High Strength and Ductile Fibrous Concrete of Enhanced Fire Resistance

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Abstract. In the present work a Fiber Reinforced Concrete of Enhanced Fire Resistance (FRCEFR) was developed and its properties are characterized by experimental research. This concrete is intended to have enough resistance for the most structural engineering applications and is reinforced with a fibrous system to assure the necessary ductility and to improve its fire resistance. Two types of fibers are used to accomplish the aforementioned requisites for the concrete. The research performed for the selection of a nonmetallic fiber type for inclusion on the FRCEFR is resumed. The experimental programs carried out to evaluate the residual compressive and flexural behavior of the developed FRCEFR are presented and the main obtained results are analyzed. The tests were executed at 28 days after FRCEFR have been exposed to the following distinct levels of temperature: 250ºC, 500ºC, 750ºC and 1000ºC.

Introduction

In the last decades, technical and scientific efforts have been done to increase the concrete strength, based on the assumption that more economical, lightweight and good looking structures can be built. However, this strength enhancement has been obtained by increasing the density of the concrete internal structure, resulting concretes with a void percentage much lower than the values observed in normal strength concrete [1]. When submitted to fire, the water in the internal concrete structure is transformed into vapor, which increases the pressure in the concrete voids. If concrete offers resistance to the escape of the water vapor, high pressures will be developed in the internal concrete structure, which can lead to very brittle concrete failure [2]. The research and the fire accidents [3] have shown that the concrete failure of the structures submitted to fire is as explosive as high is the concrete strength class, since the concrete brittleness and density increase with the concrete compressive strength [2].

Considerable research has been done to assess the behavior of building materials exposed to fire. However, few experimental studies were carried out to estimate the residual strength several days after heating and subsequent cooling in concrete structures [4]. This information is particularly important for the analysis of the structural stability of concrete structures submitted to high temperatures.

Experimental program

Selection of a nonmetallic fiber. For the selection of a nonmetallic type of fiber for the FRCEFR, an experimental program was carried out. Cubic specimens of 100 mm edge were prepared to determine the concrete compressive strength and beams of 250 × 50 × 60 mm^3 were set to assess the concrete flexural behavior (see Fig. 1). A reference group of specimens without fibers (Reference) and seven groups of specimens were batched with the following distinct type of fibers (dosage of 2 kg/m^3): Ultrafiber cellulose fiber (length, l_f, of 2.1 mm); Asota AFC polypropylene

(PP) fiber (l_f = 6 mm); Duro-Fibril PP fiber (l_f = 12 mm); Polyester (l_f = 25 mm); Cotton (l_f = 25 mm). For comparison purposes, Dramix® ZP 305 hooked ends steel fibers (l_f = 30 mm, diameter, d_f, of 0.55 mm, aspect ratio, l_f / d_f, of 55 and yield stress of 1100 MPa) were also used in one composition, as the unique fiber reinforcement system (dosage of 35 kg/m^3). The mix compositions can be found elsewhere [5].

Free-of-external load specimens were placed in the cooled furnace chamber and the temperature was increased up to 800 ºC, according to Fig. 2. After 2h, the furnace was turned off and the door was opened. Tests were performed after the specimens have been cooled in a slowly process.

