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ORIGINAL STUDY

Mechanical Performance of Sustainable High-performance Concrete Containing Hybrid Polypropylene Fibers and Exposed to Elevated Temperatures

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Abstract

The purpose of this research is to investigate the impact of hybrid micro and macro polypropylene fibers (PPFs) on mechanical characteristics and microstructure of high-performance concrete (HPC). Seven concrete mixes with different contents of hybrid polypropylene fibers were tested. The tests included the slump test, compressive and flexural strength, resistance to elevated temperatures, and concrete microstructure. Compared with the control mixture, introducing macro and micro polypropylene hybrid fibers to HPC mixes dramatically enhanced the flexural and compressive strength of concrete while lowering workability. HPC compressive and flexural strengths decrease as temperature rises; nevertheless, the strength loss rate was lowered with the use of hybrid PPFs. In addition to increasing the compressive strength by 14.6, 14.28, and 11.4% at ages 7, 28, and 56 days, respectively, the combination of 0.75 kg/m^3 micro and 5 kg/m^3 macro PPFs also raised the flexural strength by 41.9% at age 56 days. Furthermore, the highest residual compressive and flexural strength of concrete after being exposed to 200, 400, and 800 °C was achieved. The residual flexural and compressive strength were up to 45.6%, and 64.3%, respectively, of the initial strength after exposure to 800 °C. The network structure generated by macro and micro polypropylene fibers in the matrix is well demonstrated by microstructural analysis. The incorporation of hybrid polypropylene fibers prevents capillary cracks in concrete and probable disintegration between aggregate and cement paste.

Keywords: Compressive strength, Concrete microstructure, Elevated temperature, Flexural strength, High-performance concrete, Polypropylene fibers

1. Introduction

Concrete, which is manufactured at a rate of 20 billion tons annually, is one of the building materials most commonly used (Yazõcõ et al., 2007; Afroughsabet and Ozbakkaloglu, 2015a; Kou and Poon, 2009) due to its numerous well-known benefits, including its low cost, a wide range of uses, and common availability (Brandt, 2008; Mohammadi et al., 2008a; Thomas and Ramaswamy, 2007; Makul, 2020). Two main problems in traditional concrete have made it difficult for use in structures: brittle behavior and weakness under tension, which results in low ductility (Ansari and Sharma, 2017; Wu et al., 2020). Concrete is a material that is semi-brittle and only slightly deforms into the plastic range to absorb energy. To considerably enhance concrete quality and decrease the probability of cracking, brittleness can be reduced by adding additives like fibers (Hosseinzadeh et al., 2023; Shi et al., 2020a).

Due to its potential benefits in structural performance such as high durability and strength over conventional normal-strength concrete (NSC), the construction industry has recently expressed a lot of

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interest in using high-strength concrete (HPC). HPC is used in numerous applications, including infrastructure projects, offshore constructions, and bridges. Its application has expanded in recent years to include high-rise buildings (Tahwia et al., 2022; Elemam et al., 2023a; Zhou et al., 2022). The production of HPC has grown due to technological development and greater innovation in the building material industry. The economic and technical aspects of production have improved with the use of this material in the manufacture of concrete sections. The concrete tensile strength does not significantly enhance as its compressive strength improves, and it instead becomes more brittle. The limitations of this type of concrete, such as its insufficient ductility and low tensile strength compared with its high compressive strength, have been the subject of intense research (Mohammadi et al., 2008b; Afroughsabet and Ozbakkaloglu, 2015b). Early high heat of hydration is the major issue with high-strength concrete that can cause thermal cracking. To manage this, decrease porosity, and boost durability, a considerable amount of cementitious materials (SCMs) with set retarders should be used in the concrete mix (Elemam et al., 2023b).

