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Effect of short-term exposure to moderate temperatures on the residual strength of cracked fibre reinforced concretes

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Abstract. This work studies the effect of short-term exposure to the temperatures of -15°C, 5°C, 40°C and 60°C on the flexural performance of Fibre Reinforced Concretes (FRCs) with steel and synthetic fibres in cracked conditions. The results will be compared with the performance in cracked conditions at 20°C (submerged and air environments). The content of the fibres was chosen to guarantee similar residual strength in all the mixes. The beams were pre-cracked following EN 14651 at ambient temperature after 28 days, up to a crack mouth opening displacement (CMOD) of 0.5 mm. Afterwards, these beams were exposed for 3 days to moderate temperatures, and they were re-loaded up to failure maintaining the target temperature during the test. The residual strength at CMODs of 1.5, 2.5 and 3.5 mm was analysed. Concrete mixes were also characterised by compressive strength, air content, fresh density, and workability. The results show that residual strengths of cracked FRC are more sensitive to sub-zero temperatures than to warm temperatures, similar to the behaviour of uncracked specimens. Synthetic and steel FRCs presented enough flexural response after short-term exposure to moderate temperatures under cracked conditions.

1 Introduction

Cracking is a common type of damage in reinforced concrete structures, and it may have significant adverse effects on its mechanical and durability properties, for example, corrosion [1] or embrittlement [2].

In Fibre Reinforced Concrete (FRC), fibres influence the transmission of tensile stresses across cracks with a bridging effect. This well-known effect contributes to controlling crack width and improving the post-cracking behaviour of concrete, increasing the flexural and ultimate load carrying capacity [3]. Once an FRC element is cracked, fibres are exposed to environmental conditions, which may alter their performance. This alteration will potentially depend on the fibres' material (*e.g.* steel, polypropylene, glass, etc.), and there is some concern about the performance of materials whose Young's modulus is affected by time and/or thermo-hydrometrical phenomena.

The mechanical behaviour of cracked FRCs under different environmental conditions, especially temperatures, is a topic of great interest. However, there is scarce information available in cracked conditions and tested at the target temperatures.

Several studies have been performed in plain concretes. Bazant and Prat [4] studied the effects of the temperature and the humidity on fracture energy from 20 ºC to 200 ºC, obtaining that it decreased smoothly as temperature increased. For temperatures below 20 ºC and below zero, Maturana et al. [5] evaluated the fracture behaviour of saturated concrete in a low-temperature range (from -170 °C to 20 °C). They found that the toughness of concrete increases at low temperatures, reaching a three-fold increase in saturated elements at -170 °C if compared with room temperature elements. Maturana et al. [5] explain that part of this increase in toughness can be explained by extrapolating from Bazant and Prat studies [4] but highlight that water freezing and degradation by microcracking could also be affecting their response.

In FRCs, Del Prete et al. [6] studied the flexural strengths of two Macro-Synthetic Fibre Reinforced Concretes (MSFRCs) in cracked and uncracked conditions, at 20 and 40 °C. The results indicated that 48 hours of exposure to these temperatures produced a decrease in the residual strength of the MSFRC as the temperature increased from 20 to 40°C (around a 15-25 % decrease). These authors did not find differences between cracked and uncracked specimens exposed to 20 and 40 °C. Navarro et al. [7] carried out flexural (without precracking), compression, and Barcelona tests for a MSFRCs with a polyolefin fibre, at temperatures: -30 °C, -20 °C, -10 °C, 22 °C, 55 °C and 100 °C. They observed the same general trend described by other authors [4-6]. The decrease measured in [7] for the compression strength at 55 °C was less than 5 % and at 100 °C less than 15 %. The increases measured at -10 °C, -20 °C and -30 °C were around 5, 10 and 20 %, respectively. The decreasing trend in [7] for the flexural strength was similar; for temperatures below zero, the strength was around 1.5 times the value at 22°C, while for temperatures between 55 and 100°C, the strength was around 0.25-0.5 times the value at 22°C. Aidarov et al. [8] elaborated MSFRC notched beams to analyse their flexural strengths at 20 °C (reference temperature), 0 °C, -10 °C, and -30 °C by means of three-point bending

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tests. Their results show that the flexural strength of all MSFRCs increased around 50-70% when the temperature decreased to below zero.