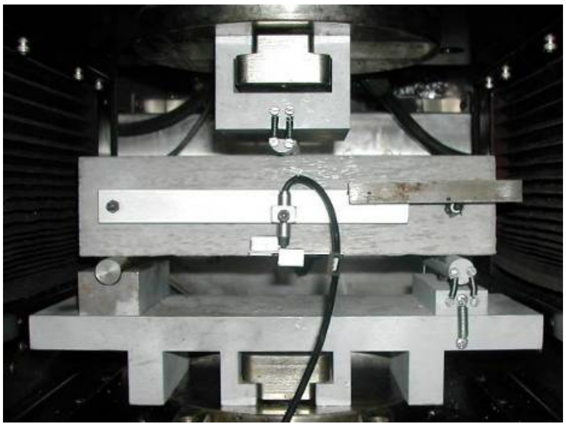


Fig. 1 – Three point beam bending test

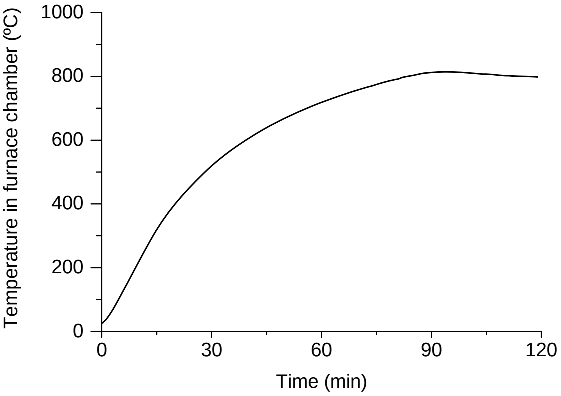


Fig. 2 – Temperature-time curve

Fig. 3 shows that, if the mass loss of the Reference specimen is taken for basis of comparison, this property was not significantly affected by the addition of steel fibers to concrete. For nonmetallic fiber concrete, however, mass loss occurred at lower temperatures, since the micro channels formed into the concrete structure when nonmetallic fibers melted provided paths for the escape of the water vapor [6], resulting an increase in the mass loss. The mass loss started at a temperature in the ambient chamber of about 150 ºC. Explosive spalling occurred in Reference specimens (see Fig. 4), which was not happened in fibrous specimens. Therefore, all used nonmetallic fibers are able of improving the concrete fire resistance but only PP fibers allowed a relative easy fiber distribution into concrete. The higher mass loss registered in the non metallic fibrous specimens indicates that this type of fibers has large efficiency in terms of assuring high volume of void micro-channels in the concrete microstructure for the escape of the water vapor.

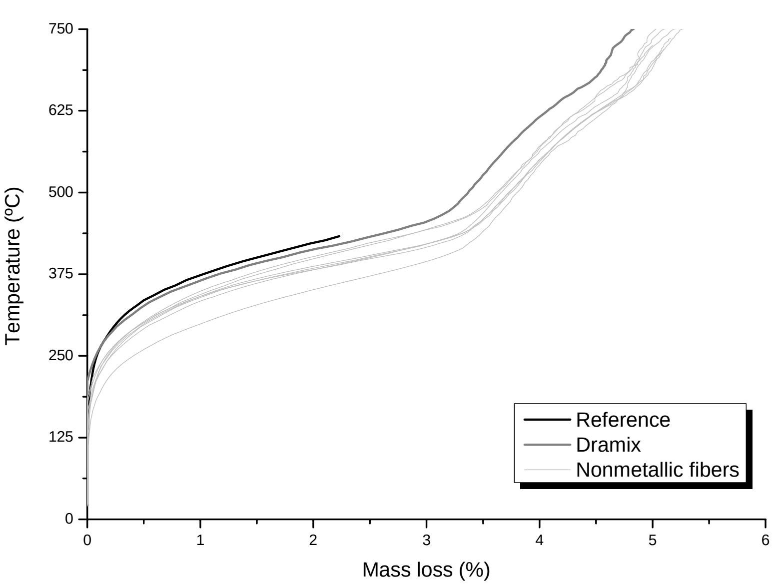


Fig. 3 – Mass loss (heating phase)

Fig. 4 – Before and after test: explosive spalling

The ratio between the resistance of unheated and heated specimen, for each fibrous concrete specimen, both for compressive and flexural strength, is represented in Table 1 (average of three experimental results). The obtained results show that, after high temperature exposure, concrete compressive strength ranged from 40% to 65% of the one of its homologous unheated specimen. The influence of temperature was more pronounced in terms of the concrete flexural resistance, since a strength reduction higher than 80% was recorded.

This experimental program revealed that PP fiber type is, amongst the used nonmetallic fibers, the one that provides higher benefits for the improvement of the concrete resistance when submitted to high temperatures. More details can be found elsewhere [5].

