

The Influence of Concrete Strength on the Effect of Synthetic Fibres on Fire Resistance

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RESEARCH ARTICLE

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Abstract

Numerous studies have verified that increased concrete strength reduces its resistance to fire, leads to a higher degree of strength reduction and higher chances of spalling of concrete surfaces.

The risks of spalling of concrete surfaces can be reduced by adding synthetic polypropylene fibres. Numerous experiments have shown that the risk of spalling of the concrete surface is significantly lower when using short, small diameter fibres of polypropylene synthetic, because the pore structure created by the burning of fibres reduces the risk of cracking.

However, the question arises whether other types of fibres of greater diameter and length are still able to prevent spalling of concrete surfaces without drastically reducing the strength and if so, in what range of concrete strength it is true.

The experiments are aimed to determine the effects of micro and macro synthetic fibres on the post-fire residual compressive strength, flexural strength and porosity of concrete.

Nine kinds of mixture were prepared and tested. Three of them are without fibers (reference concretes) with diverse strength, three with synthetic micro-fibres with diverse strength and three with synthetic macro-fibres of diverse strength. The experiment was conducted with three concretes with different strength. Each type had a reference concrete without fibre reinforcement, one with micro- and one with macro-fibres.

Keywords

fire, concrete strength, syntetic polypropylene fibers

1 Introduction

Concrete is a composite material consisting of two main components (aggregate and cement stone). When exposed to high temperatures, both undergo changes.

Strength properties of concrete deteriorate with increasing temperature. After cooling back, concrete does not regain its original characteristics, properties, since irreversible changes take place in its structure due to heat exposure, its structure becomes decomposed and ultimately destroyed.

The destruction of concrete is basically due to two reasons [1]:

- chemical transformation of concrete components;
- spalling of concrete surface.

The changes in concrete strength properties at high temperature levels depend on the following parameters [2]: the type of cement, the type of aggregate, the water-cement ratio, the aggregate-cement ratio, the initial water content and the method of heating.

High temperature causes concrete structure to change. Chemical processes in concrete as a result of increasing temperature can be examined with thermoanalytical methods (TG/DTG/DTA). TG (thermo-gravimetric) and DTG (derivative thermo-gravimetric) curves allow quantitative analysis of transformations accompanied by mass change. DTA (differential thermal analysis) curves can keep track of exothermic (heat releasing) and endothermic (heat absorbing) processes resulting from temperature increase in the specimens.

Around 100 °C, the loss of weight is caused by water leaving through the macro-pores. The decomposition of ettringite ($3\text{CaOAl}_2\text{O}_3 \cdot 3\text{CaSO}_4 \cdot 32\text{H}_2\text{O}$) occurs between 50 °C and 110 °C [3, 4, 5, 6, 7]. Around 200 °C further dehydration processes take place, which lead to a further small-scale increase in mass loss. The mass change of specimens of various initial water content will be different as long as the pore water and the chemically bound water evaporates. Depending on the initial water content, there are significant differences in mass loss in the case of lightweight concrete. Further mass loss depending on initial water content cannot be observed between 250–300 °C. Between 450 °C and 550 °C the decomposition of non-carbonated portlandite takes place ($\text{Ca}(\text{OH})_2 \rightarrow \text{CaO} + \text{H}_2\text{O}\uparrow$). This process leads to an

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endothermic (heat absorbing) peak and further mass loss at the same time [8]. In ordinary concrete, the crystal transformation of quartz from α to β causes an endothermic peak of small intensity at 573 °C. The transformation of quartz is accompanied by a 5.7% increase in volume [9], resulting in substantial damage to the concrete. Above this temperature the concrete does not possess significant strength. At 700 °C, the CSH (calcium silicate hydrate) compounds decompose through water loss, which is accompanied by an increase in volume and further loss in strength [10].

Numerous studies have shown that as concrete strength increases, its resistance to fire decreases, there will be a higher degree of strength reduction and a higher chance of spalling of concrete surfaces [11, 12, 13, 14, 15].

