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Mechanical Properties of HPC Incorporating Fly Ash and Ground Granulated Blast Furnace Slag After Exposure to High Temperatures

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Abstract

The behavior of concrete structures after being exposed to elevated temperatures is considered one of the great vital concerns in Civil Engineering. Moreover, as elevated temperature have adverse effects on the mechanical properties of concrete members, it's important to find solutions to improve these properties at elevated temperature. This study aims to investigate the effect of supplementary cementitious materials (SCM) on the high performance concrete (HPC) compressive, tensile, and flexural strengths after exposure to different temperatures of 200 °C, 400 °C, 600 °C, and 800 °C. In preparing HPC, different parameters were considered including SCM type, fly ash (FA) or ground granulated blast furnace slag (GGBFS), adding 0.5% (by volume fraction) steel fiber (SF), polypropylene fiber (PP) and hybrid fibers. The results were compared with those for high strength concrete (HSC) and normal strength concrete (NSC). The results showed that using FA and GGBFS, SF, and hybrid fibers can significantly improve the residual mechanical properties of HPC, while using PP fiber has an adverse effect on the residual mechanical properties of HPC especially residual tensile and flexural strengths. The standard code curves underestimate the residual mechanical properties of HPC after 200 °C.

Keywords

HPC, mechanical strengths, residual strengths, fibers, codes, high temperature

1 Introduction

In the recent decades, high performance concrete (HPC) has great spread as replacement of normal strength concrete in building construction. While HPC has great workability, durability and mechanical properties than normal strength concrete (NSC), its failure is more dramatic under fire characterized by explosive spalling. Thus leading to direct fire exposure of the steel rebar, which reduce the fire resistance of structure [1]. As a result of this, it's important to find solutions to improve the mechanical properties of these concrete at different temperatures. Numbers of studies up to date have been conducted to study the effect of supplementary cementitious material and fibers with different types and amount on the residual mechanical properties of HPC after fire [2–13]. Their results indicated that using FA and GGBFS can improve the residual mechanical properties of concrete at high temperature, while concrete mixtures containing silica fume and metakaolin suffered more deterioration in the mechanical properties of concrete after exposure to fire. Gao et al. [7] indicated that the optimum amount of GGBFS which can enhance the residual tensile strength of concrete after fire is 30% for plain concrete and 40% for concrete with polypropylene fiber (PP), while Wang [14] showed that the optimal behavior of HPC under fire was noticed with amount of GGBFS higher than 20%. Poon et al. [2] concluded that using 30% FA can improve the residual compressive strength of concrete under fire, where the retained compressive strength values were 121%, 98%, 67% and 32% at 200 °C, 400 °C, 600 °C, and 800 °C, respectively. Khan and Abbas [15] reported that the high volume of FA led to more deterioration in concrete strength after fire. Kou et al. [16] indicated that GGBFSC displayed higher residual tensile strength as comparison with fly ash concrete (FAC) at different levels of temperatures. While GGBSC suffered a reduction in tensile strength range from 48% to 53%, FAC lost about 61–71% of its initial tensile strength after being exposed to temperature of 500 °C.

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Poon et al. [4] observed that HPC containing metakaolin suffered a quick degradation in compressive strength at high temperature, where the remaining compressive strength at 600 °C and 800 °C were 45% and 23% of its compressive strength at room temperature, respectively.

According to concrete grade, many studies observed that high strength concrete (HSC) showed more deterioration and degradation in its compressive strength than NSC at high temperatures [17–19]. While the remained residual strength of NSC at 400 °C and 600 °C was (80–90%) and (25–40%), respectively, the HSC mix retained about 60% of their original strength at a temperature of 400 °C. On the other hand, Poon et al. [3] concluded that HSC maintained higher residual compressive strength than NSC. This is attributed to the fact that NSC contains more voids ratio than HSC concrete, which weakens the concrete microstructure; consequently the compressive strength decreases at high temperatures.

Regarding to the fibers, several researchers have studied the effect of adding steel fiber (SF), polypropylene fiber (PP), and hybrid fibers on the mechanical properties of concrete at high temperature. Some researchers showed that the presence of fibers can enhance the mechanical properties at high temperature [6, 11, 20, 21]. Other authors have reported that adding SF fibers led to more explosive spalling for structural members [1, 22]. This may be due to the capacity of SF in bridging the crack and limiting water evacuation [1]. Others have shown that although the use of PP fibers can prevent concrete spalling, it has an adverse effect on the concrete mechanical properties at high temperature [23, 24]. This is because the PP fibers begin to expand and melt around 160–170 °C and creates additional porosity, which weakens the concrete structure and thus decreases the residual mechanical properties of concretes.

Poon et al. [4] concluded that the use of SF can minimize the compressive strength degradation of HPC at high temperature as SF doubled the energy absorption capacity of concrete at normal temperature, while using PP has an adverse effect on the HPC at high temperature which reduced the energy absorption capacity. Novák and Kohoutková [10] observed that the use of PP in combination with SF (hybrid fiber reinforced concrete, HFRC) resulted in a more deterioration of the compressive and tensile strengths of concrete as compared with plain concrete or concrete containing SF only, where the retained compressive and tensile strengths for HFRC were (98%, 88%, and 45%) and (97%, 88%, and 41%) at 200 °C, 400 °C, and 600 °C, respectively.

Regarding the repair techniques used for restoring the mechanical properties of fire-damaged concrete, Noman et al. [25] investigated the effects of various low-cost repair techniques to restore the mechanical properties of fire-damaged concrete. The repair techniques include; water curing, cement-based slurry injection and water re-curing, steel wire mesh with epoxy resin mortar, and epoxy injection. The results showed that the use of cement-based slurry injection along with the water-curing repair technique provided the best results in restoring the original strength, which could regain almost 90% of its ultimate strength and secant stiffness after being exposed to 700 °C.

It's important to achieve most understanding of using FA and GGBFS combined with SF, PP, and hybrid fibers on the mechanical properties of HPC after exposure to different temperatures.

2 Mix proportion

2.1 Properties of materials

Materials used in this experimental work were obtained from local Egyptian sources that are commonly used in Egyptian constructions. Eight concrete mixes were prepared using crushed limestone with a nominal maximum size of 12.5 mm and river sand as fine aggregate. The bulk specific gravity and the absorption for coarse and fine particles were obtained as (2.6 and 2.58) and (2.3 and 2.4), respectively, according to ASTM-C127 and C128 [26]. The fineness modulus of coarse and fine particles was 7.4 and 3.3, respectively, according to ASTM-C136 [26]. The unit weight of coarse aggregate was determined according to ASTM-C29 [26], and was found to be 1500 kg/m^3. The cement used to produce NSC and HPC was ordinary Portland cement (CEM I 42.5 N) complying with EN 197-1 [27]. The Chemical, physical, and mechanical properties of the used cement are shown in Table 1. Ordinary Portland cement was replaced by fly ash (FA) or ground granulated blast furnace slag (GGBFS) to produce HPC. The physical properties and the chemical analysis of the used FA and GGBFS are illustrated in Table 1. Two types of fibers were used in producing HPC, hooked steel fiber and polypropylene fiber. The mechanical and geometrical properties of steel and polypropylene fibers are given in Table 2. A commercially available modified polycarboxylate ether high range water-reducing admixture (HRWRA) with 44% solid particles, which confirms with ASTM-C494 [28] was used to prepare the concretes.

Table 1 Chemical, mechanical and physical properties of the used cement, GGBFS, and FA

Chemical component	Cement	GGBFS	FA
SiO_2	20.65	35.6	60.28
Al_2O_3	4.4	11.2	28.59
Fe_2O_3	5.05	0.6	4.99
Total $SiO_2 + Al_2O_3 + Fe_2O_3$	30.1	47.4	93.86
CaO	62.20	42.47	2.38
Na_2O	0.38	0.4	0.48
MgO	1.90	5.6	2.92
Loss on Ignition	1.34		
Insoluble Residue	0.88	0.93	1.1
Physical properties			
Specific gravity	3.15	2.89	2.3
Specific surface area (cm^2/g)	4066	4000	3500

Table 2 Properties of the investigated fibers (as per producer)

Properties/types of fibers	Steel	Polypropylene
Length (mm)	35	Gradient of 6–18
Diameter	0.8 (mm)	18 [μm]
Specific gravity	7.85	0.91
Shape	Hooked end	Fiber mesh
Tensile strength [MPa]	≥1000	300-400
Elastic modulus [GPa]	210	3.6
Melting point [°C]	1530	160
decompositions point [°C]	-	360

2.2 Concrete mix

Eight concrete mixes were designed according to the absolute volume method. The mix proportions are shown in Table 3. The investigated mixes were designed to study the influence of the following parameters under fire considering a control mix of normal strength concrete (NSC). In preparing HPC, different parameters were considered including SCM type, fly ash (FA) or ground granulated blast furnace slag (GGBFS), adding 0.5% (by volume fraction) steel fiber (SF), polypropylene fiber (PP) and hybrid fibers. Whereas, mix 2 (HSC) was considered to investigate the high strength concrete under fire and, mixes 3 (FAC) and 4 (BFSC) were considered to assess the influence of replacing 30% of cement by FA or GGBFS, respectively, on the mechanical properties of HPC. Moreover, mixes (5 to 7) were considered to determine the effect of adding SF, PP, and hybrid fibers, respectively, with a volume fraction of 0.5% on the residual mechanical properties of concrete containing 30% FA (FAC). Finally, mix 8 was considered to assess the influence of adding SF by 0.5% volume fraction on the residual mechanical properties of BFSC.

