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Influence of short-term operating temperatures on compression and flexural behaviour of Macro Synthetic and Steel Fibre Reinforced Concretes

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ABSTRACT

This study investigates the influence of operating temperatures on the mechanical properties of Fibre Reinforced Concretes (FRCs) when exposed during short-term periods (3 days). The studied parameters include types of fibres (macro synthetic and steel fibres), exposure to different environmental scenarios (with temperatures of −15, 5, 20, 40 and 60 °C as well as air exposition or submerged condition), and cracking conditions (precracked up to 0.5 mm or uncracked). A total of 126 cubes of 150 mm side and 182 prisms of 150 × 150 × 600 mm^3 were tested in compression and flexion at the operating temperatures. The compression results obtained show similar effects in FRC and in plain concrete, with higher strength at low temperatures and slightly lower strength at higher temperatures. Similar effects were detected for the strength at the peak load, and to a minor extent, for the residual flexural strengths, for all the FRCs.

1. Introduction

1.1. Context

The development of fibres as reinforcement for concrete emerged in the construction sector in the sixties, resulting in Fibre Reinforced Concrete (FRC). FRC is a composite material used in a wide variety of structural applications [1–4]. Different types of fibres can be added to the concrete matrix with the aim of enhancing its mechanical post-cracking performance and durability [5]. Fibres are produced in different materials and shapes to be incorporated in different types of structures. Steel fibres are the most extensively commercialised fibres and consequently, most standards and codes prescriptions on FRC [6–8] are based on experiences with Steel Fibre Reinforced Concrete (SFRCs). Macro Synthetic Fibre Reinforced Concretes (MSFRCs) have been introduced into the market more recently, especially, with polypropylene fibres, and also offer economical and labour savings, manufacturing advantages, reinforcing effects as well as alkaline and corrosion resistance [9,10]. Despite the frequent use of MSFRCs, they are not yet considered in structural concrete guidelines. In fact, Model Code 2010 includes a warning statement related to FRCs, indicating that fibres made of materials whose Young's modulus is significantly affected by time and/or thermo-hygrometrical phenomena are not covered by the code [7].

In this regard, numerous investigations focused on the characterization of macro synthetic fibres (individually, as a material) to evaluate their response, since their characteristics are dependent on temperatures. At elevated temperatures, Takaku [11] and Liu et

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al. [12] found that changes in temperature (from 40 to 130 °C, and from −30 to 70 °C respectively) had significant effects on the creep rate of polypropylene fibres. Hunger et al. [13] studied short- and long-term behaviour of the filaments at varying temperatures from −10 to 60 °C. These authors indicated that the performance of synthetic fibres and especially, creep performance cannot be generalized since high-performing polypropylene macro fibre can sustain a load level of 40% related to maximum strength in short-term tests even at a temperature of 40 °C, which would be enough for several applications. At temperatures below freezing, Hall [14] stated that polypropylene tends to become brittle due to its nature, which is a serious drawback in certain applications when mechanical performance at such temperatures is required.

These results generated mistrust in using this type of fibres in several applications due to the fear that they could compromise the mechanical behaviour of MSFRC. However, the former results only explain the behaviour on a fibre level. The decrease in performance detected will not necessarily have an equivalent effect in a FRC concrete level, since the matrix provides a protective cover, minimising the susceptibility to environmental effects. There is scarce and disperse information about the performance of FRCs exposed to operating temperatures. The authors understand as operating temperature values between −40 and 85 °C because this range of temperatures can be reached in situations under natural environmental conditions or in industrial applications. Therefore, to ensure FRC structures in operating conditions, this influence should be studied, with attention to concrete's properties and fibre-matrix interactions.

Studies related to curing temperatures or high temperatures (i.e., fire situations) are outside of the scope of this work. Studies in the literature that have been carried out after a conditioning regimen and tested at room temperature are also not included (transient exposures). Only studies conducted on FRCs exposed at operating temperatures and tested at theses temperatures are discussed.

1.2. FRC exposed at sub-zero and cold temperatures until standard temperature (from −40 up to 20 °C)

In the low temperatures and sub-zero range, several authors [15,16] indicated that decreasing the temperature of concrete below 0 °C leads to enhancements in the compression and tensile of concrete. This could be originated by the ice formation of gel and pore water, and chemically bound water inside the matrix [17–19]. A similar effect is detected on flexural strengths on concrete; however, this decreasing in temperatures also increases brittleness, as pointed out in various studies [20–24].

Pigeon et al. [25] reported the mechanical flexural strengths of SFRC at low temperatures, following ASTM C1018. The tests were performed at standard temperature (20 °C), at −10 °C and at −30 °C. The results show that, under flexural loading, the toughness of SFRC increases with a temperature decrease. This increase appears to be related to the increase in the strength of the matrix at low temperatures, which increases the energy required for fibre pull-out. In addition, Richardson and Ovington [26] examined the temperature's effect on SFRCs and MSFRCs at −20 °C on flexural strengths, bond strength and toughness of FRCs. All beams tested at −20 °C exhibited a significant increase in flexural strengths when compared to the same beams tested at room temperatures (20 °C). The flexural strength at the limit of proportionality (LOP) showed an average of 150% increase in the MSFRC beam (polypropylene fibres) and, an average of 79% increase in the SFRC beam. Navarro et al. [27] studied compression, flexural and Barcelona tests of polyolefin FRC at −30 °C. They detected that compression strength increased a 20% when the temperature decreased from the temperature reference (22 °C) up to −30 °C and the results of the flexural and Barcelona tests showed consistent results. Aidarov et al. [28] evaluated the flexural behaviour of MSFRC at different temperatures (up to −30 °C) of notched prisms by three-point bending tests according to EN 14651 [29], once the temperature was reached in the core of the beams. The results proved that low temperatures (below 0 °C) led to rise the energy required to produce fibre pull-out, and therefore, post-cracking flexural behaviour was improved: f_{R1} increased to 54% and f_{R3} increased to 71%.

1.3. FRC exposed at warm and hot temperatures (between 20 and 85 °C)

In the warm moderate temperatures range, Richardson and Ovington examined the effect of temperature on plain concrete, MSFRCs (polypropylene fibres) and SFRC under 60 °C [26]. All beams had decreased flexural strengths at 60 °C if compared to the results at room temperature. The MSFRC beams showed an average of 12% reduction and the SFRC beams showed an average of 49% reduction. Buratti et al. [30] presented the experimental results of short- and long-term behaviour on cracked MSFRC (polypropylene fibres) elements at different temperatures. Short-term behaviour was evaluated through three-point bending tests at 20 and 40 °C and they found that increasing the temperature reduced the residual strengths of some of the analysed MSRFCs in the short-term. Navarro et al. [27] studied the behaviour of a polyolefin FRC at 55 °C and 100 °C. They observed that compression strength decreased up to 20% when the temperature increased to 100 °C. Caballero-Jorna et al. [31] studied the effect of moderate temperatures (5, 20, 35 and 50 °C) on the flexural strengths of MSFRC (polypropylene) and SFRC in reduced-size specimens (100 × 100 × 600 mm) after two months of exposition. The findings suggested that these temperatures did not deteriorate the FRC behaviour to a great extent.

