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The effects of high temperature on mechanical properties of cementitious composites reinforced with polymeric fibers

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ABSTRACT

Polymeric fibers are cheap and popular materials used in the concrete industry, and they may improve the mechanical properties of cementitious composites under high temperature. In this study, three different types of polymeric fibers – Copolymer Polypropylene/polyethylene (CPP), Homopolymer Polypropylene (HPP), and Aramid (AR) – are added to cement mortars with the aim to investigate their mechanical contributions to mortars under high temperature, comparatively. These fibers are added into mortars in five different ratios (0.0%, 0.3%, 0.6%, 0.9% and 1.2%) by volume. The mortars are subjected to following temperatures: 21 °C (normal conditions), 100 °C (oven dry), 450 °C, 650 °C and 850 °C. It is concluded that polymeric fibers used in this study contribute to the flexural strength of mortars under normal dry conditions (100 °C). This effect continues clearly up to 450 °C and polymeric fibers show effects on flexural strength especially at 450 °C. Each fiber shows the best performance different addition ratio when flexural and compressive strength are taken into consideration at the same time under high temperature. The highest increase in flexural strength and the lowest decrease in compressive strength are at 0.3–0.9% fiber addition ratio for HPP, at 0.3–0.6% fiber addition ratio for CPP and at 0.9% fiber addition ratio for AR for every temperature.

1. Introduction

Cementitious composites are typically characterized as brittle, with a low tensile strength and strain capacity. 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 [1–3].

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 [4,5]. This phenomenon is called thermal incompatibility of concrete components and could be the result of two mechanisms: the vapor pressure build-up mechanism [5,6] or the restrained thermal dilatation mechanism [7,8]. 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 [9–11]. 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 [12,13]. Several studies [14–21] show that concrete thermal stability is improved by incorporating polymeric fibers to the mix. Since the polymeric fibers melt at approximately 160–170 °C, they produce expansion channels. The additional porosity and small channels created by melting polymeric fibers may lower internal vapor pressure in the concrete and reduce the likelihood of spalling. The additional porosity due to the melting of polymeric fibers can lead to a decrease of the residual mechanical performances of concretes. The spalling resistance of concrete is affected by the type and the length of the polymeric fibers. Multifilament polymeric fibers are more effective at spalling resistance than fibrillated bundle polymeric fibers. This is because the diameter of multifilament polymeric fibers is less than that of fibrillated bundle polymeric fibers, so the former has more fibers per unit dimension than does the latter, forming a matrix with excellent air permeability [22,23].

Polymer is a solid, nonmetallic (normally organic) compound of high molecular weight the structure of which is composed of small repeat (or mer) units. Homopolymer is a polymer having a chain structure in which all mer units are of the same type. The homopolymer type (HPP) used in this study is polypropylene (PP) fiber.

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Copolymer is a polymer that consists of two or more dissimilar mer units in combination along its molecular chains. The copolymer (CPP) used in this study is polypropylene/polyethylene blend macrosynthetic fiber. The term of Aramid fiber is abbreviation of aromatic polyamide fiber. Their molecular chains are highly aligned in the fiber direction and are relatively inflexible. Molecules are arranged in parallel hydrogen bonded sheets. They have high longitudinal strength (covalent bonds) and low transverse strength (hydrogen bonds) [24–26]. The studies mentioned above are interested mostly in polypropylene that is one type of polymeric fibers. However, in this study it is investigated uncommon polymeric fiber for building industry like AR.

The main objective of this study is to investigate the effects of the different types of polymeric fibers on mechanical properties of cement mortars under high temperature. For this purpose, 13 different types of cement mortars are produced with three types of fibers and five addition ratios. These mortars are subjected to five different temperatures. Copolymer Polypropylene/polyethylene (CPP), Homopolymer Polypropylene (HPP) and Aramid (AR) fibers are chosen for the fibers and these are added to mortars in five different ratios (0.0%, 0.3%, 0.6%, 0.9% and 1.2%) by volume. The mortars are exposed to different temperatures: 21 °C (normal conditions), 100 °C (oven dry), 450 °C, 650 °C, and 850 °C. The mechanical properties investigated are flexural strength, deflection, and compressive strength of the cement mortars. Additionally, thin section images of fibers in mortars are examined.

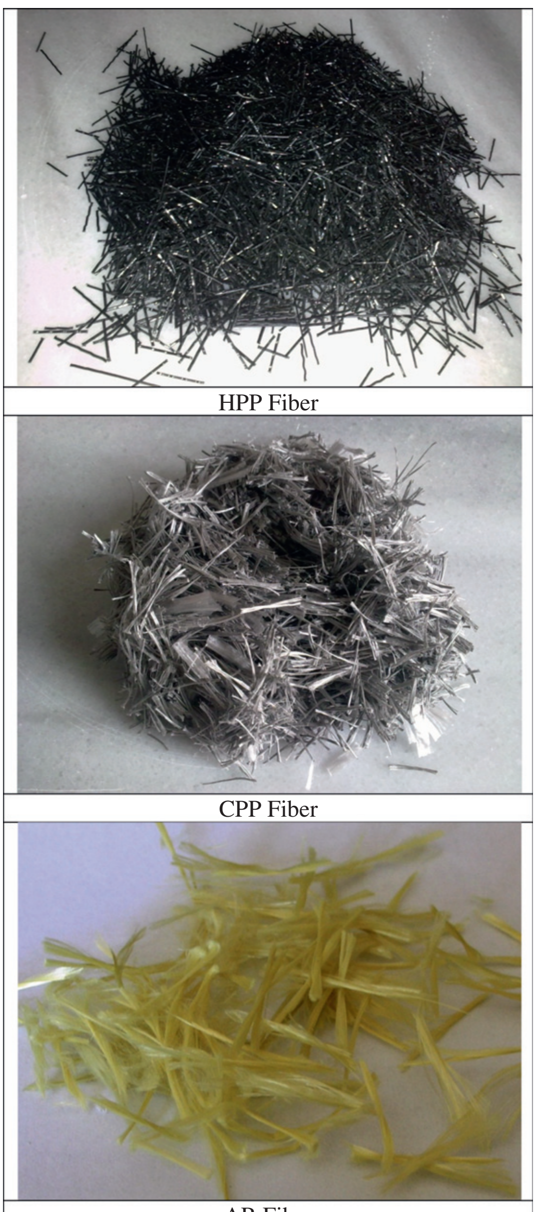


Fig. 1. The fibers used in the experiments.

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

Properties	Homopolymer Polypropylene (HPP)	Copolymer Polypropylene (CPP)	Aramid (AR)
Specific mass (g/cm^3)	0.88–0.92	0.91	1.44
Fiber diameter (μm)	750	550–750	12
Melting point (°C)	150–170	162–168	149–177
Ignition point (°C)	350	593	450 (roasting)
Elongation (%)	15–25	8–10	3.6
Tensile strength (N/mm^2)	338	570–660	2920
Young's modulus (N/mm^2)	1550	4700	83000

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 brought up clearly.

