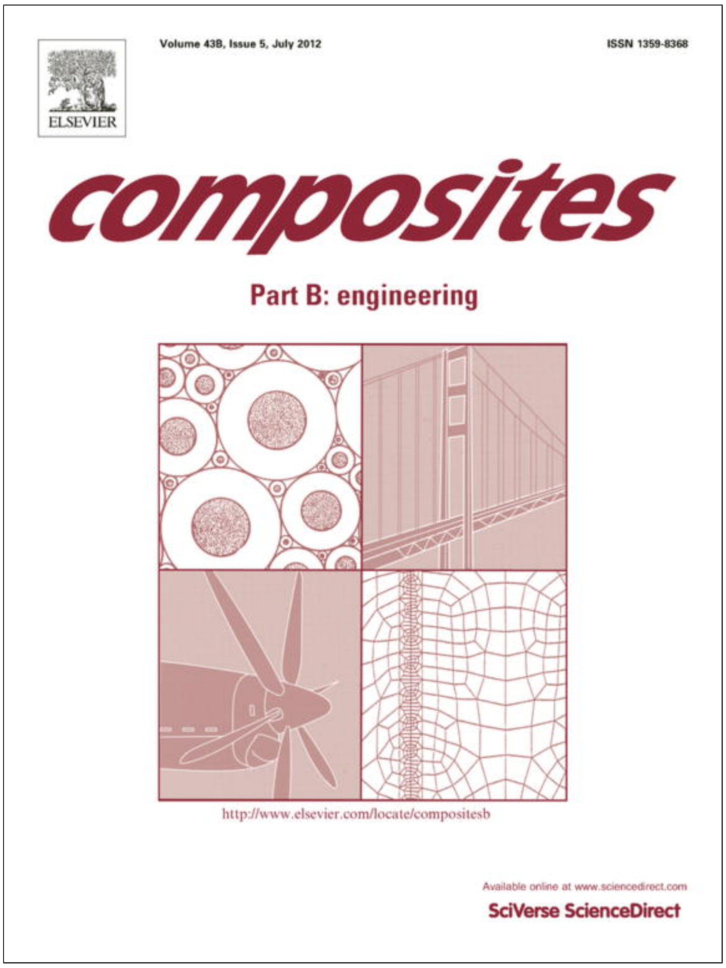
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A study on the effects of high temperature on mechanical properties of fiber reinforced cementitious composites

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ABSTRACT

The flexural strength and ductility properties of cementitious composites (mortar) under high temperature may be significantly improved by incorporating different types of fibers. In this study, four different types of fibers are added to cement mortars with the aim to investigate their mechanical contributions to mortars under high temperature, comparatively. Polypropylene (PP), carbon (CF), glass (GF) and polyvinyl alcohol (PVA) fibers are chosen for research. These fibers are added into mortars in five different ratios (0.0%, 0.5%, 1.0%, 1.50% and 2.0%) by volume. The mortars are subjected to the following temperatures: 21 °C (normal conditions), 100 °C (oven dry), 450 °C and 650 °C. The mechanical properties investigated are flexural strength, deflection and compressive strength of the cement mortars. In addition, thin sections of mortars are investigated to obtain changes in mortar because of high temperature. It is concluded that all fiber types contribute to the flexural strengths of mortars under high temperature. However, this contribution decreases with an increase in temperature. The samples with PVA show the best flexural performance (75–150%) under high temperature. CF which does not melt under high temperature also gives high flexural strength (11–85%). The compressive strengths of the mortars reduce under high temperature or with fiber addition. The highest increase in flexural strength and the lowest decrease in compressive strength is at 0.5–1.5% for CF if all temperature conditions are taken into consideration. The optimum fiber addition ratios of the samples containing PP and GF are 0.5% by volume. And for PVA, it is between 0.5% and 1.5% by volume.

1. Introduction

Exposure to fire or any extreme heat source can have adverse effects on concrete's mechanical properties; for plain concrete or cement mortars, changes can occur in the pore structures, resulting in cracking and spalling, the destruction of the bond between cement paste and aggregates and the deterioration of the hardened cement paste [13]. This phenomenon is called thermal incompatibility of concrete components and could be the result of two mechanisms: the vapor pressure build-up mechanism [2,15] or the restrained thermal dilatation mechanism [5,32]. High strength concrete is believed to be more susceptible to the pressure build up because of its low permeability, compared to that of normal strength concrete [9,23,27]. The dense microstructure of high strength concrete reduces the migration of liquid and vapor water. As a result of thermal incompatibility, thermal stresses are induced between the expanding aggregate and the shrinking cement paste. The induced stress results in the breakdown of the interfacial bond between the aggregate and the surrounding cement paste, which further results in strength loss of concrete specimens [8,34]. The mechanical properties of concrete depend largely on the hydration products (calcium silicate hydrate gel, calcium hydroxide, and ettringite) formed during the hydration reaction between the cementitious constituents and water. When concrete is exposed to a fire attack, free water in the concrete matrix will first be removed through a physical process such as evaporation at a lower elevated temperature. As the temperature further increases, disintegration of hydrates and loss of chemically bonded water will take place. The decomposition of calcium hydroxide occurs at about 350 °C, and partial volatilization of calcium silicate hydrate gel commences at about 500 °C. The pore size and porosity of the hydrate matrix will increase, and the mechanical properties (strength and elastic modulus) of the hydrates will be weakened. Moreover, at 573 °C, the crystal structure of quartz in a siliceous aggregate transforms from a low temperature phase to a high temperature phase. Such transformation is accompanied by an approximate one percent volume increase, which accelerates the disintegration process of the hydrates. All these changes make the mechanical properties of a heated concrete (in a macro-scale) temperature-dependent.

On the other hand, cementitious composites are typically characterized as brittle, with a low tensile strength and strain capacity.

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Fibers are incorporated into cementitious matrices to overcome this weakness, producing materials with increased tensile strength, ductility and toughness and improved durability. The efficacy of the fiber reinforcement is dependent upon many factors, including the properties of the matrix as well as the fiber geometry, size, type, volume and dispersion [4,17,19]. Steel, glass, carbon and polymer based fibers are commonly employed in many fiber reinforced composite applications [10]. Glass fiber (GF) is the most commonly used [3]. Polypropylene (PP) fiber is a cheap and popular material used in the concrete industry, and many researchers have studied the mechanical properties of PP reinforced concrete [29]. Polyvinyl alcohol (PVA) based fibers perform extremely different in cement based matrix due to their surface formation and high strength [11,18]. In relation to most functional properties, carbon fibers are exceptional compared to other fiber types [7,12,35].

Several studies [16,21,22,33,36] show that concrete thermal stability is improved by incorporating polypropylene fibers to the mix. Since the fibers melt at approximately 160–170 °C, they produce expansion channels. The additional porosity and small channels created by melting polypropylene fibers may lower internal vapor pressure in the concrete and reduce the likelihood of spalling. The additional porosity due to the melting of polypropylene fibers can lead to a decrease of the residual mechanical performances of concretes. Results in literature on this subject are contradictory. Several studies carried out by different authors [28,14] show a decrease of residual strength in agreement with the additional porosity, while others [33,6] show an improvement in the residual strength. The difference between the results can be related to the experimental conditions, the cure condition of the specimen (dry or saturated state) and the heating rate.