1.4. Research significance

This work aims to characterize the performance of FRC at the operating temperatures of −15, 5, 20, 40 and 60 °C. In order to guarantee that the specimens are tested at the target temperature, they are exposed to these temperatures during a period of 3 days, which is enough time to reach the target temperature at the geometrical centre of the prism. The test is performed following the standard methods with some modifications to maintain the temperature at the core of the specimens close to the exposure temperatures. The experimental campaign objectives are to quantify the influence of these temperatures on compression and flexural behaviour, as well as comparing these effects in non-cracked specimens versus already cracked specimens, which is a possible situation in service conditions.

2. Materials and methodology

2.1. Materials and mixes designs

The materials and mix designs used in this study are detailed in Table 1. The strength class of the two fibre-reinforced concrete mixes was C30/37. The mixes contained Portland cement type CEM I 42.5 R SR5 from Lafarge. The effective water/cement ratio of the mixes was 0.55. Two fine aggregates from a local provider were also used of sizes 0/4 mm and 0/2 mm. The coarse aggregates were crushed limestone of three different sizes: 4/8 mm, 8/16 mm, and 16/20 mm. A polycarboxylate-based superplasticizer was used to guarantee the consistency of the mixes. Air-reducing additive was also added in a percentage of 0.4% volume of weight cement to control the air content and to avoid potential air entrapment due to the fibres.

FRCs were prepared with various types of fibres. Three different types of macrosynthetic fibres and one steel fibre were used. Macrosynthetic fibres are identified as PF1 (reference), PF2 and PF3 respectively. All these fibres are made of polypropylene (PP), PF1 is an embossed PP macro fibre, PF2 is extruded from a polypropylene homopolymer (polyolefin 100%) formed into a macro crimped profile, and PF3 is a chemical base polymer of a modified polypropylene macro fibre. The hooked-end steel fibre used for comparison purposes is named SF and has an aspect ratio similar to PF1 fibre. The dosage of fibres in each FRC was decided to obtain similar residual strengths following the indications provided by the manufacturers. The characteristics of all the fibres are detailed in Table 2.

2.2. Methodology

2.2.1. Mixing and producing specimens

Batches were performed in a P375T08 planetary concrete mixer with a total volume of 500 L. Each batch produced had a volume of 270 L and a total of 16 batches were cast. After demoulding, FRC specimens were cured for 28 days in a standard humidity chamber at 20 °C and RH 95%. Three cubes of 150 mm side were produced per mix for testing compression strength and seven prisms of 150 × 150 × 600 mm (width × height × length) per mix for testing flexural strengths, in both cases tested at the target temperatures. Additionally, three cubes of 150 mm side were cast to characterize each concrete mix at standard conditions. In this experimental campaign, a total amount of 182 prims and 126 cubes were tested.

2.2.2. Experimental program on short-term mechanical properties at different temperatures

This experimental program is carried out to understand and quantify the influence of short-term operating temperatures on the compression and flexural strengths of FRCs, also comparing any differences due to the elements being precracked or and non-precracked. Table 3 summarized the combinations of variables tested in this work. The variables considered are the type of fibres, precracked versus non-precracked state of the specimens, target operating temperatures (−15, 5, 20, 40 and 60 °C) and availability of water (air or submerged conditions). The code letters assigned to each group considers: fibre type (PF1, PF2, PF3 or SF), state (N for

Table 1
FRCs mixes designs used in this study.

Materials (kg/m^3)	MSFRC	SFRC
CEM I 42.5 R SR5	280	280
Coarse aggregate (16/20 mm)	183	183
Coarse aggregate (8/16 mm)	402	402
Coarse aggregate (4/8 mm)	146	146
Fine aggregate (0/4 mm)	897	897
Fine aggregate (0/2 mm)	211	211
Effective Water	154	154
Fibres	7	21
Superplasticiser	0.75 (1% btwc)	0.6 (0.8% btwc)
Air-reducer admixture	0.3 (0.4% btwc)	

Table 2
Fibres characteristics (data provided by the manufacturers).

Properties	Code			
	PF1	PF2	PF3	SF
Raw material	PP	PP	PP	Steel
Equivalent diameter (mm)	0.81	0.85	0.7	0.55
Length (mm)	54	48	40	35
Aspect ratio	67	56.5	79	65
Tensile strength (MPa)	552	400 (>400)	500	1345
Modulus of Elasticity (GPa)	7	4.7(>6)	7	210
Density (kg/m^3)	910	910	910	7850
Melting point (°C)	150–170	160	150–170	1375
Image				

Table 3
Outline of the combination adopted in the present study. *Note: M15 stands for -15 °C.*

Exposure		Air condition				Submerged	
Temperatures (°C)		M15	05	20	40	20S	60S
RH (%)		65–95	75–95	95	30–50	100	100
PF1	P	X	X	X	X	X	X
	N	X	X	X	X	X	X
PF2	P						
	N	X		X			X
PF3	P						
	N	X		X			X
SF	P	X		X		X	X
	N	X		X		X	X
Total of series		6	2	6	2	4	6

non-precracked and P for precracked), temperatures (M15, 05, 20, 40 and 60), and conditions (S after the temperature, if the specimen is submerged).

To characterize the concrete mixes, several properties were tested. Slump, fresh density, and air content were evaluated in the fresh state. The results showed that the consistency class was S4 for all the mixes, the density in a fresh state was around 2350 kg/m^3, and the air content was always under 2%. Compression strength was assessed at 28 days after curing in standard conditions, in three specimens per batch. The result of the average of the compression strength was 35 MPa.

2.2.2.1. Programmed scenarios. After curing the specimens for 28 days, prisms (precracked and uncracked) and cubes were stored for a short-term of 3 days in different scenarios. The duration of the exposure was defined to guarantee that the interior of the prisms reached the target temperatures.

The scenarios selected are environmental simulations that can occur when concrete is put into service. These temperatures are extreme service temperatures that may take place in cold or hot regions (or during some industrial applications), corresponding to very cold, cold, normal, hot, and extremely hot weather. The scenarios simulated in this study are: M15 (−15 °C and RH 65–95%), 05 (5 °C and RH 75–95%), 20 (20 °C and RH 95%), 20S (20 °C and in water immersion), 40 (40 °C and RH 30–50%), and 60S (60 °C and in water immersion).

