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Elevated Temperature Performance of Concrete Reinforced with Steel, Glass, and Polypropylene Fibers and Fire-proofed with Coating

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ABSTRACT

Concrete has good strength and durability; however, it suffers from spalling and significant reduction of strength when exposed to fire. This study was aimed to enhance the fire resistance of concrete by applying two different techniques: 1) reinforcing with fiber, and 2) applying a fire-proof coating. For this purpose, mixes were made with steel fiber (SF), glass fiber (GF), and polypropylene fiber (PPF) applied at 0.5-2% of cement weight; in addition to a mix prepared with a 15 mm layer of fireproof coating material and a control mix. All mixes were subjected to elevated temperatures of 200-800 °C, and physical and mechanical properties were evaluated. According to the test results, both techniques were effective in enhancing the fire resistance of concrete mixes. The maximum residual compressive and flexural strengths were obtained for mix containing 0.5% GF, which were 117% and 145% higher than that of the control mix at 800 °C, respectively. Also, concrete with fireproof coating showed up to 76% and 113% higher compressive and flexural strengths compared to that of the control mix, respectively. It was found that addition of fibers in the manufacturing process of the concrete is a more desirable and economically-efficient approach to enhance the fire resistance. However, for an existing concrete structure, applying fireproof coating is the only option and can enhance the fire resistance comparably.

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1. INTRODUCTION

Concrete is one of the most used construction materials worldwide due its good mechanical and durability properties, availability of raw materials, and relatively low maintenance cost [1]. However, concrete shows a significant strength loss when exposed to fire due to moisture loss, excessive cracking, and impairment of the cement matrix [2]. The study of concrete under fire dates back to the early 1900's and it was mainly focused on the behavior of cement paste and mortars [3]. Ma et al. [4] presented a comprehensive review on the effects of high temperatures on the mechanical properties of concrete. Exposure of concrete to elevated temperatures results in spalling [5], i.e., removal of some portions of the surface layer of the concrete, and external cracking, which is caused by the evaporation of the free water and decomposition of the paste [6]. The previously mentioned phenomena can expose the steel reinforcements inside the concrete to heat, which can have devastating effects on the load-bearing capacity and stability of the concrete structure. Furthermore, the alkalinity tends to reduce as a result of carbonation, which is intensified by fire, and thus the corrosion risk of steel rebars escalates [7, 8]. At temperatures beyond 400 °C, the paste begins to shrink and the aggregates expand, which cause a significant strain gradient in the matrix [9]. It increases the cracking in the matrix and reduces the bond between paste and aggregates, resulting in further degradation of strength. At extreme temperatures, e.g., 800-1000 °C, the decomposition of the hydration products and loss of chemically-bound water lead to significant impairment of the microstructure and result in 60-80% reduction of strength [10].

Due to the risks associated with exposure of concrete to fire and its widespread application in civil engineering

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structures such as buildings, bridges, tunnels, etc, it is of paramount importance to enhance the fire resistance of concrete through effective and cost-efficient techniques [11]. In order to enhance the performance of concrete under fire, various methods have been proposed and examined. One of the most effective practices is the utilization of fibers such as steel, glass, basalt, and polypropylene fiber (PPF) in concrete [12–16]. The use of fibers can improve the fire resistance of concrete by mitigating the formation and propagation of thermal induced cracks [17, 18]. Furthermore, fibers enhance the load-bearing capacity of concrete by providing additional strength by sewing effect and bridging over the cracks [19, 20]. Afroughsabet and Ozbakkaloglu [21] studied the performance of concrete incorporating a combination of PPF and steel fiber (SF) and reported that the highest enhancement in strength was achieved for PPF and SF contents of 0.15% and 0.85%, respectively. Serrano et al. [22] studied the compressive and tensile behavior of concrete subjected to an open flame with temperature of 400°C. It was shown that PPF-reinforced concrete was more resistant to fire than the SF-reinforced counterpart, and addition of 2% PPF increased the residual compressive strength of concrete by 68% over that of the control mix. Sun and Xu [23] showed that using 0.9% PPF in concrete leads to the optimal compressive strength, fatigue, and dynamic performance. However, the melting of PPF can create channels for the evaporated water to escape [24], and Lee et al. [25] reported that using high contents of PPF resulted in the formation of micro-cracks in concrete subjected to 400°C. Similar findings were reported by Yermak et al. [26] that PPF-reinforced concrete mixes were more porous than the SF-reinforced counterparts. Jameran et al. [27] studied the fire behavior of concrete with SF and PPF. The total fiber content was kept constant at 1.5% and different proportions of SF and PPF were incorporated into the concrete. The highest residual strength after fire exposure was achieved at 100% SF and 0% PPF contents. Moghadam and Izadifard [28] compared the performance of SF and glass fiber (GF) in improving the fire resistance of concrete. It was observed that mix reinforced with 0.25% GF showed the highest tensile strength, which was 213% higher than that of the control mix.

The addition of fiber for enhancing the fire resistance of concrete can only be done during the manufacturing process, and thus this method cannot be used for retrofitting purposes. In order to enhance the fire behavior of existing concrete structures, a layer of fireproof coating material can be applied. In this context, several studies proposed and examined different types of coatings for improving the behavior of the concrete at elevated temperature [29–31]. Temuujin et al. [32] investigated the utilization of a metakaolin-based geopolymer coating for fireproofing concrete. The coating exhibited a thermal expansion of 3% at 800°C and concrete specimens maintained their strength for one hour at 1000°C. Hou et al. [33] used a type of cementitious thermal insulation material as fire-retardant coating to improve the fire resistance of concrete beams reinforced with 2% SF and 0.2% PPF. Results showed that the insulated beam exhibited about 38% higher fire endurance compared to that of the uninsulated one. Furthermore, several studies have investigated the effect of thermal insulation on the fire behavior of concrete structures strengthened with fiber-reinforced polymer (FRP) composites [34–37]

In the light of the previous studies, this paper aimed to present a direct comparison between the performance of concrete reinforced with different types of fibers and concrete with fireproof coating, which has not been done before. The objectives of the present research are: (1) Determining the type and content of the fiber, which leads to the maximum enhancement of fire resistance of the concrete; (2) Answering the question how effectively a fireproof coating can enhance the fire resistance of an existing concrete structure; and (3) Comparing the fire behavior of fiber-reinforced and fireproof coated concretes. The fresh and hardened properties of concrete mixes were evaluated. Furthermore, the residual compressive and flexural strengths as well as the mass loss of mixes were measured after exposure to elevated temperatures ranging from 200 to 800 °C.

2. EXPERIMENTAL PROGRAM

2. 1. Materials

2. 1. 1. Portland Cement In this study, Type II Portland cement from Ardestan cement plant was used with a density of 3.15 g/cm^3. The chemical and physical characteristics of the cement and the values recommended by the Iranian Standard No. 389 in Tables 1 and 2, respectively.

2. 1. 2. Fine Aggregate Natural sand with particle size of 0-5 mm from Isfahan Soffeh mine was used as fine aggregate in this study (Table 3). The fineness modulus of the sand was equal to 3.1 based on determined based on ASTM C-125 standard [38]. The gradation curve of the sand and the recommended upper and lower bounds of ASTM C33 [39] are shown in Figure 1.

2. 1. 3. Coarse Aggregate Natural gravel with maximum size of 19 mm was used as coarse aggregate in the present research. Sieve analysis was done for the gravel based on ASTM C33, and the gradation curve is shown in Figure 2 and the physical characteristics are given in Table 4.

TABLE 1. Chemical characteristics of the cement used in this study

Chemical composition	**Type II cement**	
	Iranian Standard ISIRI 389 result (%)	**Test result (%)**
SiO_2	> 20	22±0.4
Al_2O_3	< 6	5±0.3
Fe_2O_3	< 6	3.82±0.2
CaO	62-66	64±0.5
MgO	< 5	1.9±0.2
SO_3	< 3	1.5±0.2
K_2O	0.5-1	0.49±0.15
Na_2O	0.2-0.4	0.25±0.15
C_3A	5-8	6.51±1
Free CaO	-	1.2±0.2
L.O.I.	< 3	1±0.2

TABLE 2. Physical characteristics of the cement used in this study

	Specific surface area (g/cm^2)	**Setting time (min)**		**Compressive strength (kg/cm^2)**		
		Initial	**Final**	**3 days**	**7 days**	**28 days**
Allowable value (ISIRI 389)	> 2800	> 45	< 360	> 100	> 175	> 315
Measured value	3000±50	90±5	150±10	≥ 170	≥ 275	≥ 370

TABLE 3. Physical characteristics of fine aggregate (sand)

Property	**Value**
Apparent specific weight (kg/m^3)	2570
Water absorption (%)	4.6
Apparent density (g/cm^3)	2.54
Fineness module (F.M)	3.1
Percent passing #200 sieve (%)	3.4

2. 1. 4. Fibers

The fibers used in this study consisted of SF, GF, and PPF. SF was two-way hooks with length of 30-50 mm. Since SF can remain functional even at high temperature of 1200 °C, the incorporation of these fibers can enhance the resistance of concrete in fire condition as well as the mechanical properties [18, 40]. The GF used in the present work was of type "High Silica" with length of 12 mm. GF consists of very thin and flexible fibers, which are produced with diameters ranging from 5 to 25 µm. These fibers are more economically efficient than the other types of fibers and also possess high tensile strength. The PPF used in this study was provided from Afzir company, Iran, Tehran, and was chopped to increase their grip with paste. The properties of fibers used in the present study are summarized in Table 5 (see Figure 3).

