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Strength and porosity of concrete incorporating polypropylene and steel fibres subjected to high temperature

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1 ABSTRACT

Concrete structures in buildings or other constructions may be subjected to accidental conditions such as fire. Then, among many parameters, the safety of the structures depends on the mechanical properties of the concrete. Many research works show that, in some cases, a concrete element subjected to high temperature may present spalling or bursting. These phenomenons seem to be due to the formation of water vapour pressure and thermal stresses during the rise of temperature. Several studies show that concrete thermal stability is improved by incorporating polypropylene fibres to the mix.

The aim of this study is to investigate the effect of polypropylene and steel fibres on the behaviour of concrete subjected to high temperature. Tests were carried out on concrete elements subjected to four target temperatures: 150, 300, 450 and 600 °C. Three groups of concrete were studied: one group of concrete mixes without fibre, one group of concrete mixes with polypropylene fibres and one group of concrete with steel fibres. The specimens were subjected to heating - cooling cycles from the ambient temperature to 150°C, 300°C, 450°C and 600°C. According to RILEM recommendations for these specimens dimensions, the heating rate was 1° C/min. The amounts of the fibres in the concrete were, for the polypropylene ones 0.11, 0.17 or 0.22 % in volume and for the steel ones 0.25, 0.38 or 0.50 % in volume. The initial and residual mechanical properties and porosity of the studied concrete mixes were analysed. The evolution of compressive strength, tensile strength, modulus of elasticity and water porosity of the studied concrete mixes are expressed as a function of the temperature.

2 INTRODUCTION

The mechanical properties of the concrete can be improved with the use of additives and fine particles. To ordinary concrete, we evolved to the high performances concrete and to the ultra-high performances concrete. The main characteristic of high performance concrete and ultra-high performance concrete is their high density and low porosity. But there is a question about their thermal stability when they are subjected to high temperature. During fires and laboratory tests heated concrete can present spalling or bursting. These phenomenons seem to be due to the formation of water vapour pressure and thermal stresses during the rise of temperature. The bursting is more frequent within high performances concrete. The main reasons are their low permeability and limited porosity.

Several studies [Nishida et al. (1995), Kalifa et al. (2001), Noumowé (2005), Xiao et al. (2006)] show that concrete thermal stability is improved by incorporating polypropylene fibres to the mix. Moreover the addition of steel fibres [Cheng et al. (2004), Lau et al. (2006), Suhaendi et al. (2006)] improves residual mechanical properties of heated concretes. The aim of this study was to investigate the effect of the mix of polypropylene and steel fibres on the behaviour of concrete subjected to high temperature. C2 and C3 concretes (without fibres) were carried out. The water/cement ratios were respectively 0.45 and 0.3. The amounts of polypropylene fibres in the concretes C2 and C3 were 1 – 1.5 and 2 kg. Polypropylene fibres concretes are indicated by CP (CP2-1: C2 with 1 kg of polypropylene fibres). The amounts of steel fibres in concrete C2 are 20 – 30 and 40 kg. Steel fibres concretes are indicated by CS (CS2-20: C2 with 20 kg of steel fibres).

The various specimens resulting from these compositions were tested after 90 days. One part of the specimens was tested at the ambient temperature (20°C) and the second part was subjected to heating-cooling cycles from the ambient temperature to 150°C, 300°C, 450°C or 600°C. The heating rate was 1°C.mn^{-1}. The studied residual mechanical properties were compressive strength, tensile strength, modulus of elasticity and water porosity. The mass loss was also measured.

3 EXPERIMENTAL SCHEDULE

3.1 Materials

The type of cement used was CEM I 52.5 N CE CP2 NF and the aggregates were silico-calcareous type of fraction 0/4 (sand) and 4/22.4 (gravel). Cimfluid 2002 superplasticizer was used. It is a high water reducer containing modified polycarboxylate. The polypropylene fibres were Duomix fire (M6) of Bekaert. They were of cylindrical form, 6 mm length with a nominal diameter of 18 µm. Steel fibres were Dramix RC 80/30 of Bekaert and were 30 mm length.

3.2 Cure condition

The specimens were kept in their mould at 20°C ± 2°C covered in order to avoid any water evaporation since the day of mixing until the seventh day. They were then demoulded and kept in plastic bags until the day of the tests. The specimens were cured up to at least 90 days in order to make sure that the pozzolanic reactions were stabilized.

3.3 Tests

Heating-cooling cycles: four heating-cooling cycles were carried out in a furnace from the ambient temperature to 150°C, 300°C, 450°C or 600°C. The cycles were composed of a phase of rise in temperature, a phase of temperature dwell and a phase of cooling. The heating rate was 1°C.mn^{-1} and the dwell duration was one hour. The specimens were then free to cool down to room temperature in the furnace. The chosen heating and cooling rates refered to the RILEM TC-129 recommendations (1995).