2.2.2.2. Compression strength at room and at the target temperatures. Compression strength was obtained following the standards EN 12390–3 [32], in an IBERTEST MEH-3000-LCMD2W. To assess the influence of operating temperature after short-term exposure (3 days) of the FRCs under investigation, a modification was introduced in the mentioned method. The modification consisted of an insulation system made of 8-mm extruded polystyrene that covers the specimen and keeps constant the target temperature during the test (see Fig. 1). The insulation system is enough to keep the temperature since the test duration is short (≈2 min).

2.2.2.3. Flexural tests methods at target temperatures. Flexural tests were carried out using a three-point bending test (3PBT) configuration on notched specimens in precracked and non-precracked specimens, based on EN 14651 [29], using testing machine INSTRON 3389. The depth of the notch is 25 mm, and the width is less than 5 mm. In all the specimens, Crack Mouth Opening Displacement (CMOD) was registered by an LDTV placed at the mouth of the notch. Flexural tests were performed at operating temperatures. To do this, the modification on the set-up's test consisted of including a special insulation cell and gel packs as a cooling/heating agent which could delay heat/cool exchange (Fig. 2-a). This system allowed to keep target temperatures inside the specimens during the tests. This system was proposed in a previous work [31] and was improved in this work. Since this test duration is long (≈30–40 min), to verify the insulation system, a type K thermocouple was embedded in the core of one beam per series. The results obtained with the embedded thermocouple indicate that the internal temperature of the specimens during the flexural test

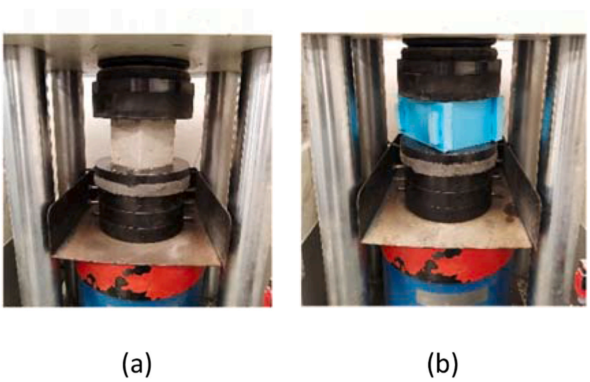

Fig. 1. Compression tests: (a) at ambient temperature and (b) at target temperature.

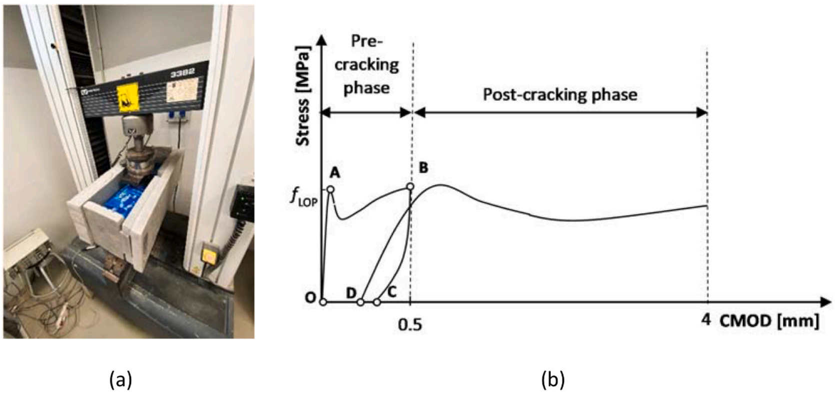

Fig. 2. (a) Set-up of flexural test (3PBT) at operating temperatures, and (b) diagram of the complete procedure for precracked specimens.

was kept within the following boundaries: for M15, from −15 up to −10 °C; for 05, from 5 up to 10 °C, for 20 and 20S, from 20 up to 25 °C; for 40, from 40 to 35 °C and for 60S, from 60 °C up to 50 °C.

At 28 days, before conditioning, some specimens were precracked at room temperature until CMOD = 0.5 mm (point B, in Fig. 2-b, after point A -limit of proportionality (LOP)- is reached). This CMOD value corresponds to the residual strength f_{R1}. Afterwards, specimens were unloaded (point C, in Fig. 2-b) and they remained during 10 min in the testing frame to register crack opening recovery (point D, in Fig. 2-b). After pre-cracking, these specimens were placed in the defined scenarios for 3 days, and afterwards, they were tested until failure (CMOD = 4 mm) at the age of 31 days, at operating temperatures.

For the non-precracked specimens, they were directly stored at the age of 28 days in the defined scenarios for 3 days, and then underwent the complete loading process following EN 14651 at the age of 31 days, at operating temperatures. Finally, all the specimens (precracked and non-precracked) were separated into two halves, and the total number of fibres at the fracture surface were counted (without taking into account the notch).

3. Results

3.1. Compression strength after short-term exposure at the operating temperatures

Table 4 collects the compression strength values (average of three specimens and CV) of the specimens tested at the operating temperatures.

For temperatures below zero, SFRC and MSFRC exhibited an increase of 25–50% in the compression strength. In this last case, the slope of the stress-strain curve increased in a 40% compared with the slope stress-strain curve at 20 °C.

For temperatures above zero degrees, in the range between 5 and 40 °C, no effects are detected, since all the results range between 34.5 MPa and 37 MPa. This indicates that, for these temperatures, the compression strength does not depend on the temperature and SFRC and MSFRC have the same response. For 60 °C, a minor decrease of 10–15% was experimented on the compression strength of SFRC and MSFRC, as well as a slight decrease in the slope of the stress-strain curve (10%, compared with 20 °C).

Table 4
Compression strengths for the studied concretes at operating temperatures.

CODE		Compression strength (MPa)	CV (%)	% Difference from 20 °C
Control mix	M15	51.5	7.7	33.8
	20	38.5	1.5	–
	60S	30.5	10.6	−20.8
PF1	M15	47.5	6.7	26.6
	05	37.0	5.4	−1.3
	20	37.5	3.1	
	20S	33.5	3.6	−10.7
	40	35.5	0.8	−5.3
	60S	31.5	5.7	−16.0
PF2	M15	44.5	12.4	32.8
	20	34.5	3.6	
	60S	28.0	13.6	−16.4
PF3	M15	43.0	1.8	25.5
	20	33.5	4.8	
	60S	30.5	4.1	−10.9
SF	M15	51.5	2.0	51.5
	20	34.0	5.3	
	20S	36.0	2.4	5.9
	60S	29.0	4.6	−14.7

Additionally, in order to discern if the effects of M15 and 60S conditions in the compression strength were produced by the matrix or a loss of bond between fibres and the matrix, a control mix without fibres was cast and tested under the same conditions. The results indicate that the effects of these temperatures in the SFRC and MSFRC tested are as noticeable as in concrete without fibres, therefore, they can be attributed to effects on the concrete matrix.

