development of pores, which is harmful to fiber-reinforced concrete. In this study, when concrete was placed in the furnace at high temperatures (600 $^{\circ}C$), this condition was exacerbated [22]. At times of fire, the pore pressure of the steam output increases significantly. Consequently, the fibers melt and fill the pores, thereby increasing strength at their melting point. With an increase in temperature, the fibers lose their properties and a descending trend in concrete strength starts. However, in concrete specimens that are exposed to furnace heat, strength decreases because the fibers melting mechanism is not present in concrete [8-9].

4. CONCLUSION

The results of analyzing the experimental data are presented in this study. It is tried to meet the accuracy standards in all the stages, from building the specimens to the failure of the specimens. The results of this study are as follows.

1. Due to the role of fibers in sewing the cracks, brittle rupture and crushing of the specimen are prevented. In fact, rupture among the fibers is accompanied by ductility and the specimen significantly maintains its consolidation.
2. Since adding fibers ruins the continuity of pores and the bonds with the flow channels in concrete, it is among the important causes of consolidation and coherence of concrete and prevention of spalling.
3. The loss of concrete homogeneity and oxidation of the fibers in concrete at high temperatures are among the causes of the abrupt decrease in the tensile strength of concrete at 600 $^{\circ}C$.
4. Adding fibers to concrete beams can help improve the modulus of rupture and change the concrete failure type from the brittle type to the ductile type.
5. The behavior of polymer fibers in concrete specimens exposed to furnace temperature differs from the behavior of concrete specimens directly exposed to fire.

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AUTHORS CONTRIBUTION
This work was carried out in collaboration among all authors.

CONFLICT OF INTEREST
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