Mass loss: the mass loss was obtained on four 16x32 cm cylindrical specimens. The specimens were weighed before and after each heating-cooling cycle in order to determine the quantity of water that escaped from the concrete during the heating.

Water porosity: the concrete porosity was obtained on ten samples of average mass of 80 g. Samples resulted from the specimens after the mechanical tests. The samples were oven dried at a temperature of 60°C until the mass was constant then immersed in water until complete saturation. Once the samples were saturated, a weighing in immersed saturated state was carried out on a hydrostatic balance then it was followed by a weighing in saturated state after the specimen was wiped with linen to remove the water in excess at the surface. The tested samples were those brought up to temperature of 20°C, 150°C, 300°C or 450°C. Taking into account the friability of the specimens heated at the temperature of 600°C he temperature was limited at 450°C.

Compressive strength: the test was carried out on four 16x32 cm cylindrical specimens in accordance with standard NF P 18-416. The loading rate was 0.5 MPa.s^{-1} until the rupture.

Tensile strength: the tests were carried out on three 10x10x40 cm prismatic specimens. Specimens were subjected to one bending moment until the rupture. In accordance with standard NF P 18-407, the loading in two points was carried out at a speed of 0.25 mm.mn^{-1} until the rupture.

Modulus of elasticity: the test was carried out on three 16x32 cm cylindrical specimens. During the testing, the specimen was connected to an extensometer frame and subjected to three loading-unloading cycles until reaching 30% of the breaking strength [Torrenti et al. (1999)]. The loading rate was 0.5 MPa.s^{-1}.

4 CONCRETE MIXES

According to compressive strength, two types of concrete were defined: C2 concrete with a water/cement (W/C) ratio of 0.45 and C3 concrete with a W/C ratio of 0.3. For all the tested concretes, the paste volume was the same. The type of concrete obtained was S4 with the slump test values between 16 and 20 cm ±1. The percentage of superplasticizer was adjusted in order to keep the workability constant. The amount of polypropylene fibres in the concretes C2 and C3 was 1 – 1.5 or 2 kg. The amount of steel fibres in concrete C2 was 20 – 30 or 40 kg. Table 1 summarizes the composition of the studied concretes.

Table 1. Concretes compositions with and without fibres

Comp. (kg/m^3)	C2	C3	CP2-1	CP2-1.5	CP2-2	CP3-1	CP3-1.5	CP3-2	CS2-20	CS2-30	CS2-40
Cement	400	500	400	400	400	500	500	500	400	400	400
Water	181	150	181	181	180	150	150	150	181	181	181
Sand	668	667	668	667	667	666	665	664	670	669	667
Gravel	1105	1102	1102	1102	1102	1101	1100	1098	1095	1093	1091
Poly. fib.	-	-	1.0	1.5	2.0	1.0	1.5	2.0	-	-	-
Steel fib.	-	-	-	-	-	-	-	-	20	30	40
Sup.	0.64	1.55	0.96	0.96	1.0	1.61	1.61	1.76	0.6	0.58	0.60
W/C	0.45	0.3	0.45	0.45	0.45	0.3	0.3	0.3	0.45	0.45	0.45
Mv	2355	2421	2353	2352	2351	2419	2418	2417	2367	2374	2380

5 RESULTS AND DISCUSSION

The results obtained on the various concretes at ambient temperature and after the heat treatment are gathered in the tables below. Relative strength are calculated by dividing the residual strength after heating-cooling cycles (f_T) by the strength of the unheated concrete (f_{20}).

Table 2. Mass loss as a function of the temperature (T).

Test	T (°C)	C2	C3	CP2-1	CP2-1.5	CP2-2	CP3-1	CP3-1.5	CP3-2	CS2-20	CS2-30	CS2-40
Mass loss (%)	150	2.5	1.1	2.1	2.0	2.2	1.5	1.4	1.5	1.3	1.4	1.1
	300	6.0	4.8	6.1	5.9	6.1	4.9	4.6	4.9	5.7	5.5	4.9
	450	7.0	6.1	7.1	7.0	7.3	6.3	6.1	6.4	6.9	6.9	6.2
	600	8.1	7.2	8.4	8.4	8.5	7.6	7.3	7.3	8.3	8.2	7.5