CF and GF are incombustible materials, so their behaviors differ from PP and PVA fibers. These fibers are added to the mixture of concrete in order to reduce crack propagation and to increase concrete ductility. Because of their incombustible properties, CF and GF fibers improve the residual mechanical properties of heated concretes [1,20,24,31]. Although there is a wide gap in the current research on other fibers like carbon, PVA and glass fiber reinforced concrete at elevated temperatures, little or no research has been conducted regarding them under high temperatures [20,24–26,30,31].

The main objective of this study is to investigate the effects of the different types of fibers on mechanical properties of cement mortars under high temperature. For this purpose, 17 different types of cement mortars are produced with four types of fibers and five addition ratios. These mortars are subjected to four different high temperatures. Polypropylene (PP), carbon (CF), glass (GF) and polyvinyl alcohol (PVA) fibers are chosen for the fibers and these are added to mortars in five different ratio 0.0%, 0.5%, 1.0%, 1.50% and 2.0%) by volume. The mortars are exposed to different temperatures: 21 °C (normal condition), 100 °C (oven dry), 450 °C and 650 °C. The mechanical properties investigated are flexural strength, deflection and compressive strength of the cement mortars. In addition to this, thin section images of fibers in mortars are examined.

Cement mortar is used instead of concrete. Since cement mortars are more homogeneous than concrete, determining the differences between the fibers will be easier. In other words, the effects of fibers on mortar under high temperatures are more visible.

The essential factors separating this study from others are:

1. In other studies, two fibers are compared to each other under high temperatures. However, in this study four different types of fibers are compared to each other in the same mix types.
2. Less common PVA and CF fibers are used in this study.

Fig. 1. The fibers used in the experiments.

2. Materials and methods

2.1. Materials

Four different types of fibers are used in the experimental process. These are PP, CF, GF and PVA fibers (Fig. 1). Some properties of these fibers are presented in Table 1. The weakest property of GF is its low alkali resistance; however, the GF used in this study is alkali resistant.

As seen from Table 1, the specific mass of the fibers vary between 0.91 and 2.68 g/cm^3, fiber diameters are between 18 and 660 μm, elongations are between 1.8% and 10%, tensile strengths are between 300 and 4200 MPa and Young modulus are between 4000 and 240,000 MPa. The most brittle material is carbon fiber and the most ductile is polypropylene fiber.

In the experiments, CEM I 42.5 R type cement is used. The compositions, and physical and mechanical properties of the cement are given in Table 2. The experiments are conducted according to EN 196, so CEN-standard sand is used as aggregate in mortars.

2.2. Methods

In accordance with the objective of the study, 17 different fiber reinforced cement mortars are prepared with four different fiber types and five different proportions (Table 3). These mortars are subjected to five different temperatures.

The flexural and compression tests were conducted according to the principles suggested in EN 196. The "test mortar" consists of 450 g of the cement mixture, 1350 g of graded standard sand, and 225 g of water, and consequently the water/cement ratio is 0.50. While the fiber reinforced mortar is being produced, following the addition of water to the cement-sand mixture, the selected fiber is added to the fresh mortar and the mortar is mixed as long as needed to obtain a homogeneous mixture. PP and GF decreased the consistency of the mortar through absorption of water. However, additional water is not added to the mixture to obtain even consistency. After the molding process, the molds (with the mortars in them) were placed in the moist room at 21 ± 1 °C for 24 h and removed at the end of this period, and the mortar prismatic specimens were stored in tap water for 30 days. According to the objective of the study, four different temperatures should be applied to the samples. The first is normal conditions temperature (21 °C). After 30 days, the samples are taken from water and wiped out. Thus, the sample becomes a saturated surface dry (21 °C) sample. The second temperature is oven dry (100 °C). For these (100 °C) samples, the samples, which are taken from the cure medium 24 h prior to the testing day, are put in the oven for 24 h dry. The last two conditions are 450 °C and 650 °C. After 30 days, the samples are taken from water and put into a furnace for an hour, while the furnace's temperature is raised to 450 °C or 650 °C. In the furnace, all the specimens are heated at an increasing rate of 6 °C/min and the peak temperature for 450 °C is maintained for 70 min, and for 650 °C it is maintained for 100 min. However, when the furnace is heated to about 400 °C, the samples explode with a high sound. This is due to the explosive spalling of mortars. To overcome this problem, the samples are first taken from the cure medium 24 h before testing day and they are put in the oven for 24 h to dry. Thus, the water is removed from the matrix and pressure build up is overcome. After this process, these oven dry samples are subjected to high temperatures (450 °C and 650 °C). When kilning the mortars, it is observed that dense and black smoke is given off from the chimney of the kiln at 350–400 °C, probably from the decomposition of calcium hydroxide.

After the kiln processes are completed, flexural and compressive tests are done. Six specimens were tested for each type of mixture at each testing age according to the Rilem–Cembureau method in EN 196. While the flexural strength is being determining, deflections are measured. The deflection used in comparisons is the maximum deformation of the midpoint of beams at the moment of breaking.

In addition, internal changes of fibrous mortars caused by high temperature are investigated via petrographic observations (Fig. 2).

Table 2
Chemical, physical and mechanical properties of the CEM I 42.5 R type cement.

Chemical analysis (%)		Blaine surface (cm^2/g)	4050
SiO_2	21.21	Initial setting time (min)	140
Al_2O_3	3.23	Final setting time (min)	195
Fe_2O_3	1.37	Specific gravity (g/cm^3)	3.08
CaO	60.44	Le Chatelier expansion (mm)	2
MgO	3.51	*Strength (MPa)*	
SO_3	2.90	1st Day	17.8
LOI	3.34	2nd Day	28.8
Total	96.00	28th Day	60.5

3. Results and discussions

The mortars containing different types and different proportions of fibers, and subjected to different high temperatures, are investigated in terms of evolution of mass properties, flexural strengths, deflections and compressive strengths.

3.1. Petrographic Investigations of the mortars under high temperature

The petrographic alterations of the mortars under high temperatures are seen via the thin section images in Fig. 2. Because the structures of mortar are similar under both 21 °C and 100 °C conditions, only 21 °C conditions are shown in Fig. 2 as normal conditions. The scales are the same for all samples and it is easy to see differences between the fibers' sizes or diameters. That all the fibers accomplished exact bond with the cement mortar is seen in Fig. 2a, d, g and j.

At 450 °C (Fig. 2b, e, h and k), some deteriorations and cracks occurred in the cement matrices. To some degree, spallings are observed on the surface of the samples. If the melting points of the fibers are taken into consideration (Table 1), PP and PVA melts under 450 °C. However GF and CF have higher melting points. It is seen from Fig. 2b that PP melted and that canal occurred in the paste. However, in the mortars containing PVA, the fiber traces cannot be distinguished with thin section images. GF does not

Table 1
The properties of the fiber used in the experiments.

Properties	Polypropylene fiber (PP)	Glass Fiber (GF)	Carbon Fiber (CF)	Polyvinyl Alcohol Fiber (PVA)
Specific mass (g/cm^3)	0.91	2.68	1.76	1.3
Fiber length (mm)	12	12	12	12
Fiber diameter (μm)	18	14	6.9	660
Melting point (°C)	160	860	3500	>200
Ignition point (°C)	360	Incombustible	Incombustible	Combustible
Alkali resistance	High	High	High	High
Elongation (%)	8–10	2.4	1.8	7
Tensile strength (N/mm^2)	300–400	1700	4200	900
Young modules (N/mm^2)	4000	72,000	240,000	23,000

Table 3
Mix design of 17 different fiber reinforced mortars.