The present work studies the effect of exposure to moderate temperatures on cracked FRCs. To evaluate this, an experimental campaign has been carried out to expose SFRC and MSFRC beams to different environmental scenarios that may occur in a serviceability state, specifically at -15, 5, 20, 40 and 60 °C, after cracking up to 0.5 mm.

2 Materials and methods

2.1 Materials and mix designs

FRC mixes of this work contained 280 kg/m^3 of Portland cement type CEM I 42.5 R SR5, limestone aggregates (three types of gravel and two types of sand), tap water and two types of additives (a superplasticiser and an air-reducer admixture). Concerning the aggregates, the maximum size was limited to 20 mm in accordance with fibre length.

A polycarboxylate ether-based superplasticiser was added to increase the workability of the mixes. The amount of superplasticiser was adjusted based on the fibre type to achieve the same consistency class in all the mixes. An air-reducing admixture was introduced to maintain the air content under 2%.

Two types of commercial fibres were selected in this study. Fibre SF was 35-mm long and was made of steel with a specific gravity of 7.85 g/cm^3. Fibre PF1 was 48-mm long and was made of polypropylene with a specific gravity of 0.91 g/cm^3. The most relevant properties of both types of fibres used are summarised in Table 1.

Table 1. Fibre properties. (* Aspect ratio = length / diameter)

Properties	**SF**	**PF1**
Material	Steel	Polypropylene
Design	Hooked end	Macro fibre embossed
Equivalent diameter (mm)	0.55	0.81
Length (mm)	35	54
Aspect ratio*	67	65
Tensile strength (MPa)	1345	552
Modulus of elasticity (GPa)	210	7
Melting point (°C)	1375	150-170
Image		

Two fibre contents were used to obtain a similar level of residual flexural strength in all the mixes: 21 kg/m^3 for steel fibres and 7 kg/m^3 for macro synthetic fibres.

The FRCs were produced with the mixed designs presented in Table 2. The water/cement (w/c) ratio was 0.55.

Table 2. FRC dosages used in this study.

Material	**SFRC (kg/m^3)**	**MSFRC (kg/m^3)**
Cement CEM I SR5 42.5R	280	280
Gravel (16-20 mm)	183	183
Gravel (8-16 mm)	402	402
Gravel (4-8 mm)	146	146
Sand (0-6 mm)	897	897
Sand (0-2 mm)	211	211
Water	154	154
Air-reducer admixture	0.4	0.4
High-performance superplasticiser	0.7-0.90	0.9-1.3

The mixing process took place in a planetary concrete mixer with a nominal capacity of 500 l. Each batch had a volume of 250 l of concrete. After mixing all dry components (cement, sand and aggregates), water and additives were added into the mix, and afterwards, fibres were added manually (Fig. 1). The mixing processes finished with an additional mixing of 3 min. The total mixing time was 10 min approximately.

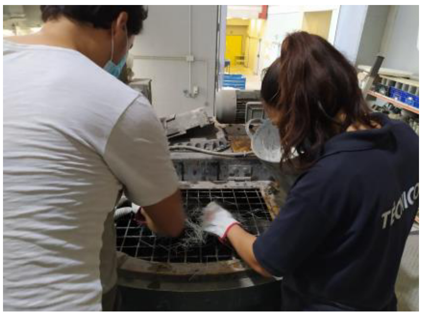


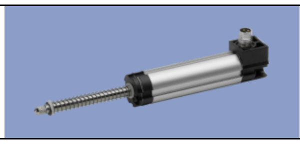
Fig. 1. Adding fibres into the mix during the mixing process.

