Iranian Journal of Science and Technology, Transactions of Civil Engineering (2023) 47:2865–2877
https://doi.org/10.1007/s40996-023-01092-z

RESEARCH PAPER

The Effects of Fiber Volume Ratio and Temperature on the Flexural Performance of Macro-Synthetic Fiber-Reinforced Concrete

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Received: 25 October 2022 / Accepted: 4 March 2023 / Published online: 6 April 2023

Abstract

In this study, the effects of macro-synthetic fiber (MSF) ratios and various temperatures on the flexural performance of MSF-reinforced concrete were investigated. MSF-reinforced concrete was produced in the C40 strength class, which is widely used in industrial concrete applications. The effects of fiber content and temperature variations on the flexural strength and toughness of MSF-reinforced concrete were analyzed. In this context, flexural specimens were produced by replacing 0.5%, 1.0%, 1.5%, and 3% MSF by volume with concrete instead of aggregate. The specimens were tested using a four-point flexural test at a negative temperature (−5 °C), ambient temperatures (20, 50 °C), and non-ambient temperature (90 °C). In addition, pull-out tests were applied to the fibers embedded in the concrete specimens to determine the bond performance between the MSF and concrete under different temperatures. The effective MSF content for the concrete was determined to be in the range of 1–1.5% according to the results of thermal performance, bending behavior, ductility, and workability factors. Although the flexural performance of MSF-reinforced concrete decreased relatively with the temperature increase, the results were promising at certain fiber volume ratios and ambient temperatures.

Keywords Ambient temperature · Fiber-reinforced concrete · Flexural test · Macro-synthetic fiber · Pull-out test · Toughness

1 Introduction

Concrete is one of the most widely used building materials owing to its advantages such as high performance, economy, and durability against external effects. As is well known, concrete shows high compressive strength. However, its low tensile strength makes it a brittle material. Therefore, concrete is reinforced with materials providing tensile strength and ductility. The most common practice in this area is to reinforce concrete with steel bars or steel grids, which are now widely used in most civil engineering structures. Short fibers have recently been produced from various materials, especially steel, glass, carbon, basalt, and vegetable fibers, as an alternative to steel bars, especially in concrete. Compared with fiber-free concrete, fiber-reinforced concrete (FRC) shows higher toughness, energy absorption, and strength after cracking. In addition, strengthening concrete with fibers is an effective way to increase the strength and ductility of concrete and prevent crack progression (Topcu 2006).

Researchers have recently studied and continue to investigate the use of fiber in concrete and its effect on concrete properties. Fibers contribute to concrete performance, especially under effects such as flexural effects, where the concrete is subjected to tensile stresses. As the purpose of adding fiber to concrete is to increase energy absorption and load-carrying capacity after the first crack, the reaction and toughness after the first crack are considered key beneficial properties of FRC (Sukontasukkul et al. 2010). Recently, the use of short and randomly distributed fibers has drawn wide attention due to their effectiveness in improving the different physical and mechanical properties of concrete materials (Bentur and Mindess 2006). However, steel fibers have certain issues with corrosion and electromagnetic characteristics in alkaline or chemical conditions (Kosa and Naaman 1990). Corrosion of steel fibers in an alkaline or chemical environment can negatively affect the crack-bridging effect of the fibers and the appearance of the concrete structure

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(Balouch et al. 2010). For these reasons, the usage of various types of synthetic fibers (polypropylene, polyethylene, polyvinyl chloride, etc.) has been investigated by many researchers in recent years (Ahmad and Zhou 2022; Aly et al. 2008; Buratti et al. 2011; Gao et al. 2010; Vrijdaghs et al. 2017; Wu 1982; Yin et al. 2015; Zheng and Feldman 1995). Polypropylene (PP) fiber-reinforced concrete shows high stability in a chemical environment (Zheng and Feldman 1995). In concrete reinforcement, two types of synthetic fibers are used: micro-synthetic fiber to compensate for micro-cracks caused by plastic shrinkage of cement (Aly et al. 2008), and macro-synthetic fiber (MSF) to improve concrete toughness and tensile strength (Yin et al. 2015). The usage of polypropylene-based MSF is increasing constantly due to the advantages compared with steel fibers, such as lower elasticity modulus (Buratti et al. 2011), higher ductility (Vrijdaghs et al. 2017), and adhesion to cement matrix (Wu 1982). It is also well known that polymer fibers are less sensitive to the effects of corrosion, alkaline reactions, acidic water, salt, chlorine, chemicals, and microorganisms (Gao et al. 2010).

PP fibers have a small effect on the strength of cement-based materials in general; however, their ability in crack resistance and effects on ductility development are promising (Reza and Ozbakkaloglu 2019). Some studies have indicated that the compressive strength of polypropylene-reinforced concrete does not change by adding fibers (Alhozaimy et al. 1996; Bei-xing et al. 2004; Clarke et al. 2022; Mazaheripour et al. 2011), while others have reported an increase of up to 20% (Bhat et al. 2022; Hsie et al. 2008; Kakooei et al. 2012). In fact, flexural strength testing seems to be a more suitable choice than compression testing to determine the properties of the fiber, because the main purpose of adding fiber to the concrete mix is to improve its ability to absorb energy and sustain loads using the fibers' ability to act as a bridge between cracks after the initial crack (Sukontasukkul et al. 2010). In studies conducted on polypropylene FRC, some researchers reported no effect in terms of flexural strength (Alhozaimy et al. 1996; Bei-xing et al. 2004), while other studies indicated an increase of 10% (Cifuentes et al. 2013; Hsie et al. 2008; Mazaheripour et al. 2011), and a decrease was found in a study by Wu (2002). In addition, some studies have reported higher flexural toughness and ductility with a percentage of fiber substitution compared to concrete without fiber reinforcement (Bei-xing et al. 2004; Cifuentes et al. 2013; Hsie et al. 2008; Wu 2002). Behfarnia and Behravan (2014) showed in their study that polypropylene fibers were not effective in improving compressive strength compared to steel fibers, but their effects on tensile strength, flexural strength, toughness, and energy absorption of concrete were important. In the study carried out by Simões et al. (2017), polypropylene fibers were added to the concrete mix at a rate of 0.5% and 2% with 0.5% increments. It was reported that while the strength and toughness index values increased in proportion to the increase in fiber addition, there was a partial decrease in the cracking loads. In the experimental studies carried out by Hasan et al. (2011), it was concluded that if MSFs are reinforced into concrete, it partially improves the compressive, tensile, and shear strength of concrete as well as its ductility. Nana et al. (2021) noted that polypropylene macro-synthetic FRC exhibited non-monotonic post-cracking behavior marked by a first drop of the load-crack mouth opening displacement (CMOD) curve after cracking to more than 67% for a CMOD of 0.5 mm, followed by strength recovery up to stress stability.