2.3 Mixing, casting and curing of test specimens

A drum mixer with capacity of 0.1 m^3 was used for mixing the concrete ingredient according to ASTM C192/C192M-05 [29]. Concrete cubic specimens 100 × 100 × 100 mm, cylinders with 100 mm diameter and 200 mm height, and beam 10 × 10 × 50 mm were cast to determine the compressive, tensile, and flexural strengths of concrete mixes after being exposed to high temperatures. After casting, all the specimens were stored in air at room temperature for 24 h prior to demolding. After demolding the specimens, they were cured in water tank for 28 days under an average 23 °C temperature, and then transferred to an open environment until the day of fire test at age of 60 days.

Table 3 Mix proportions and mechanical properties of different batches of the investigated concrete mixes

Mix No.	1	2	3	4	5	6	7	8
Mix ID	NSC	HSC	FAC	BFSC	FAC-SF	FAC-PP	FAC-(SF+P)	GGBS-SF
Concrete type	Normal strength concrete	High strength concrete	Fly ash 30%	Slag 30%	Fly ash 30%, (SF) 0.5%	Fly ash 30%, (PP) 0.5%	Fly ash 30%, SF 0.5%+ PP 0.5%	Slag 30, (SF) 0.5%
Cement	350	450	315	315	315	315	315	315
FA (kg/m^3)	-	-	135	-	135	135	135	-
GGBS (kg/m^3)	-	-	-	135	-	-	-	135
Sand (kg/m^3)	680	694	694	694	694	694	694	694
CA (kg/m^3)	1020	1040	1040	1040	1040	1040	1040	1040
Water (kg/m^3)	200	144	135	144	135	144	144	144
W/B	0.57	0.32	0.3	0.32	0.3	0.32	0.32	0.32
HRWR (kg/m^3)	-	7.65	4.5	12.15	6.75	6.75	12.15	12.15
Polypropylene fibers (kg/m^3)	-	-	-	-	-	4.5	4.5	-
Steel fiber (kg/m^3)	-	-	-	-	39	-	39	39

2.4 Heating scheme

At the age of 60 days, the fire test was conducted using an electric furnace as shown in Fig. 1(a). The concrete specimens were exposed to different temperature levels of 200 °C, 400 °C, 600 °C, and 800 °C as shown in Fig.1(c). The specimens were placed in the furnace and heated from a room temperature (25 °C) to a specific temperature with an average increase rate of 30 °C/min using temperature control as shown in Fig. 1(b), and then fixed at the target temperature for two hours. This study used an average rising rate of 30 °C/min to closely imitate the ISO 834 standard fire curve. The temperature range used in this study is similar to that which could occur in a real fire situation [30, 31]. The specimens were subjected to one cycle of heating–cooling. At the end of the fire test, the furnace was turned off and the concrete specimens were left in the furnace to allow nature cooling to room temperature.

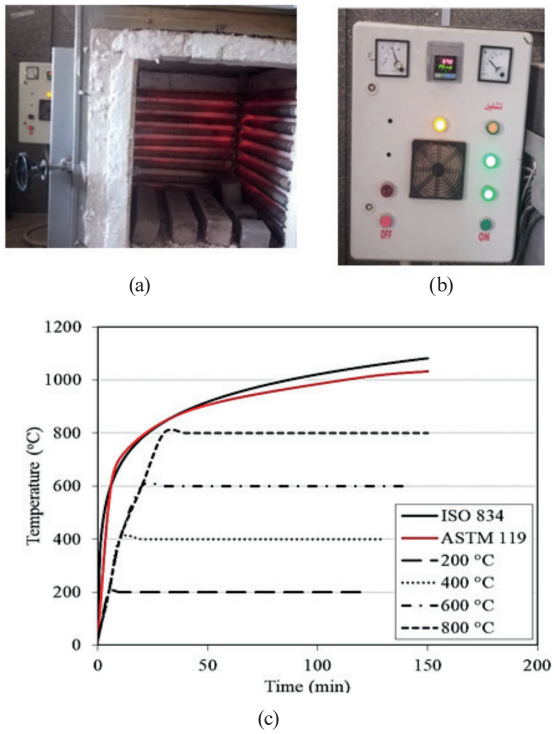


Fig. 1 Heating scheme; a) Specimens in furnace, b) Temperature control, c) Fire curves as adopted by the used furnace

2.5 Test procedure

After concrete specimens were cooled down to room temperature, compressive strength, tensile strength, and flexural strength were determined. The compressive test was carried out according to BS EN 12390-3 [32] whereas, the tensile and flexural tests were carried out according to BS EN 12390-6 [33] and BS EN 12390-5 [34], respectively. Three specimens from each concrete mix were tested for each temperature and the average value was considered.

3 Results and discussion

3.1 Compressive test

The results of the compressive test for different concrete mixes at different temperature levels are summarized in Table 4 and Fig. 2(a, b). The results include the residual compressive strength Fig. 2(a) and the ratio of compressive strength at target temperature (f_c, T) to compressive strength at ambient temperature (f_c) Fig. 2(b). The presented results indicated that all concrete types displayed a reduction in compressive strength at high temperatures because of the physical and chemical changes that occurred at high temperature, which agree with test results obtained by Iqbal et al. [35], Zhao et al. [36]. HSC exhibited a quicker deterioration in compressive strength than NSC at various temperature levels. The retained residual compressive strengths were 93.5%, 90.4%, 65.3%, and 30% at 200 °C, 400 °C, 600 °C, and 800 °C, respectively, for NSC as compared to 86%, 76.9%, 52.3%, and 35% for HSC. Similar results were obtained by Heikal et al. [17]. Because of the fact that the dense microstructure of HSC avoids moisture mitigation and produces microcracks, consequently the strength decreases as suggested by Khaliq and Kodur [6]. Besides, the loss of chemical bound water due to dehydration and disintegration of C-S-H combined with impermeability of HSC resulted in longer crack lengths and coarser crack widths at high temperatures as discussed by Akca and Özyurt [13].

Table 4 Residual compressive strength of different concrete mix as a function of temperature

mix	Residual compressive strength (Mpa)				
	25 °C	200 °C	400 °C	600 °C	800 °C
NSC	36.5	34.1 (93.5%)	33 (90.4%)	23.8 (65.2%)	13.9 (30%)
HSC	65	55.9 (86%)	50 (76.6%)	34 (52.3%)	22.8 (35%)
FAC	60.4	67.4 (90%)	71.2 (112%)	48.8 (66.2%)	32 (44.6%)
BFSC	60.3	67.4 (111%)	71.2 (118%)	48.8 (81%)	32 (53%)
FAC-SF	58.5	53 (90.6%)	66.6 (113%)	50.3 (86%)	28 (47.8%)
FAC-PP	59	63.3 (97.4%)	55 (84.6%)	32.9 (69.2%)	23 (43.8%)
FAC-SF+PP)	62.2	57 (91.6%)	70 (112.5%)	43.7 (70.2%)	25 (40%)
BFSC-SF	56	67 (119%)	69 (123%)	60 (107%)	35 (62.5%)