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 three different types of polymeric fibers are compared to each in the same mix types.
2. Less common fiber for concrete technology like Aramid fiber is also used in this study.

2. Materials and methods

2.1. Materials

Three different types of polymeric fibers are used in the experimental process. These are HPP, CPP, and AR fibers (Fig. 1). Some properties of these fibers are presented in Table 1. HPP fiber is extruded from a natural polypropylene homo polymer. CPP is color blended fiber, made of 100% virgin Copolymer Polypropylene/polyethylene. AR is polymeric fibers known as aromatic polyamide.

As seen from Table 1, the specific mass of the polymeric fibers vary between 0.91 and 1.44 g/cm^3, fiber diameters are between 12 and 750 μm, elongations are between 3.6% and 25%, tensile strengths are between 338 and 2920 MPa and Young modulus are between 1550 and 83000 MPa. It is seen that AR is more brittle than HPP and CPP.

All the fibers that are used in the experimental process are 10 mm in length and alkali resistances of them are high level.

In the experiments, CEM I 42.5 R type cement is used. The compositions and physical and mechanical properties of the cement

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

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, a total of 13 different fiber reinforced cement mortars are prepared with three different polymeric 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 polymeric fiber is added to the fresh mortar and the mortar is mixed as long as needed to obtain a homogeneous mixture. These homogenous dispersions are determined on cracked samples after

Table 3
Mix design of 13 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						
	HPP (g)	CPP (g)	AR (g)				
0.0	0.00	0.00	0.00	1350	450	225	0.50
0.3	21	21	32.5				
0.6	42	42	65				
0.9	63	63	97.5				
1.2	84	84	130				

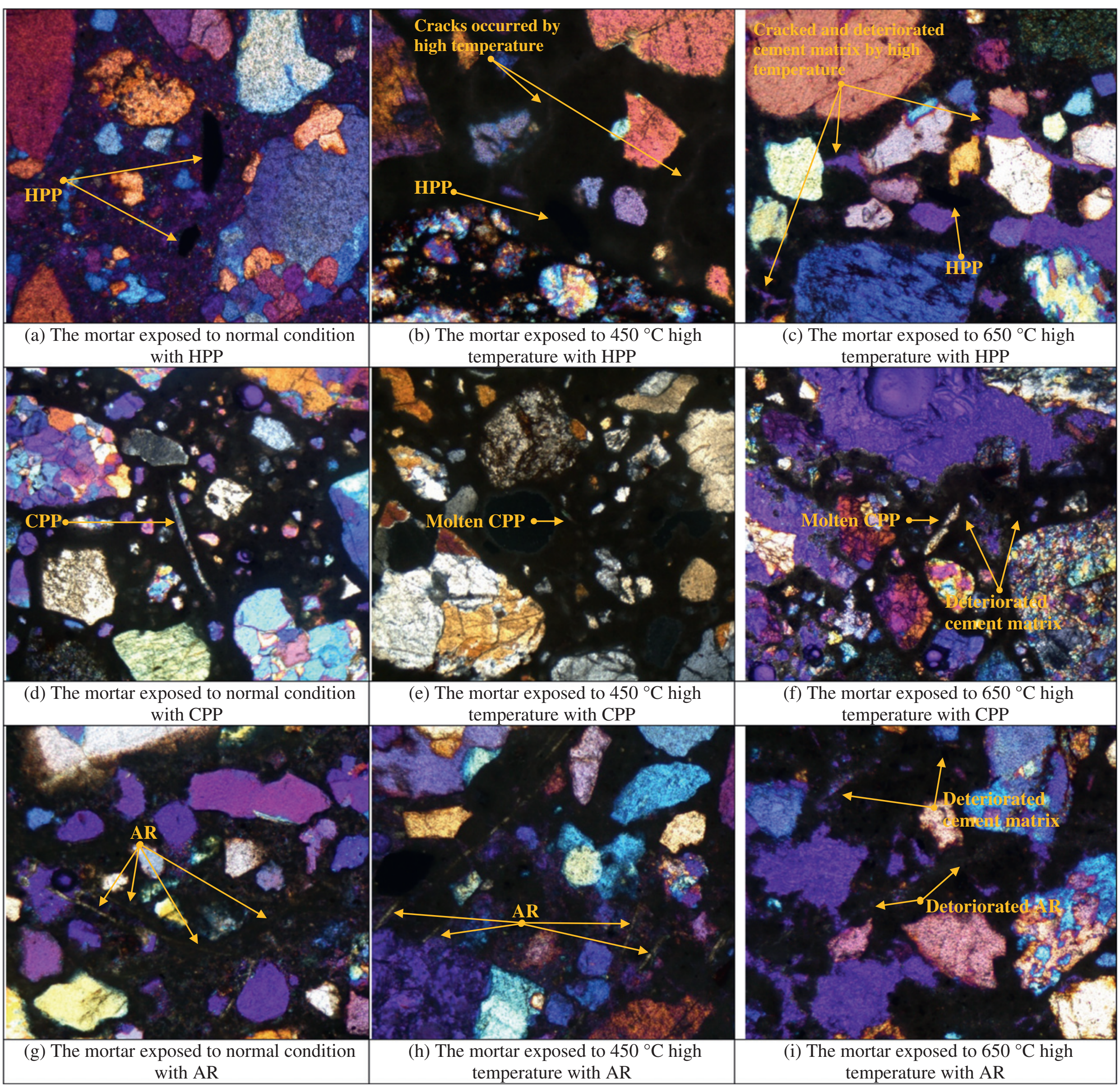


Fig. 2. Thin section images of fibrous mortars subjected to high temperature.

samples are tested. It is also seen at thin section images (Fig. 2). 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 40 days. According to the objective of the study, five different temperatures should be applied to the samples. The first is normal conditions temperature (21 °C). After 40 days, the samples are taken from water and then wiped off. 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 to dry. The last three conditions are 450 °C, 650 °C, and 850 °C. After 40 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, 650 °C, or 850 °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, for 650 °C it is maintained for 100 min and for 850 °C it is maintained for 130 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 vapor pressure build up is overcome. After this process, these oven dry samples are subjected to high temperatures (450 °C, 650 °C, and 850 °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. Deflections are measured while the flexural strength is being determined. The deflection used in comparisons is the maximum deformation of the midpoint of beams at the moment of breaking.

Additionally, internal changes to the mortars caused by the fibers are investigated via petrographic observations (Fig. 2).

3. Results and discussions

The mortars containing different types and different proportions of polymeric 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 polymeric fiber reinforced 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 polymeric fibers accomplished exact bond with the cement mortar is seen in Fig. 2.

At 450 °C (Fig. 2), 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 polymeric fibers are taken into consideration (Table 1), all fibers melt under 450 °C. Although all fibers melt under this temperature degree, each of them is distinguished in the matrix.