The performance of FRC, especially MSF-reinforced concrete, in different environmental temperatures is important, because synthetic fibers melt at temperatures of approximately 160–170 °C. The flexural performance of FRC under high and low temperatures has been studied by many researchers (Abaeian et al. 2018; Aidarov et al. 2022; Alan et al. 2018; Ashkezari and Razmara 2020; Choumanidis et al. 2016; Çavdar 2013; Müller et al. 2019; Peng et al. 2006; Poon et al. 2004; Richardson and Ovington 2017; Sukontasukkul et al. 2010). Peng et al. (2006) studied the dispersion resistance of FRC at high temperatures and found that polypropylene-reinforced concrete could provide better strength than either plain or steel FRC. This result was attributed to the fact that polypropylene fiber melts at temperatures below 170 °C, which then creates air voids and allows moisture to escape. In a study on concrete formed with MSFs, Alan et al. (2018) noted that the ability of MSF-reinforced concrete to carry stresses under pressure and tensile stress was affected very little up to 100 °C but decreased significantly at 400 °C and above. Poon et al. (2004) found that the compressive strength of fiber-free and polypropylene fiber concrete did not change at temperatures below 200 °C; however, the strength and compressive toughness of polypropylene fiber concrete decreased rapidly as the temperature rose above 200 °C. Sukontasukkul et al. (2010) reported that post-peak flexural response in FRC is affected by temperature level and fiber type. They also noted that the post-peak response improved with increased post-peak load and flexural toughness below 400 °C, but the post-peak response began to strongly depend on the fiber type above 400 °C. In addition, they found that for polypropylene fibers, large decreases in the behavior of flexural load–deflection are observed due to the melting of the fiber. As a result of their flexural tests with different fiber types at temperatures of 20 °C and 280 °C, Choumanidis et al. (2016) reported that long polypropylene fiber reinforcements contributed positively to the strength and ductility of concrete at ambient temperature, while their positive behavior was lost at 280 °C. According to Çavdar (2013), polymeric fiber reinforcement contributes to the flexural strength of mortars under normal dry conditions of 100 °C and continues to do so up to 450 °C. Moreover, the highest increase in flexural strength and the lowest decrease in compressive strength were achieved at a rate of 0.3–0.9% fiber, and this performance was negatively affected at temperatures above 450 °C. Abaeian et al. (2018) investigated the compressive, tensile, and flexural strength performance of high-strength concrete with 1, 2, and 3 kg/m^3 synthetic macrofiber at temperatures of 25, 100, 200, and 300 °C. They found that the tensile and flexural performance improved with the increase in fiber volume ratio, but the compressive strength decreased somewhat, and the best efficiency was achieved with 1 kg/m^3 fiber reinforcement. They reported that the mechanical performance decreased with the increase in temperature, but was still higher than that with the fiber-free high-strength concrete at the same temperatures. In the same study, it was emphasized that fiber reinforcement of more than 1 kg/m^3 has a negative effect on workability. Richardson and Ovington (2017) applied flexural tests on 4 kg/m^3 macro-synthetic FRC at −20, 20, and 60 °C. In polypropylene fiber-reinforced concrete, a decrease in flexural performance was observed at 60 °C compared to fiber-free concrete, while increases in performance were observed at 20 °C and −20 °C. Aidarov et al. (2022) attributed the post-cracking improvement of FRC's flexural strength by up to 71% to the increase in the energy required to pull the fiber out at low temperatures.

The behavior of polypropylene fibers in different heat environments was studied by different researchers. These studies focused mainly on the performance of polypropylene-reinforced concrete under high temperatures such as fire. The melting temperature of polypropylene fibers is around 160–170 °C, and they melt under high temperatures; therefore, their contribution to strength and ductility after the first peak is negatively affected. In terms of concrete design, it is critical to investigate the effects of these fibers and mix ratios on the performance of concrete when used in environments with temperatures lower than their melting point. There are many different types of macro-synthetic fibers studied in the literature. However, it has been determined that the behavior of the concrete produced with this type of fiber under the influence of temperature (to the best of the authors' knowledge) has not been studied yet.

In this study, the performance of MSF-reinforced concrete prepared using different fiber volume ratios was investigated under temperatures of −5, 20, 50, and 90 °C. In the experimental study, the flexural behavior, flexural strength, and toughness were examined in detail depending on the temperature and fiber volume ratio changes of MSF-reinforced concrete. In addition, the effect of temperature on the bond strength between concrete and MSF was examined with the pull-out test method.

2 Experimental Study

2.1 Research Parameters and Test Matrix

MSF has started to be used instead of steel reinforcement in reinforced concrete. However, there is no information (to the knowledge of the authors) on the strength and behavior of this MSF-reinforced concrete under the temperature effects of ambient conditions lower than its melting temperature. This study focused on the flexural performance of concrete containing MSF at different ratios by volume at ambient conditions below the melting temperature of the fibers.

Concrete samples prepared with different fiber reinforcement ratios (0.5%, 1.0%, 1.5%, and 3%) were tested under temperatures of −5, 20, 50, and 90 °C. The changes in flexural strength, flexural behavior, and flexural toughness depending on different temperatures and fiber volume ratios were investigated.

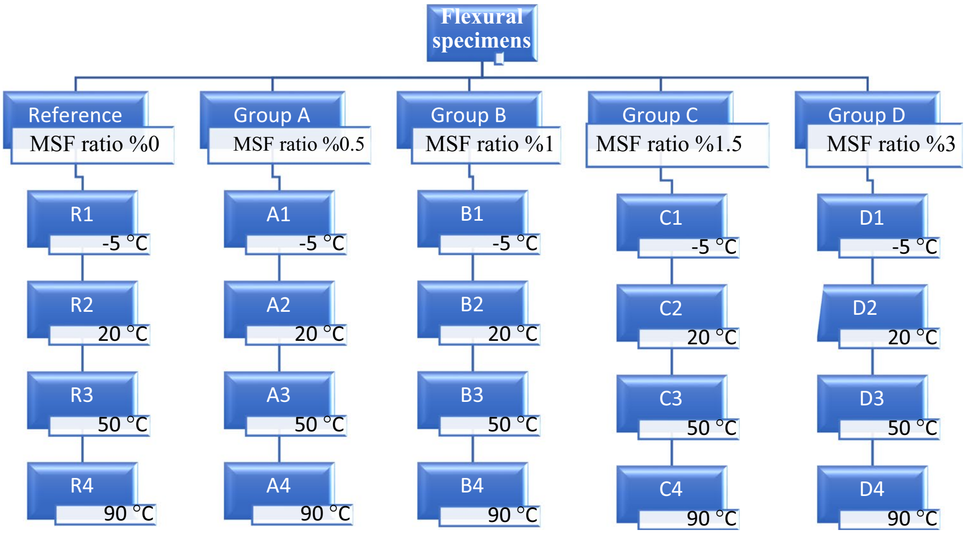
In addition, the effect of fiber content on workability and adhesion performance of concrete under different temperatures was examined. Thus, this study aims to recommend the most appropriate fiber content in MSF-reinforced concrete and to determine the relationship between the change in mechanical performance and the adherence between concrete and fibers with temperature by pull-out tests applied to the fibers at different temperatures. The names and test matrices of the flexural specimens are presented in Fig. 1. Letters and numbers were used in naming the specimens. "R" was used for reference (fiber-free) specimens, A, B, C, and D were used for 0.5%, 1%, 1.5%, and 3% rates of MSF substitution, respectively, and 1, 2, 3, and 4 were used for temperatures of −5, 20, 50, and 90 °C, respectively.