Fibers have gained popularity for use in concrete in recent years, mostly to improve toughness and get around some of the disadvantages of traditional concrete including low flexural and tensile strength and high brittleness (Alhozaimy et al., 1996; Aly et al., 2008; Paul et al., 2020; Alsadey and Salem, 2016; Uyan et al., 1992; Kene et al., 2012; Mashaly et al., 2023). Tensile weakness is compensated by using fibers. Furthermore, the existence of numerous cracks in the body of concrete restricts the appropriate transmission of tensile stresses, making concrete more ductile. In addition, adding fibers is the most well-known method to stop concrete from spalling when exposed to elevated temperatures in situations like fire in concrete structures, jet engine explosions, factories for metal extraction and melting, chemical factories when concrete is near the furnace, and nuclear-related activities (Choumanidis et al., 2016; Tanyildizi and Yonar, 2016; Bezerra et al., 2019; Düğenci et al., 2015). Polypropylene, steel, carbon, and glass fibers are the most widely used fibers (Li et al., 2019). Of course, the kind, amount, and shape of fibers all have an impact on the behavior of concrete (Fallah and Nematzadeh, 2017). Macro-type and micro-type fibers are two categories of fibers. For structural and nonstructural applications, macro fibers are used to withstand tensile stress and cracks, while micro fibers are designed to improve the pre-cracking behavior of concrete (Saidani et al., 2016). By adding fibers, plain concrete may be changed from a brittle material to a pseudo-ductile one, increasing its ductility, impact toughness, and resistance to crack growth (Barluenga, 2010). Polypropylene fibers (PPFs) are frequently used among the fibers that can be used in concrete because of the alkalinity of concrete's chemical stability, accessibility, and affordability (Tahwia et al., 2023a). It has a lower strength and elasticity modulus when compared with other fibers made of HPC. The fibers can nevertheless boost the strength of concrete at high pressures as they are extremely ductile despite having low strength (Yew et al., 2015; Tahwia et al., 2023b; Abaeian et al., 2018).

To solve these HPC disadvantages, researchers have recommended a variety of solutions, including the addition of PPFs in concrete mixtures. Abaeian et al. (Sultangaliyeva et al., 2023) studied the mechanical behavior of HPC incorporating macro PPFs when exposed to elevated temperatures. The results showed that a 1 kg fiber addition to HPC increased its compressive, flexural, and tensile strength by up to 14, 8.5, and 17%, respectively. Sultangaliyeva et al. (Noushini et al., 2018) determined the best PPF geometry to prevent fire-related spalling of HPC. The findings indicate that the aggregate size should be taken into account while choosing the optimal PPF length. The prevention of spalling has not been proven to be significantly impacted by PPF diameter. Noushini et al. (Deng et al., 2021) studied the fracture characteristics of fly ash-based geopolymer concrete including PPFs and demonstrated that PPFs improve geopolymer toughness. Tahwia (2017) focused on the potential of polypropylene (PP) fibers to replace steel fibers. He revealed that PP fibers melt before steel fibers in the event of fire. Thus, they act as sacrificial agents that create voids in the UHPC matrix, reducing internal pressure and preventing (or delaying) failure.

The corrosion process of steel fibers used in concrete causes degradation and limits its durability. Therefore, there was a need to use other types of fibers that achieved the desired concrete properties and improved its durability. However, few research has been conducted to investigate the behavior of HPC reinforced with hybrid PPFs when subjected to elevated temperatures. This study investigates the impacts of micro and macro hybrid PPFs on the mechanical, elevated temperature resistance, and microstructure properties of HPC. The primary focus is on the ideal amount of hybrid PPFs for maximum compressive, flexural, and residual strength of concrete at high temperatures. In addition, the microstructure of hydrated cement and the bonding qualities between cement, aggregate, and hybrid polypropylene fiber were investigated using scanning electron microscopy (SEM).

2. Experimental procedures

2.1. Material properties and mix design

In this research, Portland cement (PC) CEM I 52.5 N conforming to BS EN 197-1:2011 (BS EN 197-1, 2011) was used. Silica fume (SF) was used to replace part of the cement to improve the bond between the cement paste and the aggregate particles as well as increase the density of the cement paste. The PC and SF chemical compositions are summarized in Table 1. Chemical Analysis of PC was performed in accordance with ASTM 114-20 (ASTM 114-23). SF complies with ASTM C1240-20 standards (a). In line with BS EN 12620, natural siliceous sand with 4.75 mm, 2.65, 2.725, and 0.7% maximum size, specific gravity, fineness modulus, and water absorption, respectively, was used as fine aggregates (b). The coarse aggregates were crushed stones with 12 mm, 2.68, and 0.42% nominal maximum size, specific gravity, and water absorption, respectively. A superplasticizer with an ASTM C494 (ASTM C494/C494M−08) type F specific weight of 1.1 was used. As indicated in Fig. 1, this study used two distinct types of PPFs obtained from Sika company, Egypt:

(a) Macro fiber with 30 mm length, 0.3−0.5 mm thickness, 1.0−1.3 mm width, 0.9 gm/cm^3 density, 0.01−0.02% water absorption, 450−500 MPa crack tensile strength, 3.5 kN/mm^2 Young's elastic modulus, and 550/80 MPa compressive strength.
(b) Micro fibers with length 10−25 mm, 0.038 mm diameter, 1.3 gm/cm^3 density, 5 GPa elastic modulus, and 350−450 MPa tensile strength.