2.2 Method to evaluate residual flexural strength at moderate temperatures

A three-point bending test described in EN 14651 [9], was performed to study the post-cracking behaviour. The bending test was performed in three stages: bending test to pre-crack elements at room temperature, exposure at the target conditions and re-loading until failure.
A set of 7 notched prisms of 150 × 150 × 600 mm³ were cast and tested per fibre type to assess the influence of each temperature. After 24 hours from casting, they were demoulded and stored in a climatic chamber at 20 °C and 95% relative humidity until the date of pre-cracking (28 days after casting). The prisms were tested at standard temperature (20 °C), with a three-point bending test (3PBT) set up with a span length of 500 mm, using an INSTRON® 3389 hydraulic servo-controlled testing machine. The prisms had a notch of size 2 mm width and 25 mm depth, which were prepared three days before pre-craking for all the specimens.

The Crack Mouth Opening Displacement (CMOD) was controlled with a linear variable differential transformer (LVDT) placed at the notch. The specifications of the LVDT are listed in Table 3.

Table 3. Specifications of the LVDT.

LVDT TEX 0010	
Measuring capacity (mm)	10
Sensitivity (mm)	0.01 (without side loads)
Temperature range (°C)	-40 …+85
Operating humidity range (% RH)	0 … 95 (no condensation)
Image	

2.2.1 Pre-cracking at room temperature

First, a constant load rate of 0.5 mm/min was applied until the 80% maximum load peak; after that, the load rate was changed to 0.05 mm/min until cracking, and finally, a rate of 0.2 mm/min was applied up to a total CMOD of 0.5 mm. This value was decided considering the fib Model Code 2010, where the post-cracking strength considered for the serviceability limit state is the residual strength at a crack width of 0.5 mm. The unloading process was performed at a speed of 3 mm/min. Afterwards, specimens were left for 10 minutes in the INSTRON® machine while recording the additional closing of the crack.

2.2.2 Exposure to moderate temperatures

Immediately after pre-cracking, the specimens were stored in their corresponding scenario for three days. The selected scenarios are described in Table 4, and consisted of three days of exposure at -15, 5, 20, 40 and 60 °C. Some of these conditions were obtained in water immersion, while others were studied in air conditions with different RH. Because of that, the reference temperature of 20 °C was analysed in both, air and submerged conditions. To cool specimens at -15 °C and 5 °C, a Rommer® CH 402 T A+ horizontal freezer was used. At 20 and 40 °C, specimens were stored in a controlled temperature room. For the submerged specimens, tanks with tap water were used. For specimens exposed to 60 °C, the condition was also prepared using tanks with tap water and heater resistors. These scenarios were selected to represent different conditions that concrete may be exposed to during its lifetime, such as in cool or hot regions or in industrial activities.

Table 4. Scenarios selected in this study to expose the specimens.

Code	Description	Image
-15	-15 °C and RH >95%	
5	5 °C and RH >95%	
20	20 °C and RH 95%	
40	40 °C and RH 30%	
20-S	20 °C and submerged in water	
60-S	60 °C and submerged in water	

2.2.3 Residual strength at moderate temperatures

Afterwards, the beams were reloaded at a constant load rate of 0.2 mm/min until failure (up to CMOD = 4 mm) in a 3PBT set up at target temperatures. The evolution of the residual bending strength of the FRC beams at the different CMODs was registered until the end of the test while the beams were kept at the target temperature.

For this purpose, an insulation system was used to maintain the constant target temperature during this part of the test. Bags of gel packs were used as support to maintain the temperatures during the tests, as shown in Fig. 2.

The internal and external temperatures of specimens were checked. The external temperature was checked using an IR thermometer. To check the internal temperature, a thermocouple type K was placed in the core of an accompanying beam per mix during the test. This allowed registering the variation of the temperature inside the specimen. The variation detected between the internal temperature and the target for the test, depended on the temperature analysed. The condition with the highest variation was 60-S, which had a difference of 10 °C at the end of the test, while the rest of the conditions had only low variations of temperature (< 5 °C at the end of the test).

Fig. 2. Set up of three-point bending test performed in this study.

The age of the specimens at the final testing time was 31 days after casting. After the final bending test, the specimens were removed from the frame and were completely broken into two halves in order to proceed with the manual counting of the fibres contained in the cross-section.