2.2 Materials

2.2.1 Concrete Materials

The fiber-free concrete matrix consisted of 0–4 mm natural river sand, no. 1 (4–12 mm) and no. 2 (12–24 mm) crushed stone, CEM I 42.5 R cement, water, and a plasticizer additive. MSF-reinforced concrete matrix contained MSF in addition to the components in the fiber-free concrete. According to the results of experiments conducted in the laboratory, the saturated dry surface densities of the stream aggregate and crushed aggregate were 2.72, 2.69, and 2.65 kg/dm^3, respectively, and the density of the cement was 3.10 kg/dm^3. The results of the sieve analysis on the aggregates according to TS EN 12620 (TS EN 12620 2009) showed that the appropriate mixing ratios

Fig. 1 Test matrix of specimens



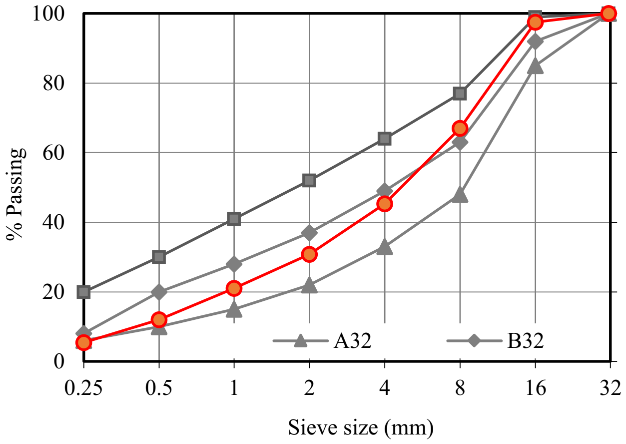


Fig. 2 Aggregate granulometry limit values and mixing

Fig. 3 Macro-synthetic fiber (KraTos Macro 40)

were 40% sand, 30% no. 1 crushed aggregate, and 30% no. 2 crushed aggregate. The granulometry curve of the designed aggregate mixture is shown in Fig. 2, along with the limit curves specified in the standard and an appropriate distribution ratio. The average compressive strength of the cube control concrete produced by making mixture calculations according to TS 802 (2010) standard (TS 802 2016) was found to be 48.07 MPa, and the standard deviation was found to be 2.26.

2.2.2 Macro-Synthetic Fiber

In this study, MSF produced under the name "KraTos Macro 40" was used in the concrete (Fig. 3) (Web Page 2021). The fiber material was polypropylene/polyethylene produced according to EN 14889–2 (EN 14889–2 2015) standard.

Fiber equivalent diameter and length were 0.433 and 40 mm, respectively, the tensile strength was 620 MPa, the melting temperature was 160 °C, and the elasticity modulus was 9500 MPa. The properties of the MSF determined by the manufacturer are presented in Table 1.

Table 1 Characteristic properties of synthetic fibers (Web Page 2021)

KraTos Macro 40	Characteristic properties
Raw material	Polypropylene/polyethylene
Density (gr/cm^3)	0.91
Length (mm)	40
Geometry (mm)	Rectangle
Cross-section (mm)	0.1 × 1.5
Equivalent diameter (mm)	0.433
Tensile stress (MPa)	620
Elastic modulus (MPa)	9500
Melting temperature (°C)	160

2.2.3 Mixture Preparation and Specimen Production

The concrete mixture design was determined according to TS 802 (2016), considering the C40 concrete strength class. The water/cement (W/C) ratio of the mixture was taken as 0.42. The amount of water was determined to make the fresh concrete slump in the range of 15–20 cm for the control concrete. However, the amount of water was reduced by adding 1% plasticizer to the cement weight. The mixing ratios were rearranged, and the W/C ratio was determined as 0.37. The computed material in 1 m^3 of concrete is shown in Table 2.

The concrete mixture was prepared in a rotary drum mixer according to the mixture calculation (Fig. 4a). The workability of fresh concrete was checked with the slump test according to TS EN 12350–2 (2000). Fresh concrete was poured into molds and compressed with a vibration table (Fig. 4b). The specimens (Fig. 4c) that had spent 24 h in the mold were kept in the curing tank (Fig. 4d) for 28 days.

2.3 Test Method

2.3.1 Four-Point Bending Test

The four-point bending test method was used for the flexural test. The experiments were carried out with a Shimadzu universal test device with a load capacity of 50 KN. The distance between the two supports was 420 mm, and the beam was divided into three equal areas (Fig. 5).

Table 2 Mixture properties in 1 m^3 concrete

	Fiber volume ratio	Cement 42.5	Water	River aggregate	4–12 mm aggregate	12–32 mm aggregate	Total
Reference	0	519	192	694	469	508	2382
A	0.5	519	192	689	465	504	2373
B	1	519	192	683	461	499	2364
C	1.5	519	192	678	458	495	2355
D	3	519	192	661	446	483	2329

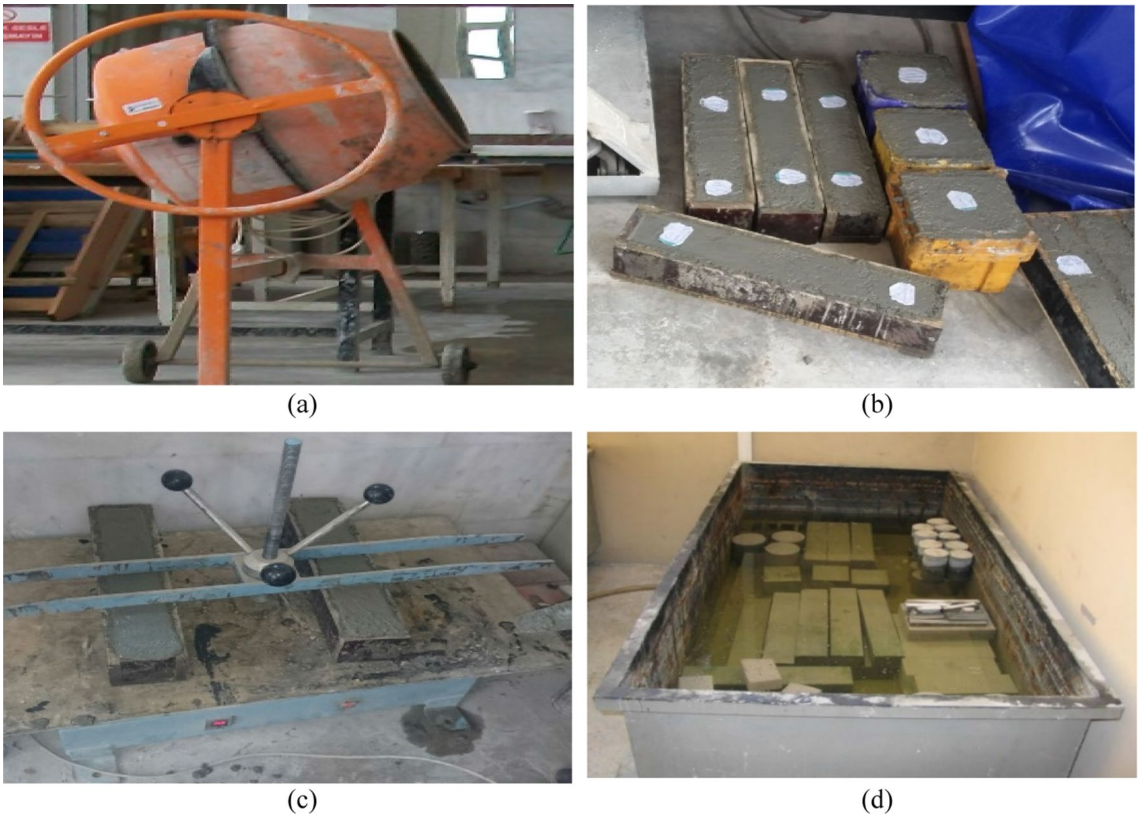

(a) (b) (c) (d)

Fig. 4 Concrete production stages: **a** mixing, **b** molding, **c** vibration, and **d** curing

Fig. 5 Four-point bending test setup

Loading speed was selected at 0.05 MPa/s in order to provide a constant stress increase rate according to TS EN 12390–5 (2019). Load and deflection values were automatically transferred from the test device to the computer, depending on the time.