3.2. Flexural strength after short-term exposure at the operating temperatures

This section analyses the flexural strength at the limit of proportionality (f_{LOP}) and the residual flexural strength at CMOD = 0.5 and 2.5 mm (f_{R1} and f_{R3} respectively). The average of the outcomes of seven prims for non-precracked specimens are collected in Table 5, as well as their CV, in brackets.

The results of the bending test of the non-precracked FRC show a dispersion of around 20–30% for small and large CMOD in most of the cases, which is a typical value for this type of test, as pointed out in Ref. [33]. On the contrary, for the results of the strength at f_{LOP}, the obtained CVs were around 10% for many of the cases, as expected since this property is mainly dependent on the matrix.

From Figs. 3–6, the Stress-CMOD curves obtained by 3PBT for non-precracked beams for each studied type of fibre and temperature are plotted. The mean values are presented with a line, obtained with the test results of seven specimens for each series, and the envelope (shaded areas) represented the scatter (maximum and minimum values of the tests) in the results.

The results show that when decreasing the temperature below 0 °C, f_{LOP} increased up to twice its value (compared with f_{LOP} at 20 °C), due to the freezing process of the water inside the concrete matrix. When increasing the temperature, f_{LOP} decreased by 10–20%. As previously mentioned, f_{LOP} is a mechanical property that depends mainly on the material matrix. The results in this work show similar values in f_{LOP} for all the mixes independently of the fibre type. This result is consistent with the compression results, where all the mixes showed similar response.

For f_{R1} and f_{R3} values, the range of operating temperatures tested in this work did not affect the post-cracking behaviour of the FRCs to a great extent, and the results for all the studied fibres and temperatures are equivalent (see Table 5). Some differences in the shape of the post-cracking average curves can be noticed, however, the dispersion of this test is intrinsically high. In fact, the coefficient of variation of the series tested is around 20–30%, which is a typical value when measuring residual strengths in FRC. The reasons for this variability include the number of fibres in the ruptured surface and the distribution and orientation of the fibres, parameters affected by the mixing and pouring processes among others. The curves suggest the presence of a secondary flatter peak stress (after cracking) at cold temperatures (at 5 °C and −15 °C) for both types of FRCs while at standard and warm temperatures the curve is flat or continuously increasing for the CMODs studied. The results show that the values of residual flexural strengths obtained (f_{Ri}), do not vary significantly with temperature. In both SFRC and MSFRCs, the residual flexural strengths of these materials were not improved nor deteriorated after 3 days at the tested conditions, indicating that these fibres do not seem to be negatively influenced when embedded inside concrete for the conditions of this work.

Moreover, the effect of pre-cracking was also studied in the MSFRCs with fibre type PF1 and in SFRC, exposed to the pre-defined scenarios. For these precracked specimens, the outcomes are displayed in Table 6, with their corresponding CV in brackets. In this case, the results of the bending tests show a scatter of around 15–30% for small and large CMOD in most of the cases and around 10% for the peak load, for many of the cases, being like those obtained for non precracked specimens. It is also important to remark that for these specimens, f_{LOP} and f_{R1} were obtained at room temperature. The same scatter was obtained for all the PF1 specimens, while for SFRC, the dispersion in the precracked elements was higher than in uncracked specimens, which could be explained by the distribution of the fibres.

Fig. 7-a and Fig. 7-c represent the average stress-CMOD curves obtained from seven non-precracked prisms by means of the three-point bending tests at different temperatures. Fig. 7-b and Fig. 7-d depict the average stress-CMOD curves obtained from seven precracked prisms in the different scenarios. The phase of pre-cracking up to 0.5 mm was carried out at 20 °C and is therefore depicted

Table 5
Results of the f_{LOP} and the residual flexural strengths obtained at operating temperatures for non-precracked specimens. Average and CV in % (in brackets) values.

Code		f_{LOP} (MPa)		f_{R1}(MPa)		f_{R3}(MPa)	
PF1–N	M15	6.76	(4)	2.11	(31)	3.02	(22)
	5	4.03	(4)	1.80	(30)	2.28	(28)
	20	3.27	(8)	1.45	(18)	1.99	(15)
	20S	3.55	(6)	1.15	(15)	1.45	(26)
	40	2.72	(18)	1.63	(10)	2.18	(11)
	60S	2.49	(6)	1.26	(19)	1.57	(22)
PF2–N	M15	6.11	(7)	1.31	(36)	1.73	(33)
	20	3.03	(4)	1.18	(16)	1.38	(24)
	60S	2.37	(6)	0.75	(11)	0.89	(16)
PF3–N	M15	5.11	(6)	1.66	(14)	2.50	(23)
	20	2.76	(8)	1.37	(20)	2.17	(26)
	60S	2.59	(7)	1.01	(21)	1.55	(18)
SF-N	M15	5.99	(6)	1.01	(47)	1.25	(22)
	20	2.58	(3)	1.29	(20)	1.26	(21)
	20S	3.54	(13)	1.60	(26)	1.44	(19)
	60S	2.80	(6)	0.98	(21)	1.02	(16)