For each mortar only one addition ratio and one type fiber are used					Standard sand (g)	Cement (CEM-I/42.5R) (g)	Water (g)	W/C
Fiber ratio by volume (%)	Fiber type and content by mass				1350	450	225	0.50
	CF (g)	GF (g)	PP (g)	PVA (g)				
0.0	0.00							
0.5	6.75	10.30	3.50	5.00				
1.0	13.50	20.60	7.00	10.00				
1.5	20.25	30.90	10.50	15.00				
2.0	27.00	41.20	14.00	20.00				

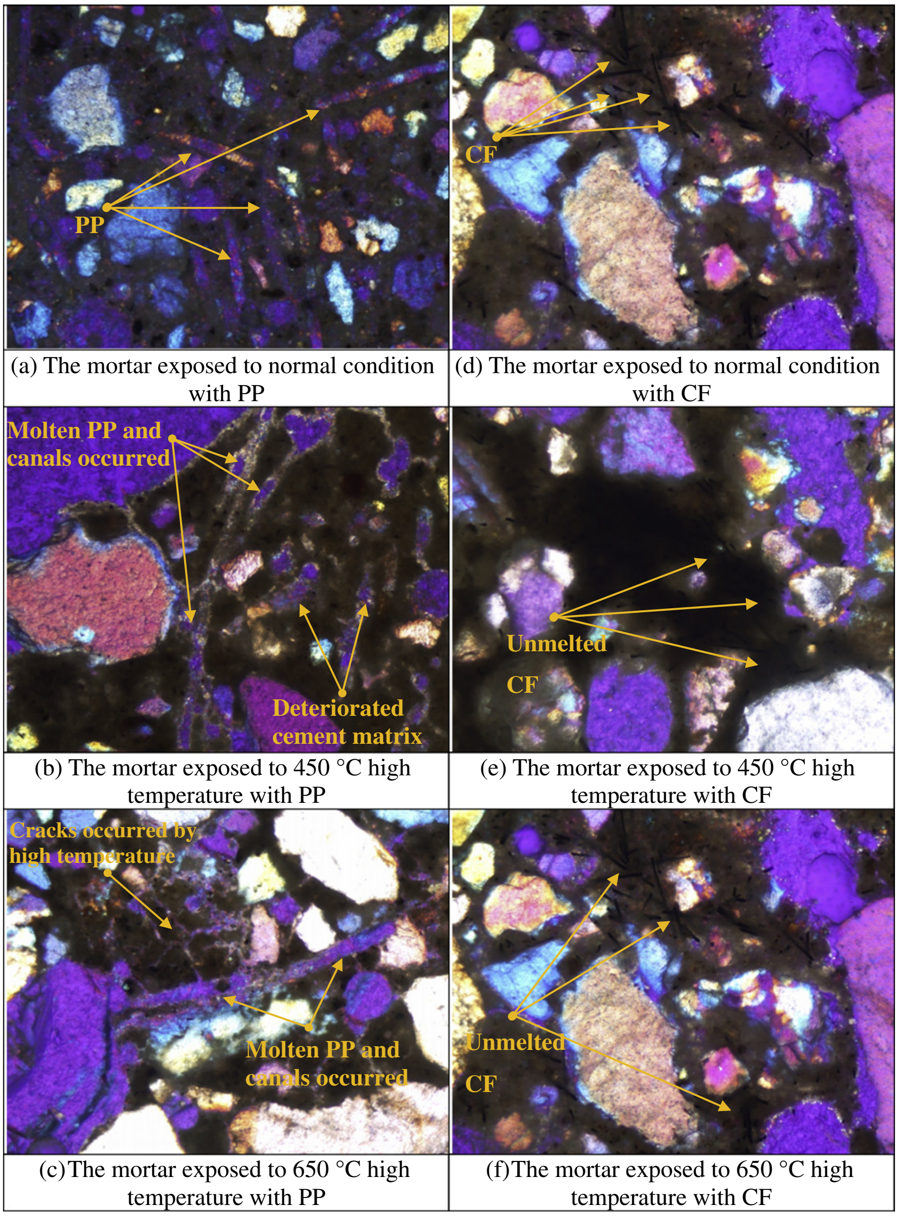


Fig. 2. Thin section images of fibrous mortars subjected to high temperature.

deteriorate at this temperature. However, the weak matrix is cracked. CF do not melt and they are easily observed in the matrix.

For 650 °C temperature conditions, the matrices are weakened, spoiled and cracked. At this temperature, because matrices are weakened, taking thin sections is very difficult. It seen from Fig. 2f that CF does not melt anymore. However, all other fiber types have melted or deteriorated.

3.2. The effects of fiber type and content on unit mass of mortars under high temperature

While the concrete or mortars are subjected to high temperature, some chemical reactions occur. Because chemically bonded water, especially, removes from the body, a decrease is expected in specific masses.