Table 3. Water porosity as a function of the temperature**.**

Test	T (°C)	C2	C3	CP2-1	CP2-1.5	CP2-2	CP3-1	CP3-1.5	CP3-2	CS2-20	CS2-30
Water porosity (%)	60	13.9	10.7	12.9	13.1	14.0	10.4	10.1	12.2	13.4	14.2
	150	14.6	11.3	13.5	14.7	15.2	11.6	11.8	13.7	14.2	14.8
	300	15.4	12.8	15.8	16.7	18.6	13.3	15.3	18.6	16.0	15.5
	450	19.4	14.9	19.7	19.8	21.3	16.4	19.2	20.5	18.8	20.8

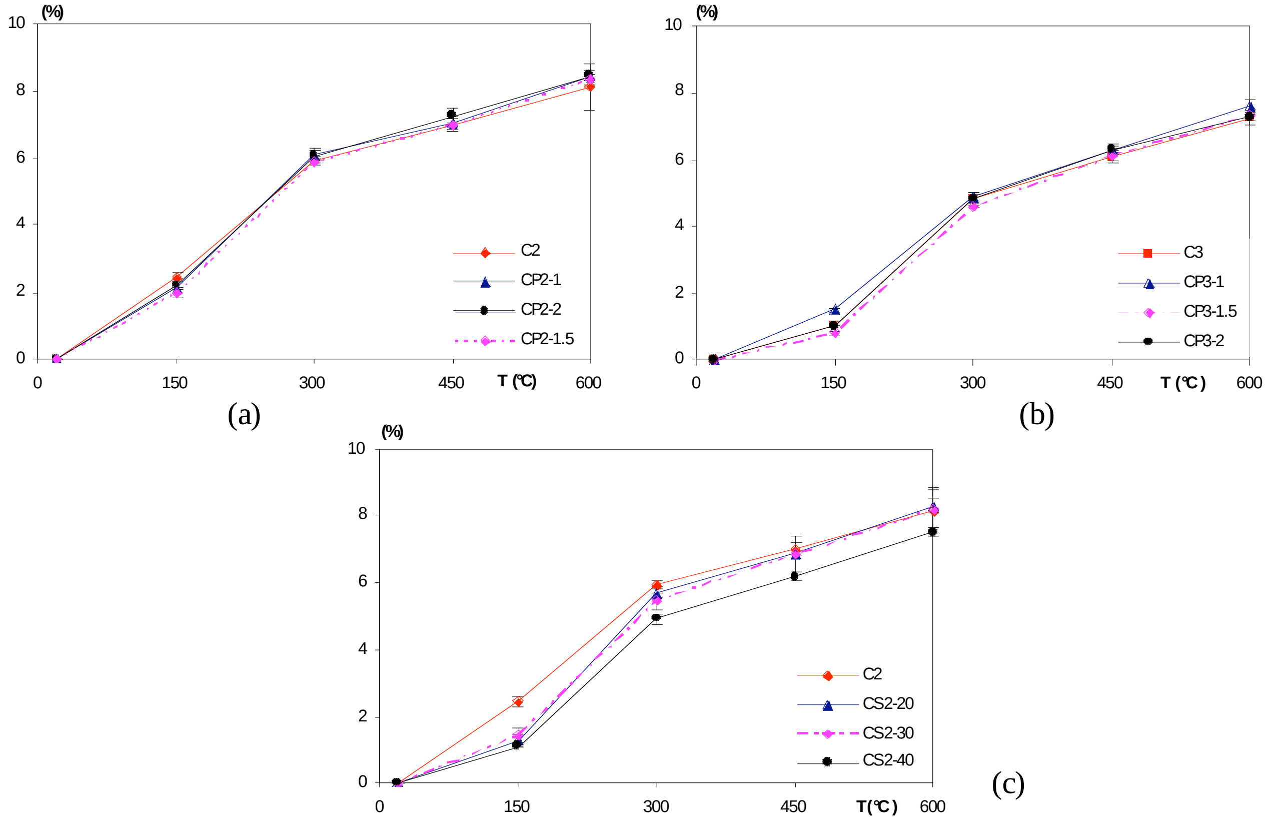
Table 4. Mechanical properties as a function of the temperature.