Table 2 shows the mix design of concrete mixtures. HPC with a target strength at age 28 days of 60−70 MPa and 150−200 mm slump was considered in the design of the control mixture in this investigation. Using trial and error, and the targets for workability and strength as a guide, the final control mixture proportions were established. Seven different concrete mixtures were created. Four types of concrete mixes were presented: one ordinary concrete mixture (Mo), one concrete mixture including 4 kg/m^3 of macro fiber, and one concrete mixture comprising 0.75 kg/m^3 of micro fibers, and four mixtures containing a hybrid polypropylene micro and macro fibers. All mixtures contain the same proportions of PC, SF, coarse aggregates, fine

Table 2. Components of mixtures (kg/m^3).

Mix	PC	SF	Sand	Dolomite	SP	water	Micro fibers	Macro fibers
M_O	450	50	740	1110	12.5	125	–	–
M_1	450	50	740	1110	12.5	125	0.75	–
M_2	450	50	740	1110	12.5	125	–	4
M_3	450	50	740	1110	12.5	125	1	4
M_4	450	50	740	1110	12.5	125	0.75	5
M_5	450	50	740	1110	12.5	125	0.75	3
M_6	450	50	740	1110	12.5	125	0.5	4

Table 1. Portland cement and Silica fumec chemical composition.

Oxide component	SiO_2	CaO	Al_2O_3	MgO	Na_2O	K_2O	SO_3	P_2O_5	Fe_2O_3
PC	21.6	64.93	4.18	1.61	0.09	0.78	3.35	0.09	3.32
SF	94.65	0.36	0.25	3.47	0.13	0.84	0.69	0.17	0.15

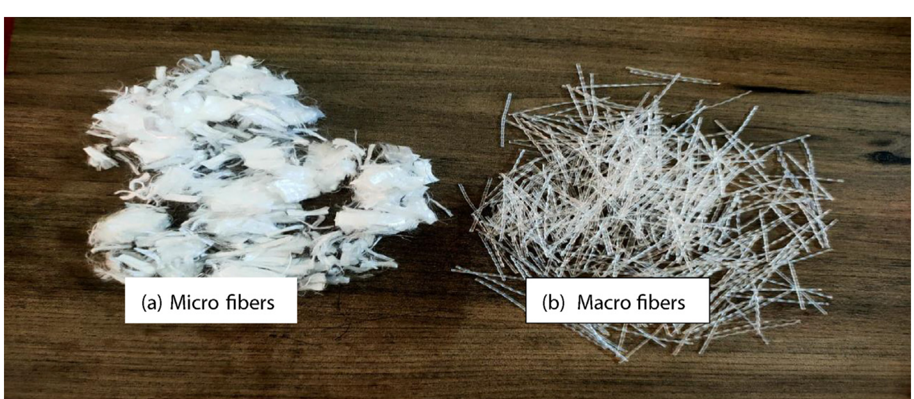

Fig. 1. Polypropylene fibers used.

aggregates, water, and superplasticizer (SP). The SCMs were divided into 90% cement and 10% SF. Dolomite to sand ratio and water to SCMs ratio were kept constant at 1.5 and 0.25, respectively. Superplasticizer was used at a rate of 2.5% of the weight of SCMs.

2.2. Test methods

2.2.1. Tests on fresh concrete

Workability is a physical property of concrete that affects its strength, durability, labor cost, and appearance. According to ASTM C143/C143M−20 (ASTM C143/C143M-15a), the workability of concrete mixtures was evaluated using the slump test.

2.2.2. Tests on hardened concrete

Compressive strength: Following mixing and testing for workability, concrete was poured into 100 mm cubes, and the samples' compressive strength was measured using ASTM C39 (BS EN 12390-3. Testing hardened concrete, 2019) after 7, 28, and 56 days. Testing was performed at a loading rate of 0.4 MPa/s on a 1000 kN capacity electronic servo testing machine. The value of compressive strength was the average of three specimens.

Flexural strength: Three-point loading was used to test flexural strength in accordance with ASTM C1609-19a (ASTM). Concrete samples were prepared, and poured into 100 × 100 × 500 prismatic molds, and their flexural strength was assessed after 56 days.