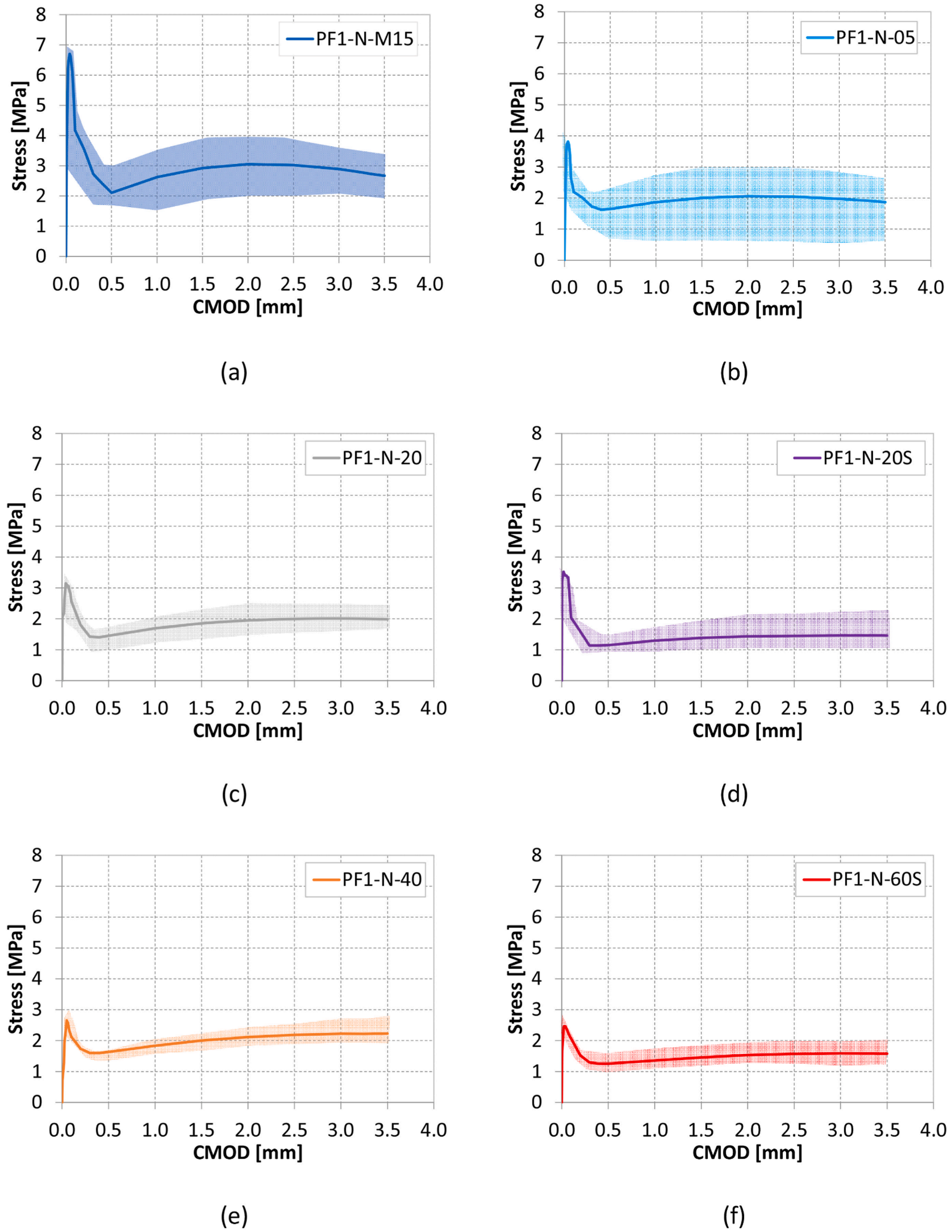

Fig. 3. Flexural behavior of MSFRC with PF1: (a) at −15 °C; (b) at 5 °C; (c) at 20 °C; (d) at 20 °C, in water inmersion; (e) at 40 °C, and (f) at 60 °C, in water inmersion.

with grey lines. The effect of the temperature (after cracking) on the residual tensile strengths (f_{R1}, f_{R3}) was studied for both groups. The results indicate that no significant differences can be detected between precracked and non-precracked specimens reinforced with PF1 nor with steel fibres, to the exception of below zero temperatures, which showed higher increase of residual strengths in PF1 when compared with SF.

However, the previous curves did not consider the number of fibres in the cross section, which is crucial in this analysis since this parameter affects the variability of 3PBTs. To evaluate this, the fibres at the fracture surface were manually mattered after failure, for all the tested specimens.

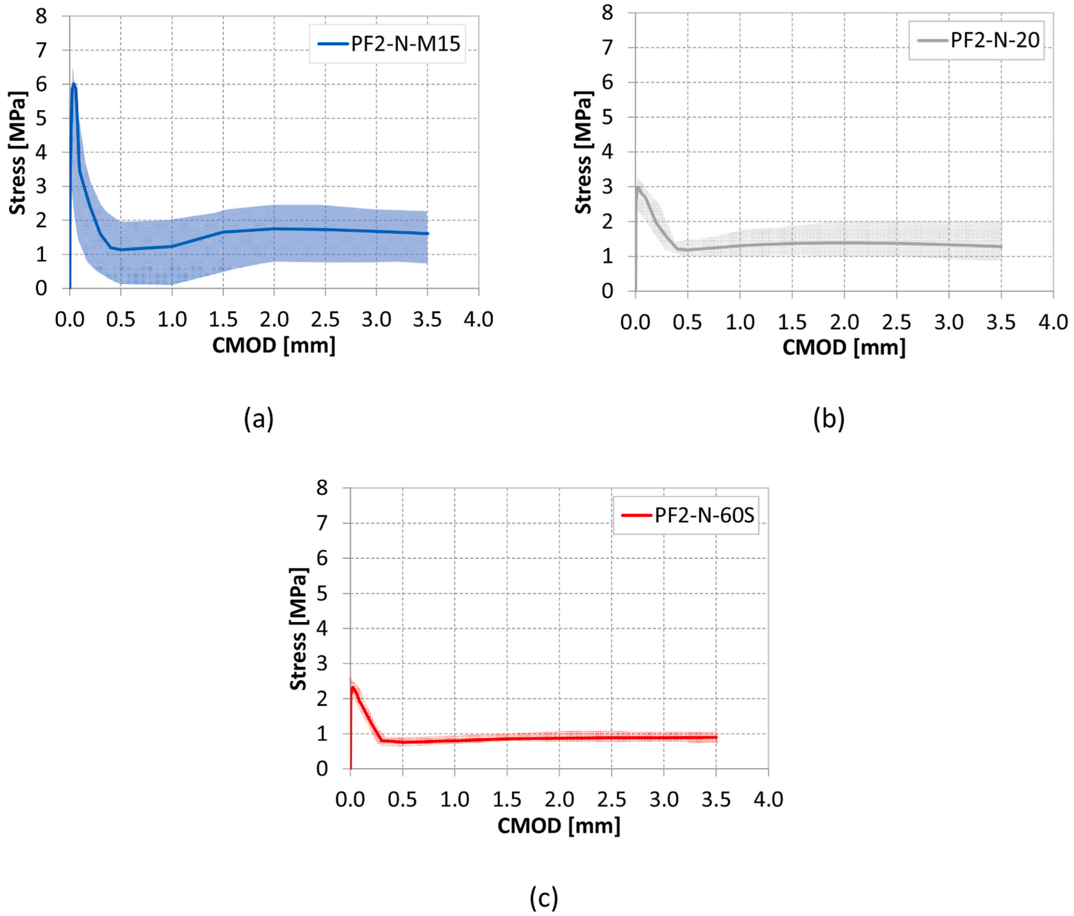

Fig. 4. Flexural behavior of MSFRC with PF2: (a) at −15 °C; (b) at 20 °C, and (c) at 60 °C, in water inmersion.

The results show that the number of fibres present in the cross-surface of MSFRC specimens (between 80 and 120 fibres in average) was higher than that of SFRC specimens (from 40 to 60 fibres in average). The content of macro-synthetic fibres was one-third of the weight of the steel fibres, and this quantity is enough for reaching similar residual strengths. However, the amount of macro synthetic fibres represents more volume than the correspondent amount of steel fibres (0.75% vol. vs 0.25% vol). The distribution of fibres for non-precracked and precracked specimens was similar and followed a normal distribution independently of the fibre type. The ratios f_{R1}/N and f_{R3}/N were calculated for all the temperatures for non-precracked and precracked specimens, with N being the total number of fibres. The normalized values of f_{R1}/N and f_{R3}/N indicate an increasing trend for low temperatures when compared to the standard temperature of 20 °C and a decreasing trend for moderate temperatures, in both, steel and macro synthetic fibres. The effect of temperature is more pronounced for large CMOD than for small CMOD, but the CV of the data also increased in f_{R3}/N if compared with f_{R1}/N but in all the series.