2.3 Characterization of the mixes

To characterise the concrete mixes, air content, compression strength, fresh density, and workability tests were carried out, in compliance with UNE-EN 12350-6 [10], UNE-EN 12390-3 [11], UNE- EN 12350-7 [12] and UNE- EN 12350-2 [13]. Compression strength was determined at 28 days using cubes of the side of 150 mm³ (3 specimens for each batch) in an IBERTEST MEH-3000-LCMD2W press.

3 Results and discussion

The results of the characterisation tests are described in Section 3.1. The results of the flexural behaviour at peak load and the post-crack behaviour in the defined scenarios are presented and discussed in Section 3.2.

3.1 Results of characterisation tests

Table 5 shows the slump of the FRCs tested in this study. The results showed that the consistency class varied between S3 and S4 in all the mixes. Due to the additive content, the specimens with polymeric fibres did not experience a reduction in workability compared to the specimens with steel fibres.

Moreover, the average compressive strength (f_{cm}) of the concrete was calculated from three specimens. According to Table 5, tested cubes showed low standard deviation (SD) values, indicating good mixing and casting procedures. For compression strength, the characteristic compressive strength of all of the concrete was around 35 MPa.

The weight of the specimen was measured before testing to calculate the density in a fresh state, which is around 2349-2381 kg/m³ for all the mixes. Air content was also determined and resulted in under 2 %, as was planned.

To sum up, these results of characterisation tests support a good mixing and casting process and allow a direct comparison between them.

Table 5. Characterisation results for all the series in this study.

Code		Slump (mm)	Air content (%)	Fresh density (kg/m³)	f_{cm} (MPa)
SF	-15	170	1.1	2377	36.5
	20	180	0.5	2374	34.0
	20-S	200	1.9	2381	38.0
	60-S	190	1.7	2381	34.5
PF1	-15	220	0.8	2349	35.0
	5	170	1.1	2377	36.0
	20	220	0.6	2368	36.0
	20-S	140	1.8	2368	36.0
	40	210	0.6	2369	34.5
	60-S	190	0.3	2371	35.0

3.2 Results of flexural strengths

FRC concrete beams with SF and PF1 fibres have been tested with 3PBT to investigate load versus CMOD behaviour. Since pre-cracking was performed at room temperature until a CMOD of 0.5 mm, the parameters

f_{LOP} and f_{R1} were studied at room temperature. The rest of the residual strength parameters, f_{R2}, f_{R3} and f_{R4} have been analysed at the target temperature.

The obtained results for the flexural strengths and their dispersion are reported in Table 6 and Table 7. The values represent the average of seven specimens and their corresponding standard deviation (SD).

Table 6 shows results obtained at pre-cracking, that is, at 28 days, and the parameters obtained are the proportionality limit (f_L) and the f_{R1} specified in the standard EN 14651 for a crack width equal to 0.5 mm. These two parameters are obtained at a normal temperature.

In contrast, the rest of the residual strength values were obtained at 31 days at f_{R2} (CMOD = 1.5 mm), f_{R3} (CMOD = 2.5 mm) and f_{R4} (CMOD = 3.5 mm) at the target temperatures (see results in Table 7).

The flexural strength of each beam was calculated using the following equations (1) and (2):

$$f_L = \frac{3}{2} \cdot \frac{F_j l}{b h_{sp}^2} \tag{1}$$

$$f_{R,j} = \frac{3}{2} \cdot \frac{F_j l}{b h_{sp}^2} \tag{2}$$

Where F_j is the axial load recorded during the test; l, the distance between supports (500 mm); b, the width of the sample cross-section (150 mm) and h_{sp}, the distance between the top of the notch and top of the cross-section (125 mm).

Table 6. Results of 3PBT at f_L and at f_{R1}, testing at 20 °C. Average and standard deviation (SD).