Elevated temperatures: To determine how elevated temperatures affect the compressive and flexural strength of HPC-integrated hybrid PPFs, the samples were heated to temperatures of 200 °C, 400 °C, and 800 °C for 1 h. Concretes were heated and then allowed to cool naturally in the laboratory to room temperature and then the compressive and flexural tests were conducted.

Microstructure: Utilizing SEM analysis, it was possible to determine how the research factors affected the internal microstructure of HPC. From the core of a 100 mm cube sample, slices of the samples selected were obtained for examination.

3. Results and discussion

3.1. Workability

The slump test was utilized to evaluate how PPFs affected the concrete mixtures' capacity to be produced. The preliminary testing results demonstrated that the various PPF contents significantly impacted the fluidity of concrete mixtures. Fig. 2 clearly shows that incorporating macro and micro fibers into the concrete mixtures resulted in a decrease in the slump value of concrete mixtures. When macro and micro PPFs were combined, the total amount of slump reduction would be greater than merely adding the slump reduction of these two distinct types of fibers due to different mechanisms and interactions. The high reduction in slump value was obtained at mixture M_4, which contains 5 kg/m^3 macro fibers and 0.75 kg/m^3 micro fibers; the slump has decreased from 20 cm to 15.5 cm. The fiber's lateral surface, which absorbs more cement paste and decreases the slump, was thought to be the cause of the decreased workability in concrete containing fibers (Shi et al., 2020b). These results

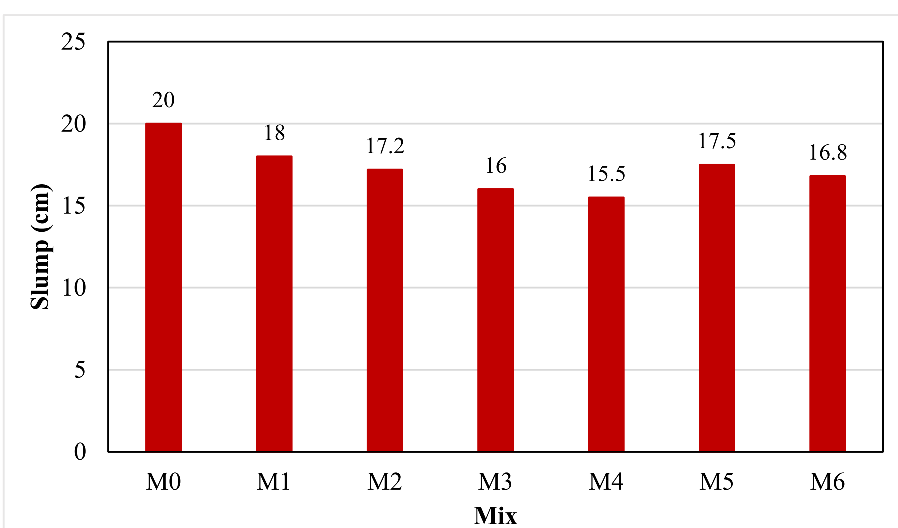

Fig. 2. Effect of hybrid polypropylene fibers on slump values of high-performance concrete.

agreed with Bing Chen and Juanyu Liu (Chen and Liu, 2005), and Tabatabaeian et al. (2017).

3.2. Compressive and flexural strength

Compressive and flexural strengths for all concrete mixtures are shown in Figs. 3 and 4, respectively. In comparison to concrete without fibers, the fiber-reinforced specimens' results demonstrate that the use of PPFs, in any shape and volume fraction, increased compressive and flexural strengths. It is illustrated that the increase in micro and macro fiber dosage increased compressive and flexural strength results. There was an insignificant impact on concrete compressive strength for the mixture incorporating 4 kg/m^3 macro fiber (M_1) and the mixture containing 0.75 kg/m^3 micro fibers (M_2) at ages 7, 28, and 56 days. The same result was obtained for flexural strength at age 56 days. Concrete reinforced with hybrid PPFs has significantly improved compressive strengths; the increase in compressive strength was 4.6%14.6%, 3.87%—14.28%, and 2.1%—11.4% at ages 7, 28, 56 days, respectively, compared with the control mix (M_0). Compressive strength increased for all fiber dosages as a result of confinement provided by the fiber, which enhances the bonding properties of concrete. This result is in agreement with Mohammadi et al. (2008c). Fig. 4

