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Research Article

Investigation of the effects of re-curing on mechanical properties of basalt-polypropylene hybrid fiber concretes after exposure to high temperature

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ABSTRACT

Fiber reinforced concretes have attracted significant attention in recent decades due to their superior flexural and toughness properties compared to traditional concrete in civil engineering structures. In addition, cementitious materials can undergo significant mechanical deterioration under high temperature. Therefore, the investigation of the properties of FRC for fire-resistant design has become an important research topic in recent years. On the other hand, there is very little research on the repair of FRCs damaged by fire. In this study, high temperature resistance of mixtures prepared using basalt and polypropylene fibers was investigated. In addition, the ability of FRCs exposed to high temperatures to regain their properties by applying water re-curing process was investigated. In this context, ultrasonic pulse velocity (UPV), compressive and flexural strength of FRC series after different stages were investigated. In the use of water curing single basalt fiber, 18.56% and 13.82% increase in relative compressive strength was obtained after 600 °C and 800 °C, respectively. These increase rates were determined as 22.25% and 22.81% in relative flexural strength. Recovery was more significant in the hybrid mixture formed with 0.2% polypropylene fiber. 29.22% and 15.93% recovery was reported in relative compressive strength after 600 °C and 800 °C, respectively. It was determined that re-curing significantly increased the mechanical properties of FRC mixtures.

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1. Introduction

Normal concrete provides low tensile and flexural strength, fracture energy and ductility (Kızılkanat et al. 2015; Wang et al. 2019). However, significant improvements occur especially in terms of tensile strength, toughness and durability as a result of reinforcing concrete with fibers. The purpose of incorporating fibers is to enhance the tensile strength of concrete by improving its load-bearing capacity through crack bridging (Şengel et al. 2022). Concrete reinforced with a single type of fiber can only benefit from the improvement of its properties in a limited direction (Ahmed and Maalej 2009). In recent decades, the strengthening and repair of structures using fiber-reinforced polymer composite materials, produced with various fiber types, has gained significant importance (Çelik et al. 2024). However, with the hybrid use of two or more fibers that can show different performances, different properties of each fiber can be utilized (Ahmed and Maalej 2009; Banthia et al. 2014; Qian and Stroeven 2000). In addition, fiber-reinforced concretes (FRC) exhibit more positive behavior in terms of the safety requirements of civil engineering structures exposed to fire compared to normal concrete (Hou et al.

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2019; Chinthapalli et al. 2020; Yao et al. 2022). Significant changes in temperature during fire are reported to cause deterioration and spalling of components in the concrete matrix structure, resulting in significant strength reductions (Li et al. 2020).

Polymer fibers are preferred to fill the cement paste and voids in the concrete and to improve strength and durability (Alaskar et al. 2021). Basalt fiber (BF) is a new type of environmentally friendly fiber that has been widely used in recent decades, produced by melting basalt rock (Jiang et al. 2014; Branston et al. 2016). Basalt fibers are manufactured with lower energy consumption compared to commonly used fiber types, such as steel, glass, and carbon (Gultekin 2023). Basalt fiber can improve the physico-mechanical properties of concrete with its high tensile strength and elasticity modulus. In addition to these properties, it is a type of fiber with high melting temperature and chemical corrosion (Yao et al. 2022; Deng et al. 2020; Niaki et al. 2018). Literature studies report that the temperature range of basalt fiber is between −200 °C to 800 °C (Fiore et al. 2015; Guo et al. 2018). On the other hand, polypropylene fiber (PPF) has a restrictive effect on the plastic shrinkage of concrete at an early age (Deng et al. 2021). Additionally, adding polypropylene fiber can strengthen the matrix fiber bond and strengthen crack resistance (Yao et al. 2022).

Fire poses a significant threat to all constructional components, often resulting in the loss of life and property (Koşatepe and Yazici 2023). The residual properties of FRC exposed to elevated temperatures are significantly affected by the materials and fibres (Han et al. 2005; Serrano et al. 2016; Wu et al. 2020). Previous studies have found that the residual properties of FRC exposed to heating will be significantly affected by the type of fibres added to the concrete (Sideris et al. 2009; Choumanidis et al. 2016). Fiber types can be broadly divided into two groups in terms of improving the high temperature resistance of concrete. A group of materials with significant thermal stability during heating, such as steel, basalt and carbon fiber, can limit the formation of microcracks during and after fire by fiber bridging effect (Wu et al. 2020). Fibers such as PPF and PVA, on the other hand, show melting properties at low temperatures in cement composite structures, reducing internal vapor pressure and preventing microstructure deterioration represents the other group that provides pathways for water to evaporate (Wu et al. 2020). Yao et al. (2022) reported that the hybrid use of BF and PPF was significant in improving the mechanical performance of mortar specimens at target temperatures. In the study of Fu et al. (2021), BF compared to PPF reported that the effect on strength was more positive. It was also found that the improvement effect on ductility was more effective in the use of hybrid BF/PPF compared to those using only PPF or BF.