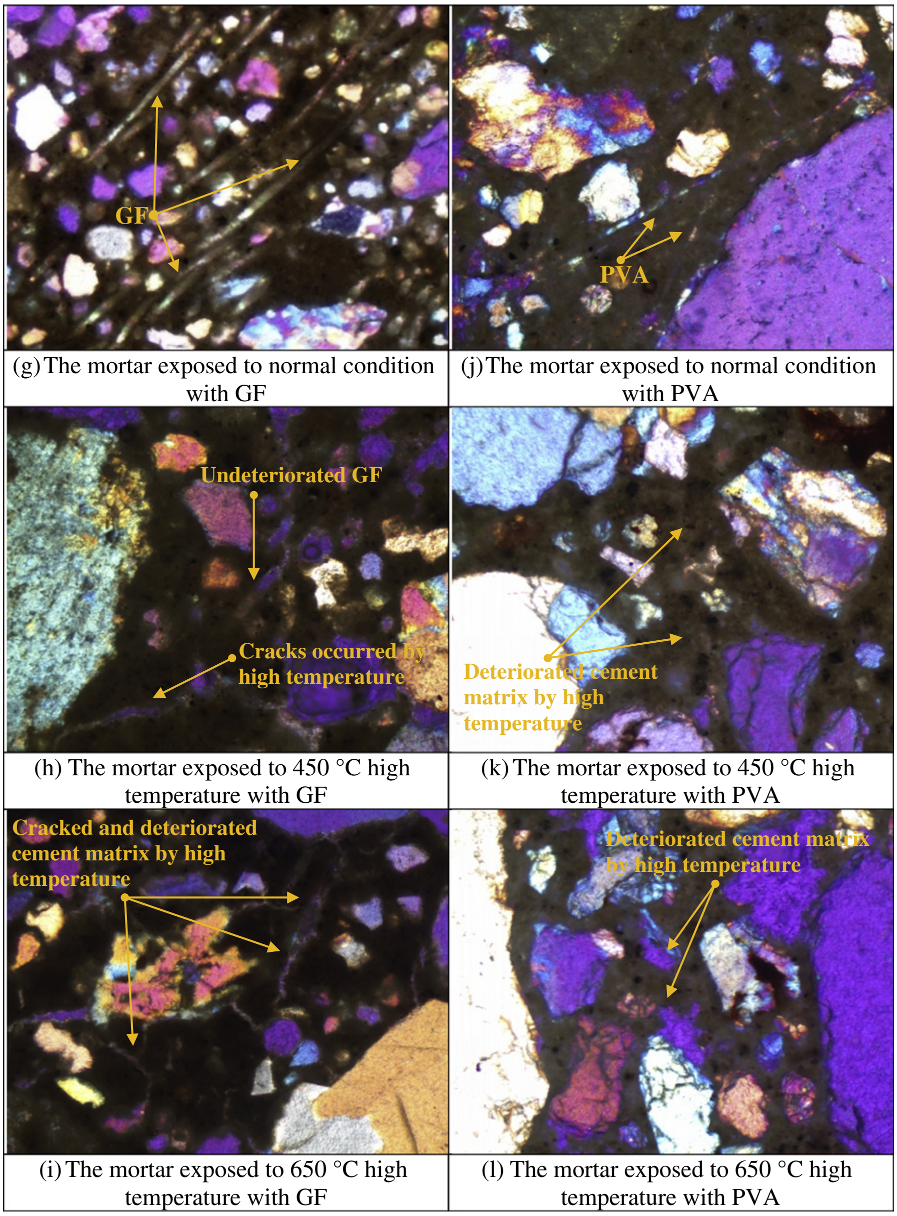


Fig. 2 (*continued*)

For non-fibrous mortars, specific masses are down from 2.1 g/cm^3 to 1.99 g/cm^3 (5%) for both 450 °C and 650 °C.

When PP fiber, with a specific mass (0.91 g/cm^3) that is rather lower than mortar (2.1 g/cm^3), is added to mortar, it is expected that the mortar's unit mass decreases. It is seen from Fig. 3 and Table 4 that the addition of PP fiber decreases the unit mass of mortar by 5–10% for normal conditions. On the other hand, after the mortars are subjected to 450 °C and 650 °C temperatures, the masses are decreased approximately 5% and 6%, respectively, compared with the samples with the same ratio of PP and under the same temperatures. However, at these temperatures, the masses are decreased in total by about 14% and 16%, respectively, compared with un-kilned non-fibrous samples.

PVA has a lower specific mass than mortar as well. It is seen that PVA presents similar results to PP. The unit mass of mortar decreases down to 1.90 g/cm^3 with the addition of 2.0% by volume of PVA. In addition, its specific mass decreases about 4% at 450 °C and 6% at 650 °C. For 450 °C and 650 °C, the masses are totally decreased by about 13% and 14%, respectively, compared with un-kilned non-fibrous samples.

At both normal conditions and high temperatures, the situation is the similar to PP and PVA for CF.

The specific mass of GF is quite high (2.68 g/cm^3). So, when it is added to mortar, it would not necessarily change unit mass. However, the unit mass of mortar decreases dramatically (20%). It is thought that GF adsorbs one part of the mixing water thanks to its hydrophilic structure, so the consistency of mortar decreases and placement does not occur exactly. The mortar, now with many voids, has a lower unit mass. The unit mass of mortar decreases down to 1.69 g/cm^3 with the addition of 2.0% by volume of GF. For high temperature this decrease is more than normal. Its specific mass decreases about 5% at 450 °C and 7–10% at 650 °C. And compared to normal conditioned non-fibrous mortars, they totally decrease up to 23% and 27% under high temperatures.

3.3. The effects of fiber type and content on flexural strength of mortars under high temperature

Because of the decomposition of calcium based binding minerals of the mortars under high temperature, the mechanical properties of the mortars are expected to reduce. However, with fiber addition especially, the flexural strength of the mortars should be increased to some degree.

For non-fibrous mortars, as the temperature increases, the flexural strength decreases dramatically. The flexural strength of non-fibrous mortar decreases about 76% at 450 °C and about 87% at 650 °C. The flexural strength of the mortars with PP decreases on average 73% at 450 °C and about 88% at 650 °C (Fig. 4e). For CF, the decreases are on average 56% at 450 °C and about 84% at 650 °C (Fig. 4f). For GF, the decreases are on average 58% at 450 °C and about 88% at 650 °C (Fig. 4g). And for PVA, the decreases are on average 58% at 450 °C and about 81% at 650 °C (Fig. 4h). This means the flexural strengths of mortars containing each fiber are affected from high temperature by about the same level respectively. However, this does not mean different fibers contribute to the flexural strength of the mortars similarly under high temperature, as is explained below.

At 21 °C, the samples are newly taken from the water, and they are wet. If the effects of the different range of (0.0–2.0%) fiber contents on the flexural strength of mortars is investigated, it is seen that in wet conditions (21 °C), PP, CF and GF fibers present unstable behavior (Table 5 and Fig. 4). However, PVA shows good performance between 0.5% and 1.5% fiber content in wet conditions (21 °C). For these ratios, flexural strength of PVA samples increase from 23% to 43% compared with control samples. Flexural strength of control samples, under 21 °C condition, is 12.13 N/mm^2; the samples consisting of 1.5% PVA have 17.36 N/mm^2 flexural strength.

For the samples under dry (100 °C) condition (Table 5, Fig. 4), fibers show better performance compared with wet (21 °C) condition. A sharp fall in flexural strength is proven for the upper range of 1.0% GF content. Because GF adsorbs part of the mixing water thanks to its hydrophilic structure, the mortar that has not set well has lower flexural strength. Even if flexural strength of the mortar consisting of PP fell at the upper range of 1.0% fiber addition, these also become higher than the control sample that has no fiber. Flexural strengths of the mortars always increase by increasing the CF ratio of mortar. The mortars containing PVA fiber present good performance at all addition ratios. After 1.5% of PVA addition, a slight decrease is observed; however, flexural strength is still more than the control sample. PP at 0.25–0.75%, GF at 0.25–0.50%, CF at 1.0–2.0% and PVA at 0.5–2.0% ranges present better performance, when compared to the control (0.0% fiber) samples. From this it is understood that different types of fibers contribute to flexural strength at different addition ratios. PP and GF show the best increase in flexural strength at 0.5% fiber content as 19% and 13%, respectively. For CF, a 30% increase in flexural strength is obtained at 2% fiber content by volume. PVA presents surprising increases compared to other fiber types. 1.0–1.5% by volume PVA addition increases flexural strength about 79%. Flexural strength of control samples, under dry condition, is 11.05 N/mm^2; the samples consisting of 1.5% PVA have 19.80 N/mm^2 flexural strength; the samples consisting of 0.5% PP have 13.19 N/mm^2 flexural strength; the samples consisting of 0.5% GF have 12.55 N/mm^2 flexural strength; and the samples consisting of 2% CF have 14.44 N/mm^2 flexural strength.

At 450 °C, fibrous mortars show good performance compared with control samples. While CF and PVA present high flexural strength at all addition ratios, PP and GF give high flexural strength

Table 4
Specific mass of fiber reinforced mortars exposed to high temperature.