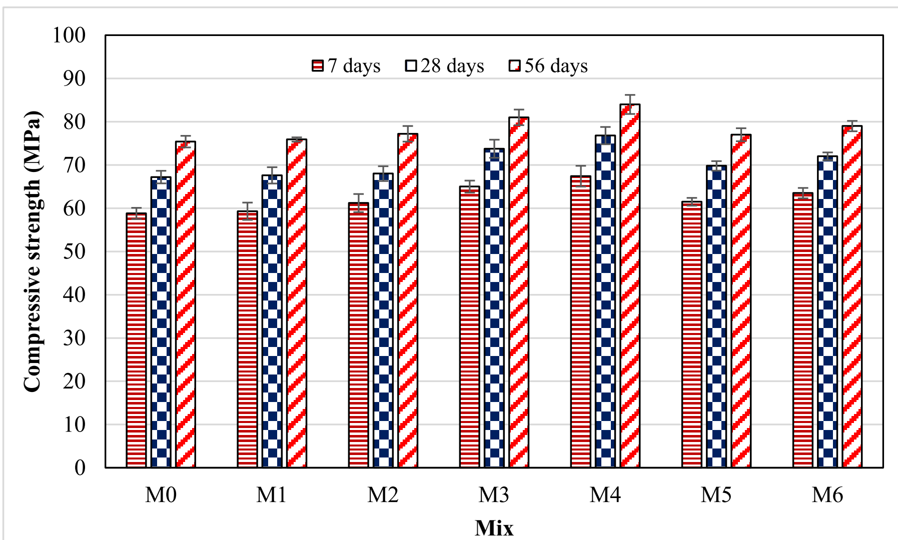

Fig. 3. Effect of hybrid polypropylene fibers on compressive strength of high-performance concrete.

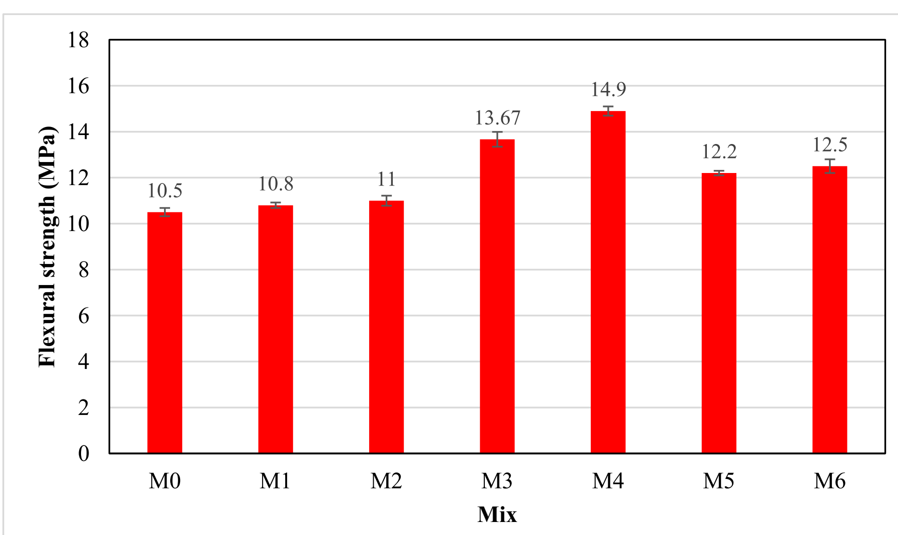

Fig. 4. Effect of hybrid polypropylene fibers on flexural strength of high-performance concrete.

shows a remarkable effect of hybrid PPFs on increasing concrete flexural strength. Among the different combinations of macro and micro PPFs considered in this study, the hybridization of 5 kg/m^3 macro PPFs and 0.75 kg/m^3 micro PPFs achieved a 41.9% increase in 56 days flexural strength of concrete. The outcomes of PPF-reinforced concrete demonstrate that the addition of PPFs significantly affected the concrete's flexural strength. The flexure strengths increased as predicted when the fiber volume percentage increased. The improvement in the bond between fiber and the cement paste is the reason the flexural strength increases remarkably. Moreover, fibers have a bridging mechanism that prevents cracks from spreading and decreases them. As the amount of fiber in the mixture rises, the effectiveness with which cracks widen is substantially improved. This shows that flexural strength and polypropylene fiber have a significant, direct relationship. Flexural strength may have increased as a result of concrete's better ductility, which has been improved by the inclusion of hybrid polypropylene fibers. These results are in agreement with A. Nkem and A. Oluwabambi (Ede and Ige, 2014). This is due to the behavior of a composite fiber concrete element that stops fiber concrete elements from brittle failure. Fig. 5 depicts the test configuration and specimen failure during the flexural strength test.