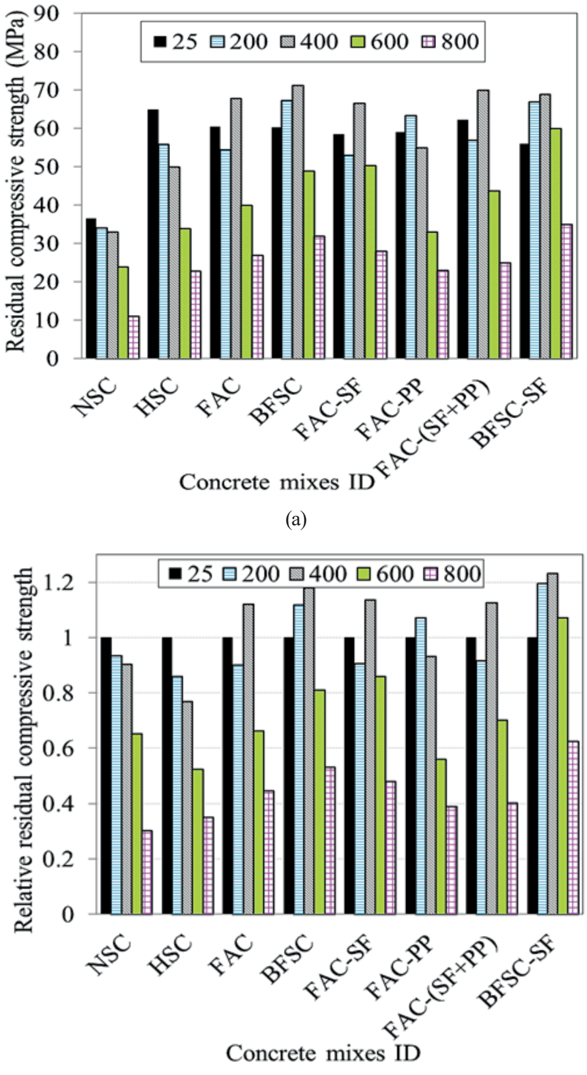


Fig. 2 Residual compressive strength of different concrete types; (a) Residual compressive strength for the investigated mixes, (b) Relative residual compressive strength for the investigated mixes

In a comparison, concrete containing FA and GGBFS showed high residual compressive strengths at different temperatures than HSC and NSC, where BFSC recorded the highest residual compressive strength with ratios of 111.7%, 118%, 81%, and 53% of its initial compressive strength at room temperature for 200 °C, 400 °C, 600 °C, and 800 °C, respectively. The results agree with results obtained by previous results Poon et al. [2], Xiao and Falkner [5]. The raise in compressive strength is due to the reduced amount of calcium hydroxide $Ca(OH)_2$, which otherwise results in strength loss and disintegration Abdelmelek and Lublóy [37]. Further, due to the FAC and GGBFS mixtures are enriched with fine particles in which the hydration of un-hydrated particles is more compared to the ordinary mixture as mentioned by Poon et al. [2], Akca and Özyurt [13]. Furthermore, the residual compressive strength of FAC and BFSC increased with increasing temperature up to 400 °C. This is due to the internal autoclaving effect that develops as a result of the flow of produced steam from the elimination of capillary, physically adsorbed, and bound water in cement pastes at high temperatures, which causes an internal autoclaving reaction, which produces hydration products, as well as the improvement of the pozzolanic reaction of FA GGBFS with $Ca(OH)_2$, which results in the formation of additional C-S-H gel and improve the microstructure and consequently increase the concrete compressive strength which agree with Poon et al. [2], Heikal et al. [17].

Effect of fibers on strength appears at temperatures of 600 °C and 800 °C; whereas the BFSC-SF displayed the highest value of residual compressive strength at different temperature levels of 119.6%, 123.2%, 107%, and 62.5% at 200 °C, 400 °C, 600 °C and 800 °C, respectively. This increase may be due to the heat accelerate the hydration process between the un-hydrated cement particles and GGBFS and the leftover water around the interfacial zone. This could cause the fiber–matrix interfacial bond strength to increase as previously mentioned by Babalola et al. [38], in addition, SF bridges the crack propagation and delays the crack initiation by absorbing developed stresses at the fiber's tip, similar to the results given by Poon et al. [4], Li et al. [39]. On the other hand, PP fiber had a negative effect on the residual compressive strengths of concrete at high temperature, where the residual compressive strength of FAC-PP decreased to 55.8% and 38.9% at 600 °C and 800 °C, respectively, which in agreement with results of Pilya et al. [23] and Müller et al. [24]. The reduction is due to the PP fibers started to melt around 160–170 °C and create additional porosity in the specimen consequently the compressive strength decreased as mentioned by Pilya et al. [23]. Moreover, Hybrid fiber PP and SF experienced lower compressive strength than using SF only but slightly higher than concrete without fiber. This is attributed to the fact that the high volume fraction of the two fiber types produces more void in concrete mix and weakens the bond between concrete and fibers, which in agreement with results of Li et al. [39].

Fig. 3 presents the comparison between residual compressive values for tested specimens and those from literatures Poon et al. [2], Poon et al. [3], Xiao and Falkner [5], Khaliq and Kodur [6], Yermak et al. [20] and codes limits EN 1992-1-2 [40]. From the Fig., it can be seen that the residual compressive strength for FAC and BFSC with

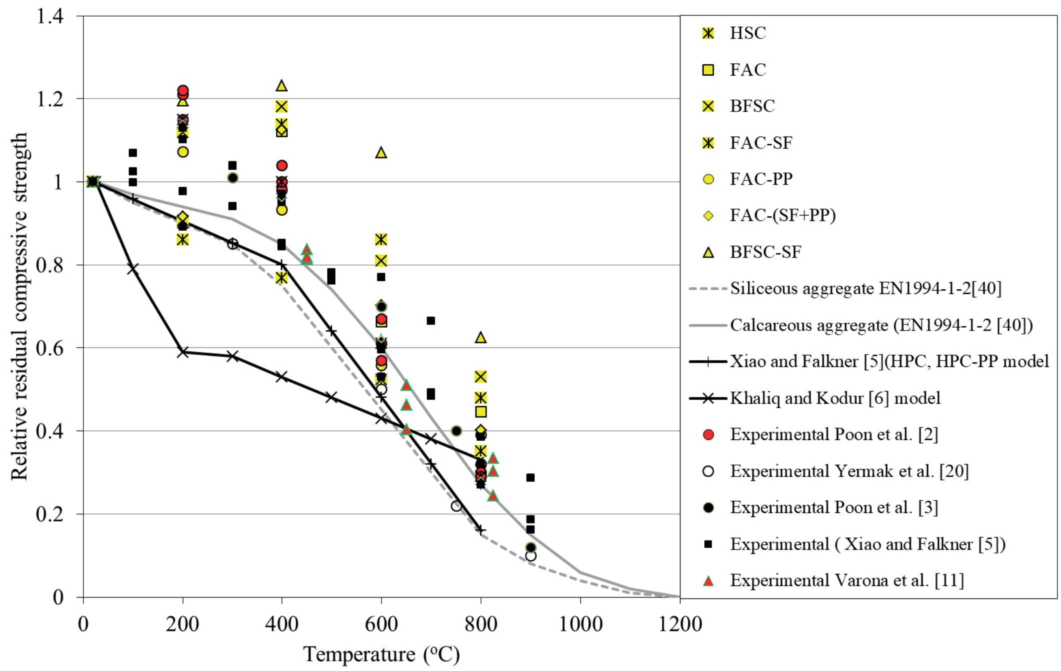


Fig. 3 Comparison between the residual compressive strength values and previous data from literatures

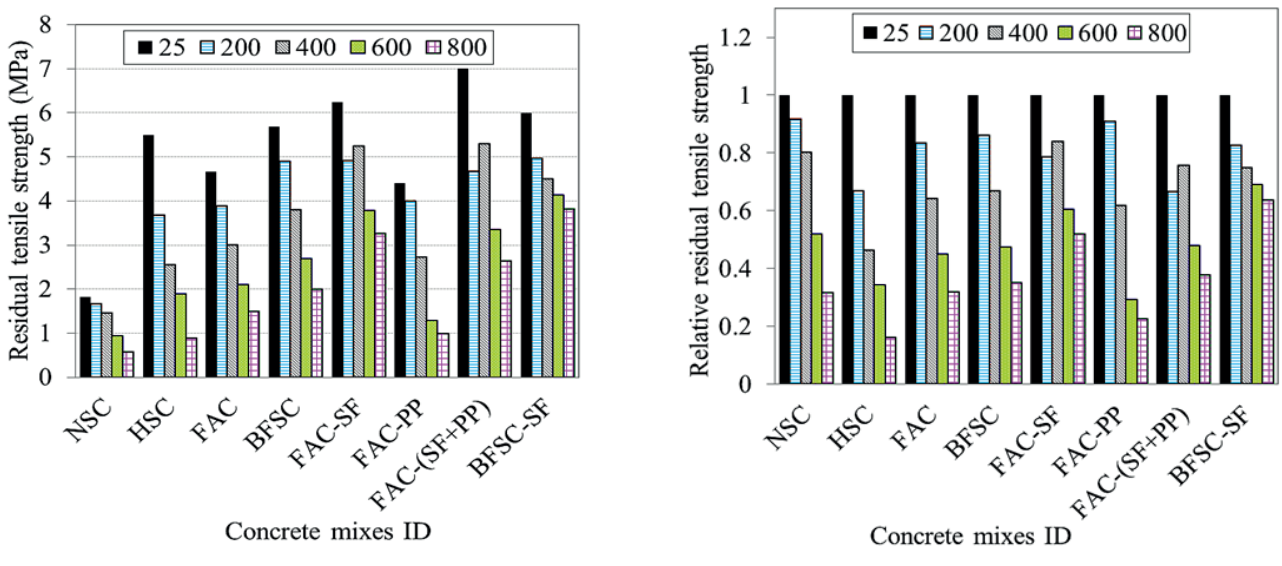


Fig. 4 Splitting tensile strength of different concrete types at different temperatures; (a) Residual indirect tensile strength for the investigated mixes, (b) Relative residual indirect tensile strength for the investigated mixes