Serie	Compressive strength [MPa]			Flexural strength [MPa]		
	Unheated	Heated		Unheated	Heated	
Reference	49.6	0.0	0.0%*	7.12	0.00	0.0%*
Dramix	48.7	26.0	52.4%*	6.51	0.78	11.0%*
Ultrafiber	42.7	24.1	48.9%*	6.24	0.42	5.9%*
Barchip F	47.6	21.6	43.5%*	5.43	0.82	11.6%*
AFC	51.2	18.4	37.1%*	5.64	0.63	8.9%*
Duomix Fire	49.0	20.2	40.7%*	6.51	0.50	7.0%*
Duro-Fibril	50.0	27.8	56.0%*	5.49	0.82	11.6%*
Cotton	56.6	27.7	55.8%*	7.16	0.46	6.5%*
Polyester	51.3	30.6	61.7%*	6.58	0.44	6.2%*

Table 1 – Experimental results (* - percentage of the strength of reference specimens)

Concrete compressive residual strength stabilization. Experimental tests [5] demonstrated that the residual compressive strength of specimens submitted to high temperatures is dependent on the period of time between the end of the specimen heating process of the specimen and the testing phase. Figs. 5 and 6 show the visible damage due to crack propagation phenomena from the end of the specimen heating process up to a stabilizing phase. From the preliminary research, 14 days (at least) seem to be the period of time for the cooling process to evaluate the compressive residual strength of a concrete submitted to high temperatures.

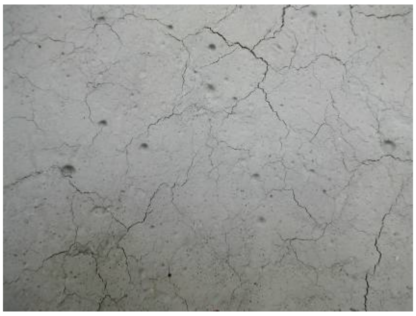


Fig. 5 – Concrete surface appearance at the beginning of the cooling process

Fig. 6 – Concrete surface appearance after 14 days of cooling

FRCEFR residual properties. Cylinder specimens (150 mm diameter and 300 mm high) were set to determine the concrete residual Young’s modulus and stress-strain relationship. Beam specimens ($600 \times 150 \times 150\ \text{mm}^3$) were also prepared to assess the residual concrete flexural behavior. One (PP1) and two (PP2) kg per m^3 of concrete of PP fibers (Duro-Fibril, l_f = 6 mm) were used to manufacture the tested specimens. The mix compositions can be found elsewhere [7].

Mechanical tests were performed at 28 days after the concrete exposure to distinct levels of temperature. For each type of concrete and target test temperature, three cylinders and two beam specimens were tested and the average of the corresponding results was used as the final values. The target test temperatures were: 20 ºC (room temperature), 250 ºC, 500 ºC, 750 ºC and 1000 ºC. Concrete specimens were heated, without any applied external load, at a constant rate near to 25 ºC / min until the ambient temperature inside the furnace reaches the target test temperature. Then, the temperature was kept constant for 4 hours [7]. The exposure to the 1000 ºC level of temperature led to the destruction of the concrete specimens, therefore the determination of the residual behavior of these specimens was not possible.

The variation of the Young's modulus, compressive and flexural strength with the variation of the target test temperature is shown in Figs. 7 to 9.

The flexural tests were carried out according to the RILEM TC 162-TDF recommendations for the determination of the $f_{eq,2}$, $f_{eq,3}$ and F_L parameters that characterize the concrete flexural post-cracking behavior [8]. The obtained results, shown in Fig. 10, reveal that up to 250 ºC the values of these parameters have increased, but after this level of temperature, they have decreased significantly.