3.3. *Effect of elevated temperatures*

HPC samples with and without PPFs were placed inside the furnace and heated for 1 h at 200, 400, and 800 °C. After heating, the concrete was left to room temperature in laboratory conditions for normal cooling in the air. Fig. 6 shows the heating regimen used in this investigation. The findings of the compressive and flexural strength tests conducted on HPC at age 56 days with various PPF dosages at various temperatures are listed in Table 3 and shown in Figs. 7 and 8. The concrete samples frequently revealed a reduction in strength when subjected to high temperatures. He et al. (2021a) and Liu et al. (2020) revealed that above 400 °C, the internal structure of concrete has altered substantially; the interior pores gradually expand, resulting in a reduction in mechanical characteristics. Such degradation would be attributed to the concrete material's chemical and physical reactions when exposed to high temperatures, including thermal cracking, the rise in water vapor pressure, and the deterioration of hydrates. Furthermore, during the heating process, the concrete matrix primary hydration products go through chemical breakdown processes that have a significant effect on the mechanical characteristics. These include calcium silicate hydrate (C−S−H) and calcium hydroxide (CH) (He et al., 2021b; Elemam et al., 2022). Samples containing PPFs were damaged less than the control sample without fibers. The result illustrated that the hybridization of 5 kg/m^3 macro PPFs and 0.75 kg/m^3 micro PPFs outperformed the control mixture in terms of residual compressive and flexural strength. The drops in compressive strength of the control mixture were 2, 28.8, and 46.9% when heated to 200, 400, and 800 °C, respectively. However, when concrete was heated to 200, 400, and 800 °C, respectively, the compressive strength of the combination comprising 5 kg/m^3 macro PPFs and 0.75 kg/m^3 micro PPFs decreased by 0.6, 16.2, and 35.7%. These results were consistent with those of Srikar et al. (2016), who discovered that the concrete

(a) (b)

Fig. 5. (a) Flexural strength test setup and (b) failure of the specimen.

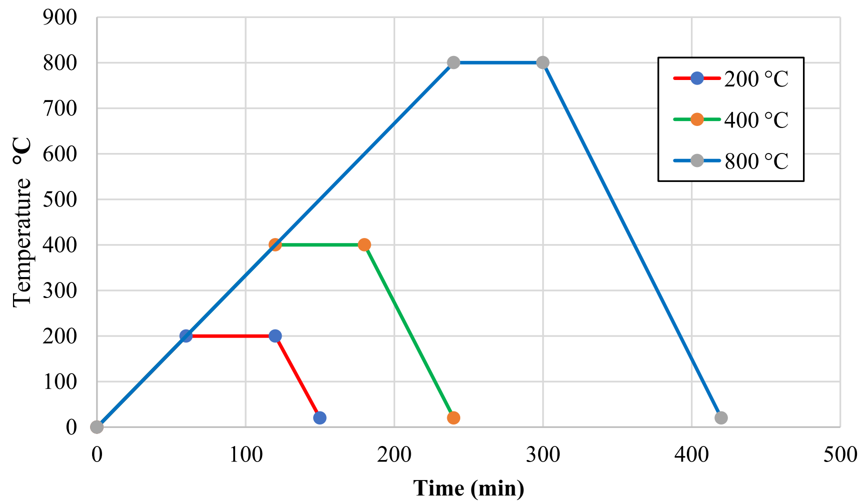

Fig. 6. Heating regime.

Table 3. Testing results of high-performance concrete mixtures with polypropylene fibers exposed to elevated temperatures.