The flexural specimens were heated in an oven and frozen in a freezer. The specimens were stored for 24 h in various temperature environments (−5, 20, 50, and 90 °C) with a 5 °C tolerance. The temperature of the specimens was measured both before and after testing. Since the laboratory conditions were 20 ± 3 °C, the experimental temperatures of the specimens were maintained under laboratory conditions. Other specimens, which were kept at 5 °C above the test temperature in the heat cabinets, were placed in the test device and tested after they reached the desired surface temperature (Fig. 6).

Fig. 6 Temperature control

The load–deflection graphs of the specimens were prepared, and the flexural strength of the specimens was calculated by Eq. (1) defined in TS EN 12390–5 (2019).

$$f_{cf}=\frac{FL}{d_1 d_2^2} \tag{1}$$

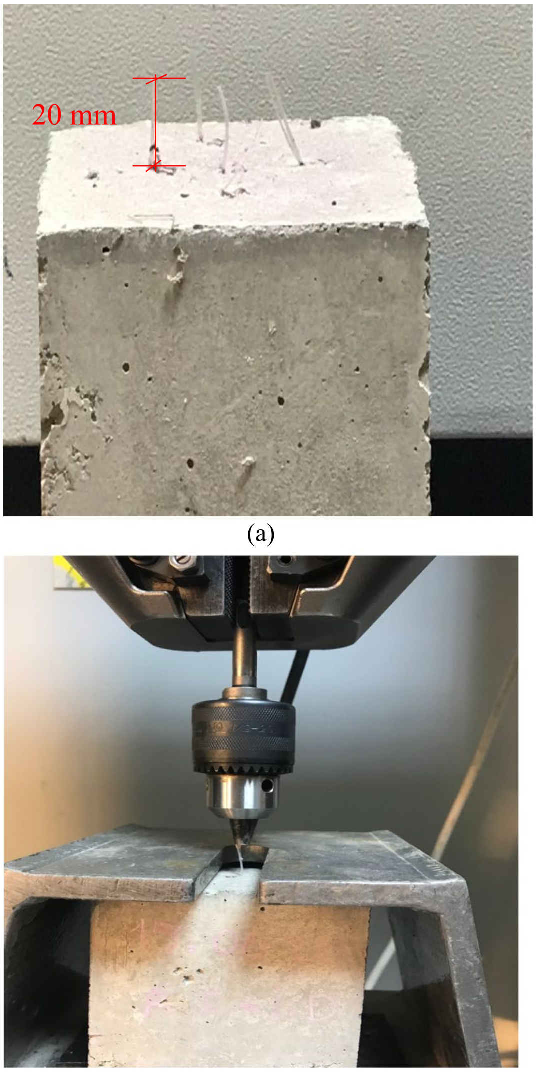
Here, f_{cf} is the flexural strength (N/mm^2), F is maximum load (N), L is the effect span of the rollers (mm), and d_1 and d_2 refer to the cross-sectional dimensions of the specimens (mm).

2.3.2 Pull-Out Test

Pull-out tests were applied to the fibers embedded in the concrete specimens to determine the bonding performance of MSF with concrete under different temperatures. MSFs were embedded vertically up to half of their length (20 ± 2 mm) into concrete. After the samples completed the 28-day strength-gain process, they were stored at temperatures specified in the bending test for 24 h. The experiments were carried out with a Shimadzu universal tester. The specimens and the pull-out test set are given in Fig. 7a, b. The concrete specimen was fixed in a frame at the bottom of the designed pull-out test system. The frame of the specimen was attached to the tester from the bottom. Part of the MSFs outside the concrete specimen was held tightly with the help of a drill head and tied to the upper head of the test device. After the specimens were placed in the test device, their temperatures were controlled and tested when they reached the desired temperature. During the experiment, while the lower head of the set was fixed, the upper head was pulled upward at a 30 mm/min test speed. The load and slip data obtained from the pull-out test were collected via computer, and the results were analyzed.

2.3.3 Concrete Slump Test

The slump test was applied to the fresh concrete mixtures with different fiber volume ratios according to the TS EN 12350–2 (2000) standard to determine the effect of substituted MSFs on the consistency and workability of the concrete. For this purpose, the concrete mixtures with fiber reinforcement in different proportions were mixed in the mixer and then filled into the slump cone in three stages. The cone was slowly removed and put next to the collapsed concrete. The distance between the inverted upper part of the cone and the upper part of the fresh concrete was measured with a tamping rod.



(a)

(b)

Fig. 7 Pull-out test: **a** pull-out test specimen and **b** pull-out test setup

3 Test Results

MSF-reinforced concrete beams were tested by a four-point bending test under constant speed loading and at specified temperatures. The load–deflection, toughness, and flexural strength data obtained from the bending test results of MSF-reinforced concrete beams are presented in Table 3. In addition, the effect of temperature change on concrete with the same and different MSF content is discussed in the relevant sections.

3.1 The Effect of MSF Rates on Workability

The slump test results, which are a criterion for workability, are presented in Fig. 8.

The slump value of the fiber-free concrete was found to be 16 ± 3 cm. The workability of concrete decreased as the fiber volume ratio increased, which had a negative impact on the placement of the concrete into the mold. Fibers increase the viscosity of the concrete and cause a decrease in workability by restricting the distribution of the cement matrix. Similar results were found in the literature (Mazaheripour et al. 2011; (Yap et al. 2013; Akça et al. 2015). For instance, Mazaheripour et al. (2011) observed that the presence of polypropylene fibers in lightweight concrete greatly reduced the slump flow. They reported that the addition of 0.3% polypropylene fiber resulted in a 40% reduction in flow. Yap et al. (2013) revealed that the workability of fresh concrete was dependent on microfiber geometry.

The experimental observations revealed that there were problems in placing the concrete into the mold if the MSF substitution was above 1.5% by volume. The fiber volume ratio in concrete can be increased up to 1.5%, but in this case, it will be necessary to choose a higher consistency to be more fluid and to use superplasticizers. Akca et al. (2015) also found that macro-synthetic fiber negatively affected the workability of concrete, but they reported that this problem could be solved by adding a superfluidizer additive to the concrete mixture. However, it should not be ignored that fibers may be piled up towards the upper region of the cross-section because MSF is the lightest material in the concrete matrix during the placing of fresh concrete.

3.2 Flexural Behavior

3.2.1 Effects of MSF Ratios on Flexural Behavior

In the experimental study, the effect of MSF ratios on concrete flexural performance was investigated under specified temperature conditions. The load–deflection graphs obtained from the four-point bending test results of the flexural specimens produced using MSF at 0.5%, 1%, 1.5%, and 3% by volume in one cubic meter of concrete are presented in Fig. 9.