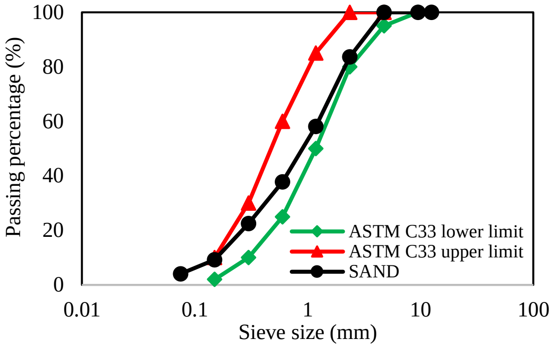

Figure 1. Gradation curve of fine aggregate (sand)

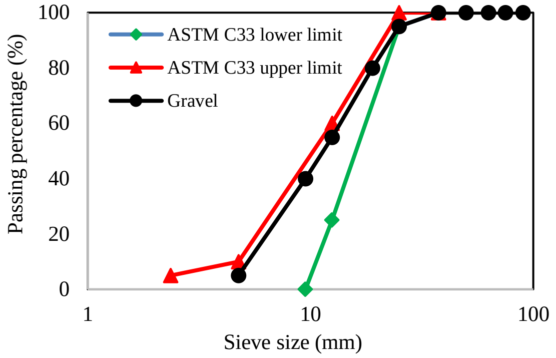

Figure 2. Gradation curve of gravel

TABLE 4. Physical characteristics of coarse aggregate (gravel)

Property	**Value**
Apparent specific weight (kg/m^3)	2693
Water absorption (%)	1.2
Apparent density (g/cm^3)	2.68
Saturated moisture with a dry surface (%)	0.5

TABLE 5. Characteristics of fibers used in this paper

Fiber type	**Length (mm)**	**Color**	**Elasticity module (GPa)**	**Diameter (mm)**	**Specific weight (g/cm^3)**	**Melting temperature (°C)**
SF	30-50	Copper	200	0.8	7.85	-
GF	12	White	70	0.011-0.015	2.6	550
PPF	12-13	White	5	0.02	0.91	160

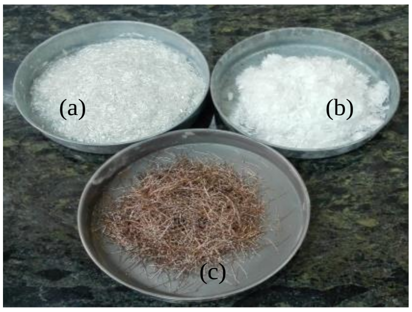

Figure 3. Fibers used in this study: (a) GF, (b) PPF, (c) SF

2. 1. 5. Fireproof Coating In this study, mineral coatings were used, which can be applied to the concrete by spraying or manual application. This coating is a powder (Figure 4), which is a combination of mineral adhesives, lightweight fine materials, fibers, and additives. It can turn into fireproof mortar when mixed with water. Fire retardant coating or fire resistance coating has some special additives in it, which provide a very high durability against fire and reduces the potential of cracking and spalling. It was purchased from Iran Construction Clinic located in Tehran. The properties and technical information of the coating used are given in Table 6. The mix design for the fireproof coating and the mix design for the subbase used for better adhesion between concrete and coating are shown in Table 7.

Figure 4. Fireproof coating used in this study

TABLE 6. Physical characteristics of the fireproof coating

Test result	Test standard	Technical characteristic
Specific weight (kg/m^3)	ASTM E-605	About 700
Compressive strength (kg/m^2)	ASTM E-761	More than 35
Electrical conductivity (W/m.C)	-----	Less than 0.2
Surface burning spread characteristic	ASTM E-84 BS 476	Class A Class O
Fire resistance	ASTM E-119 ISO 834	More than 4 hours based on thickness

TABLE 7. Mix design of fireproof coating and subbase

Coating type	Liquid to powder ratio	Powder (kg/m^3)	Water (kg/m^3)	Liquid (kg/m^3)
Sublayer coating	0.5	500	---	250
Fireproof coating	0.6	500	300	---

2. 2. Mix Design Concrete mixes were prepared with different fiber types including SF, GF, and PPF and different fiber contents including 0.5%, 1%, 1.5%, and 2% of the cement weight. For comparison purposes, a control mix was prepared as well without any fibers. Furthermore, in order to compare the two methods of enhancing the fire resistance of concrete, the control mix was coated with a 15 mm fireproof layer and its behavior at elevated temperatures of 200, 400, 600, and 800 ℃ was compared to that of the other concrete mixes. The mix proportioning of concrete mixes is presented in Table 8. It should be noted that all mixes were prepared with a constant water-to-cement (w/c) ratio of 0.52. In Table 8, the control mix is denoted as Normal Concrete (NC) and fiber-reinforced mixes are referred to with a two-part code name: the first part denotes the fiber type and the second part denotes the fiber content in percentage. Also, the mix with fireproof material is referred to as FPC-NC.

The mixing process consisted of dry mixing of the coarse and fine aggregates for 2 minutes in the mechanical mixer. Then, 50% of the water was poured into the mixer with the cement and mixing was continued for 90 s. After that, fibers (if any) were gradually added to the mixture with the remaining water. The substances were mixed together until a homogenous mix was obtained and the fibers were properly dispersed. As for the concrete mix with fire proof coating, the coating layer was prepared in advance to the mixing day. In order to prepare the coating layer, the powder was mixed with water to achieve a mortar with average consistency.

The fresh mix was poured into the molds in three layers and each layer was compacted by using a standard rod. The specimens were left in the laboratory environment for 24 h and then were demolded and submerged in a water tank at 23 ± 2 °C for further curing. For mix with fireproof coating, first, the concrete specimens were cured at temperature of 23 ± 2 °C and humidity of 50% ± 5% for 24 h. Then, the surface of the specimens was carefully dried and cleaned; then, placed at the center of a 130 mm×130 mm×130 mm mold. Next, the coating was poured into the mold around the specimen. After 48 h, the molds were opened and the specimens were placed in the moist room. Note that the curing was not done inside of a water tank for mix with fireproof coating.

TABLE 8. Concrete mix designs (kg/m^3)

Name	Cement	Water	Sand	Gravel	Fiber
NC [1]	420	220	800	880	---
SFC-0.5 [2]	420	220	800	880	2.1
SFC-1	420	220	800	880	4.2
SFC-1.5	420	220	800	880	6.3
SFC-2	420	220	800	880	8.4
PPFC-0.5 [3]	420	220	800	880	2.1
PPFC-1	420	220	800	880	4.2
PPFC-1.5	420	220	800	880	6.3
PPFC-2	420	220	800	880	8.4
GFC-0.5 [4]	420	220	800	880	2.1
GFC-1	420	220	800	880	4.2
GFC-1.5	420	220	800	880	6.3
GFC-2	420	220	800	880	8.4
FPC-NC [5]	420	220	800	880	---

[1] NC: Normal concrete
[2] SFC-0.5: Fiber-reinforced concrete with 0.5% SF
[3] PPFC-0.5: Fiber-reinforced concrete with 0.5% PPF
[4] GFC-0.5: Fiber-reinforced concrete with 0.5% GF
[5] FPC-NC: Normal concrete with fireproof coating

3. TESTING METHODS

The workability of the fresh concrete was evaluated by using slump test following the guidelines of C143/C143M-12 [41]. The compressive and flexural strengths of cubic and beam specimens with dimensions of 100 mm×100 mm×100 mm and 100 mm×100 mm×500 mm were determined based on the provisions of ASTM C39/C39M-16 [42] and ASTM C78/C78M-16 [43], respectively. Note that the tests were conducted on three specimens for each mix in order to ensure repeatability of the test results.

The specimens were heated at temperatures of 200, 400, 600, and 800 °C to evaluate the effects of fiber type and dosage as well as the fireproof coating on the elevated temperature behavior of concrete mixes. This was done in an electric oven at a heating rate of 6 °C/min until the target temperature was reached. The specimens were kept in the oven for 2 h to obtain steady-state thermal condition. Finally, after 24 h of cooling, the mass loss, residual compressive strength, and residual flexural strength of specimens were determined.

4. RESULTS AND DISCUSSIONS

4. 1. Slump

The results of slump test for different concrete mixes are shown in Figure 5.