Studies conducted in recent decades have reported that concrete that has deteriorated after high temperatures can regain its strength and durability properties by re-curing with water or exposing it to a humid environment (He et al. 2022; Bouhafs et al. 2024; Poon et al. 2001; Li 2021). Crook and Murray (1970) first reported the post-fire re-curing process in 1970. In this study, they found that re-curing had a significant effect on the recovery of the compressive strength of concrete. After the high temperature curing process, the chemical deteriorations that occur during heating are reversed and the dehydrated matrix is rehydrated by re-curing with water (Wu et al. 2020; Shui et al. 2008). In this context, past studies have focused on the effect of substitute materials on re-curing (Poon et al. 2001; Poon and Azhar 2003; Li 2021; Kharrazi et al. 2023). However, studies on the re-curing of FRC with water are limited and mostly focused on steel fiber. Bouhafs et al. (2024) investigated the effect of water re-curing on concrete mixtures containing steel fibers exposed to high temperatures. He et al. (2023) reported significant improvements in compressive strength of hybrid fiber concrete containing steel and PPF after water re-curing after heating.

As a result of the examination of literature studies, it was observed that there is limited study on the high temperature resistance of concretes reinforced with BF and PPF. In addition, in recent years, the performance research of FRC, especially exposed to fire, after water re-curing has gained importance. However, there is no study in the literature discussing the effect of water re-curing on concretes containing BF and PPF after heating. In this context, both the high temperature resistance of concretes with BF and PPF added, used individually or as hybrids, and their performance after water re-curing process were investigated in this study. Three different temperatures (400 °C, 600 °C and 800 °C) were targeted in the study and subjected to re-curing after heating. After the specified stages UPV, compressive and flexural strengths were determined.

2. Materials and Method

2.1. Materials

CEM I 42.5 R ordinary Portland cement (OPC) was used to prepare the mixture specimens. Chemical compositions and physical characteristics of OPC are presented in Table 1. In the study, 0-5 mm river sand was used as fine aggregate. Crushed stone aggregate in the size range of 5-15 mm was used as coarse aggregate. The specific gravity of fine and coarse aggregate was determined as 2.64 and 2.60, and the water absorption values were determined as 1.10 and 0.92, respectively.

To improve the workability of concrete mixtures, the third-generation polycarboxylic ether-based, highly water-reducing BASF Master Glenium 123 superplasticizer with a density of 1.13 g/cm^3 and a pH of 5.5 ± 1 was used. In addition, two types of fibers produced from different geometries and materials were used in the study. The properties and images of the fibers are presented in Table 2 and Fig. 1.

2.2. Mix design, curing and experimental program

In order to investigate the effect of two different fibers on the performance of FRC before and after heating and after re-curing with water, 3 different mixtures were designed in the study. In all mixtures, the cement amount was fixed as 450 kg/m^3 and the water/cement ratio was fixed as 0.42. In the first mixture (M1), 0.40% basalt fiber was used alone. In the second (M2) and third mixtures (M3), basalt fiber was replaced with 0.10% and 0.20% polypropylene fiber and designed as a hybrid. Basalt fiber was preferred in the study because it has a high melting point and is cheaper than steel fiber and has better chemical resistance compared to glass fiber. In addition, it was adopted to investigate the effect of PPF on re-curing due to its low melting temperature. The material ratios of these three mixtures are given in Table 3. As a result of experiments, a slump diameter of 110–125 mm was reached. This slump range belonged to class S3 according to EN 206 (2016).

Table 1. Chemical compositions and physical properties of cement.

Chemical compositions	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	SO_3	LOI (%)
	17.73	4.56	3.07	62.80	2.07	0.62	2.90	2.05
Physical properties	Specific gravity	Insoluble residue (%)	Fineness (cm^2/g)					
	3.15	0.66	3450					

Table 2. Properties of fiber.

Type	Length (mm)	Diameter (µm)	Density (g/cm^3)	Tensile strength (MPa)	Modulus of elasticity (GPa)
Basalt	24	9–23	2.60–2.80	4840	89
Polypropylene	12	18–20	0.91	350	3.50

Fig. 1. View of fibers: (a) Basalt fibers; (b) Polypropylene fibers.

Table 3. Mixture proportions and slump values.

Mixture code	Cement (kg/m^3)	W/C	Fine agg. (kg/m^3)	Coarse agg. (kg/m^3)	Super plasticizer (kg/m^3)	BF (%)	PPF (%)	Slump (mm)
BF0.40 (M1)	450	0.42	934	754	10.50	0.40	–	125
BF0.30PPF0.10 (M2)	450	0.42	934	754	10.50	0.30	0.10	120
BF0.20PPF0.20 (M3)	450	0.42	934	754	10.50	0.20	0.20	110

The cured specimens were kept in the oven at 40 °C until the mass values stabilized. Specimens removed from the oven were exposed to the target temperature of 400, 600 and 800 °C with a constant heating rate of 5 °C/min. At each target temperature, the oven was fixed for 1 hour and then allowed to cool. After cooling, half of the specimens were tested, while the other half was placed in water for re-curing for 30 days.

All concrete series were subjected to non-destructive testing (UPV) according to ASTM C597-02 (2016). UPV test was performed on cube specimens with dimensions of 100x100x100 mm^3 using the Pundit Lab device with a nominal frequency of 54 kHz. The compressive strength of the specimens subjected to different conditions was determined according to the EN 12390-3 (2009) standard on cube specimens of 100x100x100 mm^3 dimensions.