and without fibers was higher than those from the literature at different temperatures. This is because the uses of FA, GGBFS combined with fiber significantly improve the fire resistance of concrete. In addition, the different test conditions. EN 1992-1-2 [40] curve for calcareous aggregate is more suitable than other codes and models for HSC and FAC-PP. For FAC and BFSC with and without fibers, the models and codes curves underestimated the residual compressive strength at different temperatures.

3.2 Tensile strength

The tensile strength of concrete is an important property as it is responsible for the cracking of concrete. The tensile strength at high temperature is more important because tensile strength controls the spalling of concrete.

Fig. 4(a, b) illustrate the residual indirect tensile strength for different concrete types at various temperature levels. The results indicated that all concrete types exhibited a gradual loss in tensile strength with increasing temperature as shown in Table 5. HSC exhibits more deterioration in residual tensile strength than NSC, where the retained residual tensile strength was 16% and 31.8% for HSC and NSC, respectively, after exposure to 800 °C. The reduction is due to the concrete tensile strength is more sensitive to thermal and micro-cracks. When concrete is heated to 200 °C, the free and adsorbed water evaporates and due to the dense microstructure of HSC prevents vapor water from mitigating consequently the pore pressure increases and produces microcracks. At 450 °C, more cracks initiated due to the decomposition of $Ca(OH)^2$ which reduced the residual tensile strength. The decomposition of paste at 600–700 °C produced extensive cracks, thus led to significance deterioration in concrete that agreed with Wang [14]. In addition to deterioration of interfacial transition zone between cement matrix and aggregate result from the incompatibility of the thermal expansion between cement paste and aggregate as mentioned by Khan and Abbas [15]. BFSC showed the highest residual tensile strength followed by FAC; the residual tensile strength values were (83.5%, 64%, 44.9%, and 32%) and (86.2%, 66.9%, 47.5%, 35.2%) for FAC and BFSC, respectively, at 200 °C, 400 °C, 600 °C, and 800 °C. This agrees with Gao et al. [7], Kou et al. [16].

The effect of fiber is more evident in tensile strength, where concrete mixtures containing SF display the highest tensile strength at different temperature increases. The relative tensile strength at temperatures of 200 °C, 400 °C, 600 °C, 800 °C differ between (66.8–82.7%), (70–84%), (48–69%), and (37.8–63.7%), respectively. The results agree with Khaliq and Kodur [6]. This is because SF has thermal conductivity higher than those of cement matrix and aggregate which leads to a uniform temperature in concrete and consequently reduces cracking formation as stated by Gao et al. [7], Babalola et al. [38]. On the other hand, FAC-PP recorded the least tensile strength beyond 200 °C and recorded 90.1%, 62%, 29.3%, and 22.7% at 200 °C, 400 °C, 600 °C, and 800 °C, respectively. As mentioned in the previous section, the decrease in tensile strength is attributed to the melting of PP fiber, as mentioned by Khaliqu and Kodur [6]. This agrees with Eidan et al. [12] who observed that the critical temperature for concrete containing PP was 400 °C.

Comparing the experimental residual tensile strength results with the results from previous studies and empirical relations from Khaliqu and Kodur [6], Gao et al. [7], Kim et al. [9], and EN 1992-1-2 [40] are presented in Fig. 5. It can be seen from Fig. 5 that, there is a large variation in the tensile strength at different temperatures due to the difference in constitutive material of concrete and test conditions. In addition, BFSC and BFSC-SF have higher relative residual tensile strength than those from Gao et al. [7] and Kim et al. [9]. This is due to the fact that the inclusion of GGBFS improves the fire resistance of HPC and increases the residual strength. Moreover, most of the results are in between the upper and lower ranges for Gao et al. [7].

Table 5 Splitting tensile strength of different concrete types as a function of temperature

mix	Residual tensile strength (MPa)				
	25 °C	200 °C	400 °C	600 °C	800 °C
NSC	1.82	1.67 (91.7%)	1.46 (80.2%)	0.94 (51.9%)	0.58 (31.8%)
HSC	4.67	3.68 (66.9%)	2.56 (46.5%)	1.9 (34.54%)	0.89 (16.2%)
FAC	4.67	3.9 (83.5%)	3.0 (64.2%)	2.1 (45%)	1.5 (32%)
BFSC	5.68	4.5 (86.2%)	3.8 (66.9%)	2.7 (47.5%)	2 (35.2%)
FAC-SF	6.25	4.92 (78.7%)	5.25 (84%)	3.79 (60.6%)	3.26 (52.1%)
FAC-PP	4.34	4.0 (90.9%)	2.73 (62%)	1.29 (29.3%)	1 (22.7%)
FAC-(SF+PP)	7.0	4.68 (66.8%)	5.3 (75.7%)	3.36 (48%)	2.65 (37.8%)
BFSC-SF	6.0	4.96 (82.7%)	4.2 (70%)	4.14 (69%)	3.82 (63.7%)

Whereas, the empirical relation from Khaliq and Kodur [6] is more suitable for predicting the tensile strength of FAC-SF and FAC(SF+PP) after exposure to fire up to 800 °C. On the other hand, EN 1992-1-2 [40] underestimated the residual tensile strength of HPC with and without fibers beyond 200 °C. While no residual tensile strength can be assessed above 600 °C according to EN 1992-1-2 [40], the remained residual tensile strength of test results range from 16% to 63 % after exposure to temperature of 800 °C.

3.3 Flexural strength

The presented diagrams in Figs. 6(a) up to 6(h) Show the load displacement curves resulting from three-point loading test for different concrete types after being exposed to various temperature levels of 200 °C, 400 °C, 600 °C 800 °C. The flexural load increases linearly to peak flexural load then a sudden fall in load occurred for NSC, HSC, FAC, BFSC, and FAC-PP due to the concrete weak in tension as mentioned by Gao et al. [7] and

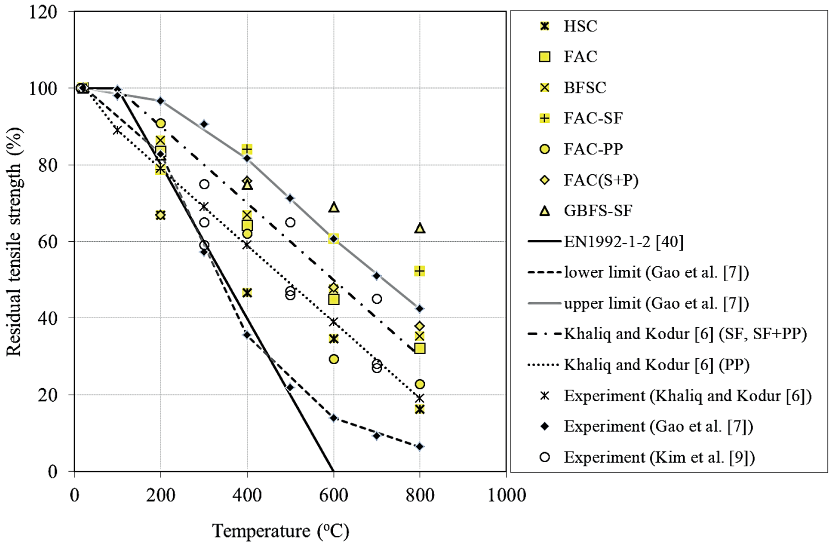


Fig. 5 Comparison between the residual tensile strength values and previous data from literatures

Novák and Kohoutková [10], while FAC-SF, FAC-(S+P), and BFSC-SF exhibit a sudden decrease in flexural load after the first crack due to the absence of SF is not enough (0.5%) to prevent the sudden decrease in a load then a tension softening curve was observed. This is due to the fibers, which are gradually activated with increasing loading until they are fully activated as suggested by Novák and Kohoutková [10]. For all concrete types, the flexural load decreases significantly with temperature increases as compared to unheated specimens.