It is important to avoid spalling of concrete surfaces. Its risk can be reduced by adding synthetic (polypropylene) or steel fibres to the concrete [16, 17, 18, 19, 20, 21, 22]. Based on Chen's research, steel fibres decreased the number of cracks appearing between 400 °C and 600 °C, thus reducing the risk of spalling of concrete surfaces [14]. Numerous experiments have proved that the risk of spalling of the concrete surfaces is significantly lower when using short, small diameter fibres of polypropylene synthetic, because the pore structure created by the burning of fibres reduces the risk of cracking [23].

Mörth, Haberland, Horvath and Mayer [24] conducted experiments on tunnel segments (span 11 m, height 2 m), which indicated that concrete reinforced with synthetic polypropylene fibres do not undergo spalling in case of fire (with heat loading of 1200 °C).

Another research teams in Austria [25, 26, 27, 28] examining depressed slabs arrived to the same conclusions. In case of ordinary concrete, spalling of the concrete surface started after two hours of fire exposure, whereas it could not be perceived on concrete slabs reinforced with polypropylene fibres.

It is an important issue, however, that – in addition to all these benefits – compressive strength should not fall drastically either compared to ordinary concrete. Horiguchi [29, 30] examined compressive strength of fibre-reinforced concrete in high temperature ranges. The compressive strength of cylinders (diameter 100 mm, length 200 mm) was tested after cooling down to room temperature. The heating speed was 10 °C per minute and specimens were kept at the given temperature for one hour. The applied water-cement factor was 0.3 (with cement content of 583 kg/m³). The first concrete had no fibre reinforcement, the second contained polypropylene fibres of 0.5 V%, the third steel fibres of 0.5 V%, the fourth polypropylene fibres of 0.25 V% and steel fibres of 0.25 V%.

Compressive strength values of concretes with and without fibre-reinforcement had a similar tendency. Concretes without fibre reinforcement and with synthetic fibres showed much lower figures following heat loadings of 200 °C and 400 °C than concretes with steel fibres and hybrid fibres (polypropylene fibres of 0.25 V% and steel fibres of 0.25 V%). Increased

reduction in strength may be caused by the burning of synthetic fibres and the resulting growth in porosity.

It is still to be answered whether other types of fibres with larger diameter, larger length are also able to prevent spalling of concrete surfaces without drastically reducing its strength.

2 Experimental program

2.1 Applied materials

The experiment was conducted with three types of concrete, each of different strength (C20/25, M1; C30/37, M4; C50/60 M7). Each type had a reference concrete without fibre reinforcement (M1, M4, M7), one with micro (M2, M5, M8)- and one with macro-fibres (M3, M6, M9). The composition of the concretes is summarized in Table 1. The type of cement was CEM III/B 32.5 N L-(M-S)/ R in each case. Dosage of micro-fibres was 1 kg/m³ (M2, M5, M8), whereas dosage of macro-fibres was 4 kg/m³ (M3, M6, M9). The consistency of concrete was F4 and was determined by flow table test. The material of the fibres was polypropylene in both cases. The length of micro-fibres was 18 mm, their diameter was 0.24 mm. The length of macro-fibres was 42 mm, their diameter was 0.8 mm.

Table 1 Composition of the concretes (kg/m³)

kg/m ³	M1	M2	M3	M4	
cement	300	300	300	350	
aggregate					
0-4 mm	794	794	794	783	
4-16 mm	435	435	435	429	
16-32 mm	662	662	662	653	
water	174	174	174	158	
superplasticizer	0	0	0	0	
fibre	0	1	4	0	
kg/m ³	M5	M6	M7	M8	M9
cement	350	350	385	385	385
aggregate					
0-4 mm	783	783	783	783	783
4-16 mm	429	429	429	429	429
16-32 mm	653	653	653	653	653
water	158	158	154	154	154
superplasticizer	0.44	0.44	2.22	0	1.11
fibre	1	4	0	1	4

2.2 Test methods

After demoulding the 1-day-old specimens, they were kept in lime water until day 7, then in laboratory air (20 °C) until day 28. Heat loading began on day 28. In the experiment, the electric furnace was heated in line with the standard temperature-time curve ISO 834, using 6 temperature ranges of 20 °C, 150 °C, 300 °C, 500 °C, 800 °C. Heat exposure of each specimen lasted for 120 minutes, thus ensuring they are evenly heated. Following heat loading, specimens were cooled down in ambient conditions (20±3 °C). Laboratory measurements were carried out afterwards.