70x70x280 mm³ prism specimens prepared from each series were subjected to flexural tests according to EN 12390-5 (2009). For UPV, compressive, and flexural tests, the average of 3 specimens was taken for each different stage.

3. Results and Discussion

3.1. Ultrasonic pulse velocity results of FRC

The ultrasonic pulse velocity (UPV) test results of all FRC mixture series are given in Table 4. Before exposure to high temperature, the UPV values of the specimens were measured as 4.48 to 4.55 km/s. The highest UPV value was obtained from the BF0.40 series. Decreases in UPV values were observed with the addition of PPF to the mixtures. A slightly decrease of 1.54% was detected in the UPV value as a result of replacing 0.20% PPF with BF. This situation can be attributed to the fact that the addition of PPF to the mixtures reduces the workability and consequently increases the voids. Nik and Omran (2013) reported that steel and glass fiber had no effect on the UPV value, but the use of PPF reduced the UPV value. Özkan and Çoban (2021) reported the UPV results of mixtures using PPF and BF fibers in their research. They reported that there was an approximately 2% improvement in the UPV value by replacing the PPF fiber with BF at a rate of 25%.

Table 4. Ultrasonic pulse velocity (UPV) test results of FRC.

Mixtures	20 °C	400 °C	600 °C	800 °C
BF0.40 (M1)	4.55	4.02	2.72	1.13
BF0.40-R (M1-R)		4.17	3.88	2.42
BF0.30PPF0.10 (M2)	4.53	3.92	2.67	1.12
BF0.30PPF0.10-R (M2-R)		4.12	3.93	2.46
BF0.20PPF0.20 (M3)	4.48	3.78	2.54	1.08
BF0.20PPF0.20-R (M3-R)		4.13	3.99	2.48

The effect of high temperature and subsequent water re-curing on the relative residual UPV values of the specimens is given in Fig. 2. As the high temperature value to which FRC mixtures were exposed increased, their UPV decreased. The UPV value of the specimens exposed to 400 °C was measured between 4.02 and 3.78 km/s. The lowest UPV value at 400 °C occurred in the mixture using 0.20% PPF (M3). The relative UPV value of the M3 series at 400 °C is 84.38%. This situation can be attributed to the increased pores and cracks in the concrete due to the melting of PPF fibers at high temperatures (Boğa et al. 2022). As the temperature increased to 600 °C, the relative UPV values of FRCs were in the range of 56.70% to 59.78%. Significant decreases were detected in UPV results as the temperature increased to 800 °C. A decrease of 75.16% to 75.89% was obtained in the UPV value of all FRC series.

Relative UPV values of the mixture series were remarkably improved after water re-curing. This can be attributed to the fact that the new products formed as a result of water re-curing repair cracks and refine pores in thermally damaged concrete, which will also improve the mechanical properties (Bouhafs et al. 2024). The relative ultrasonic pulse rate of M1 series increased from 88.35% to 91.65% at 400 °C, showing a recovery rate of approximately 3.30%. The recovery rate of M2 mixture using 0.10% PPF was determined as 4.42%. The maximum recovery rate was % It was obtained from the M3 series, which increased from 84.38 to 92.19%, providing 7.81% improvement. This can be attributed to the filling of cracks and voids caused by the melting and evaporation of PPFs with rehydrated products (He et al. 2023).

It was determined that at 600 °C and beyond, water re-curing showed more significant recovery than 400 °C. Re-curing after 600 °C increased the relative UPV of M1 series from 59.78% to 85.27%. The recovery rate of M1 series was % It was determined as 25.49. This ratio was calculated as 27.81% and 32.36% in M2 and M3 mixtures, respectively. At 800 °C, the relative UPV values of the mixtures approached each other. The recovery rates in M1, M2 and M3 mixtures were 28.35%, 30.64% and 31.25%, respectively. It was observed that re-curing had more significant effects at temperatures above 400 °C. This can be attributed to the presence of more dewatered products in the concrete with increasing temperature and the rehydration and carbonation products of these products formed with the absorbed water (Bouhafs et al. 2024).

Table 5. Compressive strength test results of FRC.

Mixtures	20 °C	400 °C	600 °C	800 °C
BF0.40	52.05	43.55	23.82	10.89
BF0.40-R		44.37	33.48	18.08
BF0.30PPF0.10	51.36	40.06	21.82	9.32
BF0.30PPF0.10-R		44.42	33.62	16.58
BF0.20PPF0.20	49.28	37.82	20.42	9.17
BF0.20PPF0.20-R		44.51	34.82	17.02

3.2. Compressive strength

Compressive strength results obtained at different stages of FRC mixtures are given in Table 5. The highest compressive strength value at room temperature was obtained from M1 (BF0.40) series with 52.05 MPa. In M2 series with 0.10% PPF added, 51.36 MPa strength was obtained, and in the mixture with 0.20% PPF, 49.28 MPa strength was obtained. This situation can be attributed to the fact that PPF has a larger diameter compared to BF and increases pores due to its air-entraining effect. As a result, it indicates that BF has a higher bond with the matrix than PPF, albeit slightly (Wang et al. 2019).