Strength		T (°C)	C2	C3	CP2-1	CP2-1.5	CP2-2	CP3-1	CP3-1.5	CP3-2	CS2-20	CS2-30	CS2-40
Compressive	(MPa)	20	46.0	70.2	48.6	48.0	50.2	67.8	85.8	78.9	57.9	57.7	55.9
	Relative (%)	150	80.4	89.2	80.3	80.4	73.2	87.9	79.4	75.9	88.5	81.0	80.2
		300	87.3	85.0	89.3	88.9	82.6	105.5	81.6	75.6	96.7	95.0	93.2
		450	44.2	38.3	43.1	47.1	34.5	29.2	32.9	27.8	62.7	65.0	67.4
		600	11.5	13.2	14.4	11.2	10.7	12.0	9.7	10.8	15.5	17.6	24.9
Tensile	(MPa)	20	5.2	7.3	5.1	4.7	4.9	6.3	7.4	5.7	5.1	6.4	5.8
	Relative (%)	150	59.5	74.1	68.7	90.1	73.0	83.2	68.6	70.3	84.4	69.1	91.5
		300	58.9	62.7	56.4	77.1	73.1	60.6	64.9	60.0	90.7	75.1	91.2
		450	27.2	38.2	27.0	39.8	32.3	26.5	36.5	24.6	51.9	61.6	59.6
		600	7.3	9.4	10.2	11.1	11.8	10.4	10.0	9.8	28.2	26.5	40.7
Modulus of elasticity	(GPa)	20	37.7	44.1	39.1	37.7	38.9	45.7	45.8	49.5	39.7	39.2	37.6
	Relative (%)	150	77.8	86.5	74.4	78.3	74.0	85.5	84.9	80.0	83.6	81.5	84.4
		300	56.9	58.3	52.9	57.0	51.5	64.3	62.4	57.9	68.4	67.7	65.9
		450	15.4	14.2	13.7	15.5	14.4	11.6	14.7	10.7	22.6	22.9	26.5
		600	3.4	3.6	3.9	3.5	3.4	3.7	3.8	3.5	4.7	4.6	5.6

5.1 Mass loss

The evolution of the mass loss as a function of the temperature (figure 1) depended on the type of concrete. The results obtained with concretes C2 and C3 (without fibres) showed that W/C ratio influences the mass loss. The mass loss evolution was the same for all the tested concretes. The addition of polypropylene fibres (figures 1a and 1b) or steel fibres (figure 1c) did not influence the shape of the curve. Concrete mass losses can be gathered in three fields [khoury et al. (1988), Noumowé (1995), Gaweska (2004), Kanéma (2007)]. The first field, from the ambient temperature to 150°C, was characterized by a weak mass loss (at 150°C, 2.5% for C2 concrete and 1.1% for C3). There was an escape of interstitial water and adsorbed water on the surface of the solid elements. The second field was in the temperature range of 150°C to 300°C. It showed a high increase in mass loss. Beyond 300°C, there was the third field. The mass loss slowed down. The C3 concrete mass loss remained always lower than that of C2.

There was an increase of mass loss due to the addition of polypropylene fibres (figures 1a and 1b). The mass loss rate was also increased by adding polypropylene fibres. Between 150°C and 300°C, the mass loss rate of C2 concrete without fibres was 0.02%.C^{-1} while that of C2 concrete with polypropylene fibres was 0.03%.C^{-1}. The differential thermal analysis carried out by Kalifa et al. (2001) showed three peaks on the cuves. The first peak corresponded to the fibres melting around 171°C. The second peak at 341°C corresponded to the temperature of water evaporation. The third peak represented the point of carbonation at 457°C. While melting around 171°C, the fibres are absorbed completely or partially by the porous network of the cementing matrix. The increase in the mass loss rate can be explained by the melting of the polypropylene fibres which creates a channel that make easy the vapour transport. The additional mass loss observed was thus linked to the melting and evaporation of polypropylene fibres in the concrete.