Code	SF				PF1					
	-15	20	20-S	60-S	-15	5	20	20-S	40	60-S
f_L (MPa)	3.3	2.9	3.2	3.4	3.4	3.5	3.2	2.8	3.5	3.2
SD (MPa)	0.2	0.1	0.3	0.2	0.2	0.2	0.3	0.3	0.2	0.2
f_{R1} (MPa)	1.6	1.0	1.7	1.1	1.7	1.4	1.7	1.2	1.7	1.4
SD (MPa)	0.4	0.3	0.4	0.2	0.3	0.4	0.3	0.2	0.3	0.4

Table 7. Results of 3PBT at f_{R2}, f_{R3} and f_{R4}, testing in different scenarios. Average and standard deviation (SD).

Code	SF				PF1					
	-15	20	20-S	60-S	-15	5	20	20-S	40	60-S
f_{R2} (MPa)	1.7	1.1	1.7	1.1	3.0	2.2	2.2	1.5	1.8	1.2
SD (MPa)	0.5	0.3	0.4	0.3	0.6	0.4	0.5	0.3	0.3	0.4
f_{R3} (MPa)	1.6	1.1	1.6	1.0	3.2	2.3	2.4	1.6	2.1	1.4
SD (MPa)	0.5	0.3	0.3	0.3	0.7	0.4	0.6	0.3	0.3	0.4
f_{R4} (MPa)	3.0	2.2	2.4	1.5	2.1	1.4	1.4	1.0	1.5	0.9

These results are represented in Fig. 3-a and Fig. 3-b, depending on the fibre type. A representative colour was assigned to each scenario. Blue and light blue were assigned for the cold temperatures of -15 and 5 °C, respectively. Grey colour was assigned to 20°C and purple to 20-S. Warm colours were assigned to the moderate-high temperatures, orange to 40°C and red to 60 °C. In addition, those series of specimens that were exposed to submerged conditions are identified with an S.

For f_L and f_{R1} values, the temperature effect was not considered because all the batches were tested at standard temperature. For SF and PF1 specimens in Fig. 3-a and Fig. 3-b, f_L results are around 3 MPa with small values of SD in all the cases. This may be explained because f_L values are mainly influenced by the concrete matrix, and are not significantly affected by fibre content and type. For f_{R1} results, the variation between groups is higher than for f_L values, but they are all in a similar range. For submerged specimens, the strengths at the peak load f_L and at f_{R1} show a slight decrease.

For f_{R2}, f_{R3} and f_{R4} values, which were tested after a three-days exposure to the target temperatures, some differences were detected.

Regarding cold temperatures, SFRC experiences an increase in residual strength when reducing the temperature from 20°C to -15°C (both conditions without immersion in water). In MSFRCs, at temperatures below zero, an increase in the flexural strengths (f_{R2}, f_{R3} and f_{R4}) of the beams was also detected. However, no clear differences were detected between 5°C and 20°C.