Fig. 3 shows the relative strength results of the series after high temperature and water re-curing. Decreases in compressive strength were observed with the increase in temperature. At 400 °C, a 16.33% decrease in the compressive strength of the M1 series was detected. This rate decreased more in the M2 and M3 mixtures, being

22% and 23.25%, respectively. The decreases in strength became more significant as the temperature increased to 600 °C and above. The compressive strength of the series subjected to 600 °C was between 20.42 and 23.82 MPa. These values were between 41.44% and 45.76% of the strength values at ambient temperature. In the M1 series, the compressive strength decreased by approximately 79%, reaching 10.89 MPa at 800 °C. These data obtained after high temperature were a case of internal vapor pressure and thermal effect causing the formation and expansion of cracks in the Interface Transition Zone (ITZ) and matrix (He et al. 2023, Chen and Liu 2004). After high temperature, the strength values of hybrid mixtures with BF and PPF additions were lower compared to the series using only BF. This result can be attributed that PPFs start to melt at about 170 °C and lose their bridging effect by forming pores (Boğa et al. 2022). On the contrary, BF is more resistant to higher temperatures.

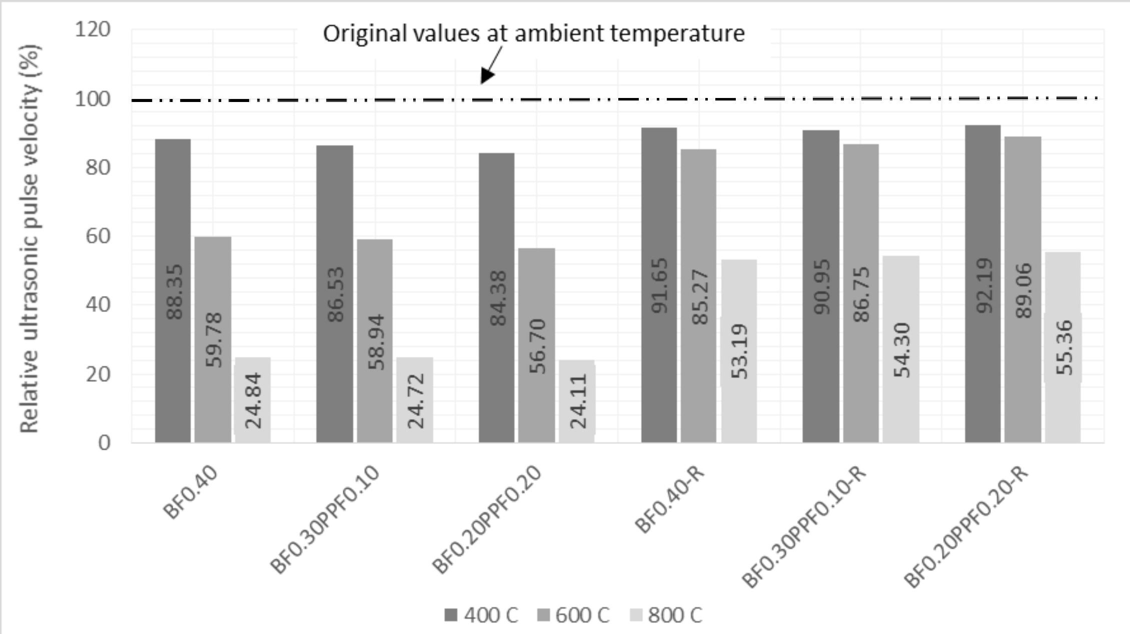


Fig. 2. Relative residual UPV values after high temperature and re-curing.