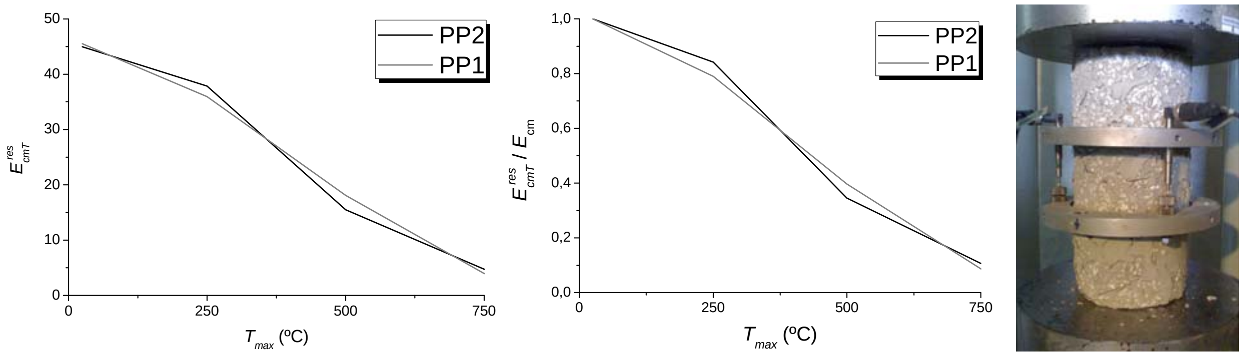


Fig. 7 – Residual Young's modulus for different level of temperature exposure

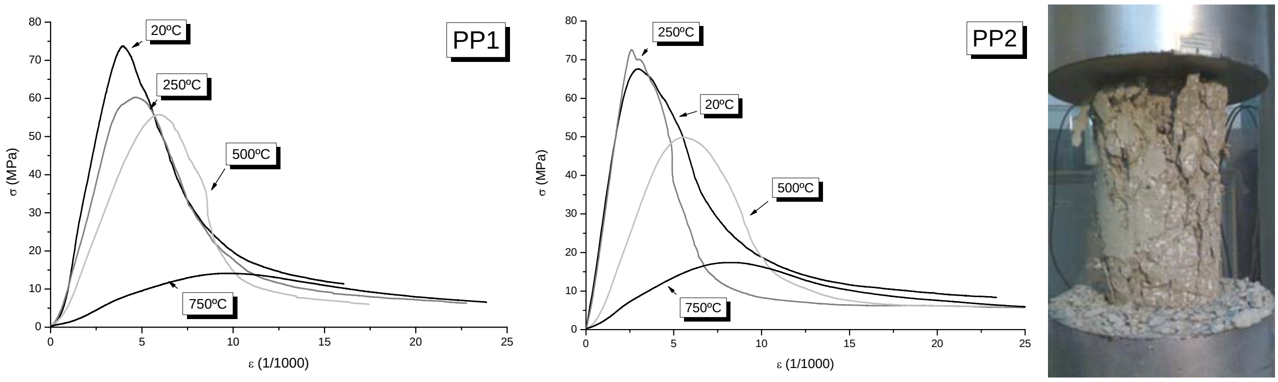
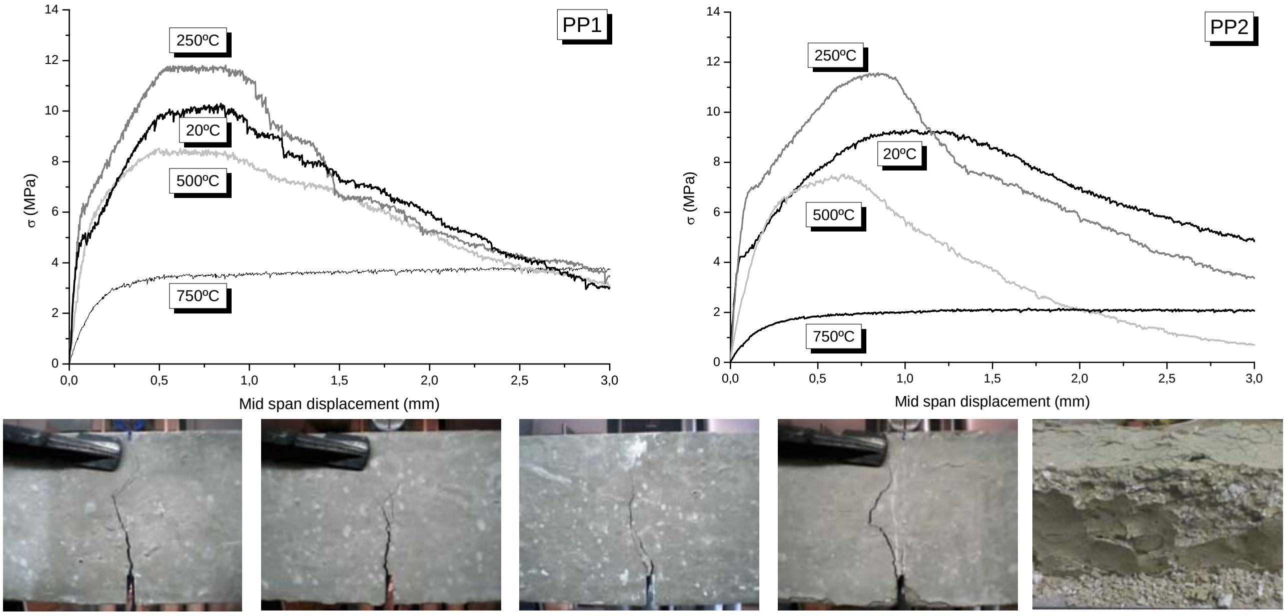