4. Discussion

4.1. Compression strength at operating temperatures

The obtained results of compression tests tested at operating temperatures in this study are similar to those obtained by several authors [19,34]. To date, the effect of environmental conditions has been studied mainly in plain concrete (without fibres), however, the influence of temperature on the compression strength of FRCs has shown to be comparable the effects in plain concrete, results supported in this study, and others [35].

For sub-zero temperatures, the compression strength increases as the temperature decreases. Some authors have shown that compression strength at low temperatures (up to −170 °C) can increase up to 400% when compared to 20 °C [36]. However, such an increase is not detected in other studies performed at temperatures closer to those defined in this work. Other researchers exposed that this relationship is linear [23]. The results obtained in this work are within the order of magnitude of compression strengths at sub-zero temperatures (considering the strength class) obtained in Ref. [23]. This phenomenon could be explained by the Van der Waals force, that increased because of the decrease of the distance between them (interatomic distance) when concrete contracts [23] or by the change of water inside concrete into ice, and this ice formation may enhance the compression strengths [34].

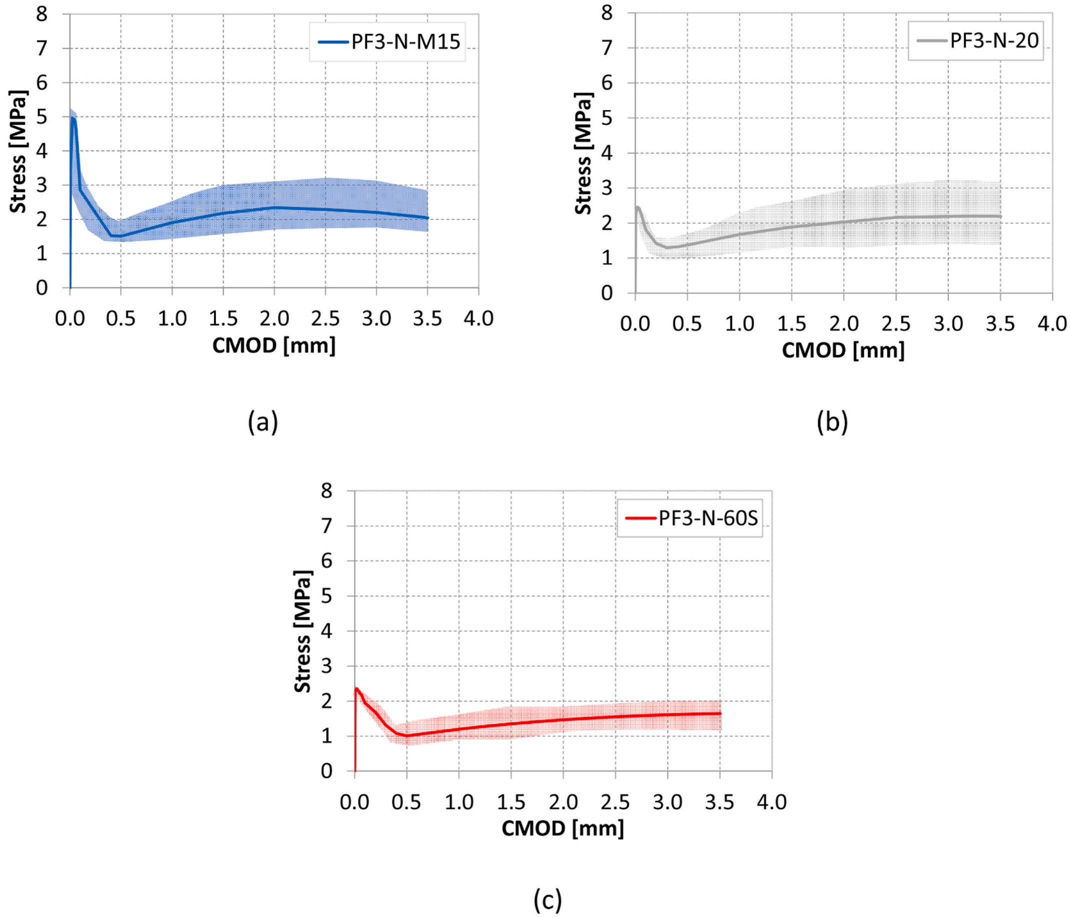

Fig. 5. Flexural behavior of MSFRC with PF3: (a) at −15 °C; (b) at 20 °C, and (c) at 60 °C, in water inmersion.

Only scarce information has been published related to compression strength in the range of 20–60 °C. Most of the studies are conducted over 100 °C, given that water inside concrete begins to evaporate at this temperature and no effects of degradation are expected for the 20–60 °C range. In one study [24], concrete lost 10–20% of its initial compression strength when heated to 100 °C but this extent of decrease was already reached at 60 °C in the current study. This result is in line with [37], which showed that the compression strength of concrete can decrease around 10–50% (depending on the strength class) with the growth of temperature (from 10 up to 30 °C) with a strong linear relationship. This could be also explained through the difference between the coefficient of thermal expansion (CTE) of cement paste and aggregates [38,39]. The coefficient of thermal expansion (CTE) of cement paste, depending on its moisture content, around 11–20 × 10^{-6} per °C, while the CTE of typical aggregates is normally lower, in most cases, 5–13 × 10^{-6} per °C [40]. Humidity is another significant environmental factor that can affect concrete behaviour. However, in the present study, saturation does not affect to a great extent the results obtained (comparing 20 and 20S specimens), which is in line with the results of previous works [41].

To sum up, the operating temperatures studied affect the compression strength of plain concrete and FRCs (MFRCs and SFRC) in a similar manner. Compression strength is reduced when the temperature increases from 20 °C and is increased when the temperature decreases from 20 °C.

4.2. Flexural strengths on FRCs at operating temperatures

Regarding the flexural strength at operating temperatures, f_{LOP} is expected to have a similar behaviour than compression strength, since this property depends mainly on the matrix.