As indicated by the load–deflection graphs, the fiber-free concrete specimen was broken suddenly and did not carry more load after the peak load. However, it was observed in MSF-reinforced concrete specimens that the concrete cracked at the first peak load, but after some strength loss, the load was carried by the fibers and had a large amount of displacement before failing. With reference to the control concrete, there was no increase in the maximum load carried by the concrete except for the C2 specimen, and a partial strength increase after the first cracking was observed in the C2 specimen with a 1.5% MSF replacement ratio. There was a gradual increase in the second peak loads up to 1.5% fiber reinforcement with the increase in MSF ratio, similar to the results found by Simões et al. (2017). In our study, it

Table 3 Flexural experiment results of the specimens

Specimen	First peak load (N)	Second peak load (N)	First peak deflection (mm)	Second peak load deflection (mm)	Average toughness values (Nmm)	Strength of first peak (N/mm^2)	Strength of second peak (N/mm^2)
R1	6258	–	0.71	–	1902	2.08	–
R2	4106	–	0.78	–	2054	1.35	–
R3	3925	–	0.59	–	1103	1.30	–
R4	2994	–	0.70	–	867	0.99	–
A1	5898	4591	2.00	3.34	36,581	1.96	1.52
A2	4426	3356	1.00	3.33	39,910	1.47	1.11
A3	4104	2888	1.00	3.45	32,963	1.36	0.96
A4	3142	2151	1.00	3.50	25,590	1.04	0.71
B1	5841	5897	0.84	4.51	60,338	1.94	1.96
B2	4486	3803	1.40	3.23	45,627	1.49	1.26
B3	2989	2959	0.75	3.75	37,837	0.99	0.98
B4	2747	2200	2.02	4.18	29,504	0.91	0.73
C1	6573	6797	5.83	10.83	86,232	2.18	2.26
C2	4108	5642	1.75	6.50	57,935	1.36	1.87
C3	3595	4208	1.17	4.67	49,956	1.19	1.40
C4	3909	4059	2.86	5.19	39,721	1.30	1.35
D1	7477	7477	3.67	3.67	70,774	2.48	2.48
D2	3489	4237	1.50	3.33	44,131	1.16	1.41
D3	3048	3064	1.50	2.25	35,147	1.01	1.02
D4	2939	–	1.83	–	27,623	0.98	–

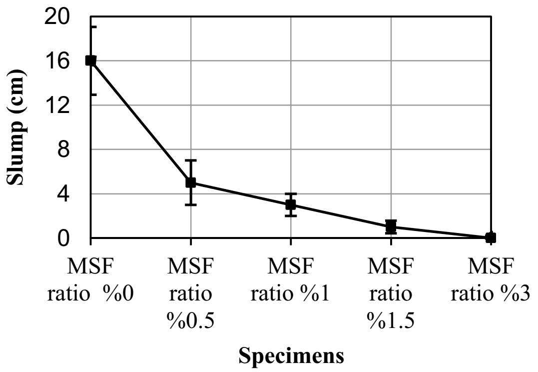


Fig. 8 Slump test results for MSF volume ratios

was seen that there was a decrease at the second peak when the amount of fiber was increased to 3%. The effect of fiber volume ratios in concrete is better understood after the first peak load, and it was seen that the contribution of fiber reinforcement was on toughness rather than strength.

Polypropylene fiber reinforcements were already expected to contribute to effects such as crack control and ductility development after the first crack rather than strength (Reza and Ozbakkaloglu 2019; Sukontasukkul et al. 2010). While no increase in initial peak load could be obtained with this fiber type, improvements could be achieved with other MSF types. This depended on the geometry, length, and diameter of the fiber and the volume ratio in the concrete (Ahmad and Zhou 2022; Akça et al. 2015; Reza and Ozbakkaloglu 2019).

The A2 specimen was the one that lost the most strength after the first peak load, and its second peak load was the lowest. The B2 specimen behaved similarly to the A2 specimen, but its second peak load was higher. Although the flexural load partially decreased with the cracking of the concrete after the first peak load in the C2 specimen, its second peak load was 37% higher than the first one on average. The behavior of the D2 specimen after concrete cracking is similar to that of the B2 specimen, and it was observed that the performance did not increase with the increasing MSF ratio, and it was lower than the C2 specimen. The behavior of the D2 specimen after cracking was similar to that of the B2 specimen. It was observed that the performance did not increase with the increasing MSF ratio, and it was lower than the C2 specimen. It was determined that 1.5% MSF substitution provided the greatest contribution to the flexural behavior at 20 °C. After the crack, there were no significant differences in the displacement increase in terms of fiber reinforcement ratios before the collapse. Changes in toughness are discussed in the relevant section.

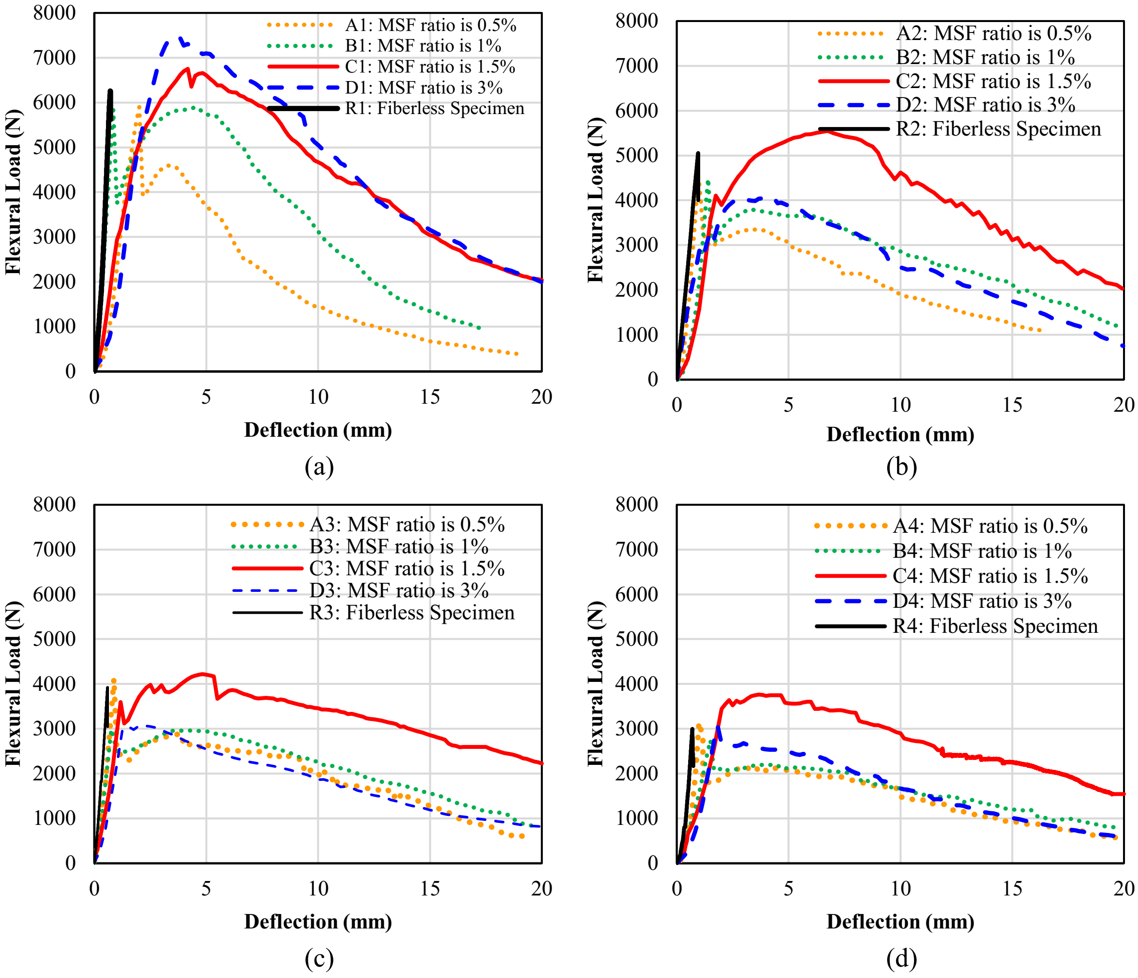


Fig. 9 Load–deflection graphs of MSF-reinforced concrete with four different fiber volume ratios at temperatures **a** −5 °C, **b** 20 °C, **c** 50 °C, and **d** 90 °C

3.2.2 Effects of Temperature on Flexural Behavior of MSF-Reinforced Concrete

In this section, the effects of temperature change on the flexural behavior of MSF-reinforced concrete with a certain volume content are presented. The concrete prepared with different fiber reinforcement ratios (0.5%, 1.0%, 1.5%, and 3%) were tested with the four-point bending test method under different temperatures of −5, 20, 50, and 90 °C. The load–deflection graphs of specimens with different fiber content under different temperatures are presented in Fig. 10a–d.