Based on the test results, it is obvious that the workability of the fresh concrete was reduced when fibers were added. Furthermore, by increasing the fiber content, a higher reduction of slump was noticed. This could be attributed to the fact that when fibers are added to the mix, a network of fiber-matrix forms, which increases the internal friction. Therefore, a higher water content is required to obtain the same slump value. However, since the water-to-cement ratio has been kept constant in this study, the slump value decreases constantly with increasing fiber content. The reduction percentage in concrete mixes containing less than 1% fiber was below 10%. This is in agreement with the results of Jhatial et al. [44] who reported 8.7% reduction in slump of concrete containing 1% SF as compared to that of the control concrete. however, at the maximum dosage of fiber, i.e., 2%, about 17%, 20%, and 19% reduction in slump was observed for mixes reinforced with SF, PPF, and GF compared to that of the control mix, respectively. Mastali et al. [45] also observed 16% reduction in slump flow of concrete with 2% GF content. Also, it is observed that the SF-reinforced mixes showed a higher workability compared to PPF- and GF-reinforced mixes. A reason behind this could be the smooth surface of SF, which facilitates a better dispersion compared to other fiber types. PPF-reinforced mixes showed the highest reduction in workability, which could be related to the hydrophobic nature of PPF [46], which repels the water, and thereby air bubbles tend to attach to the fibers. This is supported by earlier findings [47, 48].

4. 2. Effect of Elevated Temperatures on Mass Loss of Mixes

Figure 6 shows the mass loss of mixes after exposure to the elevated temperatures. According to the test results, the weight of the samples decreased with an increase in temperature. The mass losses of the control mix at temperature of 200, 400, 600, and 800 ℃ were

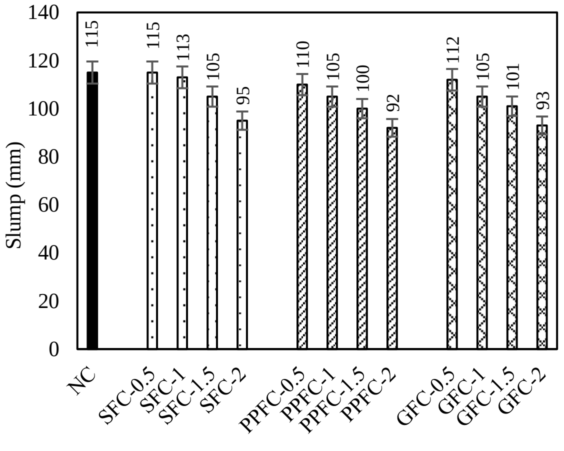

Figure 5. Slump of concrete mixes

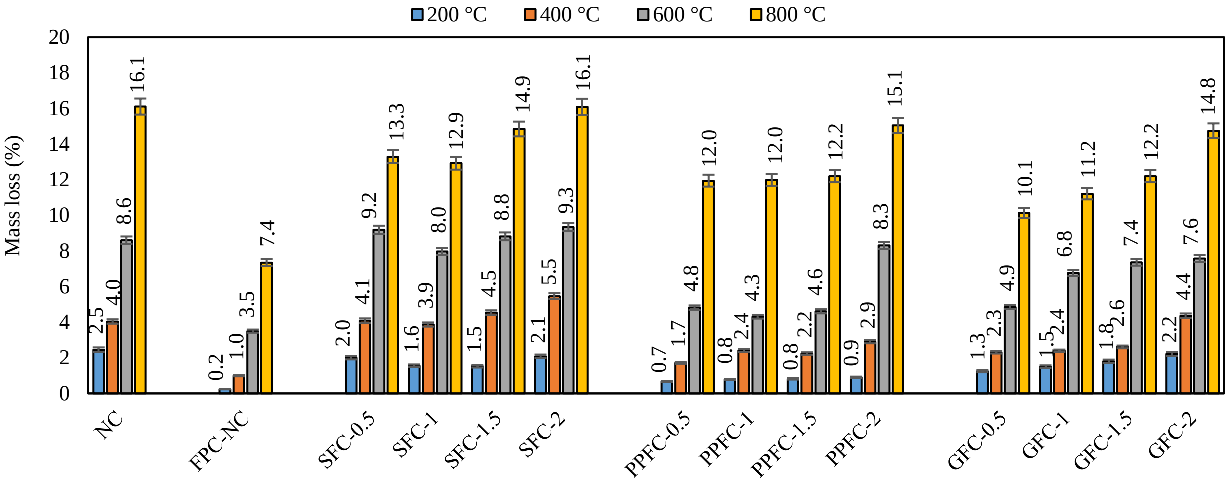

Figure 6. Mass loss of mixes at different temperatures

about 2.5%, 4%, 8.6%, and 16.1%, respectively, compared to the value of mass at room temperature. The mass loss due to exposure to temperatures in the range of 200-400 °C is mostly related to the evaporation of free water, which increased the porosity of the matrix [49]. At higher temperatures, the destruction of the hydration products of cement, i.e., calcium silicate hydrate (C-S-H) gel and calcium hydroxide ($Ca(OH)_2$), and the evaporation of free water are responsible for the decrease in the mass of concrete mixes [50]. At an extreme temperature of 800 °C, the impairment of the microstructure becomes more significant and the chemically-bound water evaporates, which further breaks the chemical bonds and causes severe decomposition of the hydration products [51].

In general, the mass loss of fiber-reinforced mixes was lower than that of the control mix. This could be related to the bridging effect of fibers, which mitigated the formation and propagation of micro-cracks due to heat exposure [15]. As a result, the stability of the specimens was enhanced at elevated temperature as less channels were available for the evaporated water to escape [52], and thereby less moisture loss occurred. The lower mass loss of fiber-reinforced mixes was more obvious at lower fiber contents. Mix with 0.5% GF demonstrated the lowest mass loss, and the weights of the specimens containing 0.5% GF were decreased by 1.25%, 2.31%, 4.85%, and 10.14% at temperature of 200, 400, 600, and 800 °C as compared to that of the plain concrete, respectively. However, the mass loss showed an increasing trend with fiber content. For example, adding 2% GF to the concrete resulted in 2.22%, 4.36%, 7.58%, and 14.75% reduction in mass at temperature of 200, 400, 600, 800 °C compared to that of the control mix, respectively. Similarly, mix containing 0.5%, 1%, 1.5%, and 2% PPF showed about 12%, 12%, 12.2%, and 15.1% mass losses at 800 °C. This could be due to the melting of fibers at elevated temperatures, which increased the porosity of concrete mixes. The higher mass loss in SF-reinforced mixes confirms this as the specific gravity of SF is much higher than that of the PPF and GF.

Moreover, test results showed that the lowest mass loss belonged to mix insulated with fireproof coating. The mass losses of mix FPC-NC were about 0.2%, 1%, 3.5%, and 7.4%, respectively, at temperatures of 200, 400, 600, and 800 °C compared to the mass at the ambient temperature. The fireproof coating prevented the heat to reach the inner parts of the specimens, and as a result, less fire-induced micro-cracks formed in the specimen and the escape of the evaporated water became more difficult.

4. 3. Effect of Elevated Temperatures on the Compressive Strength of Mixes Table 9 shows the compressive strength of mixes at different temperatures. Based on the test results, unlike the general trend of the compressive strength with increasing temperature, there was a slight increase in compressive strength at 200 °C. For example, the compressive strength of the control mix was increased about 12% when the temperature was increased from 23 °C to 200 °C. This could be due to the fact that heat treatment can promote hydration reaction of Portland cement and lead to further dissolution of CaO and SiO_2 [26]. As it can be observed in the table, an increase in compressive strength at 200 °C was more pronounced for fiber-reinforced mixes. The maximum increase for the concrete reinforced with SF, PPF, and GF was 17%, 23%, and 25% compared to the corresponding value at 23 °C, respectively.

TABLE 9. Compressive strength of mixes before and after exposure to elevated temperatures

Mix\ Temperature	23 °C	200 °C	400 °C	600 °C	800 °C
NC	45.0	50.5	40.3	25.3	11.45
FPC-NC	43.6	48.5	42.5	31.1	20.1
SFC-0.5	47.1	53.9	43.1	26.7	11.9
SFC-1	48.0	55.3	45.0	27.7	12.8
SFC-1.5	51.0	59.5	48.6	33.1	14.8
SFC-2	41.8	47.0	38.0	22.7	10.4
PPFC-0.5	52.4	64.6	50.5	37.6	22.3
PPFC-1	45.4	52.9	42.3	30.4	14.9
PPFC-1.5	44.9	51.6	41.7	28.7	14.3
PPFC-2	38.2	42.9	35.4	23.4	10.7
GFC-0.5	53.1	66.2	51.8	39.1	24.8
GFC-1	50.8	60.9	48.0	35.8	17.3
GFC-1.5	47.0	55.4	43.9	30.3	15.0
GFC-2	39.4	44.9	36.5	24.6	12.0

However, compressive strength was reduced at temperatures in the range of 400-800 °C. Exposure to temperatures of 400, 600 and 800 °C reduced the compressive strength of the control mix by 10%, 44%, and 75% compared to the corresponding value at the room temperature, respectively. The highest drop in the 28-day compressive strength of the control mix happened as the temperature increased from 400 °C to 800 ℃. Such high temperatures weakens the van der Waal's forces between C-S-H layers and reduces the surface energy, thereby resulting in the formation of weaker silanol groups with Si-OH:OH-Si bonds [53]. Furthermore, the evaporation of the free water and the chemically-bound water resulted in the formation of micro-cracks, which contributed to the loss of strength.