For low temperatures, a significant increase in terms of strengths at LOP is observed [53,54]. This increase is also associated with the embrittlement of a concrete matrix [55]. In this study, the results of strength obtained at −15 °C is doubled when compared to the values at standard temperature (for both MSFRC and SFRC). The results also showed that the behaviour of both FRCs was more brittle at low temperatures, which will have consequences in the design of concrete elements that will be exposed under such temperatures. In fact, the ratio f_{R1}/f_{LOP} defined by MC2010 for structural FRC is not achieved due to the increase in f_{LOP}. This drawback could be overcome by increasing the fibre dosage in order to increase f_{R1} and to provide sufficient ductility. Other studies showed similar re-

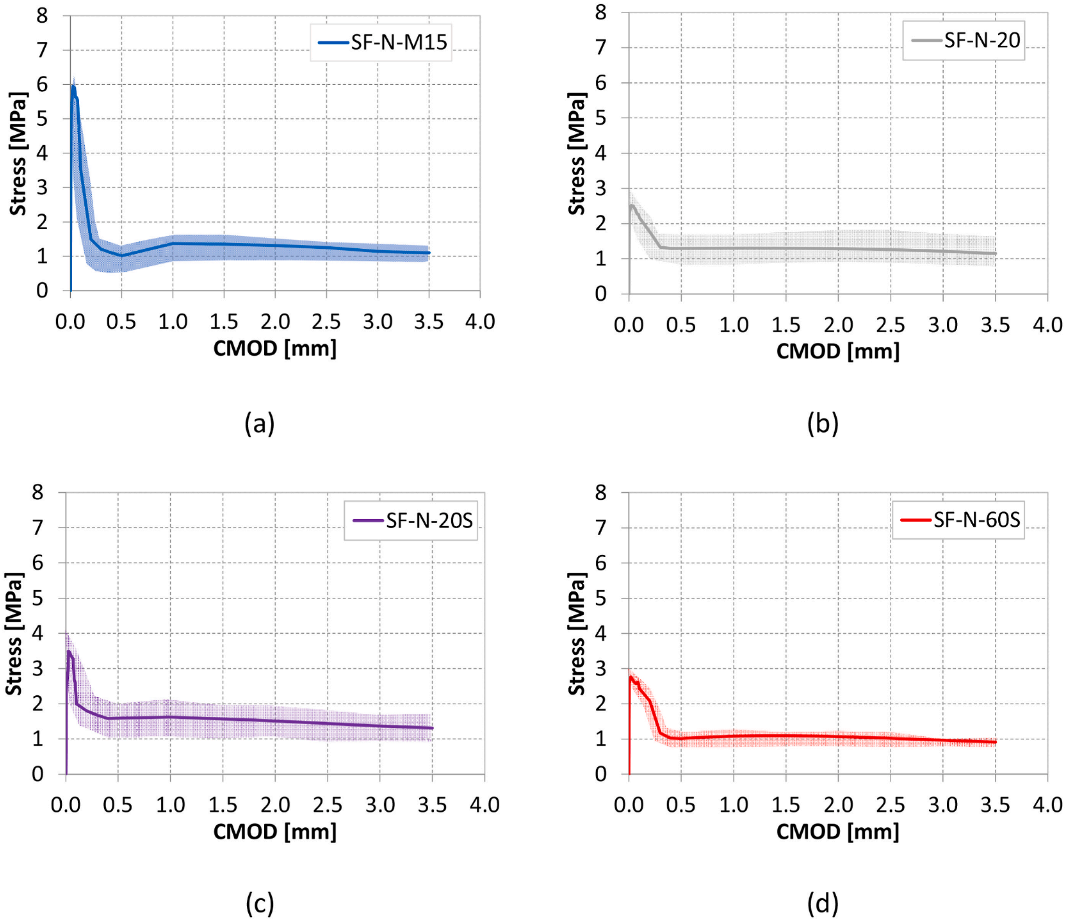

Fig. 6. Flexural behavior of SFRC: (a) at −15 °C; (b) at 20 °C; (d) at 20 °C, in water inmersion, and (d) at 60 °C, in water inmersion.

Table 6
Results of the f_{LOP} and the residual flexural strengths obtained at operating temperatures for precracked specimens. Average and CV in % (in brackets) values.

Code		f_{LOP} (MPa)		f_{R1}(MPa)		f_{R3}(MPa)	
		Tested at 20 °C		Tested at 20 °C			
PF1–P	M15	3.42	(5)	1.69	(18)	3.20	(21)
	05	3.50	(6)	1.42	(28)	2.28	(19)
	20	3.47	(19)	1.67	(18)	2.36	(24)
	20S	2.79	(9)	1.22	(16)	1.59	(22)
	40	3.47	(7)	1.73	(16)	2.05	(15)
	60S	3.18	(6)	1.41	(16)	1.38	(18)
SF-P	M15	3.25	(5)	1.59	(27)	1.58	(29)
	20	2.98	(3)	1.02	(25)	1.05	(24)
	20S	3.21	(11)	1.65	(22)	1.57	(22)
	60S	3.35	(6)	1.14	(14)	1.03	(26)

sults regarding to f_{LOP} values [26,28]. For moderate high temperatures, in this work, a decrease of f_{LOP} is observed for all FRCs studied similar to that obtained in compression strengths (around 20%).

Despite the reduced modulus of elasticity of the macro synthetic fibres compared to steel fibres (typically < 10 GPa for polymeric vs 210 GPa of steel fibres, as shown in Table 2), the load drops after reaching the peak load were equivalent for all the cases, which could be explained by the fibre content. For f_{R1} values, an increase of a 30% in average is shown at −15 °C for MSFRC and SFRC and a decrease of a 20% in average at 60 °C. f_{R3} values were also quite similar for the analysed FRCs, but the temperature effect was greater than for f_{R1} values in all the cases (a 35% higher in average were the results for FRCs at low temperatures and a 25% lower in average were the f_{R3} values at moderate temperatures).

However, regarding the influence of temperature on the post-crack behaviour (f_{R1}, f_{R3}), several factors are involved, such as the mechanical properties of the matrix and fibres characteristics (material, shape, aspect ratio), fibre content and fibre distribution