Fiber ratio by volume (%)	Temperature (°C)	Dry specific mass (g/cm^3)			
		CF	GF	PP	PVA
0.0	100	2.10	2.10	2.10	2.10
	450	1.99	1.99	1.99	1.99
	650	1.99	1.99	1.99	1.99
0.5	100	1.96	2.00	2.00	2.01
	450	1.92	1.91	1.89	1.93
	650	1.85	1.88	1.88	1.93
1.0	100	1.93	1.93	1.93	1.96
	450	1.86	1.84	1.86	1.89
	650	1.83	1.83	1.85	1.82
1.5	100	1.92	1.72	1.91	1.94
	450	1.85	1.64	1.82	1.90
	650	1.80	1.58	1.80	1.79
2.0	100	1.91	1.69	1.89	1.89
	450	1.86	1.61	1.81	1.82
	650	1.79	1.52	1.75	1.80

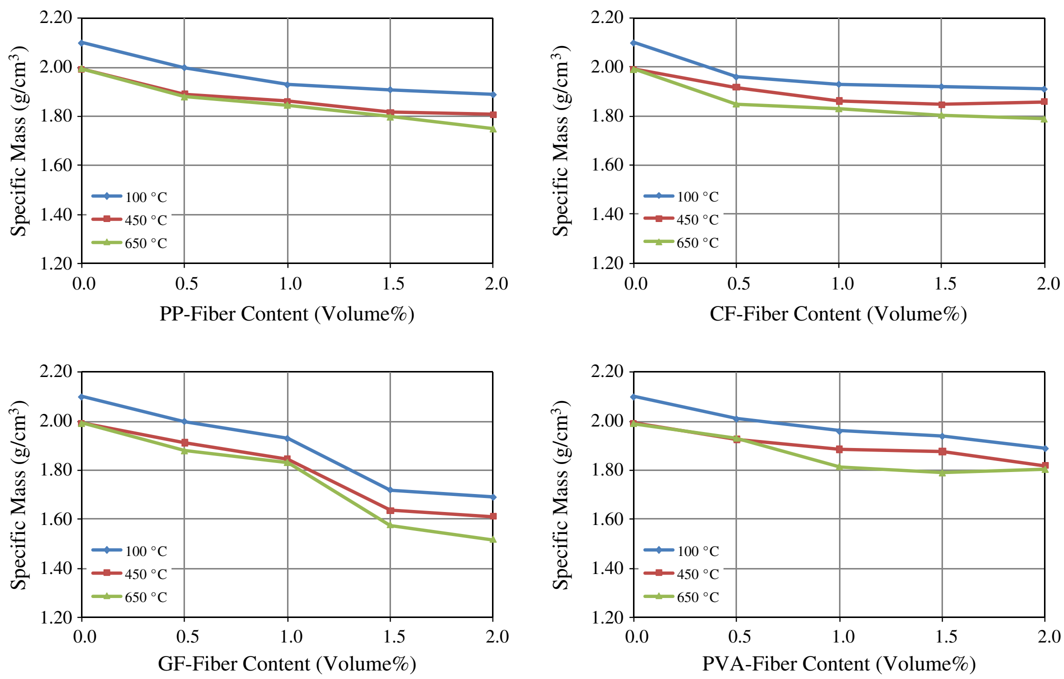
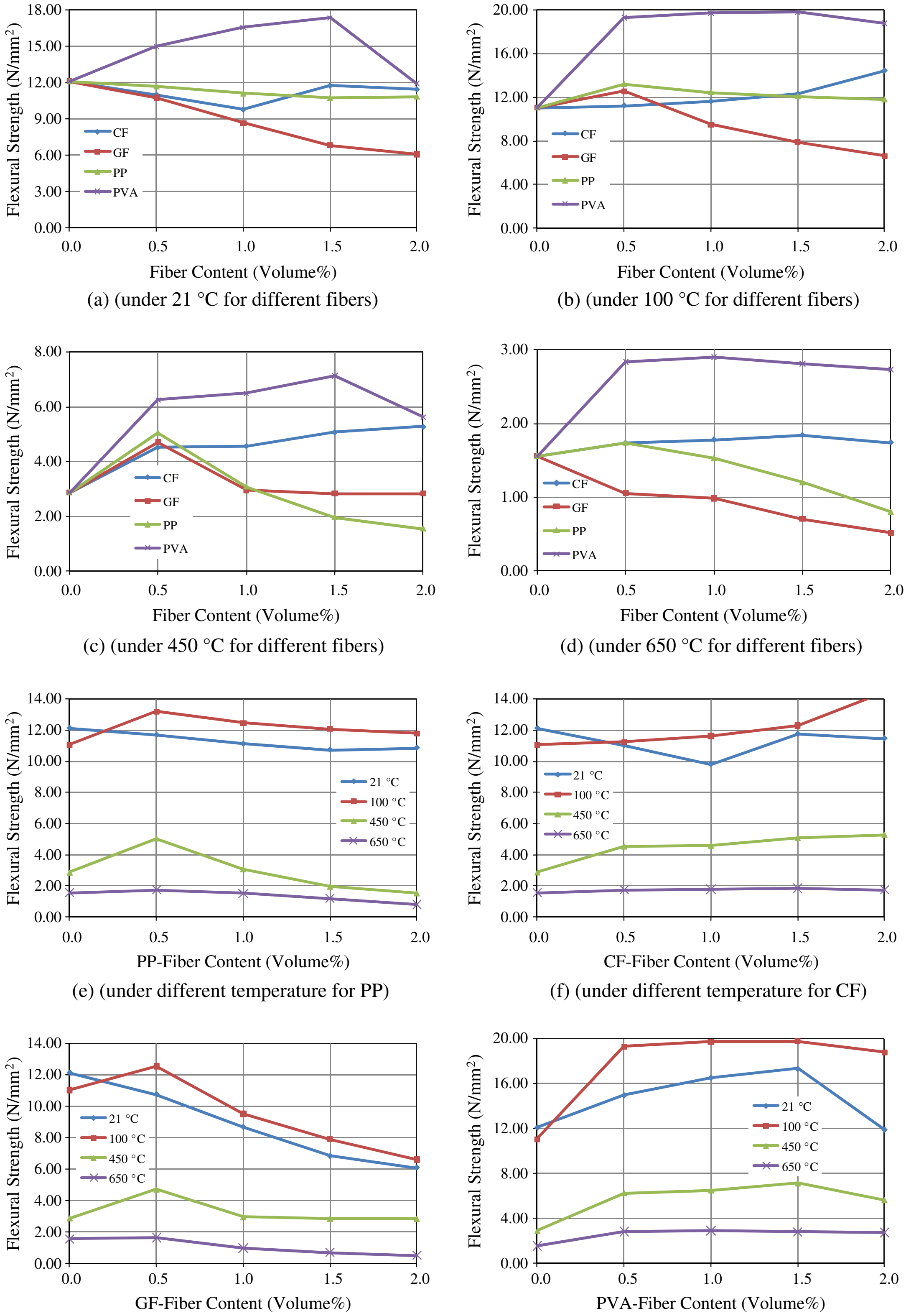


Fig. 3. Relationship between fiber content and specific mass under high temperature.



(a) (under 21 °C for different fibers) (b) (under 100 °C for different fibers)
(c) (under 450 °C for different fibers) (d) (under 650 °C for different fibers)
(e) (under different temperature for PP) (f) (under different temperature for CF)
(g) (under different temperature for GF) (h) (under different temperature for PVA)

Fig. 4. Relationship between fiber content and flexural strength under high temperature.

at 0.5% addition ratio. At this temperature, the mortar with 0.5–1.5% PVA show 120–150% more flexural strength than control samples. 0.5–2.0% CF addition increase flexural strength about 57–83%. This ratio is about 76% for PP and 64% for GF at 0.5% fiber addition ratio.

At 650 °C, the situation is different, especially for GF. Weak mortars with GF do not have higher flexural strength than control samples. The samples with PP have good results only at 0.5% of addition ratio, with about 11%. PVA and CF present good performance at this temperature. 0.5–2.0% PVA addition increases

Table 5
Flexural strength of fiber reinforced mortars exposed to high temperature.