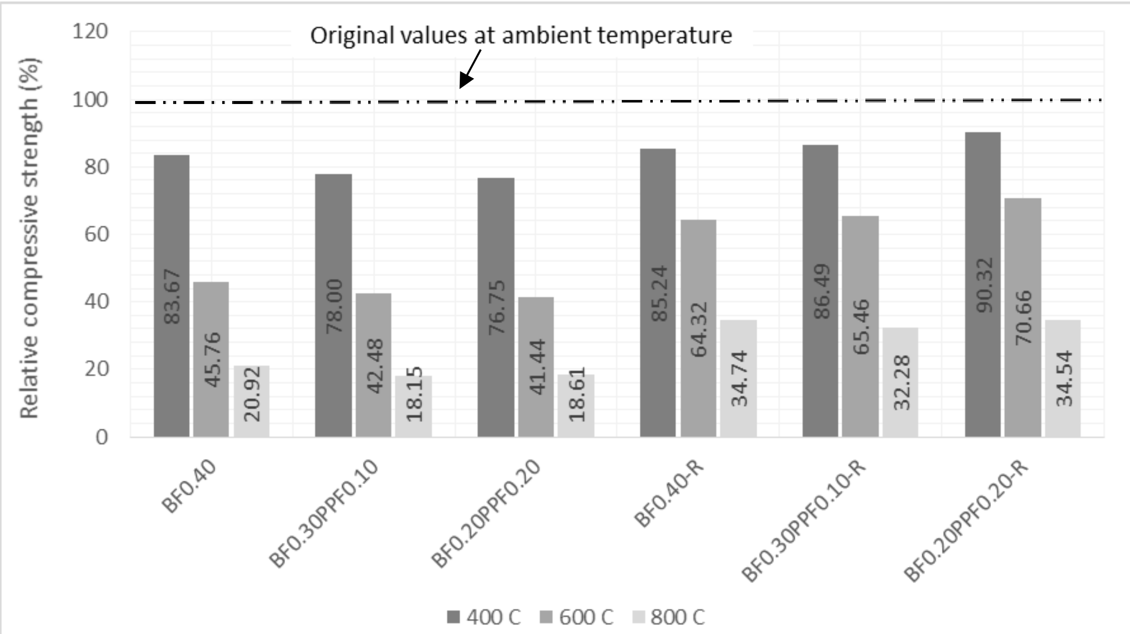


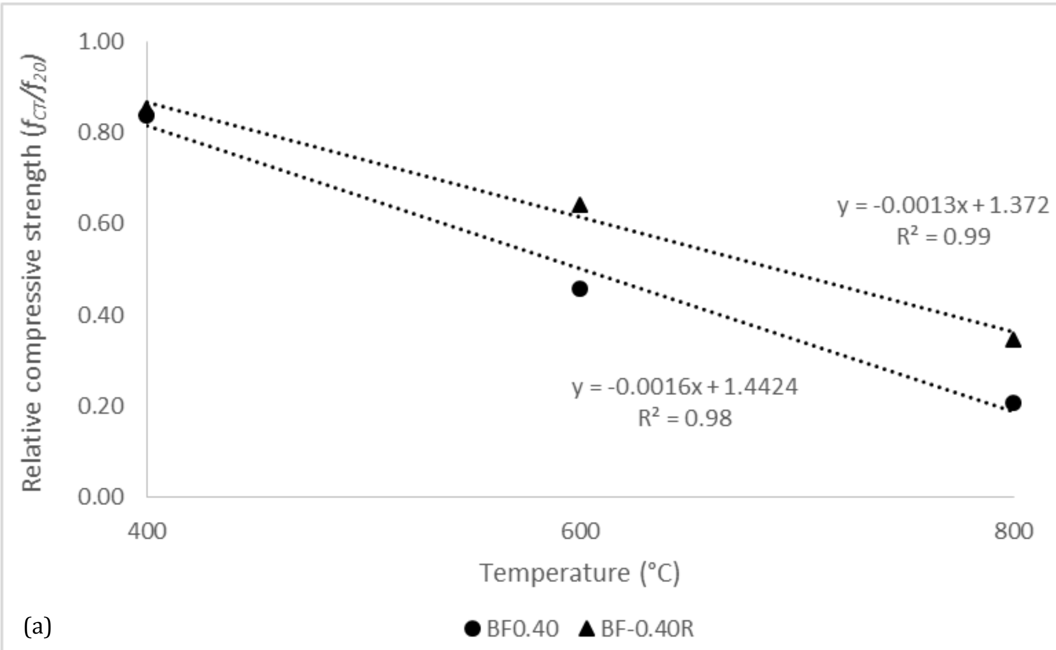
Fig. 3. Relative residual compressive strength values.

Remarkably recovery gain was obtained in compressive strength of thermally damaged basalt-polypropylene hybrid fiber reinforced specimens after water re-curing. M1 (BF0. for series 40), the relative compressive strength at 400 °C increased from 83.67% to 85.27% after water re-curing. This shows that the bonding between the basalt fiber and the matrix was not significantly damaged. With the increase of the temperature to

600 °C, the recovery is seen in series M1. The recovery rate was determined as 18.56%. The recovery rate of the M1 mixture at 800 °C was determined as 13.82%. The increase in recovery rates at 600 °C and above can be attributed to the narrowing of cracks formed by more intensive rehydration products (He et al. 2023). In addition, the increase in strength of FRCs after re-curing with water can be attributed to the improvement of the bond strength between the fiber and matrix together with the newly formed rehydration products.

With the addition of PPF to the blend series, a remarkably increase in the strength recovery rate occurred. The strength recovery rate of the M2 (BF0.30PPF0.10) series at 400 °C and 600 °C was determined as 8.49% and 22.98%, respectively. The recovery rate continued to increase with PPF content. In the M3 series, where BF was replaced by 0.20% PPF, the recovery rate at 400 °C was 13.57%. This rate continued to increase with increasing temperature, calculated as 29.22% and 15.93% at 600 and 800 °C, respectively. The higher recovery rate in mixtures using PPF is due to the filling of the gaps formed by the evaporation of PPF fibers with rehydrated products. He et al. (2023) investigated the effect of re-curing after high temperature on concrete specimens produced using single steel fiber and steel-polypropylene hybrid fiber. They reported that PPF was more effective than steel fiber in terms of recovery rate after re-curing.

The relationship between temperature and relative compressive strength was obtained in the range of 400 °C to 800 °C as shown in Fig. 4.