Specimens of 150×150×150 mm (90 specimens for compressive strength) which had been previously exposed to high temperature and left to cool down in laboratory air were tested with testing machine ALPHA 3-3000 S. The machine's load speed was 11.25 kN/s.

Porosity was tested on blocks of 250×70×70 mm (90 specimens for flexural strength and porosity measurements). The specimens broken in half were weighed in laboratory conditions (20–22 °C) with a scale of 0.1 g accuracy. Following weighing of the completely dried specimens, they were placed in water to saturate them with water. Once water-saturation was complete, they were weighed with Archimedes' scale and after being wiped, weighing was repeated with a scale of 0.1 g accuracy, after keeping them in a drying oven at 60 °C to constant weight.

3 Experimental results

3.1 Visual observation

Increased compressive strength led to a higher chance of explosion-like spalling in the reference specimens without fibre-reinforcement (M1, M4, M7). While both cube and block specimens M1 remained intact and suitable for further tests, cube specimens M4, made of greater strength concrete, were destroyed at 500 °C, while the blocks at 800 °C. Both cubes and blocks of M7 type specimens burst above 300 °C (Fig. 1). In case of fibre reinforced concrete spalling was not observed.

As the number of cracks increased – the majority of which appeared over 800 °C – the surface of the concrete became porous, thus weaker.



Fig. 1 Specimens destroyed by heat loading



Fig. 2 The surface of macro-fibre concretes after heat loading of 300 °C

Due to the presence of micro fibres (M2, M5, M8), explosive spalling did not occur, unlike on concrete without fibre. Therefore, fibres succeed in preventing explosive spalling. Not even did the specimens of higher strength suffer any particular damages from heat exposure. Surface micro cracks could only be observed at 800 °C on micro-fibre concretes, but to a smaller extent than on reference specimens.

In macro-fibre concretes (M3, M6, M9), the macro-fibres melted, became yellowish in colour and flowed out of the specimens (Fig. 2). However, besides the aesthetic damage, spalling of concrete surfaces could also be observed.

3.2 Changes the compressive strength in function of the temperature

The results from the residual compressive strength tests were averaged (3 measurements). Average strength of concrete M1 was equal to 24.58 N/mm², for M4 is achieved 36.89 N/mm², while in case of M7 is reached 54.47 N/mm². Relative compressive strength values at 20 °C (strength measured after heat loading/strength measured at 20 °C) are presented in Fig. 3.

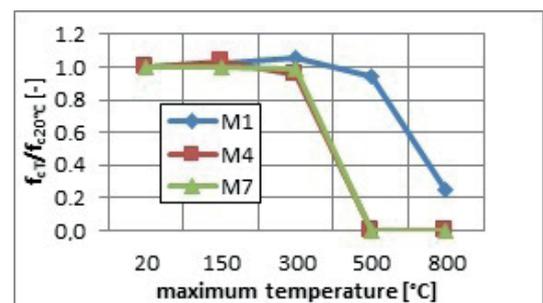


Fig. 3 Relative compressive strength values of concretes without fibres (calculated from 3 measurements) in function of temperature

It is apparent from the results that initially there is no strength reduction in concretes without fibre as temperature increases, what is more, there is a slight growth by a few per cents in case of the concrete M1 and M4, although it is only a temporary increase, the same tendencies were observed by Horguichi [30, 31]. From an engineering perspective, it can be stated that compressive strength values start to decrease over 300 °C. Another important finding is that the increase in strength results in a greater risk of spalling. While concrete M1 of lower strength could be loaded until 800 °C without spalling, specimens of M4 and M7 exploded as early as 500 °C, the same was observed by Thielen and Schneider [2, 13].

As regards micro fibre-reinforced concretes, average compressive strength of concrete Average strength of concrete M2 was equal to 21.85 N/mm², for M5 is achieved 33.80 N/mm², while in case of M8 is reached 53.66 N/mm².

Relative compressive strength values decreased at 150 °C in every case compared to the relative values of the initial 20 °C, then at 300 °C the values increased over the initial ones and as a result of further temperature increases, compressive strength values were observed to decrease again (Fig. 4), the same tendencies was observed by other researchers [6, 8, 25].

The average compressive strength of concrete M3 was equal to 22.62 N/mm², for M6 is achieved 33.23 N/mm² while in case of M8 is reached 33.68 N/mm².