Fig. 8 – Residual compressive behavior



Ambient 250 ºC 500 ºC 750 ºC 1000 ºC

Fig. 9 – Residual flexural behavior

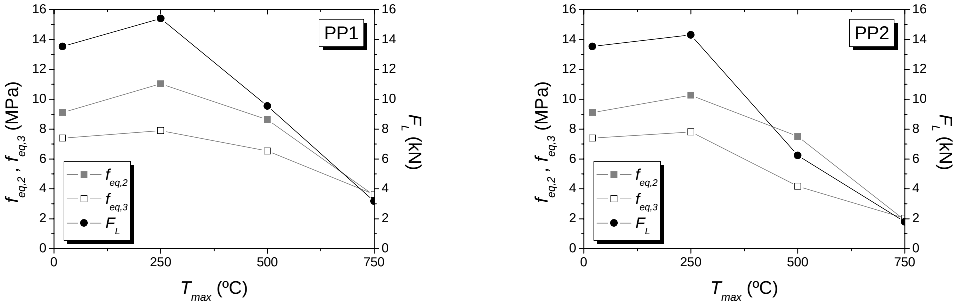


Fig. 10 – Variation of the flexural parameters with the temperature exposure

Conclusions

From the obtained results it can be concluded that all used nonmetallic fibers are able of improving the concrete fire resistance, since explosive spalling was avoided. However, only PP fibers allowed a satisfactory and easy distribution into concrete. Using 1 kg of PP fibers per m^3 of concrete, explosive spalling was avoided. Increasing the PP fiber dosage, the residual concrete behavior was not improved. These results can be used for the calibration of numerical models dedicated to the simulation of the material nonlinear behavior of concrete structures that have been submitted to high temperatures. This is the next step of the research program.

Acknowledgments

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References

[1] S. Chan, G. Peng, J. Chan, in: “Comparison between high strength concrete and normal strength concrete subjected to high temperature”, Materials and Structures, n.º 29, December (1996), pp. 616-619.

[2] L. Phan, in: “Pore pressure in high-strength concrete at high temperature”, Proceedings of ConMat '05 and Mindness Symposium, Vancover (2005).

[3] K. Ono, in: “Tunnel fire and lining protection”, ITA.

[4] J. Santos, F. Branco, J. Brito, in: “Assessment of concrete structures subjected to fire – the FBTest”, Magazine of Concrete Research, 54, n.º 3, June (2002), pp. 203-208.

[5] L. A. P. Lourenço, J. A. O. Barros, P. Souto, in: “Concrete composition of enhanced fire resistance concrete for tunnel segments – part I”, Technical report 05-DEC/E-32, Dep. of Civil Eng., University of Minho, December (2005), 42 pages. (in Portuguese)

[6] P. Kalifa, G. Chéné, C. Gallé, in: “High-temperature behaviour of HPC with polypropylene fibres. From spalling to microstructure”, Cement and Concrete Research, n.º 31 (2001), pp. 1487-1499.

[7] L. A. P. Lourenço, J. A. O. Barros, J. Rodrigues, S. P.F. Santos, A. Alves, in: “Fiber reinforced concrete of enhanced fire behaviour”, Portuguese Journeys of Structural Eng. 2006, LNEC, December (2006), 12 pages. (in Portuguese)

[8] J. A. O. Barros, V. M. C. F. Cunha, A. F. Ribeiro, J. A. B. Antunes, in: “Post-Cracking Behaviour of Steel Fibre Reinforced Concrete", RILEM Materials and Structures Journal, 38(275), (2005), p. 47-56.