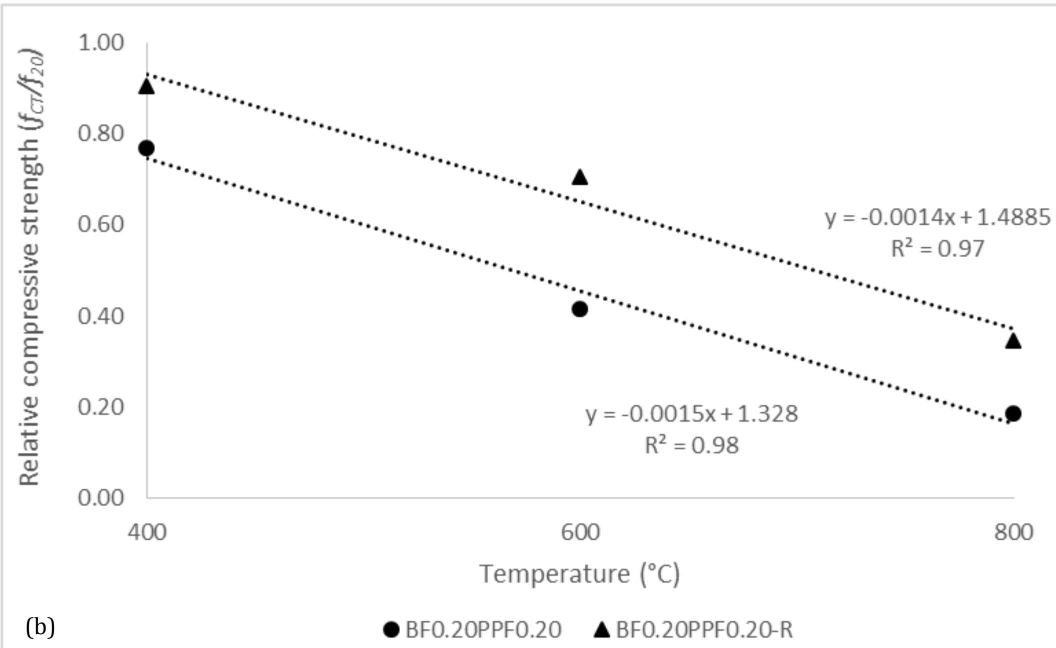


Fig. 4. Relationship between temperature and relative compressive strength: (a) BF0.40; (b) BF0.20PPF0.20.

The fitting functions between the temperature and the relative compressive strength experimental results obtained at different stages are given in Eqs. (1)–(4).

- Mix. BF0.40

After heating:

$$\frac{f_{CT}}{f_{20}} = \left[1.442 - 1.60\left(\frac{T}{1000}\right)\right] \quad 400 \leq T \leq 800 \quad R^2 = 0.98 \quad (1)$$

After re-curing:

$$\frac{f_{CT}}{f_{20}} = \left[1.372 - 1.30\left(\frac{T}{1000}\right)\right] \quad 400 \leq T \leq 800 \quad R^2 = 0.99 \quad (2)$$

- Mix. BF0.20PPF0.20

After heating:

$$\frac{f_{CT}}{f_{20}} = \left[1.328 - 1.50\left(\frac{T}{1000}\right)\right] \quad 400 \leq T \leq 800 \quad R^2 = 0.98 \quad (3)$$

After re-curing:

$$\frac{f_{CT}}{f_{20}} = \left[1.488 - 1.40\left(\frac{T}{1000}\right)\right] \quad 400 \leq T \leq 800 \quad R^2 = 0.97 \quad (4)$$

3.3. Flexural strength

The flexural strength results of the FRC specimens before and after heating and after water re-curing are given in Table 6. The flexural strength at ambient temperature is between 7.12 and 7.25 MPa. The highest flexural strength at room temperature was obtained in the M2 mixture with 0.10% PPF. Wang et al. (2019) reported that with the addition of PPF to 0.20% BF content, the flexural strength decreased compared to the single BF.

The relative flexural strengths of FRC specimens after high temperature and re-curing are given in Fig. 5. Significant decreases in flexural strength were observed with the increase in temperature. After heating to 400 °C, the relative flexural strength of the M1 mixture was determined as 62.31%, while this ratio was determined as 58.48% in the M2 mixture. The decrease in relative strength continued with the increase in PPF content and was reported as 54.21%. This decrease can be attributed to the melting and evaporation of PPFs at approximately 170 °C. As the heating temperature increased to 600 °C, the flexural strength of M1 series decreased by approximately 62%. This decrease was calculated as approximately 66% and 68% in M2 and M3 series, respectively. The relative flexural strengths of the mixtures after 800 °C were between 18.54% and 21.97%. The high relative strength of the mixture using single BF at all temperatures is an indication that BFs still effectively restrict cracks due to their high melting temperature.

Table 6. Flexural strength test results of FRC.