Generally, adding fibers to the concrete enhanced the compressive strength. In SF-reinforced mixes, the highest compressive strength at room temperature was obtained by adding 1.5% SF, which led to 13% higher compressive strength than that of the control mix as shown in Figure 7. In PPF- and GF-reinforced mixes, the maximum compressive strength at room temperature was achieved by adding 0.5% fiber, which led to 17% and 18% higher compressive strength than that of the control mix, respectively. The strength gain can be justified by the sewing effect of fibers, which bridged over the micro-cracks and increased the load-bearing capacity of concrete mixes [54]. However, it was observed that a high content of fiber has an adverse effect. For example, concrete mixes reinforced with 2% fiber, regardless of the fiber type, showed a lower compressive strength compared to that of the control mix. When the amount of fibers increases, it reduces the workability of the mixture due to the friction between fibers and paste. This has a negative effect both on the compaction of the fresh mix and dispersion of the fibers. The non-uniform dispersion of fibers can cause fiber balling, which in turn increases the porosity of the concrete and lowers the strength [55]. In addition, fibers used in this study are hydrophobic, and therefore air bubbles can attach to their surface and become entrapped inside the concrete, which further increases the porosity [20].

The test results at elevated temperature indicated that the addition of fibers benefited the fire resistance of concrete mixes. In SF-reinforced mixes, the highest residual compressive strength was obtained by using 1.5% SF, which increased the compressive strength by 18%, 21%, 31%, and 29% at 200, 400, 600, and 800 °C compared to the corresponding residual compressive strength of the control mix, respectively. On the other hand, the residual compressive strength of the PPF- and GF- reinforced mixes was reduced with fiber content, i.e., the minimum fiber content (0.5%) led to the maximum fire resistance. Among all fiber-reinforced mixes, the mix reinforced with 0.5% GF showed the highest residual compressive strength. Based on the test results, the compressive strength of mix GFC-0.5 after exposure to temperatures of 200, 400, 600, and 800 ℃ was 31%, 29%, 54%, and 116% higher than that of the control mix, respectively. It can be observed that adding 0.5% GF can have a significant contribution to the fire resistance of concrete due to the bridging effect of fibers, which limited the formation and propagation of micro-cracks. However, using a higher content of GF resulted in a constant reduction in the residual compressive strength. For example, the residual compressive strength of mix containing 2% GF was about half of that of the mix containing 0.5% GF at 800 ℃. Similarly, increasing the fiber content in PPF-reinforced mixes reduced the residual compressive strength. For example, the compressive strength of mix with 2% PPF was about half of that of the mix with 0.5% PPF at 800 ℃. This can be attributed to the low melting point of PPF, which resulted in an increase in void content when fibers melted at elevated temperatures [56].

Moreover, the results showed that insulating the concrete with fireproof coating can be effective in maintaining the compressive strength after heat exposure. According to Table 9, mix FPC-NC showed a strength reduction of 3%, 29%, and 54% after being subjected to the elevated temperatures of 400, 600, and 800 °C, respectively. Also, consistent with the other concrete mixes, there was an increase of about 11% at 200 °C compared to the corresponding value at the room

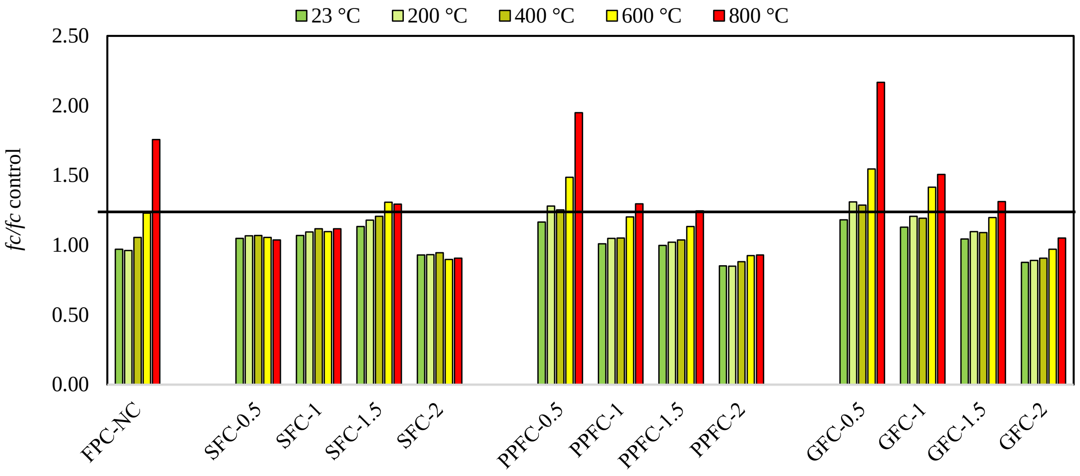

Figure 7. Ratio of compressive strength of mixes to compressive strength of the control mix

temperature. Comparing the results with fiber-reinforced mixes indicated that the fire resistance of mix FPC-NC was comparable to that of the mix GF-0.5. Thus, it can be concluded that using a 15 mm layer of the fireproof coating used in this study is as effective as reinforcing the concrete with 0.5% GF in enhancing the fire resistance of the concrete. In the insulated concrete, the fireproof layer reduces heat transfer to the inside of the concrete, and thereby mitigates the moisture loss and degradation of the microstructure. On the other hand, in fiber-reinforced mixes with fiber content up to 1.5%, the additional strength provided by the fiber-matrix bond and the bridging effect of fibers outweighed the negative influence of fiber agglomeration and increased void content.

4. 4. Effect of Elevated Temperature on the Flexural Strength of Concrete Mixes

Table 10 shows the flexural strength of mixes at different temperatures.

Generally, the reduction in the flexural strength was more pronounced than the compressive strength. This could be related to the higher dependency of the flexural behavior of the concrete on cracking as compared to the compressive strength [46, 57]. Exposure of concrete to elevated temperatures creates numerous cracks as a result of loss of moisture and degradation of the microstructure through decomposition of the hydration products. When subjected to bending, cracks tend to open and propagate, which negatively affects the flexural strength. However, the compressive load applied to the specimens can help in closing the micro-cracks and the compressive strength is more affected by the strength of the matrix itself and also the interlocking between aggregate and paste [58].

TABLE 10. Flexural strength of mixes before and after exposure to elevated temperatures

Mix\ Temperature	23 °C	200 °C	400 °C	600 °C	800 °C
NC	4.91	5.68	4.03	2.41	0.00
FPC-NC	7.02	7.95	6.62	5.12	2.55
SFC-0.5	6.13	7.22	3.84	3.14	0.00
SFC-1	6.27	7.57	5.24	3.43	0.93
SFC-1.5	7.03	8.57	6.54	4.38	1.43
SFC-2	5.37	6.16	2.75	1.53	0.43
PPFC-0.5	6.87	8.45	6.25	4.98	2.30
PPFC-1	6.24	7.47	5.41	4.03	1.11
PPFC-1.5	6.22	7.25	4.07	3.25	0.57
PPFC-2	5.49	6.11	2.89	2.09	0.24
GFC-0.5	7.92	9.83	7.63	5.90	3.29
GFC-1	7.54	9.05	6.51	5.08	2.11
GFC-1.5	7.08	8.20	4.66	3.58	1.09
GFC-2	6.52	7.07	3.25	2.68	0.79

All fiber-reinforced mixes exhibited a higher flexural strength than that of the plain concrete. The optimum fiber content for different types of fibers based on the flexural strength test results was the same as that obtained

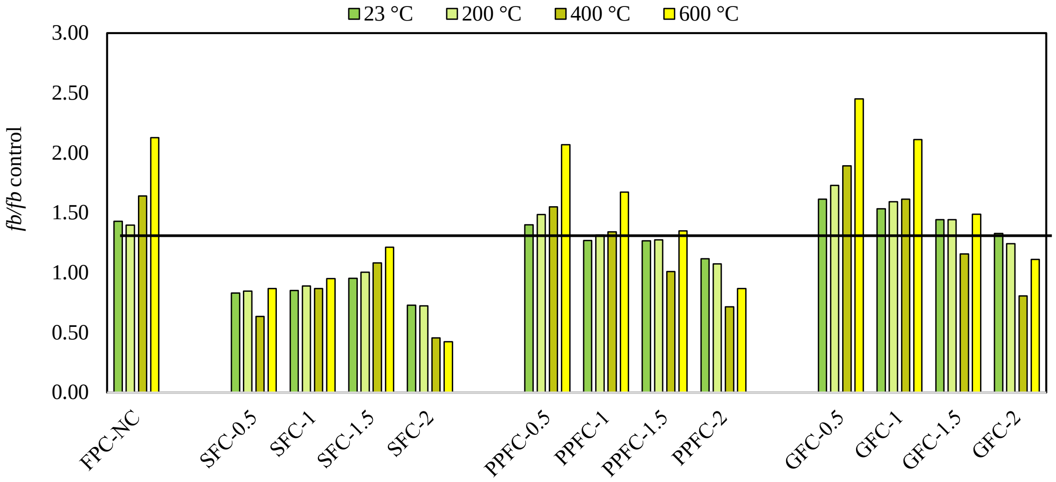

Figure 8. Ratio of flexural strength of mixes to flexural strength of the control mix

from the compressive strength results. Maximum flexural strength in SF-, PPF-, and GF-reinforced mixes was achieved by using 1.5%, 0.5%, and 0.5% fiber, respectively. The flexural strengths of mix SF-1.5, PPF-0.5, and GF-0.5 were about 43%, 40%, and 61%, respectively, higher than that of the control mix at the ambient temperature. As it can be observed, GF-0.5 with 28-day flexural strength of 7.92 MPa showed the highest flexural strength among all mixes.