The relative mean values calculated from the residual compressive strength values are related to the compressive strength values without heat loading are shown in Fig. 5.

An interesting question might be the extent of strength reduction that occurred in concretes with micro and macro fibres compared to the original concrete without them, so in Table 2 the author collected the percentage of change in strength that happened in concretes with micro and macro fibres compared to the reference concretes.

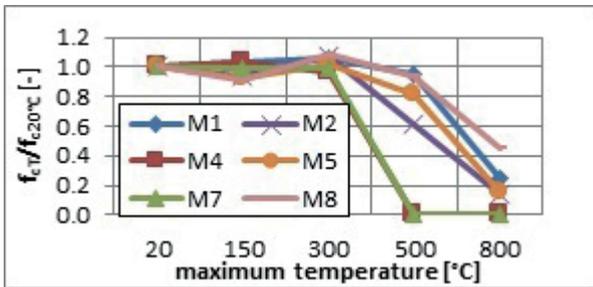


Fig. 4 Temperature-dependent relative compressive strength of reference and micro-fibre concretes (averaged from 3 measurements)

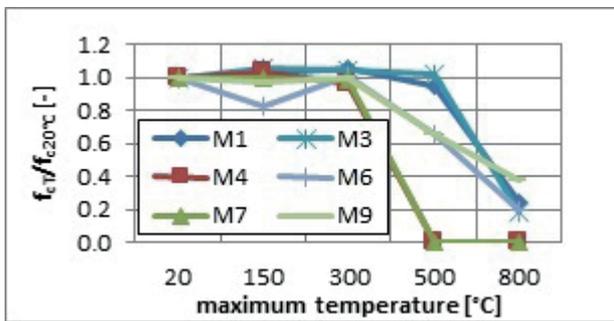


Fig. 5 Temperature-dependent relative compressive strength of concrete with macro-fibre and without fibre (averaged from 3 measurements)

Table 2 Differences in compressive strength in fibre concretes compared to the reference [31]

Temperature [°C]	Differences in compressive strength between micro- and macro-fibres compared to the reference					
	C20/25 [M2/M1]	C20/25 [M3/M1]	C30/37 [M5/M4]	C30/37 [M6/M4]	C50/60 [M8/M7]	C50/60 [M9/M7]
20	88.9%	92.1%	91.6%	90.1%	98.5%	61.8%
150	80.8%	95.0%	81.4%	71.7%	90.3%	60.6%
300	90.4%	91.2%	97.2%	94.6%	108.9%	62.7%
500	57.2%	99.5%				
800	49.3%	66.2%				

The figures clearly show that in the case of concrete C20/25 (M1) macro fibres perform better, that is, due to them there is a lower decrease in compressive strength than in non-fibre concretes. However, in concretes of greater strength (M4, M7) micro fibres possess more favourable characteristics than macro ones. Table 2 clearly presents that although the number of cracks can be reduced by applying the fibres and spalling can be prevented in case of fire, it is achieved at the expense of compressive strength loss in almost every case.

3.3 Changes the flexural strength in function of the temperature

The results from the flexural strength tests of concrete blocks were averaged (3 measurements). Average strength of concrete M1 was equal to 4.98 N/mm², for M4 is achieved 5.86 N/mm², while in case of M7 is reached 6.39 N/mm².

Flexural strength values are collected in Fig. 6. Based on Fig. 6, it can be determined that in case of M1 and M7 the initial increase in flexural strength at 300 °C can no longer be observed as temperature rises. Concrete M4 showed the most favourable characteristics, since at 300 °C a temporary increase in strength could be observed, followed by a steady decrease in concrete strength. Flexural strength decreased more drastically than compressive strength.

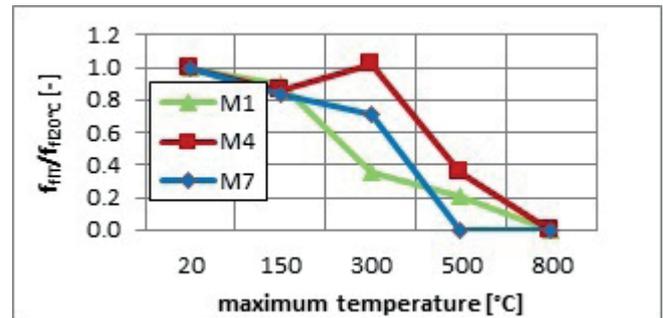


Fig. 6 Relative flexural strength values of concretes without fibres (calculated from 3 measurements) in function of temperature

As far as concretes with micro-fibre content go, average flexural strength of concrete M2 was 3.77 N/mm², M5 was 4.88 N/mm², while M8 was 5.98 N/mm².