The important finding is related to residual peak flexural strength for different concrete types as shown in Fig. 7(a, b) and Table 6. Concrete mixes containing FA and GGBFS display higher residual peak flexural strength than that of NSC at different temperatures, which can be attributed to the dense microstructure as compared to NSC. Furthermore, the improvement in the interfacial transition zone due to activate the FA and GGBFS particles as mentioned by Gao et al. [8], Kim et al. [9]. FAC displays the highest residual flexural strength and retains 96.5%, 95.7%, 74.9%, and 16% of its initial flexural strength, at 200 °C, 400 °C, 600 °C, and 800 °C temperatures, respectively. All types of concrete suffered a notable reduction in flexural strength at 600 °C and 800 °C; this agrees with results from Gao et al. [8]. This decrease is due to the flexural strength is very sensitive to cracks produced from decomposed paste.

Fibers have an important effect on the flexural strength at normal and elevated temperatures. FAC (SF+PP) displayed the highest flexural strength at different temperature as shown in Fig. 7 and recorded 90.9%, 84.3%, 79.4%, and 61% at 200 °C, 400 °C, 600 °C, and 800 °C, respectively, where FAC-PP showed the least flexural strength and recorded 90%, 66%, 28.7%, 20% at 200 °C, 400 °C, 600 °C, and 800 °C, respectively, which can be attributed to melting of PP fiber. The increase in flexural strength of FAC (SF+PP) is due to melting of PP fiber creating a network of micro-channels for relieving the water vapor; this will, in return, reduce the damage in fire. Besides, the higher thermal conductivity of steel fiber compared to that of cement matrix and aggregates allows heat caused by thermal gradient to transmit more uniformly in steel fiber reinforced concrete, thus leading to lesser cracks and enhanced splitting tensile strength of concrete Gao et al. [8].

A comparison between the residual flexural strength of the tested specimens and that from previous studies conducted by Xiao and Falkner [5], Gao et al. [8], and EN 1992-1-2 [40] are shown in Fig. 8. The results proved that the tested specimens had higher residual flexural strength compared to the results from previous studies after temperature of 200 °C. This is because of the fact that the use of FA and GGBFS which react at high temperatures and fill the voids and improve the bond between mortar matrix and aggregate and concrete mix and fiber reinforcement Gao et al. [7, 8]. In addition, adding SF and PP fibers which improve the residual mechanical properties of concrete mixes at high temperatures. Furthermore, EN 1992-1-2 [40] underestimated the flexural strength of HPC with and without fiber after exposure to temperatures higher than 200 °C.

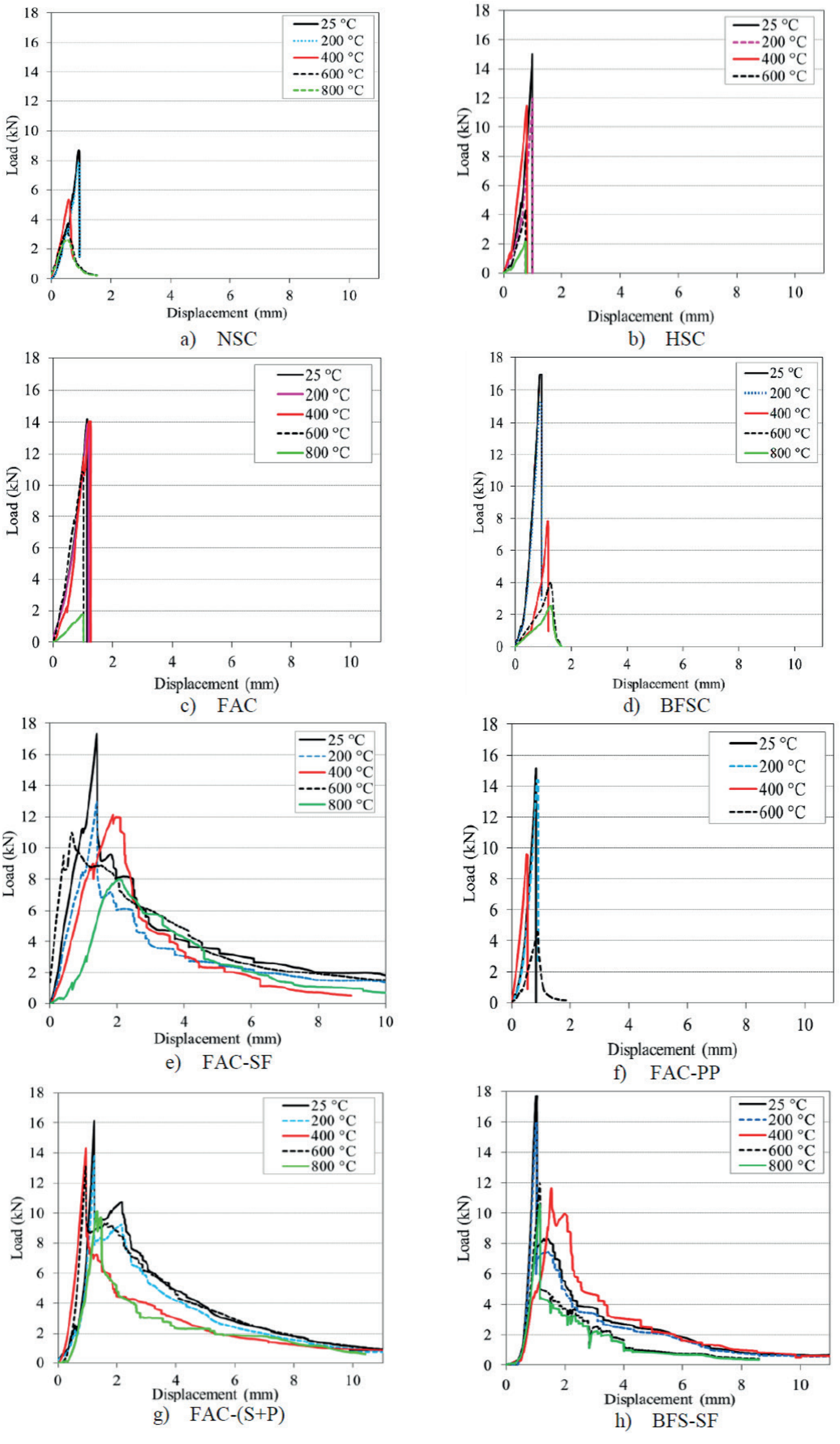
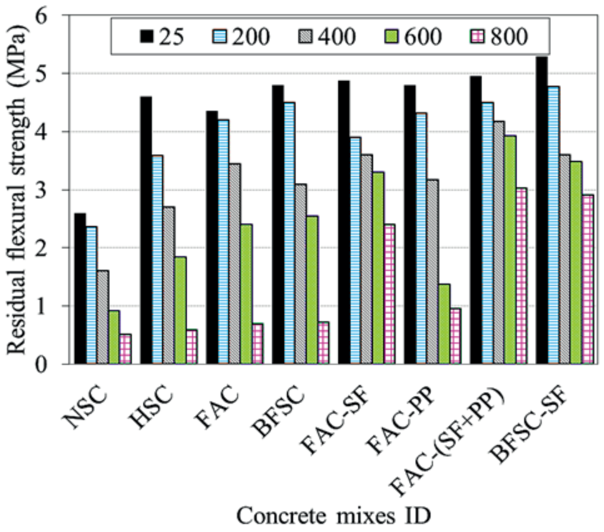
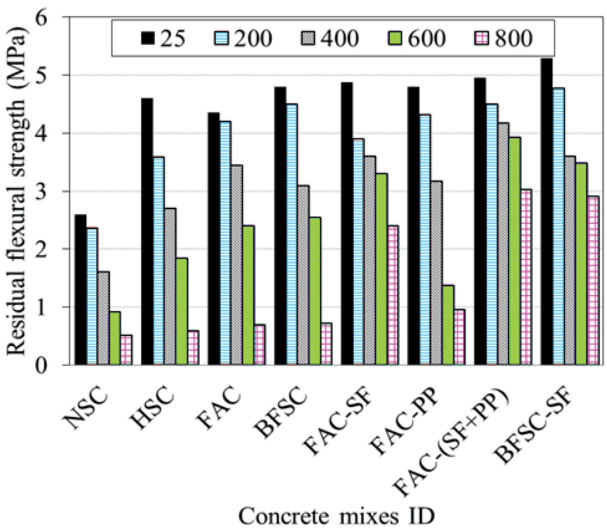