At elevated temperature, consistent with the results of the compressive strength test, the flexural strength of mixes exhibited an increase at 200 °C, and then was reduced monotonically as the temperature was increased. For example, the control mix showed 16% higher flexural strength after exposure to 200 °C, which could be ascribed to the positive effect of heat exposure on the hydration of Portland cement and formation of C-S-H gel. Similarly, fiber-reinforced mixes showed enhancements in the flexural strength at this temperature. In agreement with the compressive strength, the maximum level in the residual flexural strength of fiber-reinforced mixes at 200 °C with respect to the ambient temperature was obtained in mix GF-0.5, which was about 24%. The lowest level in the flexural strength at this temperature was observed in mix FPC-NC, which was 13%. Since the fireproof coating limited the heat transfer to the inside of the concrete specimen, the increase in strength was limited as well. By increasing the temperature, the flexural strength of the concrete mixes started to decrease. For example, the residual flexural strength of the control mix after exposure to temperatures of 400 and 600 °C was 18% and 51% lower than the corresponding value at the ambient temperature. At 800 °C, spalling occurred in the specimen and it exploded in the oven, and thus no data is available regarding the flexural strength of the plain concrete at this temperature. It could be related to the higher surface-to-volume ratio of the beam samples as compared to that of the cube samples, which increased the area of the surface exposed to heat. The degradation of the flexural strength at elevated temperature could be due to evaporation of free water, decomposition of the dehydrated products, and mismatch between the strain of the paste and that of the aggregates due to high temperature gradient. Upon exposure to fire, the paste tends to shrink as it loses water and the binding gel becomes damaged, whereas aggregates tend to expand [59, 60]. The difference between the change in the volume of the paste and aggregates reduces the paste-aggregate bond, and thereby reduces the load-bearing capacity of the concrete.

In line with the results of compressive strength, fiber-reinforced mixes showed a superior performance at elevated temperature compared to the plain concrete. In SF-reinforced mixes, the residual flexural strength increased up to a fiber content of 1.5%. Similar to the control mix, mix containing 0.5% SF failed at 800 °C and did not show any strength; however, at 200-600 °C, it showed 27%-30% higher residual flexural strength than that of the control mix as shown in Figure 8. Mix reinforced with 1% SF performed slightly better than mix with 0.5% SF; whereas, mix with 1.5% SF showed the highest residual flexural strength in SF-reinforced mixes. The residual flexural strengths of mix SFC-1.5 at 200, 400, and 600 °C were 51%, 62%, and 82% higher than that of the control mix, respectively. However, using 2% SF resulted in the lowest flexural strength in SF-reinforced mixes, which was even lower than that of the control mix. For example, the residual flexural strengths of mix SFC-2 at 400 and 600 °C were 54% and 58% lower than that of the control mix, respectively. Heat treatment had a negative effect on the fiber-matrix bond as the fibers start to soften and the paste starts to contract. Therefore, additional strength provided by the fiber-matrix bond reduces with temperature, lowering the contribution of fibers to the flexural strength [61]. Furthermore, as the amount of fibers exceed a critical value, the fiber balling effect increases the porosity of the concrete, which is further intensified when fibers melt at extreme temperatures and leave behind pores and gaps.

Moreover, the PPF-reinforced mixes performed superior to SF-reinforced mixes at elevated temperature. The flexural strengths of the optimal mix, i.e., mix PPF-0.5, were reduced by 9%, 27%, and 66%, respectively, at 400, 600, and 800 °C. It may be attributed to the flexibility of PPF, which enables it to bend in different directions and fill in the pores and gaps more effectively than SF. Also, mix PPF-0.5 outperformed the control mix by showing 49%, 55%, and 107% higher flexural strength at the same temperatures. The crack arrestment by fibers mitigated the propagation of the thermal-induced micro-cracks and the bridging action of fibers over the cracks contributed to the strength gain [16]. As the fiber content was increased, the fire resistance of PPF-reinforced mixes began to decline. For the sake of illustration, the residual flexural strengths of mix PPF-0.5, PPF-1, PPF-1.5, and PPF-2 at 800 °C were 66%, 82%, 91%, and 96% lower than the corresponding value at 23 °C, respectively. As mentioned earlier, as the content of fiber increases in the mix, the workability drops, and thus the quality of compaction of the mix and fiber dispersion reduce as well. As a result, the porosity of the concrete increases, which has a negative effect on its strength. The exposure to elevated temperatures can further increase the gaps and pores in the concrete as a result of degradation of C-S-H gel and melting of fibers.

In agreement with the compressive strength results, the highest residual flexural strength was obtained in GF-reinforced mixes. Addition of 0.5% GF led to minimum losses of strength after heat treatment at 400, 600, and 800 °C, which were 4%, 25%, and 58%, respectively. Furthermore, the residual flexural strengths were enhanced by 73%, 89%, and 145% at 200, 400, 600 °C compared to that of the control mix, respectively. Although the flexural strength was reduced with increasing fiber content in GF-reinforced mixes, the residual flexural strength of all GF-reinforced mixes was still higher than that of the control mix at all temperatures. For the sake of illustration, the strength losses at 800 ℃ in mix containing 0.5%, 1%, 1.5%, and 2% GF were 58%, 72%, 85%, and 88%, respectively. Similar reports can be found in the previous studies. Ravikumar and Thandavamoorthy [62] showed that the compressive strength losses at 300 °C in concrete reinforced with 0.5% and 1% GF were 25% and 10%, while the strength loss of the control mix was 32%.

Moreover, the fireproof coating has shown to be effective in increasing the residual flexural strength when exposed to fire. The strength reductions at 400, 600, and 800 °C were 6%, 27%, and 64%, respectively; however, the residual flexural strengths were still 40%, 64%, and 113% higher than that of the control mix at the same temperatures. Fire insulation improved the resistance and stability of the concrete against fire by limiting the amount of heat reaching to the core of the concrete [37].

4. 5. Analysis of Variance (ANOVA)

In this section, ANOVA method was employed to quantify the influence of temperature, fibers, and their interaction on compressive strength and flexural strength of concrete mixtures. ANOVA is a widely used method to calculate the contribution of variables involved in a problem [63, 64]. Since two variables were involved in this study, two-way ANOVA was performed to rank the input parameters including temperature, fiber percentage, and their interaction based on their significance to the problem.

Figure 9(a)-(f) shows the ANOVA results of compressive strength and flexural strength. Figure 9(a)-(c) illustrates the ANOVA results regarding compressive strength. As seen, the contribution of temperature was significantly higher than that of the fiber percentage. For example, the contribution of temperature for concrete reinforced with SF was 90% while the contribution of fiber percentage was 4.2%. Furthermore, it was observed that the contribution of fiber percentage was higher in case of PPF and GF and it increased to 12% and 18%,

respectively. This owed to the higher melting point of these fibers, which increased their influence on strength of mixtures at elevated temperatures. This agreed with the compression test results, where concrete containing SF showed the highest reduction in strength at elevated temperature. For example, the compressive strength of mix with the optimum SF content was reduced from 50 MPa at 23 °C to 14 MPa at 800 °C, while that of the mix with the optimum GF content was reduced from 53 MPa to 24 MPa. Similar results were observed for flexural strength. With reference to Figure 9(d)-(f), the contribution of fiber percentages for concrete containing SF, PPF, and GF were 9.8%, 14.7%, and 23.3%, respectively.