Mixtures	20 °C	400 °C	600 °C	800 °C
BF0.40	7.19	4.48	2.72	1.58
BF0.40-R		5.06	4.32	3.22
BF0.30PPF0.10	7.25	4.24	2.49	1.42
BF0.30PPF0.10-R		4.88	4.42	3.12
BF0.20PPF0.20	7.12	3.86	2.32	1.32
BF0.20PPF0.20-R		4.62	4.1	2.98

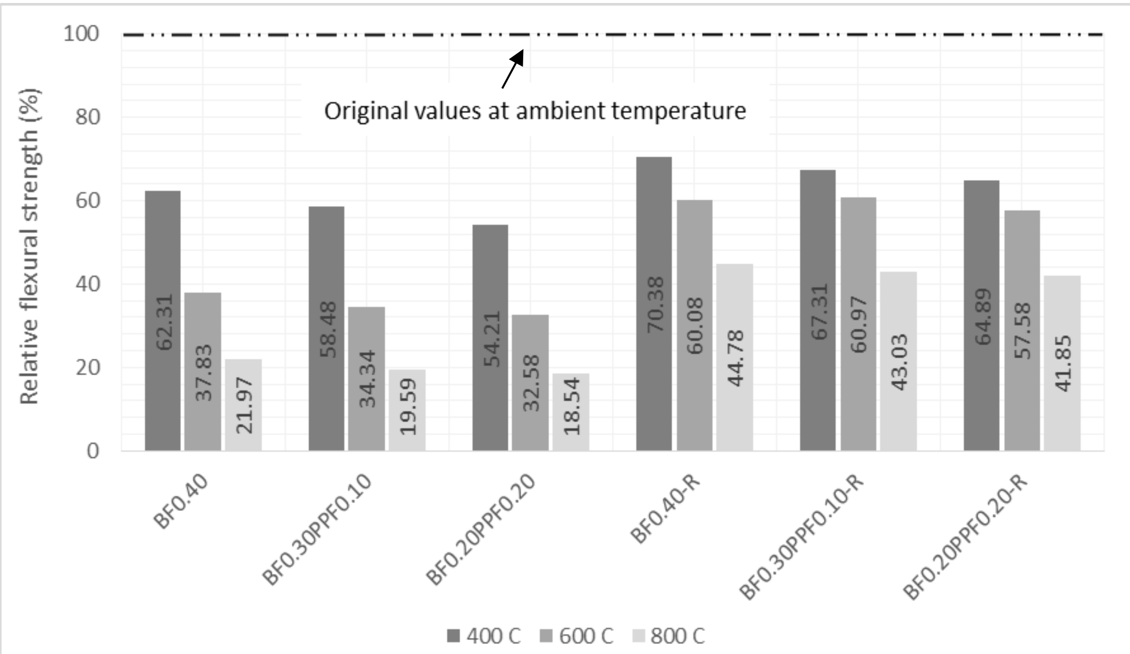


Fig. 5. Relative residual flexural strength values.

After heating, re-curing with water had a significant effect on the flexural strength. Re-curing after 400 °C increased the relative strength of M1 mixture from 62.31% to 70.38%. The flexural strength improvement rate was reported as 8.83% and 10.68% in M2 and M3 mixtures, respectively. The recovery rate after 600 °C was determined as 22.25% in the BF sample. This strength recovery rate was higher in the mixtures with PPF added. The recovery rate was reported as 26.63% in the mixture with 0.10% PPF and 25% in the mixture with 0.20%. As the temperature increased to 800 °C, the recovery rates approached each other. The relative flexural strength rates of the M1, M2 and M3 mixtures increased from 21.97 to 44.78, from 19.59 to 43.03 and from 18.54 to 41.85, respectively.

The relationship between temperature and relative flexural strength was obtained in the range of 400 °C to 800 °C as shown in Fig. 6.

The fitting functions between the temperature and the relative flexural strength experimental results obtained at different stages are given in Eqs. (5)–(8).

- Mix. BF0.40

After heating:

$$\frac{f_{FT}}{f_{20}} = \left[1.012 - \left(\frac{T}{1000}\right)\right] \quad 400 \le T \le 800 \quad R^2 = 0.98 \tag{5}$$

After re-curing:

$$\frac{f_{CT}}{f_{20}} = \left[0.968 - 0.60\left(\frac{T}{1000}\right)\right] \quad 400 \le T \le 800 \quad R^2 = 0.98 \tag{6}$$

- Mix. BF0.20PPF0.20

After heating:

$$\frac{f_{CT}}{f_{20}} = \left[0.886 - 0.90\left(\frac{T}{1000}\right)\right] \quad 400 \le T \le 800 \quad R^2 = 0.98 \tag{7}$$

After re-curing:

$$\frac{f_{CT}}{f_{20}} = \left[0.893 - 0.60\left(\frac{T}{1000}\right)\right] \quad 400 \le T \le 800 \quad R^2 = 0.95 \tag{8}$$