Fig. 6 Load displacement for different concrete types; (a) NSC, (b) HSC, (c) FAC, (d) BFSC, (e) FAC-SF, (f) FAC-PP, (g) FAC-(SF+PP), (h) BFSC-SF



(a)



(b)

Fig. 7 Residual flexural strengths of different concrete types; (a) Residual flexural strengths for the investigated mixes, (b) Relative residual flexural strengths for the investigated mixes

4 Crack patterns

Figs. 9(a–h) show the effect of temperature on tested specimens of different concrete mixes after being exposed to different temperature levels of 400 °C, 800 °C. From visual observation, it can be shown that there was no visible crack on specimens heated up to 400 °C. After exposure to 800 °C, the microcracks propagated rapidly, resulting in longer crack lengths and coarser crack widths. While FAC showed a full spalling for cylinder specimen as shown in Fig. 9(c), NSC specimen showed minor spalling at the edge of specimen as shown in Fig. 9(a). Whereas, HSC, GBFSC, FAC-PP showed one major crack in the middle height of the specimen as shown in Figs. 9(b), 9(d), and 9(f), but no splitting occurred. FAC-SF, FAC-(SF+PP), and BFSC-SF had minor cracks on the specimen surface, but no major crack was observed that would cause disintegration as shown in Figs. 9(e), 9(g), and 9(h).

Table 6 Residual flexural strengths of different concrete types as a function of temperature

mix	Residual flexural strength (MPa)				
	25 °C	200 °C	400 °C	600 °C	800 °C
NSC	2.6 (100%	2.36 (91%)	1.6 (61.7%))	0.918 (35%)	0.59 (30%)
HSC	4.6 (100%)	3.59 (78%)	2.7 (58.7%)	1.84 (40%)	0.69 (20%)
FAC	4.35 (100%)	4.2 (96.5%)	3.45 (79.3%)	2.4 (55%)	0.696 (16%)
BFSC	4.8 (100%)	4.5 (93.7%)	3 (64.3%)	2.55 (53%)	0.72 (15%)
FAC-SF	4.87 (100%)	3.9 (80%)	3.6 (73.8%)	3.3 (67.7%)	2.42 (49%)
FAC-PP	4.79 (100%)	4.31 (90%)	3.17 (66%)	1.37 (28.7%)	0.95 (20%)
FAC-(SF+PP)	4.95 (100%)	4.5 (90.9%)	4.17 (84.3%)	3.93 (79.4%)	3.03 (61%)
BFSC-SF	5.3 (100%)	4.77 (90%)	3.6 (67.9%)	3.49 (65.8%)	2.91 (55%)

5 Scanning electron microscope

To confirm the effect of supplementary cementitious materials (FA and GGBFS) on the microstructure of HPC after exposure to high temperatures, the microstructure of NSC, HSC, FAC, and BFSC were studied by using a scanning electron microscope (SEM). Figs. 10 and 11 present the SEM images of the tested specimen at room temperature and after exposure to the high temperature of 600 °C, respectively. The SEM images confirmed that, at room temperature, the microstructures of FAC and BFSC were much tighter than those of NSC and HSC, where FAC and BFSC contained a more condensed amount of C–S–H gel compared to concrete NSC and HSC as shown in Figs. 10(a–d). This is due to the pozzolanic reaction of FA and GGBFS and creates additional C-S-H gel, which fills concrete voids. After 600 °C, the micrograph of specimen after being exposed to 600 °C shows microcracks and presence of dehydration products as shown in Figs. 11(a–d), where the decomposition of C-S-H significantly starts at 450 °C and progresses with rising temperature. Remarkable fractures are seen on the paste near aggregates and at the interfacial transition zone (ITZ) between the aggregates and the paste. Consequently, a low residual compressive strength was recorded for these concretes.

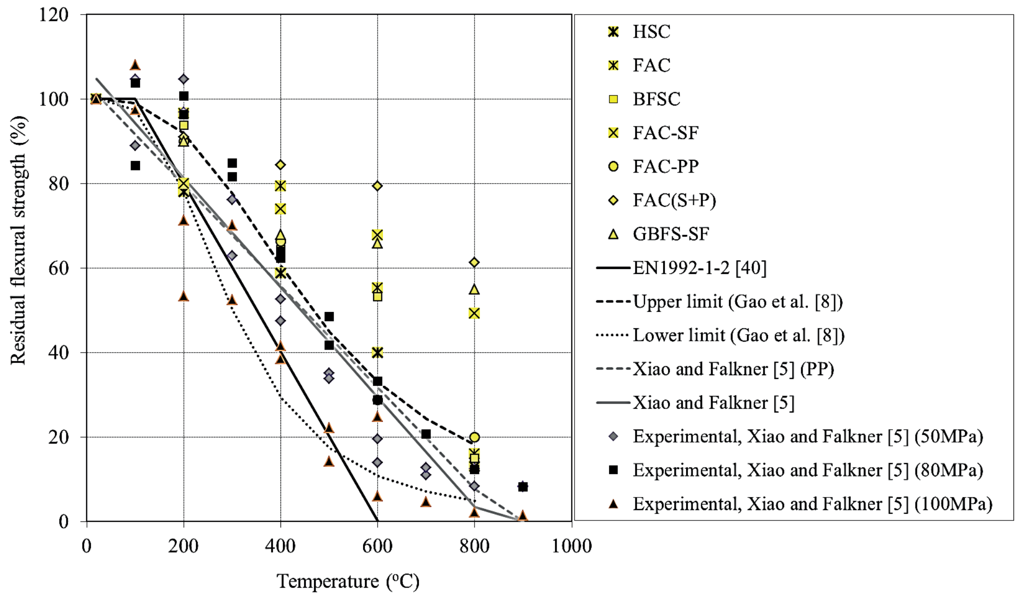


Fig. 8 Comparison between the residual flexural strength values and previous data from literatures

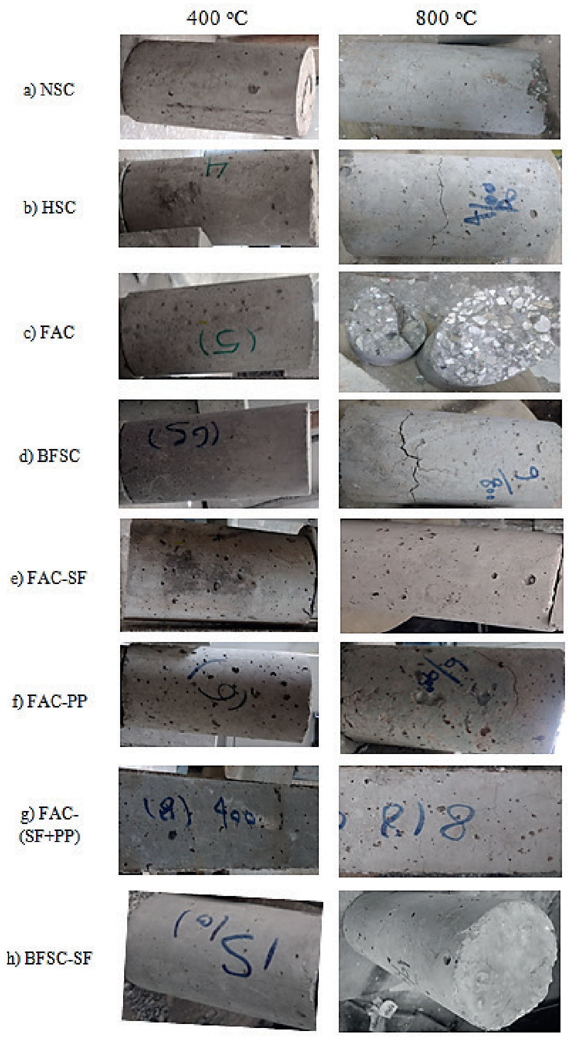


Fig. 9 Appearance of the investigated specimens after exposure to temperature of 400 °C and 800 °C; a) NSC, b) HSC, c) FAC, d) BFSC, e) FAC-SF, f) FAC-PP, g) FAC-(SF+PP), h) BFSC-SF

6 Conclusions

This investigation aims to study the effect of using fly ash and ground granulated blast furnace slag in addition to fibers type on the residual mechanical properties of HPC after exposure to different temperatures. It was found that:

- Replacement of cement by 30% fly ash or ground granulated blast furnace slag can enhance the residual mechanical properties of high performance concrete at high temperatures as compared to high strength concrete. Where BFSC gives the highest residual compressive, tensile and flexural strengths and retains about 53%, 35%, and 15% of its initial compressive, tensile and flexural strengths, respectively, after exposure to 800 °C.
- Adding steel fibers can significantly enhance the mechanical properties of high performance concrete after exposure to high temperatures. Where concrete containing 30% ground granulated blast furnace slag and 0.5% steel fibers gives the highest residual compressive and tensile strengths with retained residual strength values 35% and 63.7%, respectively, after being exposed to temperature of 800 °C, FAC-(SF+PP) recorded the highest flexural strength and retained about 61% of its initial flexural strength after exposure to 800 °C.
- Polypropylene fibers had an adverse effect on the residual mechanical properties of HPC, where FAC-PP showed more deterioration in residual compressive, tensile, and flexural strengths, especially after 400 °C.
- Compared with normal strength concrete, the

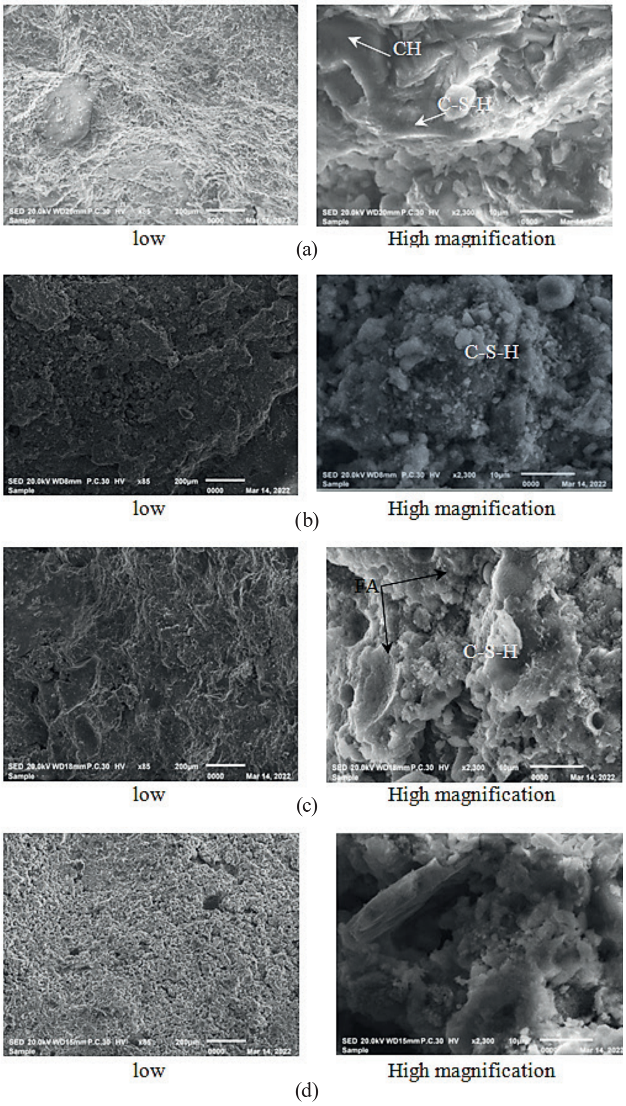


Fig. 10 SEM images of different concrete mixtures at room temperature, a) Normal strength concrete, b) High strength concrete, c) Fly ash concrete, d) Blast furnace slag concrete

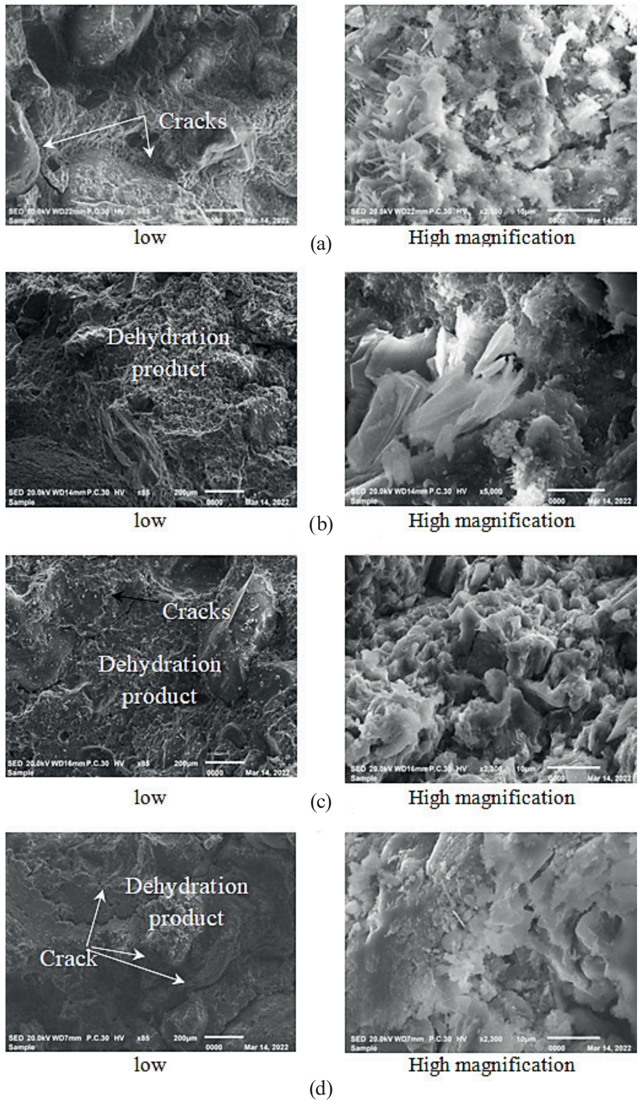


Fig. 11 SEM images of different concrete mixtures after being exposed to temperature of 600 °C; a) Normal strength concrete, b) High strength concrete, c) Fly ash concrete, d) Blast furnace slag concrete

mechanical properties of high-strength concrete decreased significantly, especially in terms of residual tensile and flexural strength. Where the retained compressive, tensile, and flexural strengths for HSC after exposure to 800 °C were 35%, 16.2%, and 20%, respectively, the retained compressive, tensile, and flexural strengths for NSC were 30%, 31.8%, and 30%, respectively.

- The residual compressive strengths of high-strength concrete and concrete containing 30% fly ash combined with 0.5% polypropylene fibers correlate well with the EN 1992-1-2 [40] residual compressive strength limits for calcareous aggregates.
- EN 1992-1-2 [40] standard ignored the residual tensile strength after exposure to 600 °C, while the residual tensile strength after exposure to 800 °C in this study varied from 16% to 63%.
- Tested specimens in this study have higher flexural strength as compared to previous studies, especially at 600 °C and 800 °C. This may be due to differences in the constitutive materials of concrete and test conditions.

References

[1] Algourdin, N., Pliya, P., Beaucour, A.-L., Simon, A., Noumowé, A. "Influence of polypropylene and steel fibres on thermal spalling and physical-mechanical properties of concrete under different heating rates", Construction and Building Materials, 259, Article number: 119690, 2020.
https://doi.org/10.1016/j.conbuildmat.2020.119690

[2] Poon, C.-S., Azhar, S., Anson, M., Wong, Y.-L. "Strength and durability recovery of fire damaged concrete after post-fire-curing", Cement and Concrete Research, 31(9), pp. 1307–1318, 2001.
https://doi.org/10.1016/S0008-8846(01)00582-8

[3] Poon, C.-S., Azhar, S., Anson, M., Wong, Y.-L. "Performance of metakaolin concrete at elevated temperatures", Cement and Concrete Composite, 25(1), pp. 83–89, 2003.
https://doi.org/10.1016/S0958-9465(01)00061-0

[4] Poon, C. S., Shui, Z. H., Lam, L. "Compressive behavior of fiber reinforced high-performance concrete subjected to elevated temperatures", Cement and Concrete Research, 34(12), pp. 2215–2222, 2004.
https://doi.org/10.1016/j.cemconres.2004.02.011

[5] Xiao, J., Falkner, H. "On residual strength of high-performance concrete with and without polypropylene fibers at elevated temperatures", Fire Safety Journal, 41(2), pp. 115–121, 2006.
https://doi.org/10.1016/j.firesaf.2005.11.004

[6] Khaliq, W., Kodur, V. "Thermal and mechanical properties of fiber reinforced high performance self-consolidating concrete at elevated temperatures", Cement and Concrete Research, 41(11), pp. 1112–1122, 2011.
https://doi.org/10.1016/j.cemconres.2011.06.012

[7] Gao, D., Yan, D., Li, X. "Splitting strength of GGBFS concrete incorporating with steel fiber and polypropylene fiber after exposure to elevated temperatures", Fire Safety Journal, 54, pp.67–73, 2012.
https://doi.org/10.1016/j.firesaf.2012.07.009