When the load–deflection behavior of the specimens was analyzed, it was seen that the load-carrying capacity decreased due to the increase in temperature, while the deflection values corresponding to the peak loads partially changed. Load–deflection graphs showed that the change in the initial peak loads depending on the fiber volume ratios and temperature change was not discriminating. It was seen that the change in initial peak loads was due to the concrete behavior because similar results were observed in the fiber-free concrete. Therefore, the comparisons were made according to the second peak load as it showed the fiber performance better. After the first peak load, a decrease was observed in the load-carrying performance of fiber concrete due to the increasing temperature. Compared to the laboratory conditions (20 °C), all fiber concrete specimens showed the best strength performance at −5 °C. Here, the freezing of the water in the concrete and the tightening of the atomic bonds were considered to be effective. According to Richardson and Ovington (2017), regardless of the reinforcement type, FRC stored at −20 °C for 24 h before testing could withstand a higher load than FRC at room temperature, resulting in increased flexural strength displayed by the FRC at temperatures below the freezing point of water.

Depending on the fiber volume ratios, raising the temperature to 50 °C or above reduced the second peak

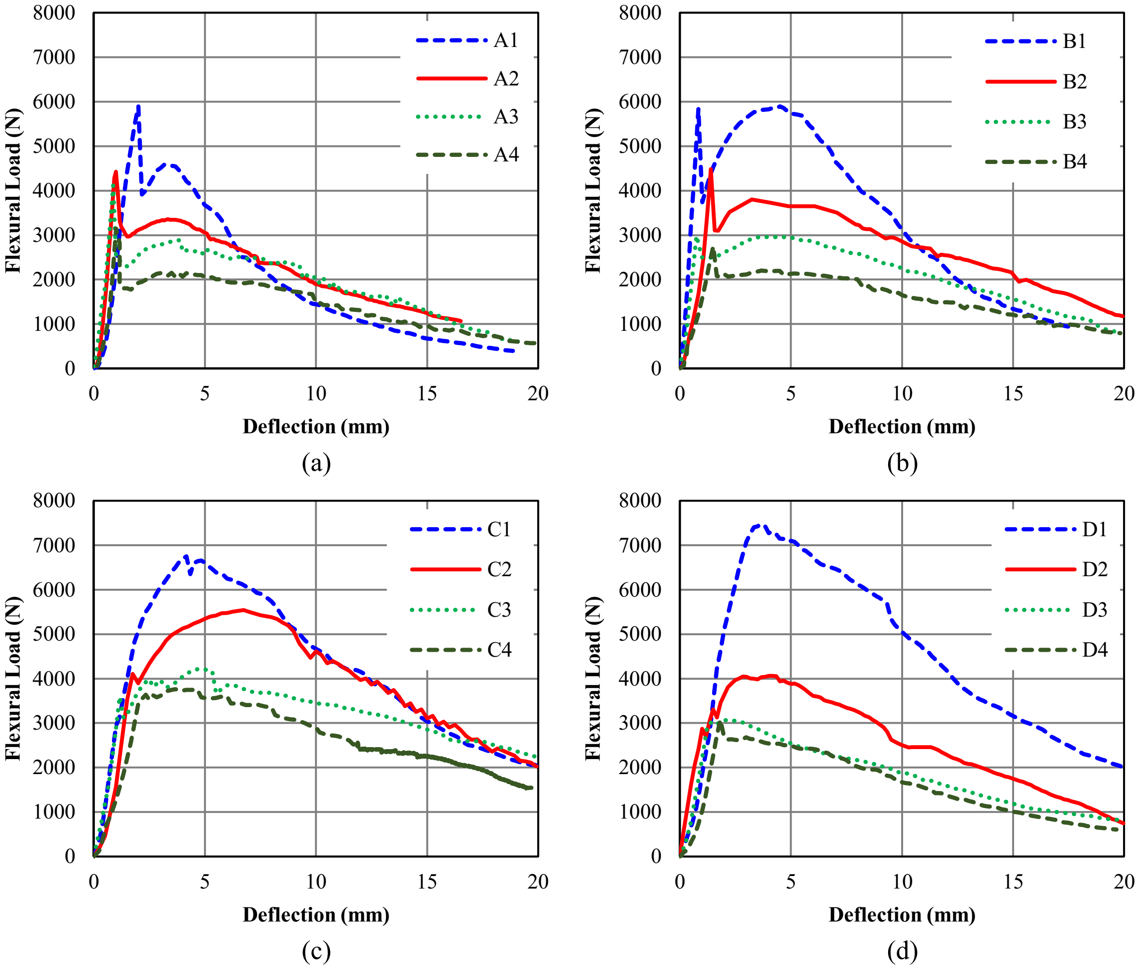


Fig. 10 Load–deflection curves of MSF-reinforced concrete at different temperatures: **a** A group specimens with 0.5% fiber volume ratio, **b** B group specimens with 1% fiber volume ratio, **c** C group specimens with 1.5% fiber volume ratio, and **d** D group specimens with 3% fiber volume ratio

load-carrying capacity rather than the first peak load-carrying capacity of the MSF-reinforced concrete.

A comparison of fiber concrete groups according to temperature changes showed the following:

(a) Among the A group specimens produced with a 0.5% fiber volume ratio, the second peak load change increased by 36% in the A1 specimen compared to the A2 specimen, while it decreased by 14 and 36% in the A3 and A4 specimens, respectively.

(b) Within the B group specimens produced with a 1.0% fiber volume ratio, the second peak load change increased by 55% in the B1 specimen compared to the B2 specimen, while it decreased by 22 and 42% in the B3 and B4 specimens, respectively.

(c) Among the C group specimens produced with a fiber volume ratio of 1.5%, the second peak load change increased by 20% in the C1 specimen compared to the

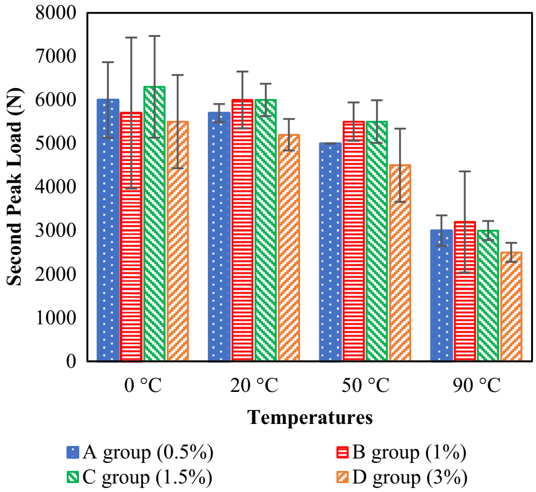


Fig. 11 Effect of temperature on peak load of MSF concrete with different fiber volume ratios

C2 specimen, while it decreased by 25 and 28% in the C3 and C4 specimens, respectively.

(d) Among the D group specimens produced with a 3% fiber volume ratio, the second peak load change in the D1 specimen increased by 76% compared to the D2 specimen, while the D3 and D4 specimens decreased by 28 and 38%, respectively. Table 3 and Fig. 11a–d explain these findings.

3.3 Temperature Performance Analysis of MSF-Reinforced Concrete

Based on the results of the flexural tests applied to concrete with different fiber volume ratios under different temperatures, the changes in the peak loads are presented in Fig. 11.