For 650 °C temperature conditions, the matrices are weakened, spoiled, and cracked. At this temperature, because matrices are

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

Fiber ratio by volume (%)	Temperature (°C)	Dry Specific mass (g/cm^3)		
		HPP	CPP	AR
0.0	100	2.10	2.10	2.10
	450	1.99	1.99	1.99
	650	1.98	1.98	1.98
	850	1.96	1.96	1.96
0.3	100	2.07	2.08	1.97
	450	1.99	1.95	1.88
	650	1.93	1.91	1.87
	850	1.94	1.93	1.85
0.6	100	2.06	2.07	1.97
	450	1.98	1.97	1.91
	650	1.94	1.86	1.83
	850	1.94	1.92	1.82
0.9	100	2.04	2.07	1.96
	450	1.96	1.90	1.87
	650	1.93	1.88	1.87
	850	1.90	1.88	1.83
1.2	100	2.02	2.07	1.96
	450	1.96	1.91	1.90
	650	1.90	1.90	1.81
	850	1.91	1.90	1.86

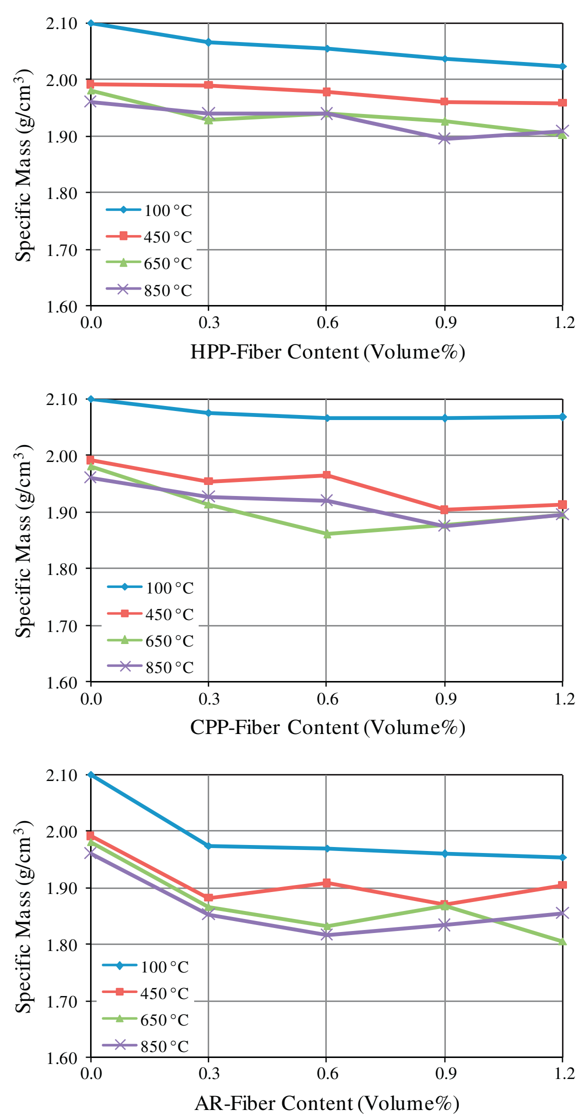


Fig. 3. Relationship between fiber content and specific mass under high temperature.

weakened, taking thin sections is very difficult. The fibers, except thin AR samples, are shown in the matrix, clearly (Fig. 2). However, all fiber types have melted or deteriorated.

For 850 °C temperature, the mechanical properties of mortars are weakened, so it is not possible to obtain thin sections from these mortars.

3.2. The effects of polymeric 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 the water that is bonded chemically is separated from the body, a decrease in specific masses is expected.

For non-fibrous mortars, specific masses are down from 2.1 g/cm^3 to 1.99 g/cm^3 (5%), 1.98 g/cm^3 (6%) and 1.96 g/cm^3 (7%) for 450 °C, 650 °C and 850 °C, respectively (Table 4).

When HPP and CPP fibers with a specific mass (0.91 g/cm^3) that is lower than mortar (2.1 g/cm^3) is added to mortar, it is expected the mortar's unit mass decreases. Fig. 3 and Table 4 show that the addition of HPP and CPP fibers decrease the unit mass of mortar by 1% and 3%, respectively, for normal conditions. On the other hand, after the mortars are subjected to 450 °C, 650 °C and 850 °C temperatures, the masses decrease approximately 4%, 6%, and 6.5%, respectively, compared with the samples with the same ratio of HPP under the same temperatures. For CPP, these decreases are 7%, 8%, and 7%, respectively.