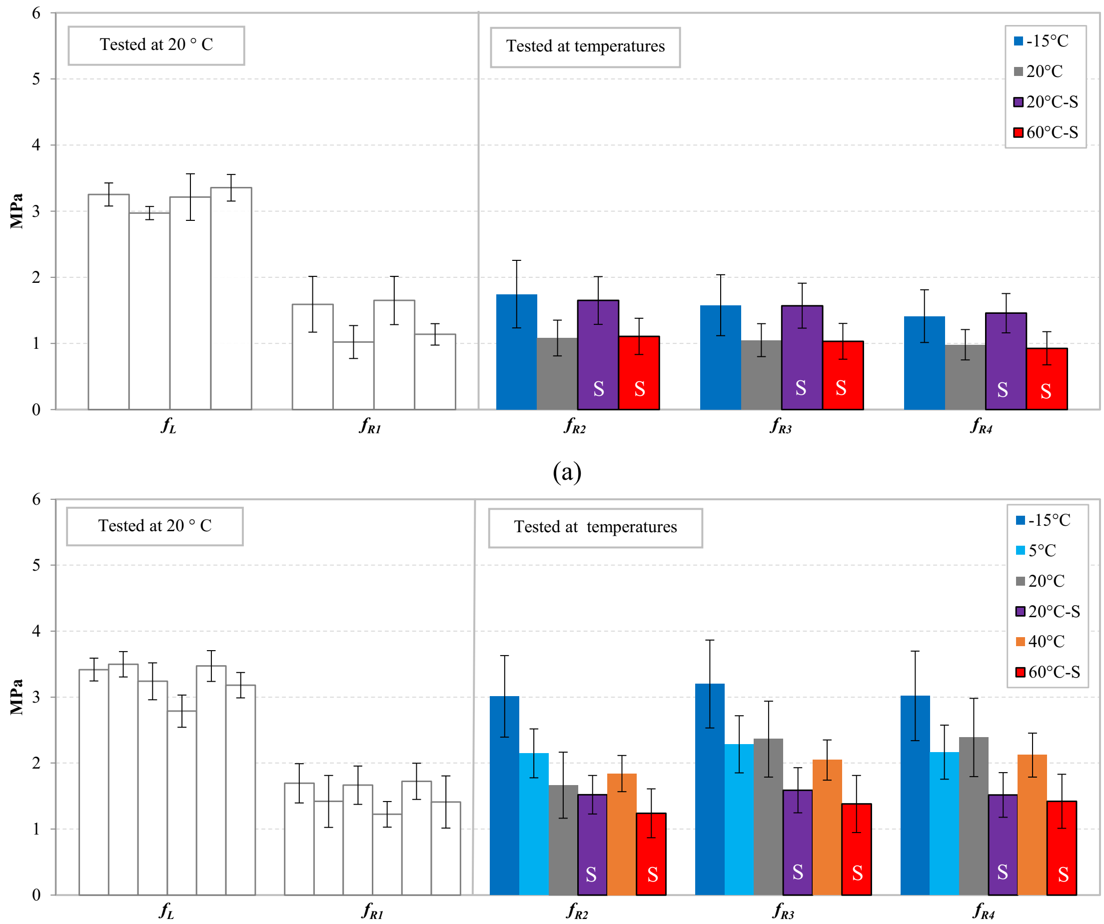
Regarding warm temperatures, in SFRC, when comparing 20°C and 60°C, both immersed, a decrease in the residual strength was detected. In MSFRC, only a very slight decrease was detected when increasing the temperature from 20°C to 60°C (both conditions immersed). However, no differences were detected between 20°C and 40°C.

As per the results obtained, it can be deduced that a three-day exposure to mild temperatures (5 and 40 °C) in cracked conditions has no significant effect on the residual strength. The variations detected for cold and warm temperatures were consistent with those reported in the literature, either for plain or for FRC mixes[4-8].

Additionally, the fibres in the cross-section were counted in order to analyse their effect on the residual strength values obtained. The results are displayed in Table 8.

Table 8. Number of fibres in the cross-section per series. Average and standard deviation (SD).

Code	SF				PF1					
	-15	20	20-S	60-S	-15	5	20	20-S	40	60-S
N. of fibres	46	60	78	56	100	85	91	78	96	78
SD	10	10	9	8	13	5	15	12	10	8



(b)

Fig. 3. (a) Residual flexural strengths for SF (b) Residual flexural strengths for PF1.

They indicate that the reduction in the residual flexural strengths for the submerged specimens can be explained by a lower average number of fibres in the cross-section. In SFRC and MSFRC, those series with a lower average number of fibres in the cross-section had lower residual strength. The extent of this variation suggests that an essential part of the variations detected is an effect of fibre distribution and not an effect of temperature.

For example, specimens with steel fibres exposed to 20S had an average number of total fibres in the cross-section higher than for the rest of the conditions, which led to high residual strength. However, at -15 °C, SFRC had the lowest average number of total fibres in the cross-section, however, no decrease in the strength was detected, which could be a counter-effect of the increase in strength produced by below zero temperatures.

As shown in Table 8, the number of fibres in MSFRC specimens was, in general, higher than that in SFRCs. Macro synthetic fibres are able to reach similar results in terms of residual strengths to steel fibres with one-third of the weight (7 kg/m³ were used for MSFRC and 21 kg/m³ for SFRC). However, macro synthetic fibres represent a greater volume than steel fibres with these dosages.