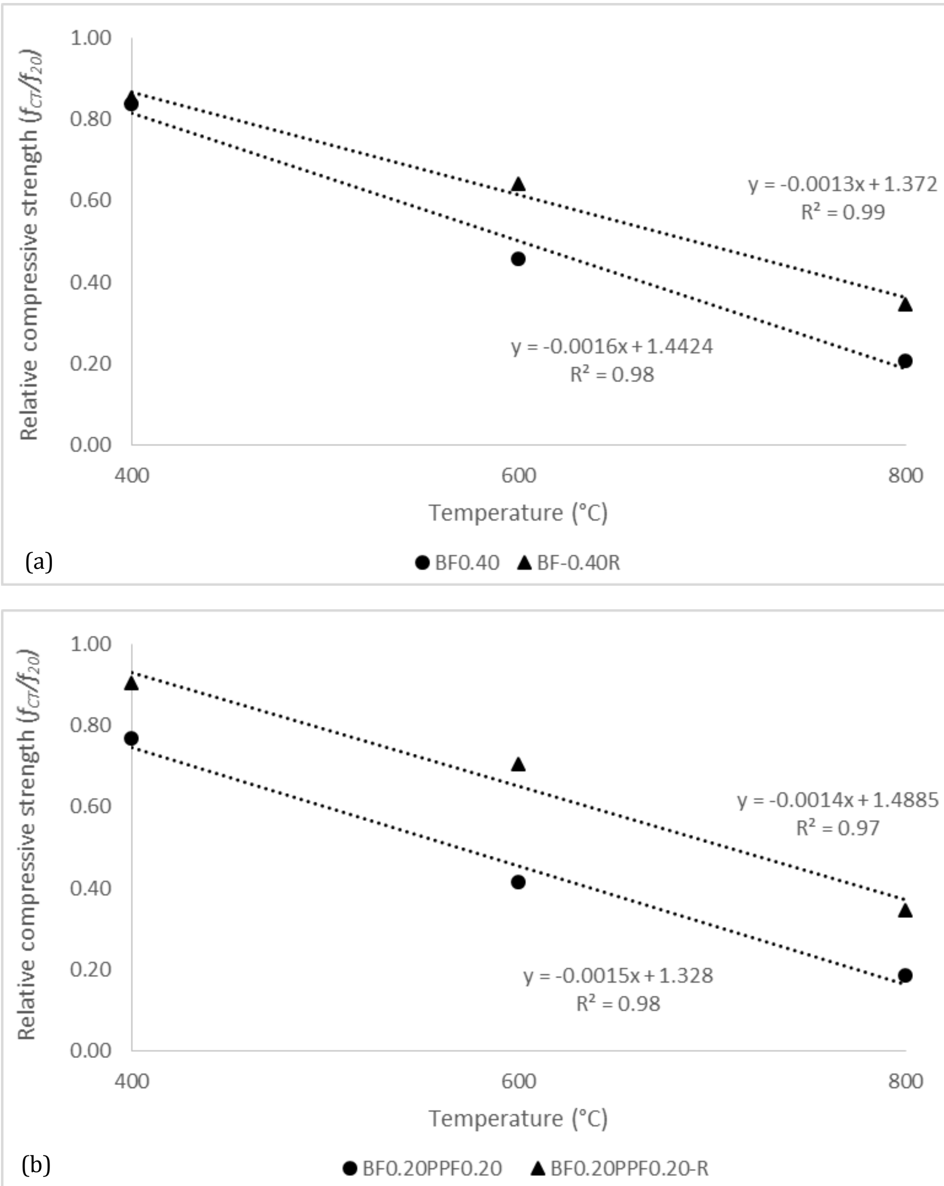


Fig. 6. Relationship between temperature and relative flexural strength: (a) BF0.40; (b) BF0.20PPF0.20.

4. Conclusions

- The UPV values of the specimens not exposed to heating were measured as 4.48 to 4.55 km/s. A slight decrease of 1.54% was detected in the UPV value as a result of replacing 0.20% PPF with BF. Significant decreases were observed in the UPV values of the specimens with the increase in temperature.
- The compressive strength of the series before heating was determined as 49.28 and 52.05 MPa. The decrease in strength was detected with exposure to high temperatures. The compressive strength of the series subjected to 600 °C was between 20.42 and 23.82 MPa. These values were between 41.44% and 45.76% of the strength values at ambient temperature.
- It was found that water re-curing had a significant effect on mechanical properties. This situation was more evident especially in mixtures containing polypropylene fibers. In the series where BF was replaced by 0.20% PPF, the relative compressive strength recovery rate at 400 °C was 13.57%. This rate continued to increase with increasing temperature, calculated as 29.22% and 15.93% at 600 and 800 °C, respectively.
- Similar to the improvements in compressive strength, significant recoveries occurred in flexural strength. The relative recovery rate in flexural strength was reported as 26.63% in the mixture with 0.10% PPF and 25% in the mixture with 0.20% PPF.
- Post-fire water re-curing is a useful method for partial recovery of the mechanical and durability properties of thermally damaged concrete. Especially civil engineering structures damaged by fire can be maintained by this method rather than demolished and become usable.
- In future studies, it is recommended to use different fibers and ratios and to work at intermediate temperature values. In addition, the bond strength between the matrix and fiber is important along with the effect of rehydration in the concrete after re-curing and this issue should be examined in detail. It is also thought that using fibers and substituting different pozzolanic materials instead of cement may have different effects.

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Conflict of Interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this manuscript.

Author Contributions

All of the authors made substantial contributions to conception and design, or acquisition of data, or analysis and interpretation of data; were involved in drafting the manuscript or revising it critically for important intellectual content; and gave final approval of the version to be published.

Data Availability

The datasets created and/or analyzed during the current study are not publicly available, but are available from the corresponding author upon reasonable request.

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