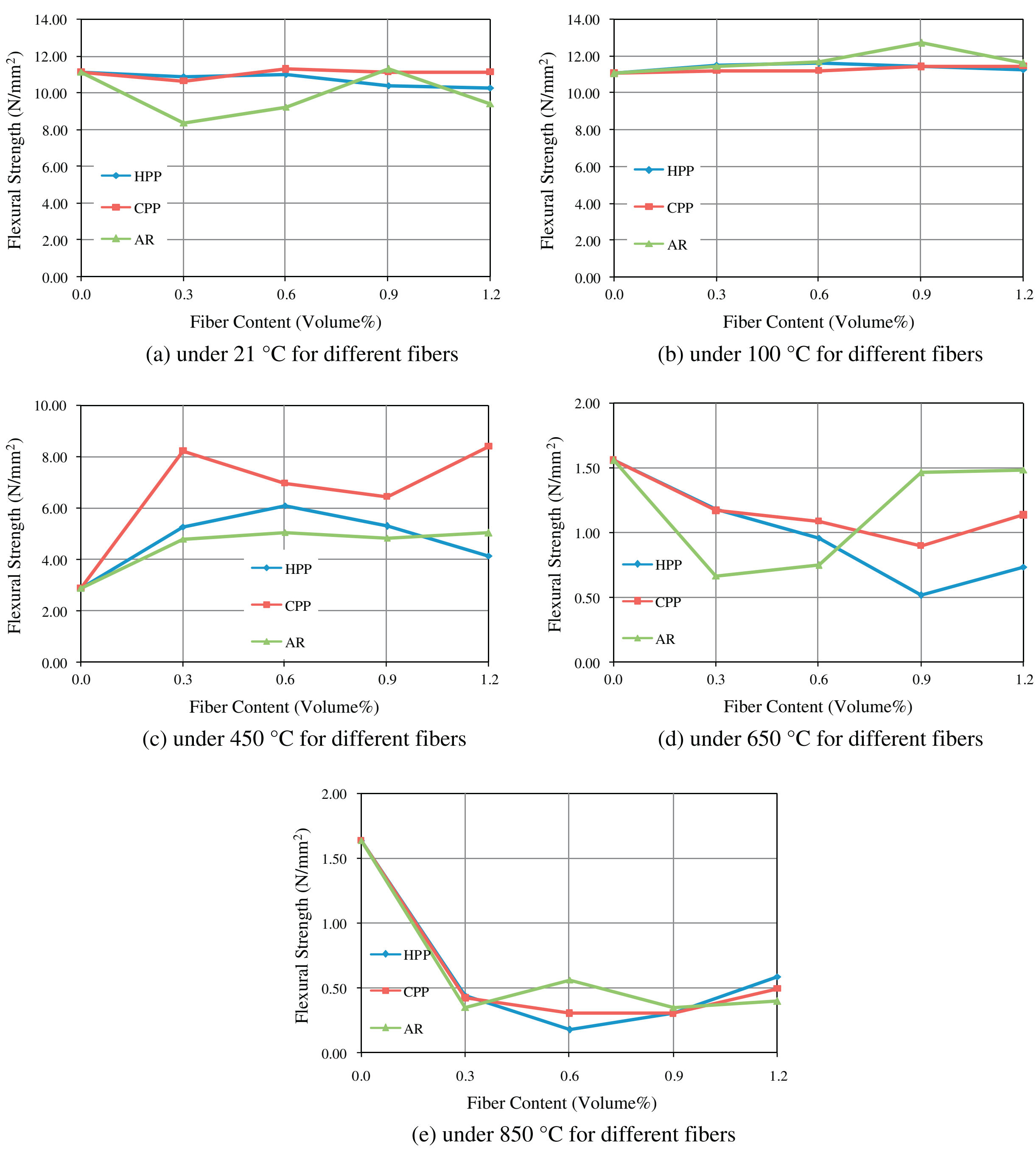


Fig. 4. Relationship between fiber content and flexural strength under high temperature.

Although AR has a higher specific mass with respect to HPP and CPP, its mortars' specific masses are lower than specific mass of mortars of HPP and CPP. The unit mass of mortar decreases to 1.86 g/cm^3 with the addition of 1.2% by volume of AR. In addition, its specific mass decreases about 3% at 450 °C, 8% at 650 °C, and 5% at 850 °C.

It is interesting that the unit masses at 650 °C are higher than the unit mass at 850 °C. The unit mass of mortar decreases to 1.91, 1.90 and 1.86 g/cm^3 with the addition of 1.2% by volume of HPP, CPP and AR, respectively, subjected to 850 °C.

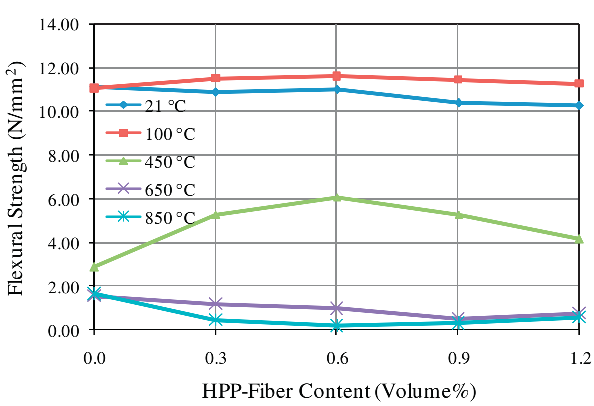
3.3. The effects of polymeric fiber type and content on flexural strength and deflections of mortars under high temperature

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 the flexural strength of the mortars in particular should increase to some degree.

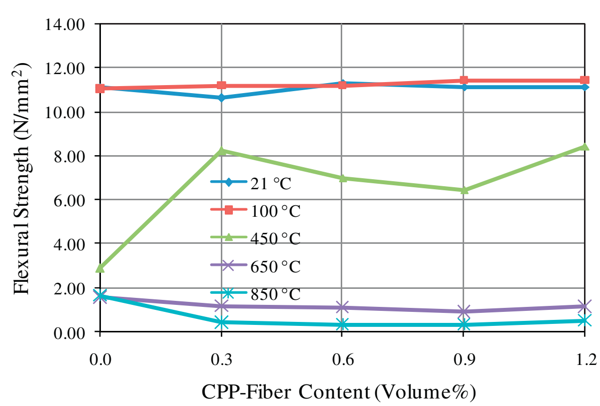
For non-fibrous mortars, as the temperature increases, the flexural strength decreases dramatically. The flexural strength of non-fibrous mortar decreases about 74% at 450 °C, about 85% at 650 °C, and about 86% at 850 °C. The flexural strength of the mortars with HPP decreases on average 51% at 450 °C, about 92% at 650 °C, and about 96% at 850 °C (Figs. 4 and 5). For CPP, the decreases on average are 31% at 450 °C, about 90% at 650 °C, and approximately 96% at 850 °C (Figs. 4 and 5). And for AR, the decreases are on average about 48% at 450 °C, about 88% at 650 °C, and about 95% at 850 °C (Figs. 4 and 5). This means all fibrous mortars are effective up to 450 °C; however, any contribution of them cannot be seen at 650 °C. At 850 °C, the control samples have higher flexural strength. The reason is the ignition points of fibers change between 350 and 593 °C (Table 1). Thus, the fibers lose their properties and have no positive effects on the flexural strength above these temperatures.

At 21 °C, the samples are newly taken from the water, and they are wet. If the effects of the different range of (0.0–1.2%) polymeric fiber contents on the flexural strength of mortars is investigated, it is seen that in wet conditions (21 °C), all fibers present unstable behavior (Table 5, Figs. 4 and 5), and none of them contribute to the flexural strength of mortars more than 2%. The flexural strength of control samples under wet conditions is 11.13 N/mm^2, the samples consisting of 0.6% CPP samples have 11.3 N/mm^2, and the samples have 0.9% AR samples have 11.3 N/mm^2 of flexural strength, too.

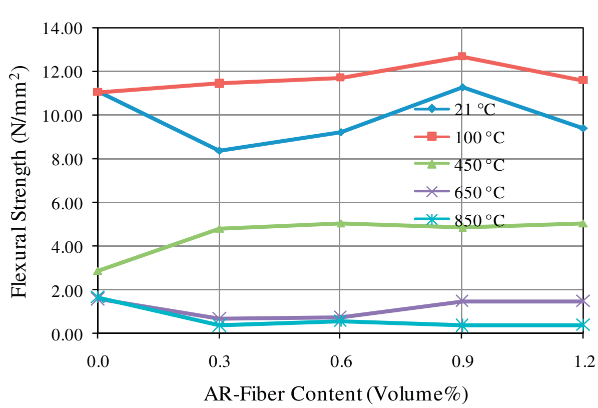
For the samples under oven dry (100 °C) conditions (Table 5, Figs. 4 and 5), fibers show better performance than compared under wet conditions (21 °C). The flexural strength of the mortar consisting of HPP falls at an upper range of 0.6% fiber addition. Flexural strengths of mortars always increase by increasing CPP ratios of mortar. The mortars containing AR fiber present good performance at all additional ratios. After 0.9% of AR addition, a small decrease is observed; however, the flexural strength is still greater than the control sample. It is understood that different types of fibers contribute to flexural strength at different additional ratios. HPP shows the best increments in flexural strength at 0.6% fiber content as 5%. For CPP, a 4% increase in flexural strength is obtained at 1.2% fiber content by volume. AR presents a surprising increase compared to other fiber types. A 0.9% by volume AR addition increases flexural strength about 15%. Flexural strength of control samples at 100 °C is 11.05 N/mm^2, the samples consisting of 1.2% AR have a 12.70 N/mm^2 flexural strength, the samples consisting of 0.6%



(a) under different temperature for HPP



(b) under different temperature for CPP



(c) under different temperature for AR

Fig. 5. Relationship between fiber content and flexural strength under high temperature for each fiber type.