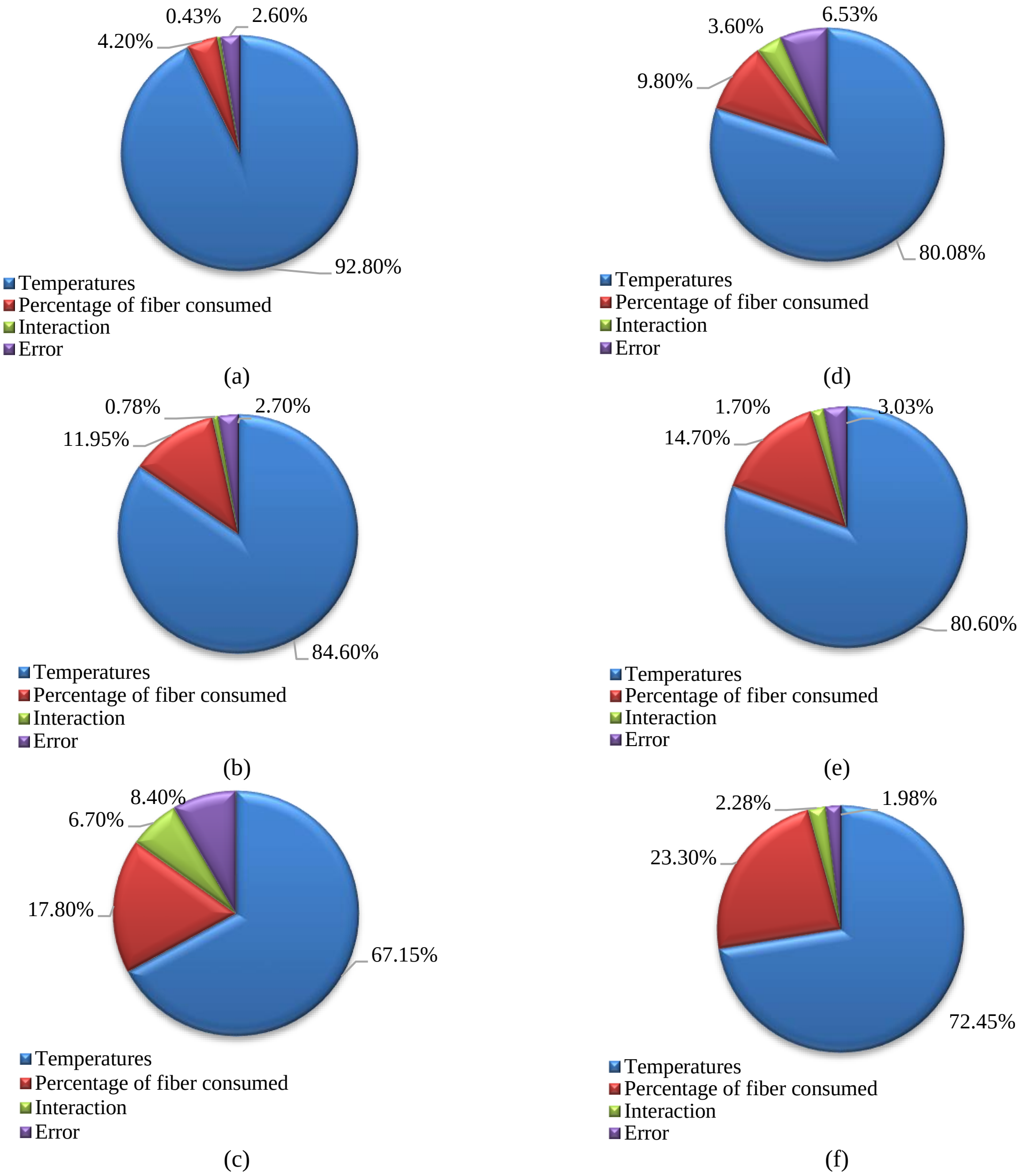

Figure 9. ANOVA results for the compressive strength of (a) SF-reinforced mixes, (b) PPF-reinforced mixes, (c) GF-reinforced mixes; and ANOVA results for the flexural strength of (d) SF-reinforced mixes, (e) PPF-reinforced mixes, (f) GF-reinforced mixes

5. CONCLUSIONS

This study investigated the fire resistance of concrete reinforced with three different types of fibers including SF, PPF, and GF incorporated at four different fiber contents including 0.5%, 1%, 1.5%, and 2%. The elevated temperature performance of the mixes was compared to that of the concrete insulated with a 15 mm layer of fireproof coating. The workability, mass loss, residual compressive and flexural strengths of mixes were evaluated. Based on the test results, the following conclusions are drawn:

- The inclusions of fibers results in reduced workability. The reduction is below 10% generally for fiber content less than 2%; however, by adding 2% fiber, the slump value reduced by up to 20%. PPF-reinforced mixes showed the lowest workability among fiber-reinforced mixes and SF-reinforced mixes are the most workable.
- Concrete mixes exhibit an increase of 8%-25% in the mechanical strength at 200 °C compared to the corresponding value at the ambient temperature. The use of fibers enhances the fire resistance. The optimum fiber content for SF-, PPF-, and GF-

reinforced mixes were 1.5%, 0.5%, and 0.5%, respectively.

- The reduction of the flexural strength was more obvious compared to the compressive strength. It can be related to the higher sensitivity of flexural strength to the presence of thermal-induced cracks than compressive strength.
- The maximum residual compressive and flexural strengths were obtained for mix containing 0.5% GF, which were up to 117% and 145% higher than that of the control mix, respectively.
- The insulation of the concrete with fireproof coating is a very effective technique to enhance the fire resistance of an existing concrete structure. As the temperature increases, the effectiveness of the fireproof coating becomes more pronounced. At 800 °C, the insulated concrete exhibits up to 76% and 113% higher compressive and flexural strengths compared to that of the control mix, respectively.

It can be concluded that in order to achieve the highest fire resistance of concrete, 0.5% GF should be added during the construction process. Whereas, fireproof coating technique can be applied after the construction process, which can enhance the fire resistance to a level comparable to that of the mix reinforced with 0.5% GF.

6. REFERENCES

1. Zareei, S. A., Ameri, F., Bahrami, N., Shoaei, P., Moosaei, H. R., and Salemi, N. “Performance of sustainable high strength concrete with basic oxygen steel-making (BOS) slag and nano-silica.” ***Journal of Building Engineering***, Vol. 25, (2019), 100791. https://doi.org/10.1016/j.jobe.2019.100791
2. Zareei, S. A., Ameri, F., Shoaei, P., and Bahrami, N. “Recycled ceramic waste high strength concrete containing wollastonite particles and micro-silica: A comprehensive experimental study.” ***Construction and Building Materials***, Vol. 201, (2019), 11–32. https://doi.org/10.1016/j.conbuildmat.2018.12.161
3. Husem, M. “The effects of high temperature on compressive and flexural strengths of ordinary and high-performance concrete.” ***Fire Safety Journal***, Vol. 41, No. 2, (2006), 155–163. https://doi.org/10.1016/j.firesaf.2005.12.002
4. Ma, Q., Guo, R., Zhao, Z., Lin, Z., and He, K. “Mechanical properties of concrete at high temperature—A review.” ***Construction and Building Materials***, Vol. 93, (2015), 371–383. https://doi.org/10.1016/j.conbuildmat.2015.05.131
5. Phan, L., and Carino, N. “Effects of the Test Conditions and Mixture Proportions on Behavior of High-Strength Concrete Exposed to High Temperatures .” ***ACI Materials Journal***, Vol. 99, No. 1, (2002), 54–66. Retrieved from https://tsapps.nist.gov/publication/get_pdf.cfm?pub_id=860335
6. Ameri, F., Shoaei, P., Zareei, S. A., and Behforouz, B. “Geopolymers vs. alkali-activated materials (AAMs): A comparative study on durability, microstructure, and resistance to elevated temperatures of lightweight mortars.” ***Construction and Building Materials***, Vol. 222, (2019), 49–63. https://doi.org/10.1016/j.conbuildmat.2019.06.079
7. Madhkhan, M., and Saeidian, P. “Mechanical Properties of Ultra-high Performance Concrete Reinforced by Glass Fibers under Accelerated Agin.” ***International Journal of Engineering, TransactionB: Applications***, Vol. 34, No. 5, (2021), 1074–1084. https://doi.org/10.5829/ije.2021.34.05b.01
8. Kashyzadeh, K. R., Ghorbani, S., and Forouzanmehr, M. “Effects of Drying Temperature and Aggregate Shape on the Concrete Compressive Strength: Experiments and Data Mining Techniques.” ***International Journal of Engineering, Transaction C: Aspects***, Vol. 33, No. 9, (2020), 1780–1791. https://doi.org/10.5829/ije.2020.33.09c.12
9. Horszczaruk, E., Sikora, P., Cendrowski, K., and Mijowska, E. “The effect of elevated temperature on the properties of cement mortars containing nanosilica and heavyweight aggregates.” ***Construction and Building Materials***, Vol. 137, (2017), 420–431. https://doi.org/10.1016/j.conbuildmat.2017.02.003
10. Sivathanu Pillai, C., Santhakumar, A. R., Poonguzhali, A., Pujar, M. G., Ashok Kumar, J., Preetha, R., and Kamachi Mudali, U. “Evaluation of microstructural and microchemical aspects of high density concrete exposed to sustained elevated temperature.” ***Construction and Building Materials***, Vol. 126, (2016), 453–465. https://doi.org/10.1016/j.conbuildmat.2016.09.053
11. Kulkarni, P., and Muthadhi, A. “Improving thermal and mechanical property of lightweight concrete using n-butyl stearate/expanded clay aggregate with alccofine1203.” ***International Journal of Engineering, Transactions A: Basics***, Vol. 33, No. 10, (2020), 1842–1851. https://doi.org/10.5829/IJE.2020.33.10A.03
12. Varghese, A., Anand, N., and Arulraj, P. G. “Influence of fiber on shear behavior of concrete exposed to elevated temperature.” ***International Journal of Engineering, Transactions A: Basics***, Vol. 33, No. 10, (2020), 1897–1903. https://doi.org/10.5829/IJE.2020.33.10A.08
13. Thomas, C., Rico, J., Tamayo, P., Ballester, F., Setién, J., and Polanco, J. A. “Effect of elevated temperature on the mechanical properties and microstructure of heavy-weight magnetite concrete with steel fibers.” ***Cement and Concrete Composites***, Vol. 103, (2019), 80–88. https://doi.org/10.1016/j.cemconcomp.2019.04.029
14. Hamad, R. J. A., Megat Johari, M. A., and Haddad, R. H. “Mechanical properties and bond characteristics of different fiber reinforced polymer rebars at elevated temperatures.” ***Construction and Building Materials***, Vol. 142, (2017), 521–535. https://doi.org/10.1016/j.conbuildmat.2017.03.113
15. Li, Y., Tan, K. H., and Yang, E.-H. “Synergistic effects of hybrid polypropylene and steel fibers on explosive spalling prevention of ultra-high performance concrete at elevated temperature.” ***Cement and Concrete Composites***, Vol. 96, (2019), 174–181. https://doi.org/10.1016/j.cemconcomp.2018.11.009
16. Li, Y., Yang, E.-H., and Tan, K. H. “Flexural behavior of ultra-high performance hybrid fiber reinforced concrete at the ambient and elevated temperature.” ***Construction and Building Materials***, Vol. 250, (2020), 118487. https://doi.org/10.1016/j.conbuildmat.2020.118487
17. Al Qadi, A. N. S., and Al-Zaidyeen, S. M. “Effect of fibre content and specimen shape on residual strength of polypropylene fibre self-compacting concrete exposed to elevated temperatures.” ***Journal of King Saud University - Engineering Sciences***, Vol. 26, No. 1, (2014), 33–39. https://doi.org/10.1016/j.jksues.2012.12.002
18. Novák, J., and Kohoutková, A. “Fibre reinforced concrete exposed to elevated temperature.” ***IOP Conference Series: Materials Science and Engineering***, Vol. 246, (2017), 012045. https://doi.org/10.1088/1757-899X/246/1/012045
19. Xie, J., Zhang, Z., Lu, Z., and Sun, M. “Coupling effects of silica fume and steel-fiber on the compressive behaviour of recycled aggregate concrete after exposure to elevated temperature.” ***Construction and Building Materials***, Vol. 184, (2018), 752–764. https://doi.org/10.1016/j.conbuildmat.2018.07.035