It was found that the load-carrying capacity of FRC decreased with the increase in temperature. All FRC specimens showed the highest and the lowest load-carrying capacity at −5 °C and 90 °C, respectively. The D group samples were most impacted by temperature, whereas the C group samples were least impacted. Tanyıldızı (2009) also reported that the mechanical properties of concrete containing more fiber were more sensitive to the degree of heat. It was found that concrete produced with MSF reinforcement showed the best performance in the range of 1–1.5% against ambient temperature conditions.

3.4 The Effect of Temperature on Toughness

The areas below the parts up to 15 mm displacement were calculated, and toughness values were found based on the load–deflection graphs obtained at the end of the flexural tests applied to concrete with different fiber volume ratios under different temperatures. The change of toughness values calculated for each specimen group at different temperatures is presented in Fig. 12.

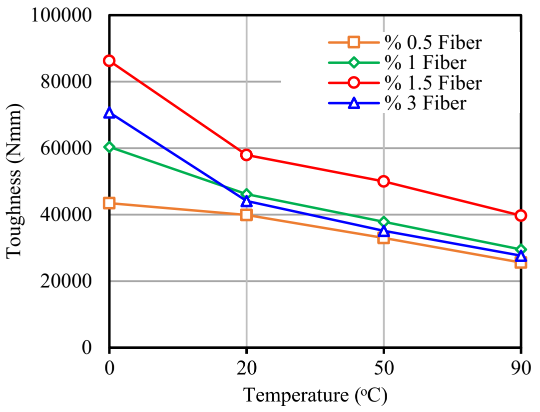


Fig. 12 Effect of temperature on toughness of MSF concrete with different fiber volume ratios

The results showed a tight link between fiber volume ratio, temperature change, and toughness. While the toughness values of the specimens were higher in cold conditions, there was a decrease in the toughness values with an increase in temperature. While the lowest toughness values were observed in the A group specimen with the least fiber reinforcement at 0.5%, the highest toughness amounts were seen in the C group specimens with 1.5% fiber reinforcement. A gradual decrease in the toughness value was observed with the temperature in all specimens. A higher rate of toughness decrease was observed in the 3% fiber-reinforced D group specimens at the transition from −5 to 20 °C. Previous studies have also revealed that both natural and synthetic fibers have a significant impact on the toughness of concrete (Ahmad and Zhou 2022). Concrete toughness, which is directly correlated with temperature, was significantly impacted by fiber content added to the mix (Wu et al. 2020).

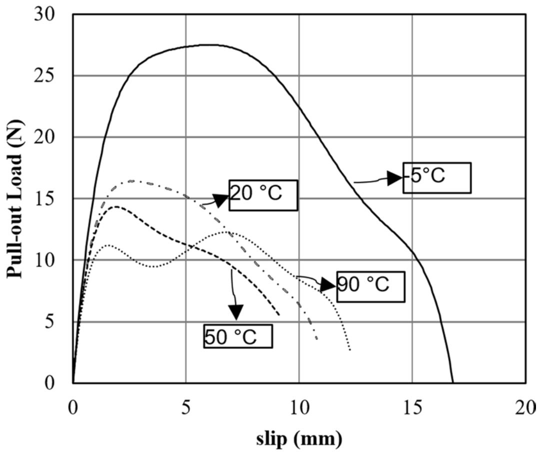


Fig. 13 Pull-out load-slip behavior of MSF at different temperature

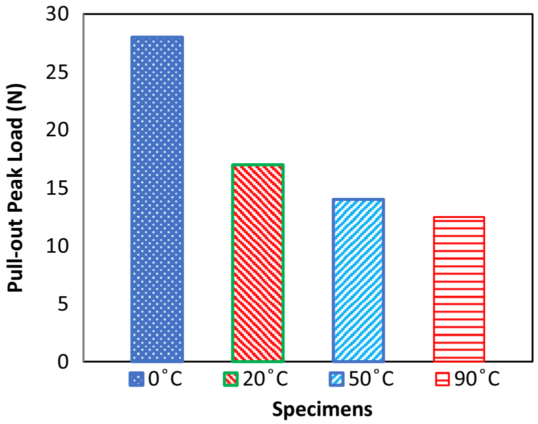


Fig. 14 Pull-out test peak loads of MSF at different temperatures

3.5 Pull-Out Test Results of MSF

MSFs embedded in concrete were tested using the pull-out test method at different temperatures, as the peak pull-out load would reflect the bond strength between the matrix and the MSF (Akça et al. 2015). The tensile load-slip graph of the experiments is presented in Fig. 13, and the peak loads are presented in Fig. 14.

The pull-out test results showed that MSF's peel strength from concrete increased by 65% at −5 °C and decreased by 17% and 29% at 50 and 90 °C, respectively, according to results at 20 °C. The tendency of the fibers to slip off the concrete increased in proportion to the increase in temperature. In parallel with the analysis of the flexural tests, the performance at −5 °C was at the highest level in the slip tests. The experimental results showed that the mechanical bond between concrete and fiber decreases with increasing temperature. It is concluded that the friction between the concrete and the fiber interface decreases as a result of the softening of the fiber with the increase in temperature, and therefore the mechanical performance of the FRC decreases as a result of the increase in the slipping potential. Aidarov et al. (2022) also reported that low temperatures lead to an increase in the energy required to pull the fiber out, thus improving the post-cracking flexural strength.

4 Conclusions

An experimental study was conducted to determine the effects of MSF content in concrete and ambient temperature on the flexural performance of MSF-reinforced concrete. The effects of fiber volume ratio and temperature on flexural strength and toughness were compared. The adhesion between concrete and MSF at various temperatures was investigated by a pull-out test.

The main results from the studies are summarized as follows:

1. Slump test results and observational data collected revealed that increasing the fiber ratio by volume had a detrimental impact on the placing of the concrete into the mold. Although MSF increases the viscosity of concrete and reduces workability by restricting the spread of fresh concrete, up to 1.5% MSF content, the appropriate workability can be achieved with a proper superplasticizer additive.
2. It was determined that the flexural strength of MSF-reinforced concrete increased up to 1.5% MSF, and the concrete with a 1.5% fiber ratio in terms of flexural strength performed better than other fiber ratios.
3. It was determined that the flexural load-carrying capacity decreased with the temperature increase within the reference and MSF-reinforced concrete groups. Concrete produced with MSF reinforcement showed the best performance against temperature in the range of 1–1.5%.
4. The toughness parameter was distinctive in determining the effect of variation in the MSF content of the concrete and its performance under various temperatures. In all specimens, the toughness decreased gradually as the temperature increased. The lowest toughness values were obtained at 0.5% MSF content, while the highest toughness values were obtained at 1.5% MSF content. There was a dramatic decrease in toughness at the 3% MSF content.
5. According to the pull-out test results, fibers pulled at −5 °C demonstrated greater slip resistance, and slip resistance dropped partially at 50 and 90 °C. This result was attributed to the weakening of the adherence between the concrete and MSF as the temperature increased. In addition, these findings also explain the reason for the softening in the bending behavior of concrete after cracking.
6. The toughness behavior of MSF-reinforced concrete at ambient temperature is promising. Based on the conclusion that the greatest contribution of MSF occurs after concrete fractures, it is recommended that the MSF content be 1% or higher.
7. In the light of this experimental study, the use of MSF instead of steel fiber in concrete will be a good choice in corrosive environments.

Funding The authors did not receive support from any organization for the submitted work.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Ethical Approval This article does not contain any studies with human participants or animals performed by any of the authors.