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

Fiber ratio by volume (%)	Temperature (°C)	Flexural strength (N/mm^2)		
		HPP	CPP	AR
0.0	21	11.13	11.13	11.13
	100	11.05	11.05	11.05
	450	2.87	2.87	2.87
	650	1.64	1.64	1.64
	850	1.56	1.56	1.56
0.3	21	10.88	10.63	8.37
	100	11.52	11.20	11.45
	450	5.27	8.23	4.80
	650	1.18	1.17	0.67
	850	0.45	0.42	0.35
0.6	21	10.99	11.30	9.25
	100	11.61	11.21	11.70
	450	6.09	6.98	5.06
	650	0.96	1.09	0.75
	850	0.18	0.30	0.56
0.9	21	10.38	11.13	11.30
	100	11.45	11.43	12.70
	450	5.30	6.45	4.84
	650	0.52	0.90	1.46
	850	0.30	0.30	0.35
1.2	21	10.27	11.13	9.43
	100	11.26	11.45	11.60
	450	4.15	8.41	5.04
	650	0.74	1.14	1.49
	850	0.59	0.49	0.40

HPP have 11.66 N/mm^2 of flexural strength, and the samples consisting of 1.2% CPP have a 11.45 N/mm^2 flexural strength.

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

Fiber ratio by volume (%)	Temperature (°C)	Deflection (mm)		
		HPP	CPP	AR
0.0	21	0.523	0.523	0.523
	100	0.406	0.406	0.406
	450	0.190	0.190	0.190
	650	0.120	0.120	0.120
0.3	21	1.885	1.191	0.542
	100	1.310	1.222	0.390
	450	1.107	1.170	0.345
	650	0.930	1.150	0.317
0.6	21	1.903	1.272	0.592
	100	1.691	1.311	0.380
	450	0.940	1.210	0.365
	650	0.900	1.180	0.292
0.9	21	1.748	1.400	0.641
	100	1.250	1.502	0.364
	450	0.670	1.330	0.292
	650	0.630	1.218	0.261
1.2	21	1.454	1.381	0.560
	100	1.042	1.373	0.309
	450	0.430	0.900	0.220
	650	0.370	0.830	0.212

At 450 °C, fibrous mortars show good performance compared to the control samples. All fibrous samples present high flexural strength at all additional ratios. At this temperature, and all addition ratio, the mortar HPP shows a 45–112% more flexural strength than do the control samples. The CPP addition increases flexural strength about 125–193%. This ratio is about 67–76% for AR.

At 650 °C, the fibrous mortars show worse flexural strength about 10–70% than non-fibrous mortars. At this temperature, the

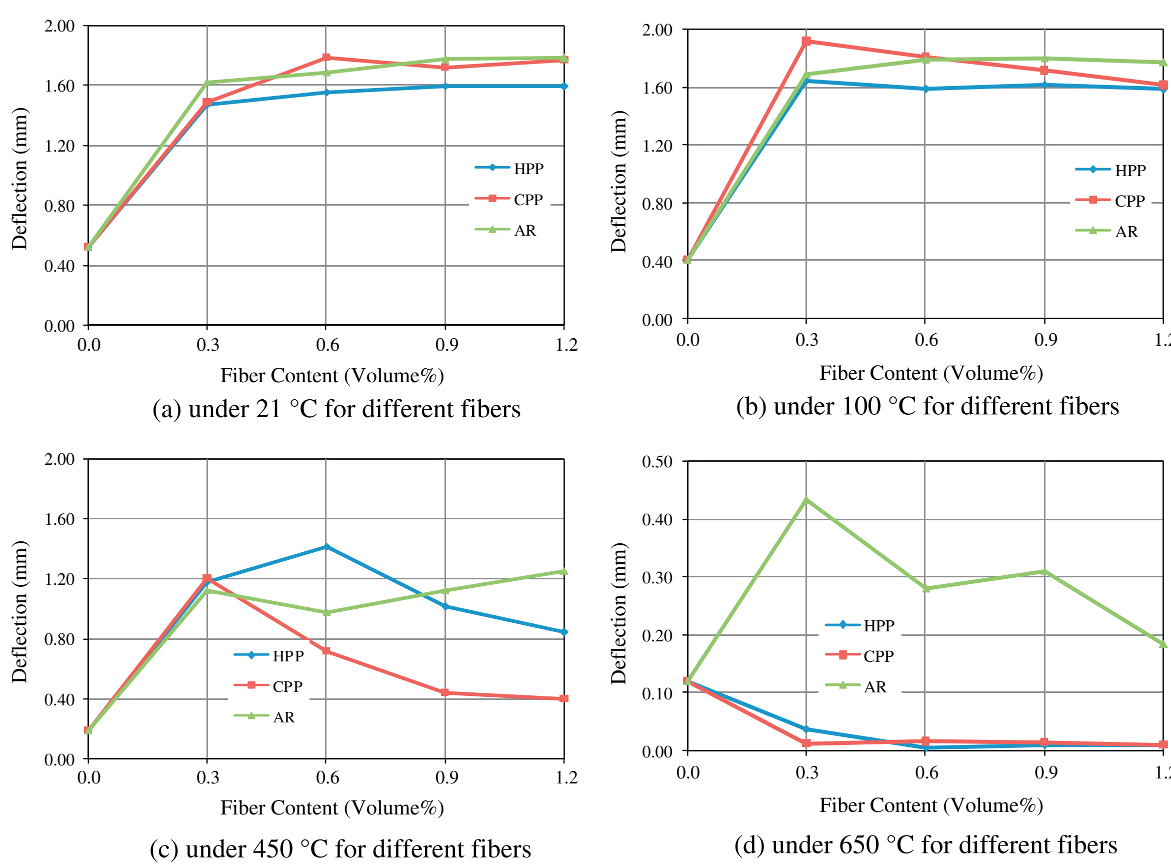


Fig. 6. Relationship between fiber content and deflection under high temperature.