20. Pakravan, H. R., and Ozbakkaloglu, T. "Synthetic fibers for cementitious composites: A critical and in-depth review of recent advances." ***Construction and Building Materials***, Vol. 207, (2019), 491–518. https://doi.org/10.1016/j.conbuildmat.2019.02.078

21. Afroughsabet, V., and Ozbakkaloglu, T. "Mechanical and durability properties of high-strength concrete containing steel and polypropylene fibers." ***Construction and Building Materials***, Vol. 94, (2015), 73–82. https://doi.org/10.1016/j.conbuildmat.2015.06.051

22. Serrano, R., Cobo, A., Prieto, M. I., and González, M. de las N. "Analysis of fire resistance of concrete with polypropylene or steel fibers." ***Construction and Building Materials***, Vol. 122, (2016), 302–309. https://doi.org/10.1016/j.conbuildmat.2016.06.055

23. Sun, Z., and Xu, Q. "Microscopic, physical and mechanical analysis of polypropylene fiber reinforced concrete." ***Materials Science and Engineering: A***, Vol. 527, No. 1–2, (2009), 198–204. https://doi.org/10.1016/j.msea.2009.07.056

24. Lura, P., and Terrasi, G. Pietro. "Reduction of fire spalling in high-performance concrete by means of superabsorbent polymers and polypropylene fibers." ***Cement and Concrete Composites***, Vol. 49, (2014), 36–42. https://doi.org/10.1016/j.cemconcomp.2014.02.001

25. Lee, J., Terada, K., Yamazaki, M., and Harada, K. "Impact of melting and burnout of polypropylene fibre on air permeability and mechanical properties of high-strength concrete." ***Fire Safety Journal***, Vol. 91, (2017), 553–560. https://doi.org/10.1016/j.firesaf.2017.04.026

26. Yermak, N., Pliya, P., Beaucour, A.-L., Simon, A., and Noumowé, A. "Influence of steel and/or polypropylene fibres on the behaviour of concrete at high temperature: Spalling, transfer and mechanical properties." ***Construction and Building Materials***, Vol. 132, (2017), 240–250. https://doi.org/10.1016/j.conbuildmat.2016.11.120

27. Jameran, A., Ibrahim, I. S., Yazan, S. H. S., and Rahim, S. N. A. A. "Mechanical Properties of Steel-polypropylene Fibre Reinforced Concrete Under Elevated Temperature." ***Procedia Engineering***, Vol. 125, (2015), 818–824. https://doi.org/10.1016/j.proeng.2015.11.146

28. Abdi Moghadam, M., and Izadifard, R. A. "Effects of steel and glass fibers on mechanical and durability properties of concrete exposed to high temperatures." ***Fire Safety Journal***, Vol. 113, (2020), 102978. https://doi.org/10.1016/j.firesaf.2020.102978

29. Cai, Z., Liu, F., Yu, J., Yu, K., and Tian, L. "Development of ultra-high ductility engineered cementitious composites as a novel and resilient fireproof coating." ***Construction and Building Materials***, Vol. 288, (2021), 123090. https://doi.org/10.1016/j.conbuildmat.2021.123090

30. Ma, X., Pan, J., Cai, J., Zhang, Z., and Han, J. "A review on cement-based materials used in steel structures as fireproof coating." ***Construction and Building Materials***, Vol. 315, (2022), 125623. https://doi.org/10.1016/j.conbuildmat.2021.125623

31. Wei, W., and Zhong-nian, F. "Effects of crystallized fire proof material on the fire resistance of concrete." ***Fire Science and Technology***, Vol. 40, No. 8, (2021), 1137–1141.

32. Temuujin, J., Rickard, W., Lee, M., and van Riessen, A. "Preparation and thermal properties of fire resistant metakaolin-based geopolymer-type coatings." ***Journal of Non-Crystalline Solids***, Vol. 357, No. 5, (2011), 1399–1404. https://doi.org/10.1016/j.jnoncrysol.2010.09.063

33. Hou, X., Ren, P., Rong, Q., Zheng, W., and Zhan, Y. "Effect of fire insulation on fire resistance of hybrid-fiber reinforced reactive powder concrete beams." ***Composite Structures***, Vol. 209, (2019), 219–232. https://doi.org/10.1016/j.compstruct.2018.10.073

34. Palmieri, A., Matthys, S., and Taerwe, L. "Experimental investigation on fire endurance of insulated concrete beams strengthened with near surface mounted FRP bar reinforcement." ***Composites Part B: Engineering***, Vol. 43, No. 3, (2012), 885–895. https://doi.org/10.1016/j.compositesb.2011.11.061

35. Firmo, J. P., Correia, J. R., and França, P. "Fire behaviour of reinforced concrete beams strengthened with CFRP laminates: Protection systems with insulation of the anchorage zones." ***Composites Part B: Engineering***, Vol. 43, No. 3, (2012), 1545–1556. https://doi.org/10.1016/j.compositesb.2011.09.002

36. Firmo, J. P., and Correia, J. R. "Fire behaviour of thermally insulated RC beams strengthened with EBR-CFRP strips: Experimental study." ***Composite Structures***, Vol. 122, (2015), 144–154. https://doi.org/10.1016/j.compstruct.2014.11.063

37. Cree, D., Chowdhury, E. U., Green, M. F., Bisby, L. A., and Bénichou, N. "Performance in fire of FRP-strengthened and insulated reinforced concrete columns." ***Fire Safety Journal***, Vol. 54, (2012), 86–95. https://doi.org/10.1016/j.firesaf.2012.08.006

38. ASTM C125, "Standard terminology relating to concrete and concrete aggregates", Annual Book ASTM Standards, 2003.

39. ASTM C33/C33M-16, "Standard Specification for Concrete Aggregates", ASTM International, West Conshohocken, PA, 2016.

40. Mirzazadeh, M. M., Noël, M., and Green, M. F. "Effects of low temperature on the static behaviour of reinforced concrete beams with temperature differentials." ***Construction and Building Materials***, Vol. 112, (2016), 191–201. https://doi.org/10.1016/j.conbuildmat.2016.02.216

41. ASTM C143/C143M-15a, "Standard Test Method for Slump of Hydraulic-Cement Concrete", ASTM International West Conshohocken, PA, 2015.

42. ASTM C39/C39M-16, "Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens" ASTM International West Conshohocken, PA, 2016.