Fiber ratio by volume (%)	Temperature (°C)	Flexural strength (N/mm²)			
		CF	GF	PP	PVA
0.0	21	12.13	12.13	12.13	12.13
	100	11.05	11.05	11.05	11.05
	450	2.87	2.87	2.87	2.87
	650	1.56	1.56	1.56	1.56
0.5	21	11.02	10.76	11.70	15.00
	100	11.23	12.55	13.19	19.31
	450	4.52	4.71	5.05	6.26
	650	1.73	1.65	1.73	2.84
1.0	21	9.81	8.68	11.11	16.56
	100	11.62	9.52	12.46	19.73
	450	4.57	2.96	3.08	6.50
	650	1.78	0.98	1.52	2.90
1.5	21	11.76	6.83	10.73	17.36
	100	12.30	7.92	12.07	19.80
	450	5.07	2.84	1.97	7.14
	650	1.84	0.70	1.20	2.81
2.0	21	11.47	6.10	10.86	11.94
	100	14.44	6.62	11.78	18.80
	450	5.28	2.84	1.55	5.63
	650	1.74	0.52	0.80	2.73

Table 6
Deflection of fiber reinforced mortars exposed to high temperature.

Fiber ratio by volume (%)	Temperature (°C)	Deflection (mm)			
		CF	GF	PP	PVA
0.0	21	0.523	0.523	0.523	0.523
	100	0.406	0.406	0.406	0.406
	450	0.190	0.190	0.190	0.190
	650	0.120	0.120	0.120	0.120
0.5	21	1.191	0.542	1.885	0.773
	100	1.222	0.390	1.310	0.399
	450	1.171	0.345	1.107	0.377
	650	1.150	0.317	0.930	0.320
1.0	21	1.272	0.592	1.903	0.681
	100	1.311	0.380	1.691	0.445
	450	1.221	0.365	0.940	0.315
	650	1.180	0.292	0.900	0.282
1.5	21	1.502	0.641	1.748	0.556
	100	1.402	0.364	1.250	0.500
	450	1.330	0.292	0.670	0.272
	650	1.218	0.261	0.630	0.237
2.0	21	1.381	0.560	1.454	0.460
	100	1.373	0.309	1.042	0.377
	450	0.902	0.220	0.430	0.240
	650	0.830	0.212	0.370	0.200

flexural strength about 75–85%. This ratio is about 11–18% for CF at the same addition ratios.

It is seen from Fig. 2 that all fiber types contribute to the flexural strengths of mortars under high temperature. However, this contribution decreases while temperature increases. Although PVA fiber does not have the best mechanical properties (Table 1) and melts under high temperature, the samples with PVA show the best flexural performance under high temperature. CF that does not melt under high temperature gives high flexural strength too. The references indicate that fibers melting at high temperatures form gaps, these gaps meet the vapor pressure.

3.4. The effects of fiber type and content on deflections of mortars under high temperature

While flexural strengths are being tested, deflections of the beam samples are determined. One important reason for fiber addition to mortar is to increase the ductility of mortars so they do not crack under small tensile stress. Thus, high level of deflection ability is desired. On the other hand, high temperatures make the mortars more brittle.

It is seen from Table 6 and Fig. 5 that as temperature rises, the deflections are decreased for all fibrous mortars. For non-fibrous mortars, as the temperature increases, the deflections decrease dramatically. The deflection of non-fibrous mortar decreases about 63% at 450 °C and about 77% at 650 °C. Deflections of the mortars with PP decreases on average 55% at 450 °C and about 60% at 650 °C (Fig. 5e). For CF, the most brittle fiber, the decreases are on average 12% at 450 °C and about 16% at 650 °C (Fig. 5f). For GF, the decreases are on average 47% at 450 °C and about 53% at 650 °C (Fig. 5g). And for PVA, the decreases are on average 51% at 450 °C and about 58% at 650 °C (Fig. 5h). It is seen that when CF, the least combustible and most brittle of the fibers, is added to mortars, the deflections decrease less at each temperature respectively than other fibers. However, if each fiber's effects are compared with each other, the results are as seen in the discussion below.

For each fiber type and for each temperature condition, fibers increase the deflections, and so, ductility. Each condition, especially for the mortars containing PP and CF, presents high levels of deflection (Table 6 and Fig. 5). The samples with PVA and GF fibers are not influenced significantly by increasing the fiber addition ratio. Surprisingly, the highest deflections are presented by the mortars containing the fibers with the greatest (CF) and the smallest (PP) young modulus (Table 1).

3.5. The effects of fiber type and content on compressive strength of mortars under high temperature

The increase in temperature deteriorates the mortars by changing the cement matrix chemistry. On the other hand, when the fibers are added to mortars, since the fibers have more ductile structure compared to the cement matrix and aggregates, they cause discontinuity in the cement matrix. This is expected to decrease the compressive strength.

If Table 6 and Fig. 5 are investigated, it is seen that as temperature rises, the compressive strengths decrease for all fibrous mortars. For non-fibrous mortars, as the temperature increases, the compressive strengths decrease dramatically, especially at 650 °C. The compressive strength of non-fibrous mortar decreases about 20% at 450 °C and about 53% at 650 °C, respectively. Compressive strengths of the mortars with PP decreases on average 41% at 450 °C and about 66% at 650 °C (Fig. 6e), respectively. For CF, the most brittle fiber, the decreases are on average 3% at 450 °C and about 49% at 650 °C (Fig. 6f), respectively. For GF, the decreases are on average 50% at 450 °C and about 71% at 650 °C (Fig. 6g), respectively. And for PVA, the decreases are on average 8% at 450 °C and about 63% at 650 °C (Fig. 6h), respectively. These decrease ratios are average values. Minimum decreases in compressive strength are obtained at minimum fiber addition ratios for all fiber types. It is seen that CF, which does not melt and has the highest young modulus, shows minimum decreases in compressive strength.

If the mortars with different fiber types are investigated, the compressive strength decreases with addition of all of the fiber types (Table 7 and Fig. 6). For all fiber types, decreases in compressive strength remain at a reasonable level for up to 1.0% fiber addition for each temperature. CF, with the highest young modulus and being the most brittle, shows best performance in the view of compressive strength for all conditions.