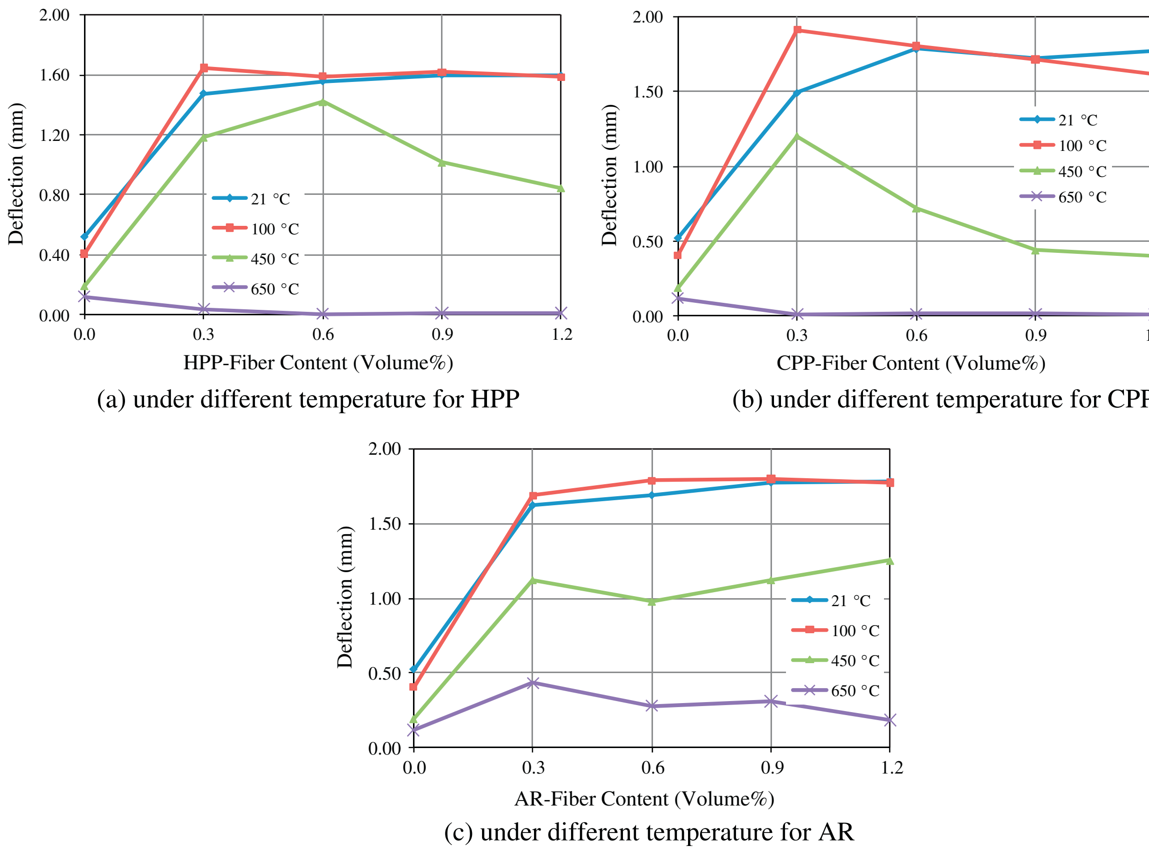


Fig. 7. Relationship between fiber content and deflection under high temperature for each fiber type.

mortars with HPP and CPP show the best performance at 0.3% by volume addition ratio, and the mortars with AR show at 0.9–1.2% addition ratios. At 850 °C, this negative difference still increases against fibrous mortars about 90%.

As a result, polymeric fibers used in this study contribute to the flexural strengths of mortars under normal dry conditions (100 °C). This effect continues clearly up to 450 °C, and polymeric fibers show effects on flexural strength especially at 450 °C. However, at higher temperatures, fibers have an adverse effect on flexural strength compared to non-fibrous mortars.

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. However, high temperatures make the mortars more brittle.

It is seen from Table 6 and Figs. 6 and 7 that as temperature rises, the deflections decrease for all fibrous mortars. At 850 °C, the mechanical properties of mortars are weakened, so it is not possible to obtain deflections. 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 HPP decrease on average 28% at 450 °C, and about 98% at 650 °C (Figs. 6 and 7). For CPP, the decreases are on average 59% at 450 °C, and approximately 99% at 650 °C (Fig. 7a). For AR, the decreases are on average 34% at 450 °C, and about 82% at 650 °C (Fig. 7b). It is seen that similar to flexural strength properties, the contribution of fibers to deflections of mortars are valid up to 450 °C. However, at higher temperatures the deflections decrease to about zero.

When fibrous samples are compared with the control sample (non-fibrous and at normal conditions), it can be seen that it gives on average 200–236% big deflection at normal conditions, and 32–114% higher values at 450 °C. These deflectional differences are seen negatively at 650 °C as about 42–97%.

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

Fiber ratio by volume (%)	Temperature (°C)	Compressive Strength (N/mm^2)		
		HPP	CPP	AR
0.0	21	61.73	61.73	61.73
	100	62.88	62.88	62.88
	450	49.38	49.38	49.38
	650	28.70	28.70	28.70
	850	9.51	9.51	9.51
0.3	21	59.43	52.71	42.54
	100	58.72	55.88	42.16
	450	55.49	49.93	39.40
	650	22.17	16.85	20.11
	850	6.59	7.18	4.83
0.6	21	61.17	60.61	44.49
	100	62.18	55.46	43.73
	450	53.59	47.12	40.90
	650	24.31	16.59	15.44
	850	7.76	7.09	3.89
0.9	21	59.05	53.29	44.43
	100	59.40	52.10	51.01
	450	52.26	39.44	40.70
	650	19.45	14.49	16.73
	850	6.51	5.67	4.24
1.2	21	57.74	58.25	46.33
	100	60.44	54.63	53.24
	450	46.88	42.18	43.45
	650	22.34	17.88	17.93
	850	6.58	7.04	3.38