Relative values of flexural strength are depicted in Fig. 7.

Due to the micro-fibre content of concretes with lower strength (M2, M5, M8), relative values of their flexural strength fell, compared to the reference non-fibre concrete.

As far as macro-fibre concretes go, the average flexural strength of concrete M3 was equal to 4.90 N/mm², for M6 is achieved 5.46 N/mm² while in case of M8 is reached 5.53 N/mm².

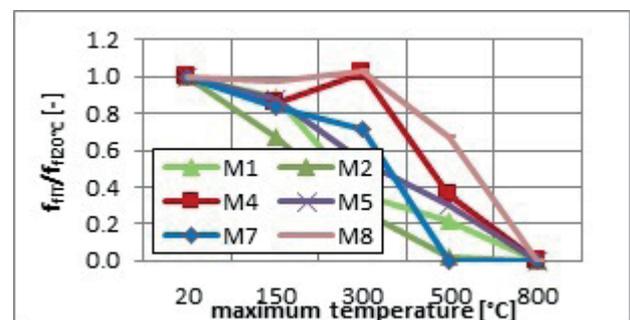


Fig. 7 Temperature-dependent relative flexural strength of reference and micro-fibre concretes (averaged from 3 measurements)

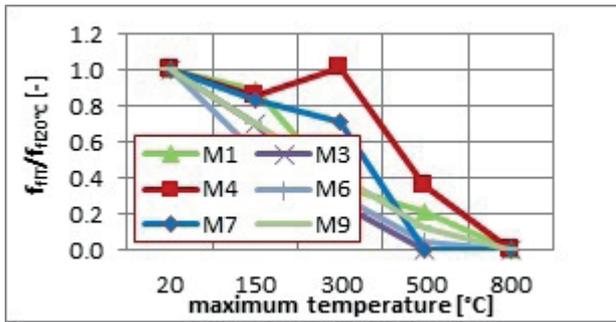


Fig. 8 Temperature-dependent relative flexural strength of concrete with macro-fibre and without fibre (averaged from 3 measurements)

Concretes with macro fibre content exploded at heat loading of 800 °C, so their flexural strength could not be measured. The results, however, do not reveal that when non-fibre concretes broke and completely lost their cohesion, macro-fibre concretes did not as long as the fibres were intact. This extra strength, however, was no longer present over 150 °C, since the synthetic fibres had already melted out of the matrix structure.

Relative values of flexural strength are depicted in Fig. 8. Fig. 8 clearly illustrates that also prior to spalling, relative values rank lower in the case of macro-fibre content. The most significant difference appears in the case of concrete C30/37, where relative values of concrete M4 is considerably higher than the values of concrete M6.

The differences in flexural strength values with micro- and macro-fibres related to the reference concrete are compiled in Table 3.

Table 3 Differences in flexural strength in fibre concretes compared to the reference [31]

Temperature [°C]	Differences in flexural strength between micro- and macro-fibres compared to the reference					
	C20/25 [M2/M1]	C20/25 [M3/M1]	C30/37 [M5/M4]	C30/37 [M6/M4]	C50/60 [M8/M7]	C50/60 [M9/M7]
20	75.8%	98.6%	83.4%	93.2%	93.6%	86.4%
150	57.3%	78.1%	85.1%	59.4%	109.2%	72.5%
300	57.7%	73.6%	44.3%	27.1%	136.3%	50.6%
500	7.8%	0.0%	72.4%	10.9%		
800						

In the case of lower strength concrete, macro-fibres perform better at all temperatures compared to the micro-fibres. The values obtained fall behind the reference concrete values in every case. As regards higher concrete quality, micro-fibres only perform better initially over 20 °C, but in the case of concrete C50/60, they exceed macro-fibres even at this temperature, in addition, above 150 °C they even surpass reference concretes.