3.6. Determining optimum fiber content from relationship between flexural and compressive strength under high temperature

As investigated above, with fiber addition, while flexural strength improves, compressive strengths are influenced negatively for each

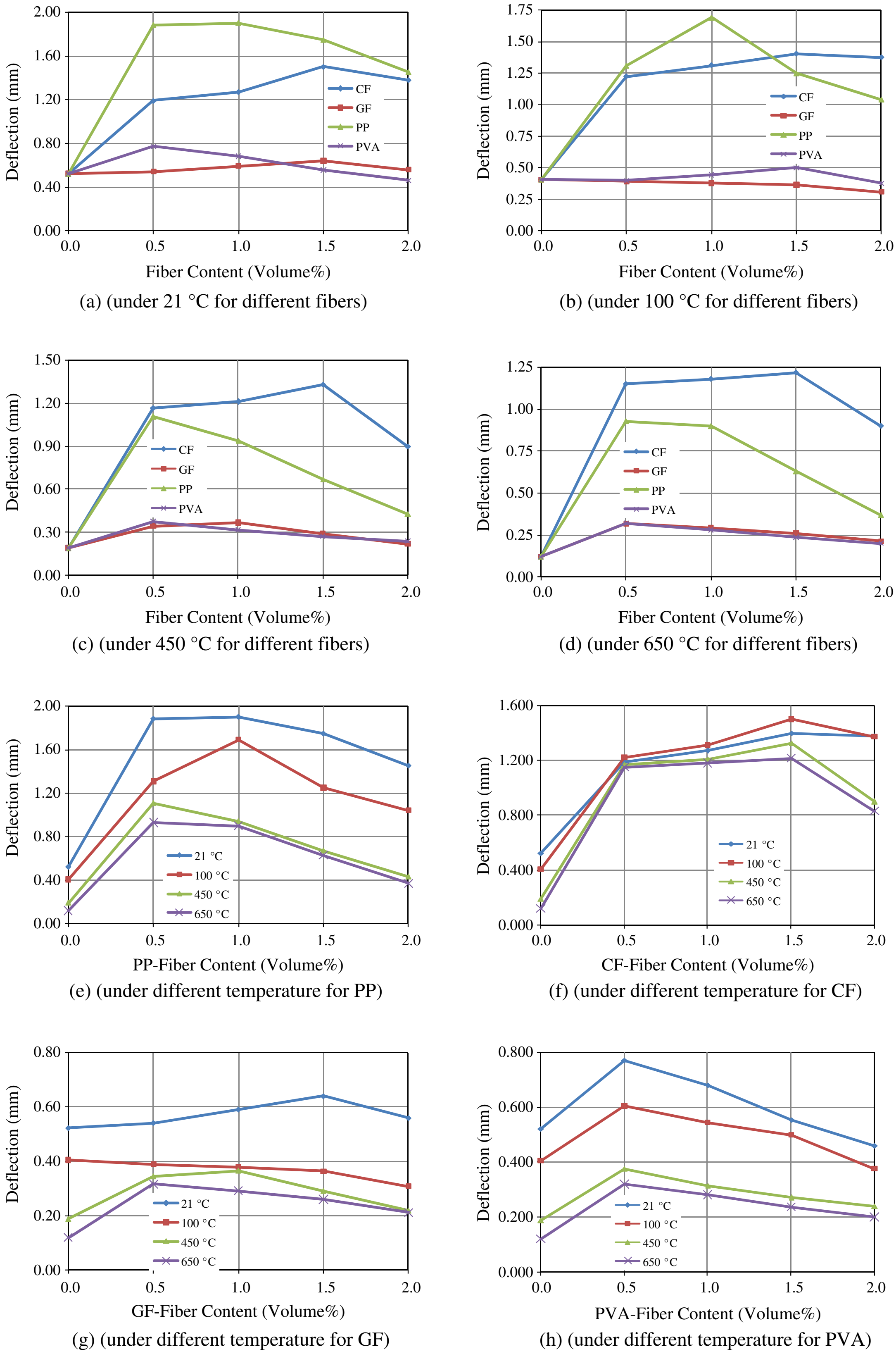


Fig. 5. Relationship between fiber content and deflection under high temperature.

temperature. In this subsection, an attempt is made to determine the optimum fiber ratio that presents better compressive strength and flexural strength for each fiber type separately.

It is understood from the discussion above that each fiber shows the best performance at different addition ratios when flexural and compressive strength are taken into consideration at the same time.

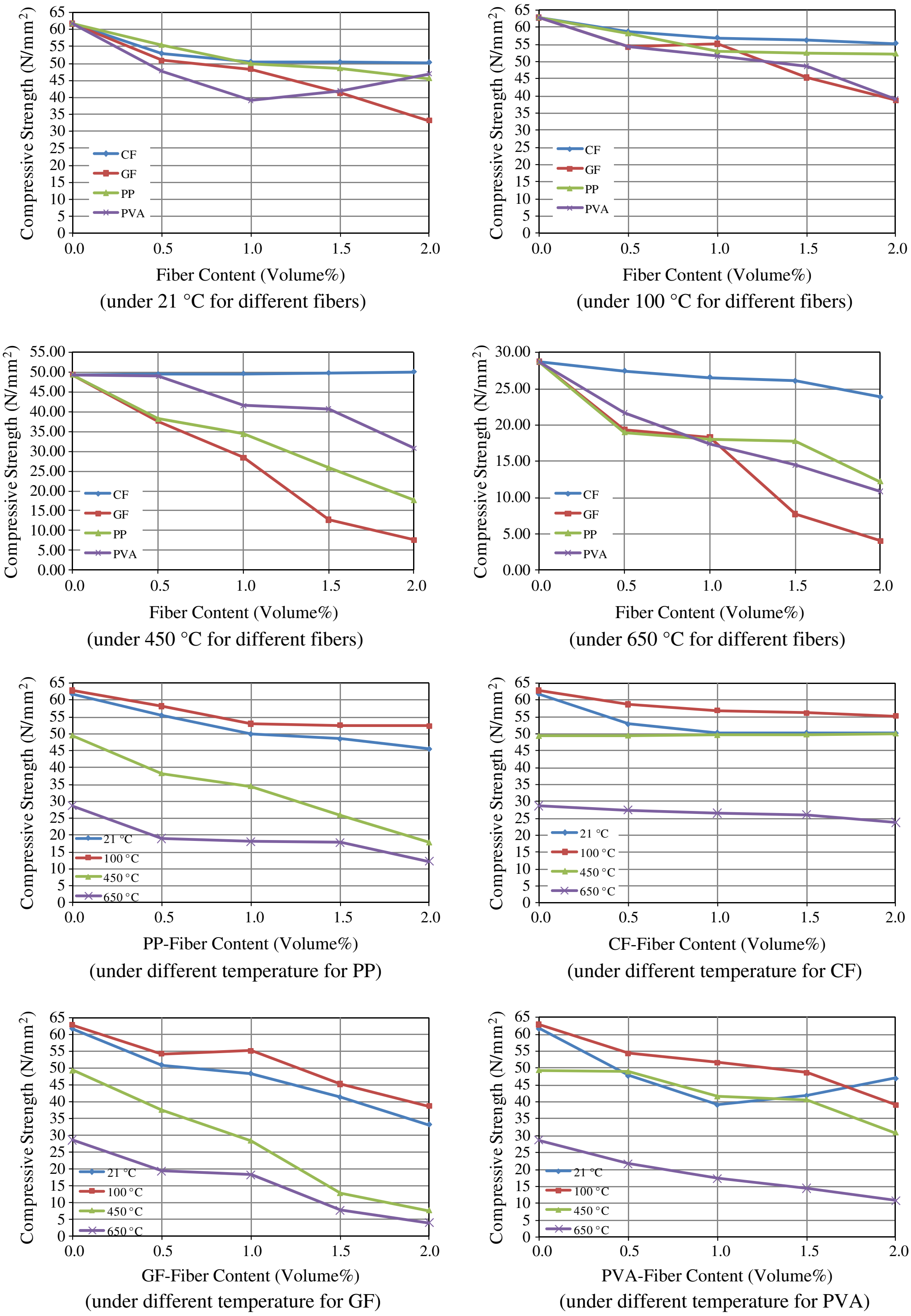


Fig. 6. Relationship between fiber content and compressive strength under high temperature.