Comparing the obtained results for SFRC and MSFRC in this work, both types of FRCs present similar post-cracking behaviour, and all the groups have significant residual strength yet after being exposed for three days to the studied temperatures. Similar results were obtained in previous studies for uncracked prisms [14,15].

The distribution of the total number of fibres was further analysed for the SFRC and MSFRC mixes, by counting the number of specimens (N) with certain ranges of total fibres. The distribution obtained is displayed in the histogram in Fig. 4.

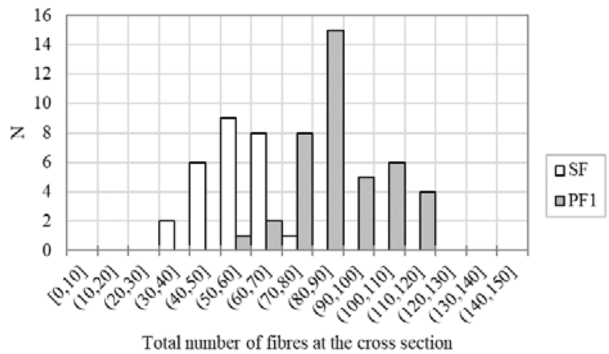


Fig. 4. The total number of fibres at the cross-section for each type of fibres according to the number of events.

The horizontal axis includes the ranges of the total number of fibres (with a step of 10), and the vertical axis indicates the number of specimens that had this range of the total number of fibres. Fig. 4, shows that the distribution of the number of fibres in the section of each specimen per group of FRC (SFRC vs MSFRC) corresponds approximately to a Gaussian distribution. This result indicates that the number of fibres around the average number of fibres of each group was a more typical case than values far from the average.

According to the fib Model Code 2010 [16] classifications for FRC, mixes with SF fibres could be classified as 1.0-1.5 (c) and mixes with PF1 fibres as 1.0-1.5 (c, d or e), see Table 9. This means that both mixes exhibit hardening behaviour with a ratio f_{R3}/f_{R1} of 1.0 and 1.9 for SF and PF1, respectively. Furthermore, FRC can be used to substitute reinforcement when $f_{R3}/f_{R1} > 0.5$ and $f_{R1}/f_L > 0.4$. The former condition is satisfied for both FRCs, but the second is only satisfied for PF1 mixes, for all the groups tested. For SF mixes, higher fibre contents should be used to achieve to fulfil the structural requirements (values in red do not accomplish the requirements).

Table 9. Summary of the results regarding structural requirements for FRCs studied.

Code	SF				PF1					
	-15	**20**	**20-S**	**60-S**	**-15**	**5**	**20**	**20-S**	**40**	**60-S**
f_{R1}/f_L	0.5	0.3	0.5	0.3	0.5	0.4	0.5	0.5	0.4	0.4
f_{R3}/f_{R1}	1.0	1.0	1.0	0.9	1.9	1.6	1.4	1.2	1.3	1.0
Class	1.5c	1.0c	1.5c	1.0c	1.5e	1.0e	1.5e	1.0d	1.5e	1.0c

To sum up, the post-cracking behaviour of concretes with macro synthetic fibres is not significantly more sensitive to short term exposure at the temperatures tested than concretes with steel fibres. Both FRCs can provide exemplary performance in terms of post-peak behaviour.

4 Conclusions

In this study, an experimental program was conducted to obtain a better understanding of the effect of short-term exposure to moderate temperatures on the residual strength of cracked FRCs with steel (SFRC) or macro synthetic fibres (MSFRC). SFRC mixes contained 21 kg/m³ of steel fibres and MSFRC mixes contained 7 kg/m³ of polypropylene fibres, in order to have comparable residual strengths.

The results obtained in this study indicate that cracked elements made with FRC, either with steel or macro synthetic fibres, experience a variation of residual strengths due to a short-term (3 days) exposure to moderate temperatures in the range (-15 – 60 ºC). This variation is more important for temperatures below zero degrees than for temperatures above zero. However, this variation of properties is similar to the variation of properties obtained in uncracked elements (from previous studies), and to the variation of properties for plain concrete. Further research is currently being performed in order to have a better differentiation of the parameters affecting the results obtained as well as for determining long-term effects.

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