Mix	Macro fibers (kg/m^3)	Micro fibers (kg/m^3)	Compressive strength (MPa)				Flexural strength (MPa)			
			20 ± 2 °C	200 °C	400 °C	800 °C	20 ± 2 °C	200 °C	400 °C	800 °C
M_0	–	–	75.4	73.9	53.7	40.0	10.50	9.80	4.0	2.4
M_1	–	0.75	75.9	74.0	54.0	42.0	10.80	10.00	4.8	3.1
M_2	4	–	77.2	75.0	57.0	45.0	11	10.20	5.9	3.6
M_3	4	1	81	79.0	61.3	44.8	13.67	12.17	8.4	4.3
M_4	5	0.75	84	83.5	70.4	54.0	14.9	14.40	11.0	6.8
M_5	3	0.75	77	75.7	55.0	35.7	12.2	11.00	5.5	3.2
M_6	4	0.5	79	79.0	62.8	40.8	12.50	11.00	7.0	3.0

compressive strength dropped by around 13% and 22%, respectively, when the samples containing PPFs were exposed to 200 °C and 300 °C. The same results were illustrated for flexural strength, the residual strength of mixes incorporating 0.75 kg/m^3 micro PPFs and 5 kg/m^3 macro PPFs were 96.6, 73.8, and 45.6% when heated to 200, 400, and 800 °C, respectively, while the residual strength was 93.3, 38, and 22% when heated to 200, 400, and 800 °C, respectively. Hybrid PPFs dissolve to lower pore pressure before

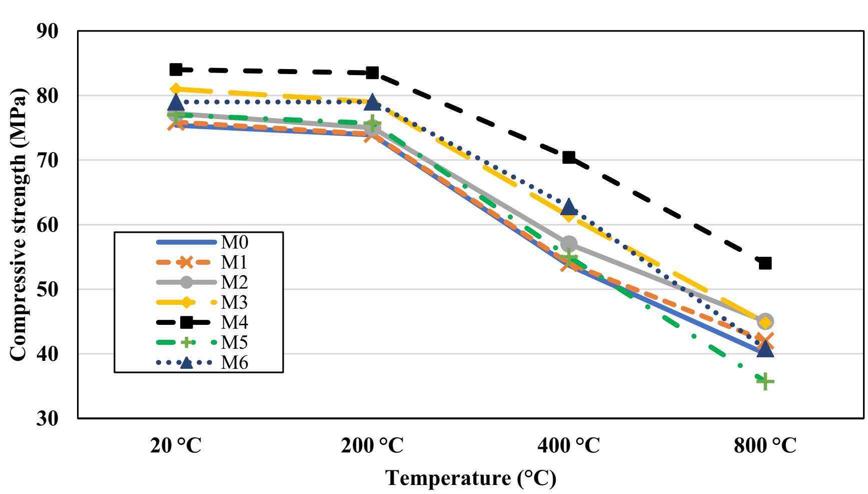

Fig. 7. Concrete compressive strength with different dosages of polypropylene fibers at different temperatures.

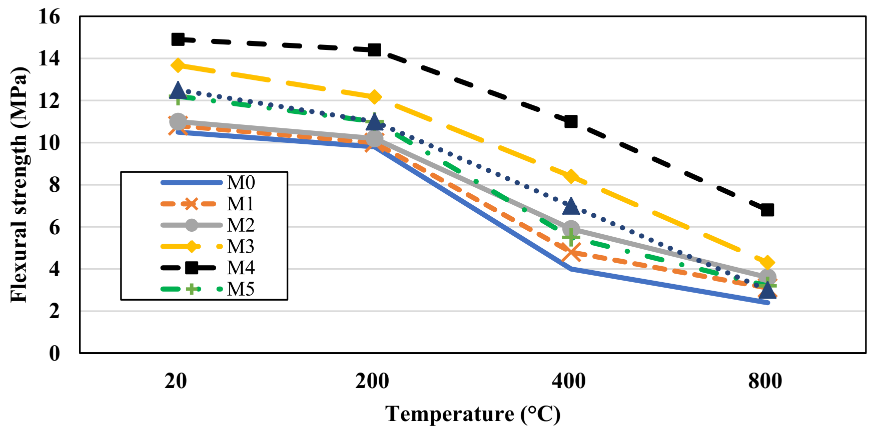

Fig. 8. Concrete flexural strength with different dosages of polypropylene fibers at different temperatures.