3.4 Changes the porosity in function of the temperature

Concretes without fibre reinforcement display increased porosity as temperature rises. Representing the porosity values in a graph (Fig. 9), it can be observed that as strength increases, the porosity of specimens that had not undergone heat loading decreases. However, as temperature rises, the greater the strength of the specimens exposed to heat loading of 500 °C, the higher their porosity values.

Compared to concretes without fibres, micro-fibre concretes are more porous. As a result of heat loading, porosity is increasing at a higher degree in micro-fibre concretes than in non-fibre ones. Presenting the absolute values in a graph (Fig. 10), it becomes apparent that micro-fibre concretes are over 1 % more porous at 20 °C than specimens of concretes C20/25. However, as strength increases, porosity values of concretes without fibres and fibre reinforced concretes are converging more and more. Specimens of 150 °C, 300 °C and 500 °C display a similar tendency regarding changes in porosity values. At 500 °C in the case of strength of C50/60, micro-fibre concretes display lower porosity values, although only slightly, than reference concretes.

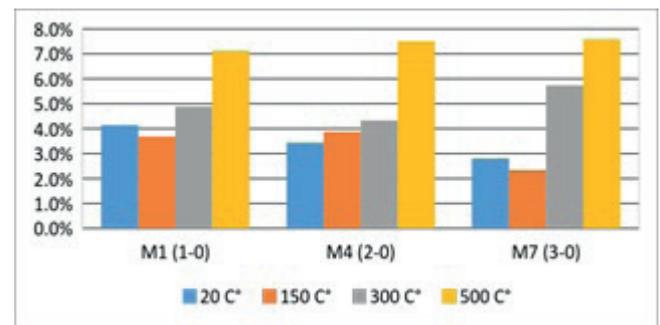


Fig. 9 Porosity values due to increased compressive strength and temperature

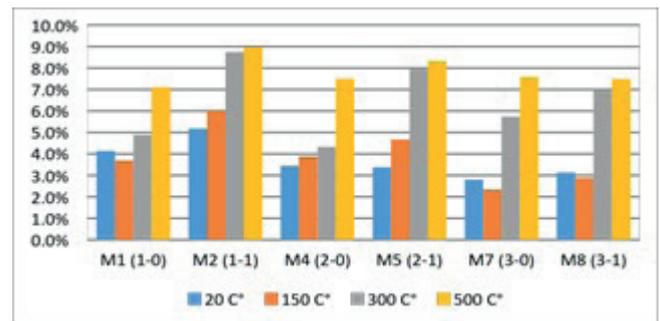


Fig. 10 Porosity values due to micro-fibres in relation to the temperature

Compared with concretes without fibres, macro-fibre concretes are significantly more porous. Relative values reveal that as a result of heat loading, porosity with increasing in macro-fibre concretes to a greater extent at 150 °C and 300 °C than in concretes without fibres. It can be explained by the lower melting point of the macro-fibres. At a higher temperature, 500 °C, relative values of macro-fibre concretes of lower strength (C20/25) were higher than those of non-fibre concretes, although as the strength increased relative values of macro-fibre concretes fell.

Nevertheless, the absolute values show that they still possess higher porosity (Fig.11).

Differences in porosity values in micro- and macro-fibre concretes compared to the reference concretes are collected in Table 4.

As regards porosity values, in the case of lower strength (C20/25) micro-fibre concretes are more porous than the macro-fibre specimens compared to the reference concretes, although as strength increases (C30/37;C50/60). Porosity values are higher with both types of fibres than in non-fibre concretes, regardless of the temperature.

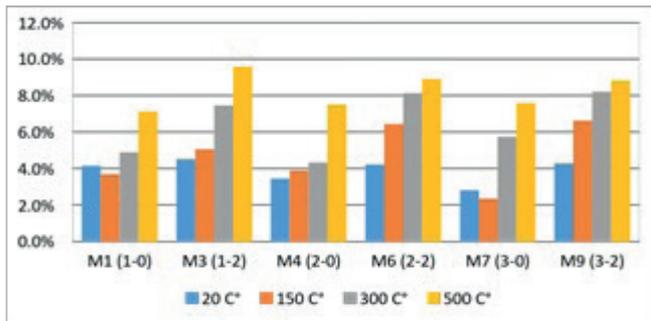


Fig. 11 Porosity values due to macro-fibres in relation to the temperature

Table 4 Differences in porosity values of fibre concretes compared to non-fibre concretes in relation to the temperature [31]