It is seen from Fig. 7 that for all addition ratios, flexural strength of CF increases and compressive strength remains at a reasonable level for normal conditions. However, the highest increase in flexural strength and smallest decrease in compressive strength is at 0.5–1.5% if all temperature conditions are taken into consideration. So, it can be said that these addition ratios are the best for CF.

For all temperature conditions, it is shown in Fig. 7 that the optimum fiber addition ratios of the samples containing PP and

Table 7
Compressive strength of fiber reinforced mortars exposed to high temperature.

Fiber ratio by volume (%)	Temperature (°C)	Compressive strength (N/mm^2)			
		CF	GF	PP	PVA
0.0	21	61.73	61.73	61.72	61.73
	100	62.88	62.88	62.88	62.88
	450	49.38	49.38	49.38	49.38
	650	28.70	28.70	28.70	28.70
0.5	21	52.92	50.94	55.4	47.8
	100	58.75	54.35	58.18	54.33
	450	49.50	37.64	38.23	48.98
	650	27.43	19.39	18.96	21.68
1.0	21	50.43	48.38	49.94	39.19
	100	56.98	55.21	52.99	51.66
	450	49.64	28.45	34.42	41.56
	650	26.56	18.34	18.05	17.40
1.5	21	50.4	41.34	48.5	41.9
	100	56.22	45.34	52.5	48.64
	450	49.82	12.75	25.95	40.69
	650	26.05	7.72	17.76	14.47
2.0	21	50.28	33.21	45.55	46.99
	100	55.35	38.74	52.3	39.13
	450	50.14	7.63	17.76	30.84
	650	23.85	4.02	12.21	10.87

GF are 0.5% by volume. The samples containing PVA fibers gives optimal results at between 0.5% and 1.5% by volume.

4. Conclusions

In this study that the effects of high temperature on the mechanical properties of fibrous cement mortars is investigated. The conclusions drawn from this study are:

1. With increase in temperature, several changes occur in the cement matrix. At 450 °C, some deteriorations and cracks occur in cement matrices. At 650 °C, the matrices are weakened, spoiled and cracked. Although other fibers deteriorated at these temperatures, CF does not lose its properties.
2. The flexural strengths of the mortars reduce under high temperature. However, with fiber addition they increase relatively. The flexural strength of non-fibrous mortar decreases about 76% at 450 °C and about 87% at 650 °C. However, these fall for all fibrous mortars on average at about 60% at 450 °C and about 88% at 650 °C, respectively. This means fibers are active especially up to 450 °C.
3. All fiber types contribute to the flexural strengths of mortars under high temperature. However, this contribution decreases as the temperature increases. The samples with PVA show the

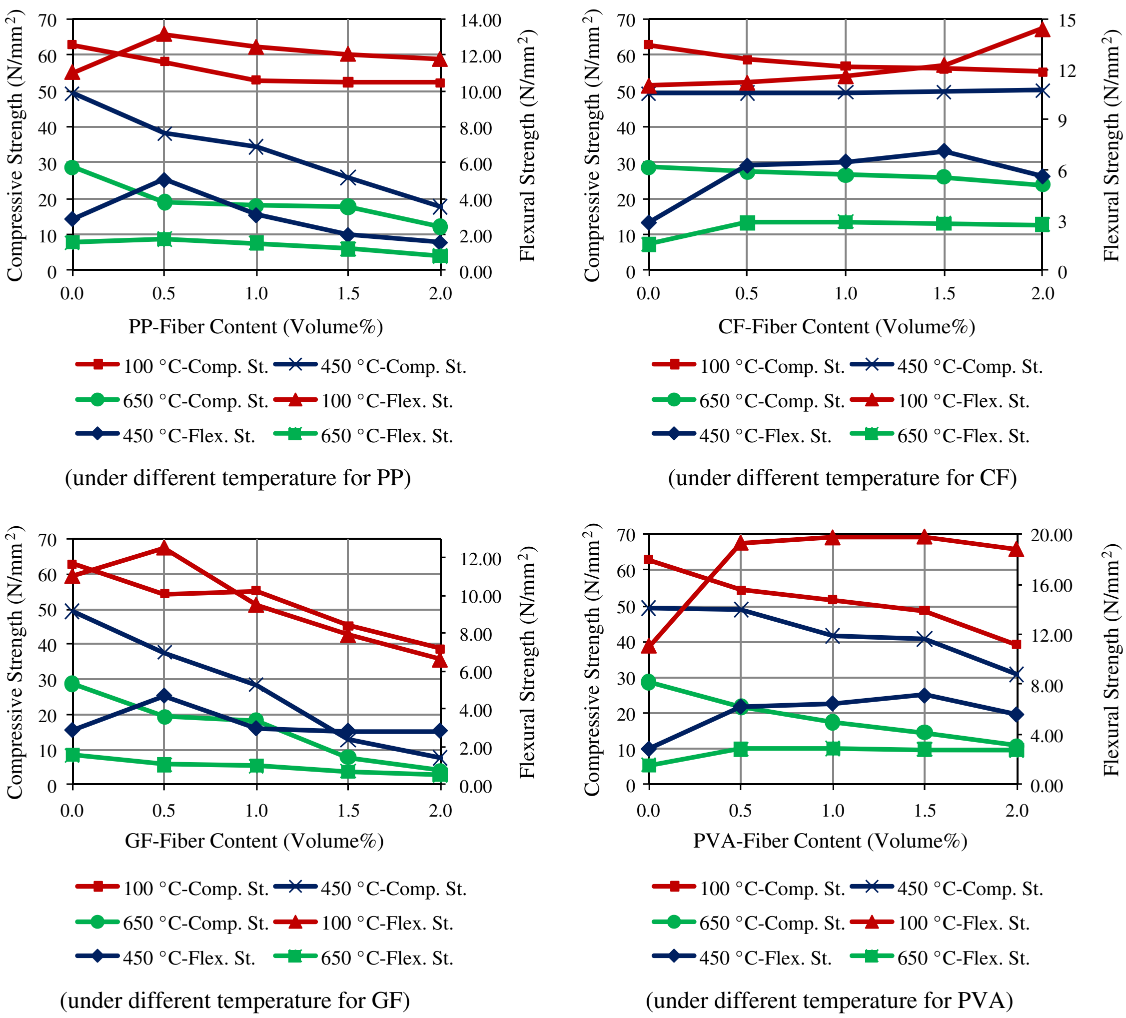


Fig. 7. Relationship between compressive strength and flexural strength of fiber types for different fiber content under high temperature.

best flexural performance (75–150%) under high temperature. CF which does not melt under high temperature also gives high flexural strength (11–85%).

4. The compressive strengths of the mortars reduce under high temperature or with fiber addition. The compressive strengths of non-fibrous mortar decrease about 20% at 450 °C and about 53% at 650 °C. These fall for PP and GF fibrous mortars at about 40–50% at 450 °C and about 55–70% at 650 °C. However, for CF and PVA these fall by about 3–8% at 450 °C and 50–60% at 650 °C. For all fiber types, decreases in compressive strength remain at a reasonable level for up to 1.0% fiber addition for each temperature.
5. Each fiber shows the best performance at different addition ratios when flexural and compressive strength are taken into consideration along with temperature. The highest increase in flexural strength and lowest decrease in compressive strength is at 0.5–1.5% fiber addition ratio for CF if all temperature conditions are taken into consideration. These optimum fiber addition ratios of the samples containing PP and GF are 0.5% by volume. And for PVA, it is between 0.5% and 1.5% by volume.

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