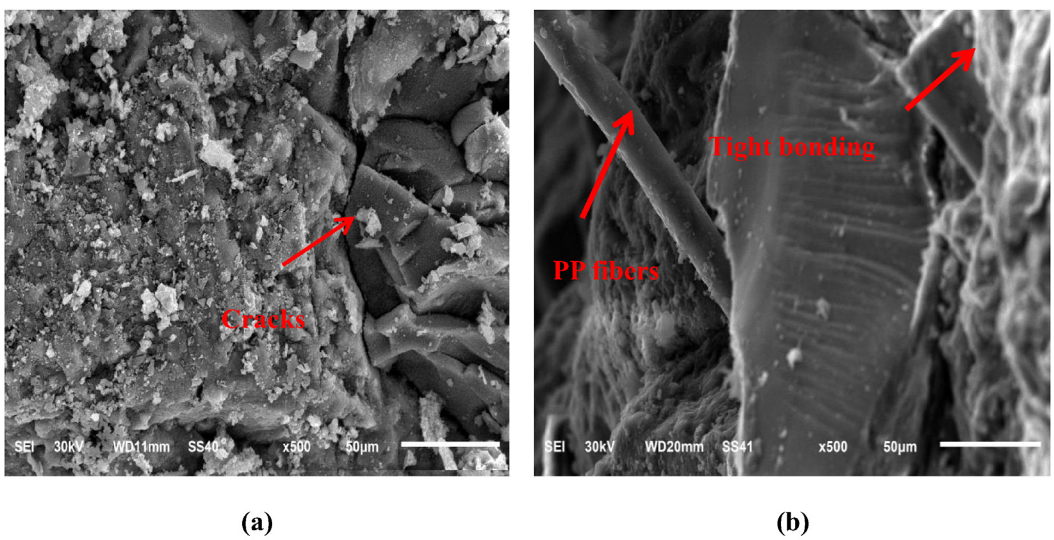

Fig. 9. Scanning electron microscopy images for (a) mix M_0 and (b) mix M_4.

spalling, which avoids concrete's explosive spalling at elevated temperatures (Zeng et al., 2021). These results are in agreement with Abaeian et al. (Sultangaliyeva et al., 2023).

3.4. Scanning electron microscope (SEM)

In this part, the SEM analysis was carried out on specimens with the same level of accuracy to take a look at the effects of hybrid PPF dose on the microstructure of concrete. In Fig. 9a the concrete appears cohesive and dense, but it has random fractures and pores that would reduce the concrete's strength. However, in Fig. 9b, hybrid PPFs have the most homogeneous and compact microstructure; the interior structure of hybrid PPF specimens is dense and without any visible holes, and their gels appear to be continuous and integral. An uneven fiber surface resulted from a cement hydro by-product process on the PPF's surface, which created a physical interlocking effect between the interfaces and increased the strength of the bond between the polypropylene fiber and the cement matrix. Fiber may perform its networking functions by bridging cracks. However, identifying the interfaces between several crystalline layers seems challenging to give the hybrid PPFs a strong binding property (Ramezanianpour et al., 2013; Liu et al., 2021).

4. Conclusion

This study intends to investigate the effect of hybrid polypropylene micro and macro fibers on the mechanical performance, resilience to elevated temperatures, and internal microstructure of HPC. The most noteworthy findings are summarized as follows:

(1) Compared with a control mixture without fibers, the workability of concrete decreased when macro and micro PPFs were added to mixtures. The use of hybrid PPFs leads to a greater reduction in slump value than these two distinct types of fibers.
(2) The inclusion of PPFs, whether in a single or hybrid form, enhanced the compressive and flexural strengths of concrete. Concrete reinforced with hybrid PPFs has significantly improved compressive strengths. The increase in compressive strength was 4.6%–14.6%, 3.87%–14.28%, and 2.1%–11.4% at ages 7, 28, and 56 days, respectively, compared with control mixture.
(3) The combination of 0.75 kg/m^3 micro PPFs and 5 kg/m^3 macro PPFs achieved a 41.9% improvement in concrete flexural strength at age 56 days.
(4) HPC's compressive and flexural strengths decrease as the temperature rises; however, the addition of hybrid PPFs reduced the strength loss rate. In comparison to the control mixture, the combination of 0.75 kg/m^3 micro PPFs and 5 kg/m^3 macro PPFs produced the highest residual compressive and flexural strength.
(5) SEM photographs show random fractures and pores in control mixtures without fibers while mixtures with hybrid PPFs are compact, dense, homogeneous, and their gels seem to be continuous and integral.

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Author contribution/author credit statement

Ahmed M. Tahwia: Visualization, supervision, final approval of the version to be published.

Marwa M. Ouda: Data collection and tools, resources, investigation, drafting the article.

Mohamed Abdellatief: Methodology, investigation, drafting the article.

Walid E. Elemam: Visualization, data analysis and interpretation, supervision, critical revision of the article.

Conflicts of interest

There are no conflicts of interest.

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