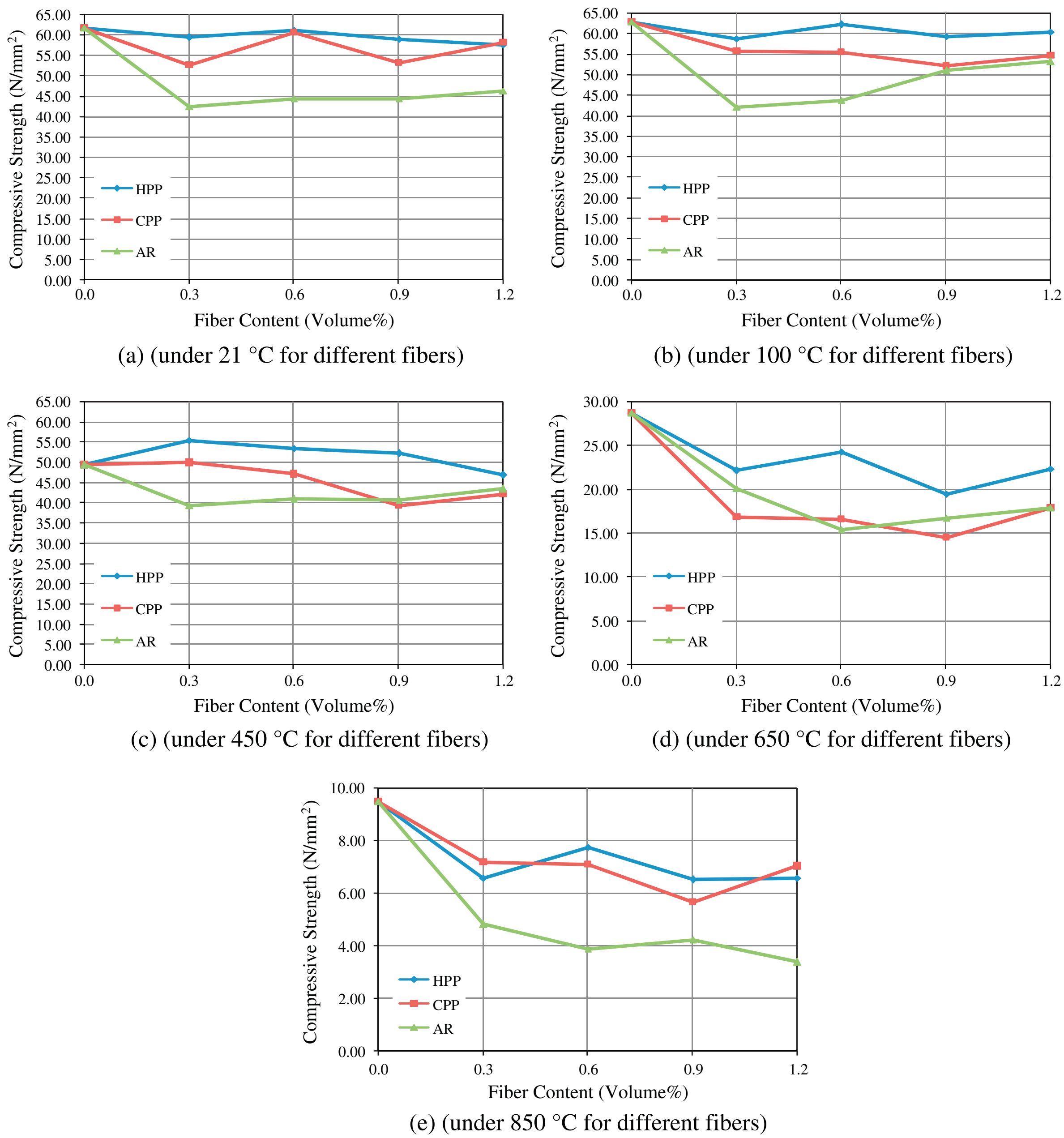


Fig. 8. Relationship between fiber content and compressive strength under high temperature.

3.4. The effects of polymeric 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.

Table 7 and Figs. 8 and 9 show 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 and higher temperatures. The compressive strength of non-fibrous mortar decreases about 20% at 450 °C, about 53% at 650 °C, and about 84% at 850 °C. Compressive strengths of the mortars with HPP decrease on average 12% at 450 °C, about 62% at 650 °C, and about 88% at 850 °C (Figs. 8 and 9). For CPP, the decreases are on average 20% at 450 °C, about 70% at 650 °C, and about 88% at 850 °C (Fig. 9a). And for AR, the decreases are on average 8% at 450 °C, about 60% at 650 °C, and about 90% at 850 °C (Figs. 8 and 9).

Reviewing mortars with different polymeric fiber types, the compressive strength decreases with addition of all of the fiber types (Table 7, Figs. 8 and 9). Under wet (21 °C) conditions, the compressive strength of HPP fiber added mortars decreases about 1–6%, for the samples contain CPP compressive strength fall about 2–15%, and for the mortar which has AR it drops about 25–31% compared with control samples at the same temperature. These decreases are about 1–7%, 11–17%, and 15–33% for HPP, CPP and AR, respectively, under oven dry (100 °C) conditions. At 450 °C, HPP interestingly shows better results (up to 12%) than does the control sample at the same temperature. Compared with control sample at the same temperature, the decreases are about 15–32%, 38–50%, and 30–46% for HPP, CPP and AR, respectively at

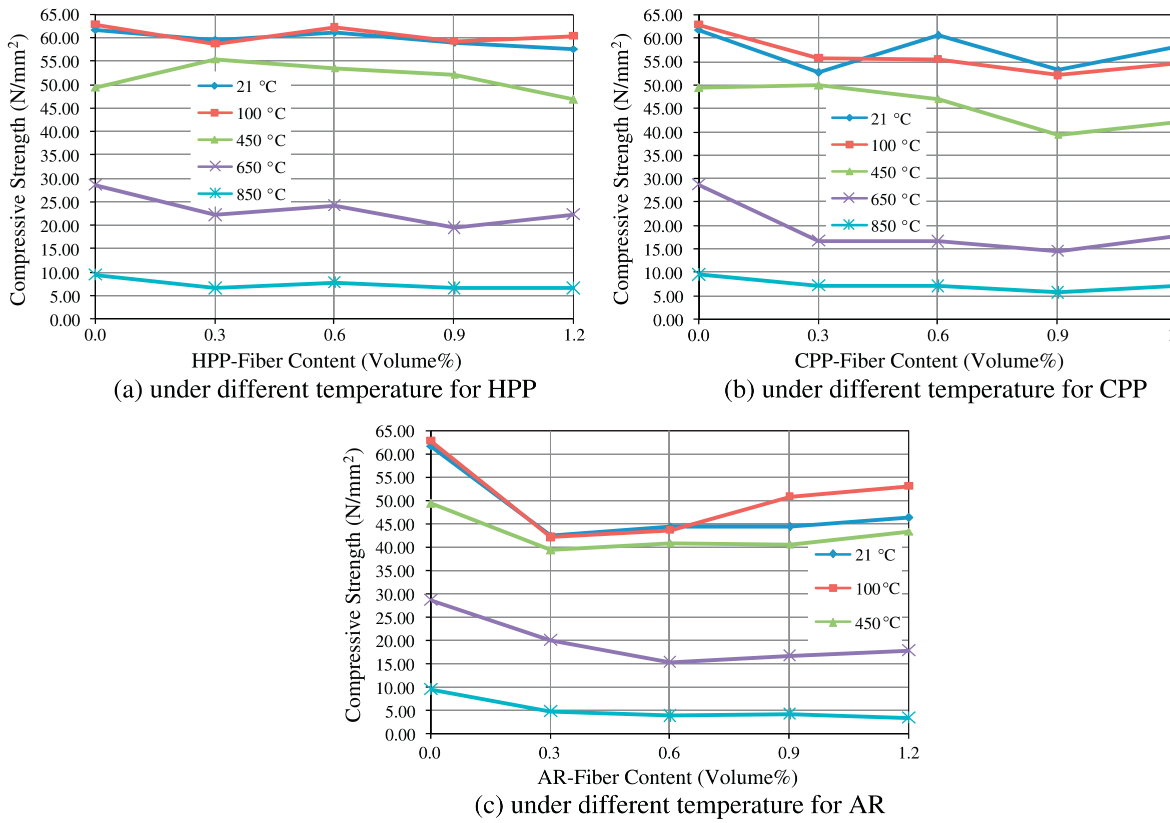


Fig. 9. Relationship between fiber content and compressive strength under high temperature for each fiber type.