[8] Gao, D., Yan, D., Li, X. "Flexural properties after exposure to elevated temperatures of a ground granulated blast furnace slag concrete incorporating steel fibers and polypropylene fibers", Fire and Materials, 38(5), pp. 576–587, 2014.
https://doi.org/10.1002/fam.2198

[9] Kim, J., Lee, G.-P., Moon, D. Y. "Evaluation of mechanical properties of steel-fibre-reinforced concrete exposed to high temperatures by double-punch test", Construction and Building Materials, 79, pp. 182–191, 2015.
https://doi.org/10.1016/j.conbuildmat.2015.01.042

[10] Novák, J., Kohoutková, A. "Fire response of hybrid fiber reinforced concrete to high temperature", Procedia Engineering, 172, pp. 784–790, 2017.
https://doi.org/10.1016/j.proeng.2017.02.123

[11] Varona, F. B., Baeza, F. J., Bru, D., Ivorra, S. "Influence of high temperature on the mechanical properties of hybrid fibre reinforced normal and high strength concrete", Construction and Building Materials 159, pp. 73–82, 2018.
https://doi.org/10.1016/j.conbuildmat.2017.10.129

[12] Eidan, J., Rasoolan, I., Rezaeian, A., Poorveis, D. "Residual mechanical properties of polypropylene fiber-reinforced concrete after heating", Construction and Building Materials, 198, pp. 195–206, 2019.
https://doi.org/10.1016/j.conbuildmat.2018.11.209

[13] Akca, A. H., Özyurt, N. "Post-fire mechanical behavior and recovery of structural reinforced concrete beams", Construction and Building Materials, 253, Article number: 119188, 2020.
https://doi.org/10.1016/j.conbuildmat.2020.119188

[14] Wang, H. Y. "The effects of elevated temperature on cement paste containing GGBFS", Cement and Concrete Composites, 30(10), pp. 992–999, 2008.
https://doi.org/10.1016/j.cemconcomp.2007.12.003

[15] Khan, M. S., Abbas, H. "Effect of elevated temperature on the behavior of high volume fly ash concrete", KSCE Journal of Civil Engineering, 19, pp. 1825–1831, 2014.
https://doi.org/10.1007/s12205-014-1092-z

[16] Kou, S. C., Poon, C. S., Etxeberria, M. "Residue strength, water absorption and pore size distributions of recycled aggregate concrete after exposure to elevated temperatures", Cement and Concrete Composites, 53, pp. 73–82, 2014.
https://doi.org/10.1016/j.cemconcomp.2014.06.001

[17] Heikal, M., El-Didamony, H., Sokkary, T. M., Ahmed, I. A. "Behavior of composite cement pastes containing microsilica and fly ash at elevated temperature", Construction and Building Materials, 38, pp. 1180–1190, 2013.
https://doi.org/10.1016/j.conbuildmat.2012.09.069

[18] Afzal, M. T., Khushnood, R. A. "Influence of carbon nano fibers (CNF) on the performance of high strength concrete exposed to elevated temperatures", Construction and Building Materials, 268, Article number: 121108, 2021.
https://doi.org/10.1016/j.conbuildmat.2020.121108

[19] Haido, J. H., Tayeh, B. A., Majeed, S. S., Karpuzcu, M. "Effect of high temperature on the mechanical properties of basalt fibre self-compacting concrete as an overlay material", Construction and Building Materials, 268, Article number: 121725, 2021.
https://doi.org/10.1016/j.conbuildmat.2020.121725

[20] Yermak, N., Pliya, P., Beaucour, A.-L., Simon, A., 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, 132, pp. 240–250, 2017.
https://doi.org/10.1016/j.conbuildmat.2016.11.120

[21] Shariq, M., Khan, A. A., Masood, A., Arif, M., Baqi, A. "Experimental and Analytical Study of Flexural Response of RC Beams with Steel Fibers after Elevated Temperature", Iranian Journal of Science and Technology, Transactions of Civil Engineering, 45, pp. 611–628, 2021.
https://doi.org/10.1007/s40996-020-00408-7

[22] Monte, F. L., Felicetti, R., Rossino, C. "Fire spalling sensitivity of high-performance concrete in heated slabs under biaxial compressive loading", Materials and Structures, 52, Article number: 14, 2019.
https://doi.org/10.1617/s11527-019-1318-0

[23] Pliya, P., Beaucour, A.-L., Noumowé, A. "Contribution of cocktail of polypropylene and steel fibres in improving the behaviour of high strength concrete subjected to high temperature", Construction and Building Materials, 25(4), pp. 1926–1934, 2011. https://doi.org/10.1016/j.conbuildmat.2010.11.064

[24] Müller, P., Novák, J., Holan, J. "Destructive and non-destructive experimental investigation of polypropylene fibre reinforced concrete subjected to high temperature", Journal of Building Engineering, 26, Article number: 100906, 2019. https://doi.org/10.1016/j.jobe.2019.100906

[25] Noman, M., Yaqub, M., Abid M., Musarat, M. A., Vatin, N. I., Usman, M. "Effects of low-cost repair techniques on restoration of mechanical properties of fire-damaged concrete", Frontiers in Materials, 8, Article number: 801464, 2022. https://doi.org/10.3389/fmats.2021.801464

[26] ASTM "Concrete and Aggregates", In: Annual Book of ASTM Standards, Section 4, vol. 04.02, American Society for Testing Materials, West Conshohocken, PA, USA, 2005.

[27] CEN "EN 197-1 Cement - Part 1: Composition, specifications and conformity criteria for common cements", European Committee for Standardization, Brussels, Belgium, 2000.

[28] ASTM "C494/C494M Standard Specification for Chemical Admixtures for Concrete", ASTM International, West Conshohocken, PA, USA, 2019. https://doi.org/10.1520/C0494_C0494M-19

[29] ASTM "C192/C192M-05 Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory", ASTM International, West Conshohocken, PA, USA, 2019. https://doi.org/10.1520/C0192_C0192M-19

[30] ISO "ISO-834 Fire-resistance tests - Elements of building construction", International Organization for Standardization, Geneva, Switzerland, 1975.

[31] ASTM "E119-08a Standard Test Methods for Fire Tests of Building Construction and Materials", ASTM International, West Conshohocken, PA, USA, 2008. https://doi.org/10.1520/E0119-08A

[32] BS "EN 12390-3 Testing hardened concrete – Part 3: Compressive strength of test specimens", British Standards Institution, London, UK, 2019.

[33] BS "EN 12390-6 Testing hardened concrete – Part 6: Tensile splitting strength of test specimens", British Standards Institution, London, UK, 2009.

[34] BS "EN 12390-5 Testing hardened concrete – Part 5: Flexural strength of test specimens", British Standards Institution, London, UK, 2019.

[35] Iqbal, H. W., Khushnood, R. A., Baloch, W. L., Nawaz, A., Tufail, R. F. "Influence of graphite nano/micro platelets on the residual performance of high strength concrete exposed to elevated temperature", Construction and Building Materials, 253, Article number: 119029, 2020. https://doi.org/10.1016/j.conbuildmat.2020.119029

[36] Zhao, H., Liu, F., Yang, H. "Residual compressive response of concrete produced with both coarse and fine recycled concrete aggregates after thermal exposure", Construction and Building Materials, 244, Article number: 118397, 2020. https://doi.org/10.1016/j.conbuildmat.2020.118397

[37] Abdelmelek, N., Lublóy, É. "Effects of Elevated Temperatures on the Properties of High Strength Cement Paste Containing Silica Fume", Periodica Polytechnica Civil Engineering, 66(1), pp. 127–137, 2022. https://doi.org/10.3311/PPci.17549

[38] Babalola, O. E., Awoyera, P. O., Le, D.-H., Bendezú Romero, L. M. "A review of residual strength properties of normal and high strength concrete exposed to elevated temperatures: Impact of materials modification on behaviour of concrete composite", Construction and Building Materials, 296, Article number: 123448, 2021. https://doi.org/10.1016/j.conbuildmat.2021.123448

[39] Li, Y., Pimienta, P., Pinoteau, N., Tan, K. H. "Effect of aggregate size and inclusion of polypropylene and steel fibers on explosive spalling and pore pressure in ultra-high-performance concrete (UHPC) at elevated temperature", Cement and Concrete Composites, 99, pp. 62–71, 2019. https://doi.org/10.1016/j.cemconcomp.2019.02.016

[40] CEN "EN 1992-1-2:2004, Eurocode 2 - Design of concrete structures - Part 1-2: General rules - Structural fire design", European Committee for Standardization, Brussels, Belgium, 2004.