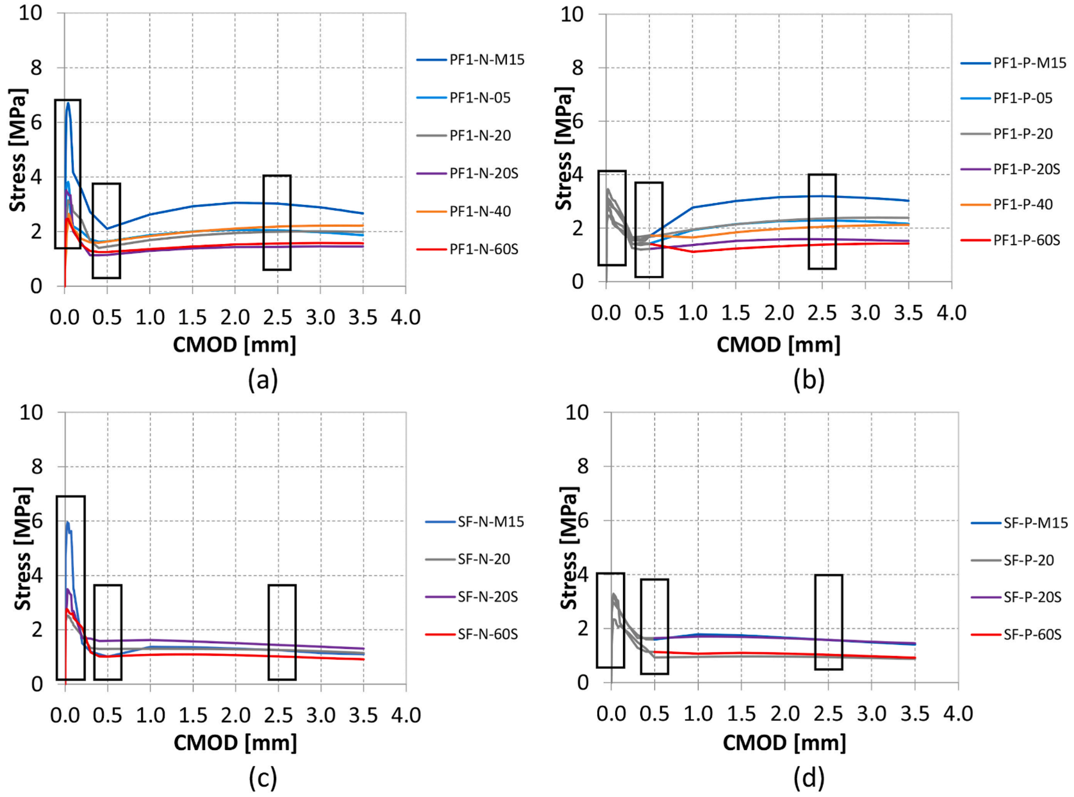

Fig. 7. Average stress-CMOD curves of precracked and non-precracked specimens: (a) PF1–N; (b) PF1–P; (c) SF-N and (d) SF-P.

within the cross-section, among others [42–44] and they should be taken into account. In fact, the normalized flexural strength values attenuated the variation of f_{R1} and f_{R3}. This variation means that an essential component of the detected differences is an effect of the distribution of fibres more than the effect of temperature itself. Once considering the number of fibres in the section, the results obtained present differences in terms of residual flexural strengths of FRC exposed to operating temperatures, but they are not critical differences to fulfil their expected requirements. The variations detected are an increase of a 5% and 20% in average for f_{R1} and f_{R3} values at low temperatures (M15) for both types of FRC and a decrease of a 15% and 20% in average for f_{R1} and f_{R3} values at moderate-high temperatures (60) for the studied MSFRCs and SFRC, even though synthetic fibres have a lower melting point compared with steel fibres. Considering the high intrinsic variability of the test, it can be said that f_{R1} and f_{R3} values were in the same range regardless of temperatures and fibre type.

These results are in line with those obtained by Ref. [28] for below zero temperatures, but the effect was more limited in this study. They showed that a MSFRC with 8 kg/m^3 increased their residual flexural strengths once temperatures dropped below 0 °C up to 71%. The researchers explained this due the energy required to produce fibre pull-out since the concrete matrix that wraps the fibres shrinks at temperatures below zero, which could provoke an increase in the constraint of the fibres and hence, improves the post-cracking flexural behaviour. This affirmation is also supported by Ref. [26] who claimed that a greater bond (18%) between concrete and polypropylene fibre was achieved.

Besides, in this study, for the temperature range from 5 to 60 °C, it seems to be affected by the temperature after 3 days with a decrease on residual strengths but keeping enough residual strength capacity for both small and large values of CMOD in terms of mechanical performance for some structural applications. In fact, the obtained results fullfil the ratios indicated by Model Code 2010 to consider as structural FRCs. As Bazant and Prat [45] suggested, the fracture toughness of brittle materials, as concrete, is known to decrease when temperature increases.

Moreover, Del Prete et al. had investigated the interaction temperature-cracked state in a recent work [46] and they concluded that pre-cracking had not an important effect for short-term exposure (pre-cracking at standard temperature up to a CMOD of 0.15 mm, then unloading and storing at 20 or 40 °C and 55% RH for two days, and finally three-point bending test to failure). In fact, their results corresponding to cracked specimens at two different temperatures (20 and 40 °C) are similar to the results for uncracked specimens. Their results are confirmed with those obtained in the present study, and it can be said that the pre-cracking process did not influence the behaviour of FRCs at the studied non-standard temperatures for short-term exposures.

To sum up, some authors attributed a positive effect to low temperatures on residual flexural strengths due to the enhancement of pull-out strengths. However, special caution should be taken when engineers design FRC in cold regions since this material also becomes more brittle. For operating temperatures above 0 °C, a decrease with the temperature was detected in f_{LOP}, similar to the decrease in plain concrete, since this property is mainly affected by the matrix. Regarding the residual flexural strengths above 0 °C, some effects could be detected after a three-days exposure. Despite some existing concerns, it is possible to obtain a satisfactory result with MSFRC in terms of residual strength values and f_{R1}/f_{LOP} ratios working at moderate temperatures. Finally, further studies are needed to study long-term effects of the exposure to moderate temperatures on FRC performance in order to increase the understanding of FRC durability and service life under these conditions.

5. Conclusions

The conclusions that can be drawn from this work regarding short-term exposure (3 days) to operating temperatures (between −15 °C and 60 °C) are:

- Operating temperatures affect the compression strength of FRCs, in the same way as in plain concrete. Temperatures below zero increased the compression strength (around 30–50%). For other above zero temperatures, when the temperature increased, the compression strength was reduced (around 15–20%).
- The mechanical properties of FRCs measured under saturation conditions are similar to that of FRCs under the control scenario in this study, thus the influence of ambient humidity does not seem to be as relevant as those of temperature.
- Exposure to below zero temperatures led to a significant enhancement of f_{LOP} in both SFRC and MSFRC (around the double), but also more brittleness. In the case of large CMODs, an increase of residual flexural strength was detected if compared with the reference at 20 °C (around 20%), but the results presented high dispersion for both MSFRC and SFRC.
- When temperature increases from 5 to 60 °C, a decrease of f_{LOP} in both SFRC and MSFRC is detected (similar to this obtained for compression strengths). Additionally, these temperatures had a relatively low influence after a period of 3 days of exposure in residual flexural strength for both types of FRCs (15–20%). However, the values obtained are enough to be used in several applications.

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Authors contributions

Marta Caballero-Jorna: Conceptualization, methodology, validation, formal analysis, investigation, data curation, writing—original draft preparation, writing—review and editing, and funding acquisition. **Marta Roig-Flores:** Conceptualization, methodology, validation, formal analysis, investigation, writing—review and editing, and supervision. **Pedro Serna:** Conceptualization, methodology, validation, formal analysis, investigation, resources, writing—review and editing, supervision, and funding acquisition.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Marta Caballero-Jorna reports financial support was provided by Spanish Ministry of Science, Innovation and Universities.

Data availability

Data will be made available on request.

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