650 °C. Additionally, at 850 °C, compressive strength drops are about 18–32%, 25–40%, and 49–64% for HPP, CPP and AR, respectively.

As a result, fibrous mortars effective on compressive strength up to 450 °C compared with the control samples.

3.5. Determining optimum polymeric fiber content from the relationship between flexural and compressive strength under high temperature

As mentioned above with fiber addition, as flexural strength improves, compressive strengths are influenced negatively for each 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 above discussion that each fiber shows the best performance at different addition ratios when flexural and compressive strength are taken simultaneously into consideration.

Fig. 10 shows that the highest increase in flexural strength and the smallest decrease in compressive strength are obtained at 0.3–0.9% addition ratio for the sample which has HPP. This situation is valid for nearly every temperature. Especially at 450 °C, this fiber shows good performance compared to non-fibrous mortars.

Although the samples containing CPP present best flexural strength with 0.9% by volume fiber addition at 100 °C, they also show good performance with 0.3–0.6% CPP addition ratio at other temperatures.

Fig. 10 shows that the optimum fiber addition ratios of the samples containing AR is 0.9% by volume for all temperature conditions.

4. Conclusions

This study shows the effects of high temperature on the mechanical properties of cement mortars reinforced with polymeric fibers. The conclusions drawn from this study include:

1. With an increase in temperature, several changes occur in the cement matrix. At 450 °C, some deteriorations and cracks occur in cement matrices. In temperatures higher than 650 °C, the matrices become weakened, spoiled, and cracked. As the temperature rises, both fibrous and non-fibrous mortars lose their masses by about 3–8% because of chemical reactions.
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 74% at 450 °C, about 85% at 650 °C, and about 86% at 850 °C. However, these decrease for all fibrous mortars on average at about 31–51% at 450 °C, about 88–92% at 650 °C, and about 95–96% at 850 °C. This means the polymeric fibers used in this study contribute to the flexural strength of mortars under normal dry condition (100 °C). This effect continues clearly up to 450 °C, and polymeric fibers show their effects on flexural strength especially at 450 °C. However at higher temperatures, fibers have adverse effects on flexural strength compared to non-fibrous mortars.
3. When fibrous samples are compared with the control sample (non-fibrous and at normal conditions), it can be seen that it gives on average 200–236% big deflection at normal conditions and 32–114% high values at 450 °C. These deflectional differences are seen negatively at 650 °C as about 42–97%.

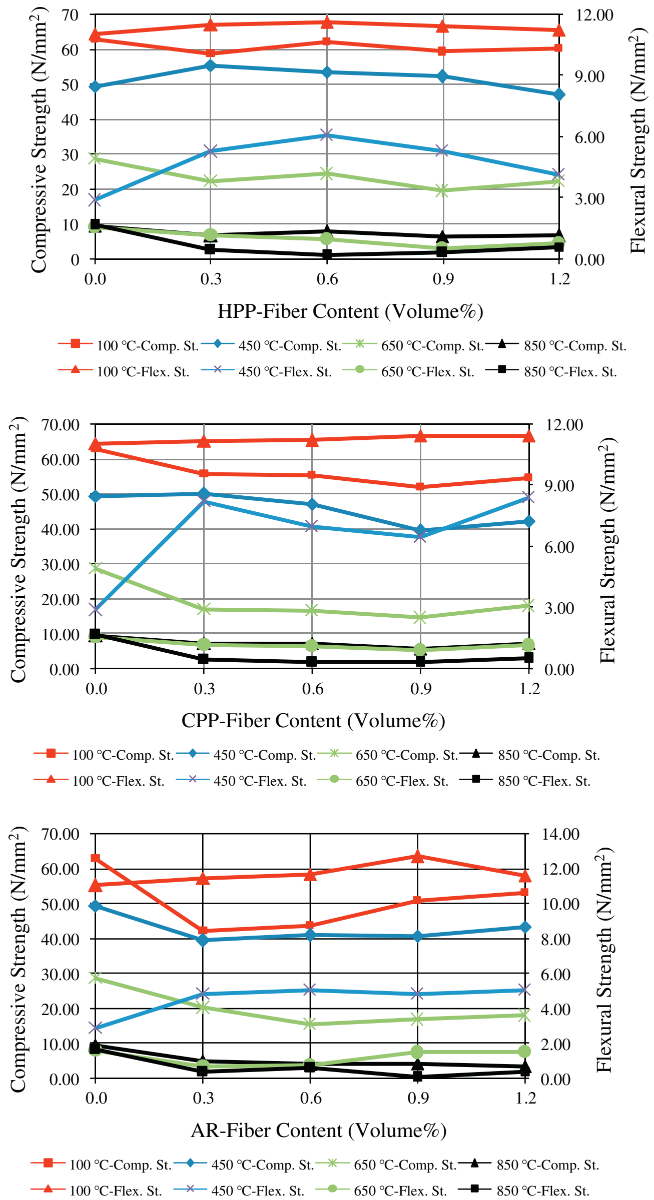


Fig. 10. Relationship between compressive strength and flexural strength of fiber types for different fiber content under high temperature.

4. The compressive strengths of the mortars decrease under high temperature or with fiber addition. The compressive strengths of non-fibrous mortar decrease about 20% at 450 °C, about 53% at 650 °C, and about 84% at 850 °C. These fall for polymeric fiber reinforced mortars on average about 8–20% at 450 °C, about 60–70% at 650 °C, and about 88–90% at 850 °C. As a result, fibrous mortars effective on compressive strength up 450 °C compared to the control samples.
5. Each fiber shows the best performance at different addition ratios when flexural and compressive strength are taken into consideration at the same time under high temperature. The highest increase in flexural strength and lowest decrease in compressive strength is at 0.3–0.9% fiber addition ratio for HPP. This situation is valid for nearly every temperature. Especially at 450 °C, this fiber shows good performance compared to non-fibrous mortars. Although the samples contain CPP present best flexural strength with 0.9% by volume fiber addition at 100 °C, at other temperatures they show good performance with 0.3–0.6% CPP addition ratio. For all temperature conditions, the optimum fiber addition ratios of the samples contain AR is 0.9% by volume.

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