43. ASTM C78/C78M-16, "Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)", ASTM International West Conshohocken, PA, 2016.

44. Jhatial, A. A., Sohu, S., Bhatti, N. K., Lakhiar, M. T., and Oad, R. "Effect of steel fibres on the compressive and flexural strength of concrete." ***International Journal of Advanced and Applied Sciences***, Vol. 5, No. 10, (2018), 16–21. Retrieved from https://scholar.google.com/citations?user=SoKy-gUAAAAJ&hl=en&oi=sra

45. Mastali, M., Dalvand, A., Sattarifard, A. R., and Abdollahnejad, Z. "Effect of different lengths and dosages of recycled glass fibres on the fresh and hardened properties of SCC." ***Magazine of Concrete Research***, Vol. 70, No. 22, (2018), 1175–1188. https://doi.org/10.1680/jmacr.17.00180

46. Rajaei, S., Shoaei, P., Shariati, M., Ameri, F., Musaeei, H. R., Behforouz, B., and de Brito, J. "RETRACTED: Rubberized alkali-activated slag mortar reinforced with polypropylene fibres for application in lightweight thermal insulating materials." ***Construction and Building Materials***, Vol. 270, (2021), 121430. https://doi.org/10.1016/j.conbuildmat.2020.121430

47. Afroughsabet, V., Biolzi, L., and Ozbakkaloglu, T. "High-performance fiber-reinforced concrete: a review." ***Journal of Materials Science***, Vol. 51, No. 14, (2016), 6517–6551. https://doi.org/10.1007/s10853-016-9917-4

48. Thirumurugan, S., and Anandan, S. "Compressive strength index of crimped polypropylene fibres in high strength cementitious matrix." ***World Applied Sciences Journal***, Vol. 24, (2013), 698–702. https://doi.org/10.5829/idosi.wasj.2013.24.06.714

49. Sedaghatdoost, A., Behfarnia, K., Bayati, M., and Vaezi, M.

sadegh. “Influence of recycled concrete aggregates on alkali-activated slag mortar exposed to elevated temperatures.” ***Journal of Building Engineering***, Vol. 26, (2019), 100871. https://doi.org/10.1016/j.jobe.2019.100871

50. Xiao, J., and Falkner, H. “On residual strength of high-performance concrete with and without polypropylene fibres at elevated temperatures.” ***Fire Safety Journal***, Vol. 41, No. 2, (2006), 115–121. https://doi.org/10.1016/j.firesaf.2005.11.004
51. Novak, J., and Kohoutkova, A. “Mechanical properties of concrete composites subject to elevated temperature.” ***Fire Safety Journal***, Vol. 95, (2018), 66–76. https://doi.org/10.1016/j.firesaf.2017.10.010
52. Memon, S. A., Shah, S. F. A., Khushnood, R. A., and Baloch, W. L. “Durability of sustainable concrete subjected to elevated temperature – A review.” ***Construction and Building Materials***, Vol. 199, (2019), 435–455. https://doi.org/10.1016/j.conbuildmat.2018.12.040
53. Naus, D. J. The Effect of Elevated Temperature on Concrete Materials and Structures - a Literature Review, Report Number: ORNL/TM--2005/553. Oak Ridge, TN (United States). https://doi.org/10.2172/974590
54. Aslani, F., and Samali, B. “High Strength Polypropylene Fibre Reinforcement Concrete at High Temperature.” ***Fire Technology***, Vol. 50, No. 5, (2014), 1229–1247. https://doi.org/10.1007/s10694-013-0332-y
55. Zareei, S. A., Ameri, F., Bahrami, N., Shoaei, P., Musaeei, H. R., and Nurian, F. “Green high strength concrete containing recycled waste ceramic aggregates and waste carpet fibers: Mechanical, durability, and microstructural properties.” ***Journal of Building Engineering***, Vol. 26, (2019), 100914. https://doi.org/10.1016/j.jobe.2019.100914
56. Lourenco, L. A. P., Barros, J. A. O., and Alves, J. G. A. “Fiber Reinforced Concrete of Enhanced Fire Resistance for Tunnel Segments.” ***Special Publication***, Vol. 276, (2011), 1–34. Retrieved from https://www.concrete.org/restrictedcountry.aspx
57. Toghroli, A., Mehrabi, P., Shariati, M., Trung, N. T., Jahandari, S., and Rasekh, H. “Evaluating the use of recycled concrete aggregate and pozzolanic additives in fiber-reinforced pervious concrete with industrial and recycled fibers.” ***Construction and Building Materials***, Vol. 252, (2020), 118997. https://doi.org/10.1016/j.conbuildmat.2020.118997
58. Behnood, A., and Ghandehari, M. “Comparison of compressive and splitting tensile strength of high-strength concrete with and without polypropylene fibers heated to high temperatures.” ***Fire Safety Journal***, Vol. 44, No. 8, (2009), 1015–1022. https://doi.org/10.1016/j.firesaf.2009.07.001
59. Guerrieri, M., Sanjayan, J., and Collins, F. “Residual strength properties of sodium silicate alkali activated slag paste exposed to elevated temperatures.” ***Materials and Structures***, Vol. 43, No. 6, (2010), 765–773. https://doi.org/10.1617/s11527-009-9546-3
60. Manjunath, R., Narasimhan, M. C., and Umesha, K. M. “Studies on high performance alkali activated slag concrete mixes subjected to aggressive environments and sustained elevated temperatures.” ***Construction and Building Materials***, Vol. 229, (2019), 116887. https://doi.org/10.1016/j.conbuildmat.2019.116887
61. Chen, G. M., He, Y. H., Yang, H., Chen, J. F., and Guo, Y. C. “Compressive behavior of steel fiber reinforced recycled aggregate concrete after exposure to elevated temperatures.” ***Construction and Building Materials***, Vol. 71, (2014), 1–15. https://doi.org/10.1016/j.conbuildmat.2014.08.012
62. Ravikumar, C. S., and Thandavamoorthy, T. S. “Glass fibre concrete: Investigation on Strength and Fire Resistant properties.” ***IOSR Journal of Mechanical and Civil Engineering***, Vol. 9, No. 3, (2013), 2320–2334. Retrieved from https://www.academia.edu/download/32785136/Glass_Fibre_Concrete-Investigation_on_Strength_and_Fire_Resistant_Properties.pdf
63. Shoaei, P., Tahmasebi Orimi, H., and Zahrai, S. M. “Seismic reliability-based design of inelastic base-isolated structures with lead-rubber bearing systems.” ***Soil Dynamics and Earthquake Engineering***, Vol. 115, (2018), 589–605. https://doi.org/10.1016/j.soildyn.2018.09.033
64. Khaneghahi, M. H., Najafabadi, E. P., Shoaei, P., and Oskouei, A. V. “Effect of intumescent paint coating on mechanical properties of FRP bars at elevated temperature.” ***Polymer Testing***, Vol. 71, (2018), 72–86. https://doi.org/10.1016/j.polymertesting.2018.08.020

Persian Abstract

چکیده

بتن استحکام و دوام خوبی دارد. با این حال، هنگام قرار گرفتن در معرض آتش از پوسته پوسته شدن و کاهش قابل توجه استحکام رنج می برد. هدف از این مطالعه افزایش مقاومت بتن در برابر آتش با استفاده از دو تکنیک مختلف: ۱) تقویت با الیاف، و ۲) اعمال پوشش ضد حریق. برای این منظور، مخلوط‌هایی با الیاف فولادی (SF)، الیاف شیشه (GF) و الیاف پلی پروپیلن (PPF) با ۰/۵ تا ۲ درصد وزن سیمان، علاوه بر مخلوطی که با لایه ۱۵ میلی‌متری پوشش نسوز تهیه شده بود، ساخته شد. مواد و یک مخلوط کنترل همه مخلوط‌ها در معرض دماهای بالای ۲۰۰–۸۰۰ درجه سانتیگراد قرار گرفتند و خواص فیزیکی و مکانیکی مورد ارزیابی قرار گرفتند. با توجه به نتایج آزمایش، هر دو تکنیک در افزایش مقاومت در برابر آتش مخلوط‌های بتن مؤثر بودند. حداکثر مقاومت فشاری و خمشی باقیمانده برای مخلوط حاوی GF ۰/۵ درصد به دست آمد که به ترتیب ۱۱۷ و ۱٤۵ درصد بیشتر از مخلوط کنترل در ۸۰۰ درجه سانتیگراد بود. همچنین بتن با پوشش نسوز به ترتیب تا ۷٦ درصد و ۱۱۳ درصد مقاومت فشاری و خمشی بالاتری نسبت به مخلوط شاهد نشان داد. مشخص شد که افزودن الیاف در فرآیند تولید بتن، رویکردی مطلوب‌تر و از نظر اقتصادی کارآمدتر برای افزایش مقاومت در برابر آتش است. با این حال، برای یک سازه بتنی موجود، اعمال پوشش نسوز تنها گزینه است و می‌تواند مقاومت در برابر آتش را به طور قابل مقایسه‌ای افزایش دهد.