	Differences in porosity due to micro- and macro-fibres compared to the values of the reference concretes			
	20 °C	150 °C	300 °C	500 °C
M2 (1-1)	125%	164%	179%	126%
M3 (1-2)	109%	137%	153%	135%
M5 (2-1)	98%	121%	183%	111%
M6 (2-2)	123%	166%	188%	119%
M8 (3-1)	112%	123%	121%	99%
M9 (3-2)	152%	283%	143%	116%

4 Conclusions

Nowadays the use of fibre-reinforced concretes is more and more widespread in various engineering structures. According to literature, concretes with synthetic micro-fibre content can be used effectively to enhance fire resistance. Synthetic macro-fibres are applied successfully to overcome the problem of corrosion of steel fibres.

Presented experiments aim at identifying the effects of synthetic micro- and macro-fibres on the residual compressive strength, flexural strength and porosity of concrete after fires.

For the experiments were prepared nine kinds of mixture, examining three types of concrete quality, which were approximately C20/25 (M1), C30/37 (M4), C50/60 (M7). Three out of them are fibreless reference concretes, three with micro-synthetic fibres and three with macro-synthetic fibres.

In the experiments, the following parameters were constant in each concrete quality:

- cement type and quantity,
- water quantity;
- aggregate type and quantity,
- superplasticizer type

Variable parameters:

- fibre type (2 types: micro and macro fibres);
- fibre content (micro-fibre 1 kg/m³, macro-fibre 4 kg/m³)

Presented studies aimed to find out how fibres of different size and type were affected by heat loading. Cube and block specimens stored in laboratory conditions were exposed to heat loading of 150 °C, 300 °C, 500 °C, 800 °C to test their compressive strength (cubes), flexural strength (blocks) and porosity (both).

- Spalling could not be observed on concretes without fibre of C20/25 (M1) concrete quality, although in the case of concretes C30/37 (M4), cubes exploded at 500 °C, blocks at 800 °C, while all specimens of concrete C50/60 (M7) were destroyed at 500 °C. In the case of fibre-reinforced concretes, both micro and macro-fibres were proven to be effective to prevent spalling. Every specimen was able to withstand heat loading up to 800 °C without spalling. Surface micro cracks appeared less in the case of micro-fibres than the macro-fibres.
 - At 20 °C, compressive strength of each concrete with synthetic fibre content was lower, compared to that of the reference concretes. With the increase in concrete quality, strength values of micro-fibre concretes were converging to the range of reference concretes, while in the case of macro-fibres, a steady decrease could be observed, which in the case of concrete C50/60 (M9) meant a drastic fall of 40% in concrete strength. As temperature rise, in the case of concretes C20/25 (M3) macro-fibres behaved more favourably, but micro-fibres performed better in the case of concretes C30/37 (M5) and C50/60 (M8).
 - As regards flexural strength, fibre-reinforced concretes performed worse in every case at 20 °C than the reference concrete. Macro-fibres only performed better in the cases of concretes C20/25 (M3) and C30/37 (M6), but with concrete C50/60 (M8) micro-fibres proved to be more effective. Temperature increase resulted in lower flexural strength with each type of concrete. At 800 °C flexural strength of the specimens fell to 0 N/mm² in every case.
 - The use of fibres results in an increased porosity in every case, regardless of the temperature. However, at 500 °C concretes of greater strength (C50/60) with micro-fibres proved to be slightly better than reference concretes.
- Therefore, our experiments have shown that in the case of lower concrete strength (C20/25), macro-fibres are recommended over micro ones, as they rank higher both in compressive and in flexural strength.
- In the case of concrete C30/37, in the temperature range of 20 °C micro-fibres caused a decline of 8–9% in compressive strength compared to the reference concretes, while

macro-fibres caused a decline of 10% in compressive strength. As regards flexural strength, macro-fibres performed better.

In the case of concrete C50/60, the use of synthetic macro-fibres is definitely not recommended. Although they do prevent spalling, they drastically reduce compressive and flexural strength values.

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