References

Abaeian R, Behbahani HP, Moslem SJ (2018) Effects of high temperatures on mechanical behavior of high strength concrete reinforced with high performance synthetic macro polypropylene (HPP) fibres. Constr Build Mater 165:631–638

Ahmad J, Zhou Z (2022) Mechanical properties of natural as well as synthetic fiber reinforced concrete: a review. Constr Build Mater 333:127353

Aidarov S et al (2022) Effects of low temperatures on flexural strength of macro-synthetic fiber reinforced concrete: experimental and numerical investigation. Materials 15(3):1153

Akça KI, Recep ÖÇ, Ipek M (2015) Properties of polypropylene fiber reinforced concrete using recycled aggregates. Constr Build Mater 98:620–630

Alan D et al (2018) Study of temperature effect on macro-synthetic fiber reinforced concretes by means of Barcelona tests : an approach focused on tunnels assessment. Constr Build Mater 158:443–453

Alhozaimy AM, Soroushian P, Mirza F (1996) Mechanical properties of polypropylene fiber reinforced concrete and the effects of pozzolanic materials. Cem Concr Compos 18(2):85–92

Aly T, Sanjayan JG, Collins F (2008) Effect of polypropylene fibers on shrinkage and cracking of concretes. Mater Struct 41(10):1741–1753

Ashkezari GD, Razmara M (2020) Thermal and mechanical evaluation of ultra-high performance fiber-reinforced concrete and conventional concrete subjected to high temperatures. J Build Eng 32:101621

Balouch SU, Forth JP, Granju JL (2010) Surface corrosion of steel fibre reinforced concrete. Cem Concr Res 40(3):410–414

Behfarnia K, Behravan A (2014) Application of high performance polypropylene fibers in concrete lining of water tunnels. Mater Des 55:274–279

Bei-Xing LI, Ming-xiang C, Fang C, Lu-ping L (2004) The Mechanical properties of polypropylene fiber reinforced concrete. J Wuhan Univ Technol Mater Sci Ed 19(3):68

Bentur A, Mindess S (2006) Fibre reinforced cementitious composites. Taylor & Francis

Bhat MD et al (2022) The effect of polypropylene and steel fibers on the properties of concrete at normal and elevated temperatures—a review. Iran J Sci Technol Trans Civ Eng 46(3):1805–1823

Buratti N, Mazzotti C, Savoia M (2011) Post-cracking behaviour of steel and macro-synthetic fibre-reinforced concretes. Constr Build Mater 25(5):2713–2722

Choumanidis D, Badogiannis E, Nomikos P, Sofianos A (2016) The effect of different fibres on the flexural behaviour of concrete exposed to normal and elevated temperatures. Constr Build Mater 129:266–277

Cifuentes H, García F, Maeso O, Medina F (2013) Influence of the properties of polypropylene fibres on the fracture behaviour of low-, normal- and high-strength FRC. Constr Build Mater 45:130–137

Clarke T, Ghiji M, Fragomeni S, Guerrieri M (2022) Mechanical properties of macro synthetic fiber reinforced concrete at elevated temperatures: a systematic review and meta-analysis. Struct Concr 24:1–27

Çavdar A (2013) The effects of high temperature on mechanical properties of cementitious composites reinforced with polymeric fibers. Compos B Eng 45(1):78–88

EN 14889–2 (2015) Fibres for concrete—part 2: polimer fibres—definitions, specifications and conformity (Turkish)

Gao S, et al. (2010) Comparison of the mechanics and durability of hybrid fiber reinforced concrete and frost resistant concrete in bridge deck pavement. In: ICCTP 2010: Integrated Transportation Systems: Green, Intelligent, Reliable—Proceedings of the 10th International Conference of Chinese Transportation Professionals, pp 2927–2935

Hasan MJ, Afroz M, Mahmud HMI (2011) An experimental investigation on mechanical behavior of macro synthetic fiber reinforced concrete. Environ Eng 11(June):18–23

Hsie M, Chijen Tu, Song PS (2008) Mechanical properties of polypropylene hybrid fiber-reinforced concrete. Mater Sci Eng A 494(1–2):153–157

Kakooei S, Akil HM, Jamshidi M, Rouhi J (2012) The effects of polypropylene fibers on the properties of reinforced concrete structures. Constr Build Mater 27(1):73–77

Kosa K, Naaman AE (1990) Corrosion of steel fibre reinforced concrete. Mater J 87:27–37

Mazaheripour H, Ghanbarpour S, Mirmoradi SH, Hosseinpour I (2011) The effect of polypropylene fibers on the properties of fresh and hardened lightweight self-compacting concrete. Constr Build Mater 25(1):351–358

Müller P, Novák J, Holan J (2019) Destructive and non-destructive experimental ınvestigation of polypropylene fibre reinforced concrete subjected to high temperature. J Build Eng 26:100906

Nana WSA et al (2021) Behaviour of macro-synthetic fibers reinforced concrete: experimental, numerical and design code investigations. Structures 32:1271–1286

Peng GF et al (2006) Explosive spalling and residual mechanical properties of fiber-toughened high-performance concrete subjected to high temperatures. Cem Concr Res 36(4):723–727

Poon CS, Shui ZH, Lam L (2004) Compressive behavior of fiber reinforced high-performance concrete subjected to elevated temperatures. Cem Concr Res 34(12):2215–2222

Pakravan HR, Ozbakkaloglu T (2019) Synthetic fibers for cementitious composites: a critical and in-depth review of recent advances. Constr Build Mater 207:491–518

Richardson A, Ovington R (2017) Temperature related steel and synthetic fibre concrete performance. Constr Build Mater 153:616–621

Simões T, Costa H, Dias-da-Costa D, Júlio E (2017) Influence of fibres on the mechanical behaviour of fibre reinforced concrete matrixes. Constr Build Mater 137:548–556

Sukontasukkul P, Pomchiengpin W, Songpiriyakij S (2010) Post-crack (or Post-Peak) flexural response and toughness of fiber reinforced concrete after exposure to high temperature. Constr Build Mater 24(10):1967–1974

Tanyildizi H (2009) Statistical analysis for mechanical properties of polypropylene fiber reinforced lightweight concrete containing silica fume exposed to high temperature. Mater Des 30(8):3252–3258

Topcu İB (2006) Concrete technology (Turkish). Eskişehir: Ugur Offset

TS 802 (2016) Design of concrete mixes

TS EN 12390-2 (2000) TS EN 12350-2 testing fresh concrete Đ part 2 : slump test (Turkish)

TS EN 12390-5 (2019) Testing hardened concrete—part 5: flexural strength of test specimens (Turkish)

TS EN 12620 (2009) Aggregates for concrete (Turkish)

Vrijdaghs R, di Prisco M, Vandewalle L (2017) Creep Deformations of Structural Polymeric Macrofibers. RILEM Bookseries, pp 53–61

Web Page (2021) Kratos synthetic fiber reinforcement technical brochure

Wu H, Lin X, Zhou A (2020) A review of mechanical properties of fibre reinforced concrete at elevated temperatures. Cem Concr Res 135:106117

Wu S (1982) Taylor & Francis polymer and adhesion. Taylor & Francis, Delaware

Wu Y (2002) Flexural strength and behavior of polypropylene fiber reinforced concrete beams. J Wuhan Univ Technol Mater Sci Ed 17(2):54–57

Yap SP, Johnson Alengaram U, Jumaat MZ (2013) Enhancement of mechanical properties in polypropylene—and nylon—fibre reinforced oil palm shell concrete. Mater Des 49:1034–41

Yin S et al (2015) Use of macro plastic fibres in concrete: a review. Constr Build Mater 93:180–188

Zheng Z, Feldman D (1995) Synthetic fibre-reinforced concrete. Prog Polym Sci 20(2):185–210