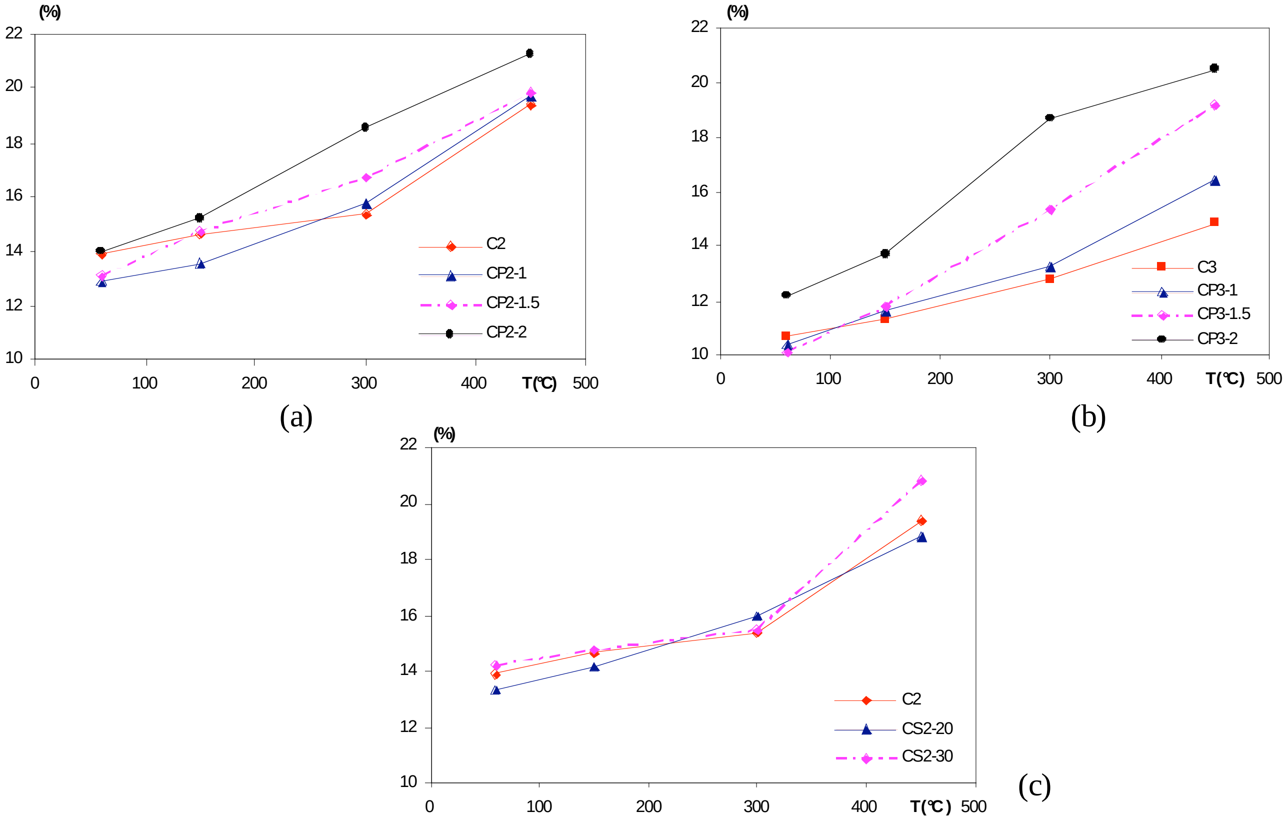
(a) (b) (c)

Figure 1. Mass loss of the polypropylene fibres (a and b) and the steel fibres (c) concretes as a function of the surface temperature.

A mass loss of steel fibres concretes (figure 1c) was observed after the heating-cooling cycles. Between 20°C and 150°C, interstitial and adsorbed water escaped from the concrete. The steel fibres concretes were obtained by replacement of part of the aggregates by an equivalent volume of fibres. The difference of mass percentage of aggregates between concrete with and without steel fibres was about 1%. At 150°C, mass loss of C2 concrete was 2.5% and that of CS2-20 concrete was 1.3%. The variation of mass loss (around 1%) can thus be linked to the decrease of the aggregates volume. Beyond 150°C, mass loss of steel fibres concretes was almost equal to that of concrete without fibres. At 450°C, C2 concrete lost 7.0% while CS2-20 concrete lost 6.9% of its initial mass. The mass loss rate of steel fibres concrete between 20°C and 150°C was 0.03%.C^{-1} while that of C2 concrete was 0.02%.C^{-1}. Water escaped (mass loss) more quickly from concrete incorporating steel fibres than from concrete without fibres. The interface between steel fibres and paste, the network generated by fibres facilitate the pressure transport.

5.2 Water porosity

Figure 2 shows the evolution of water porosity of concretes with and without fibres. The porosity increased with the temperature. This growth was linked to the departure of water and the cracking generated by the differential thermal expansion between the cement paste and the aggregates. Between the temperatures of 60°C and 300°C, porosity increase of C2 and C3 concretes was 2% on average. The porosity increased more quickly with the polypropylene fibres concretes (figures 2a and 2b). After the heating-cooling cycle at 300°C, the porosity increase was 4.6% for CP2-2 concrete while it was 6.4% for CP3-2 concrete. The fast increase of porosity can be explained by the melting of polypropylene fibres that created supplementary channels in the concrete. The studies carried out by [Noumowé (2005), Gaweska (2004)] showed the appearance of an additional porosity related to the fibres melting. When comparing CP2 and CP3 concretes, it can be noticed that fibres content influenced much the porosity of the C3 concrete (figure 2b). At the temperature of 450°C, the difference of porosity between concrete without fibre and concrete with 2 kg of polypropylene fibres was 1.9% for C2 concrete while it was 5.6% for C3 concrete. C3 concrete with fibres was more damaged at elevated temperature.



(a)

(b)

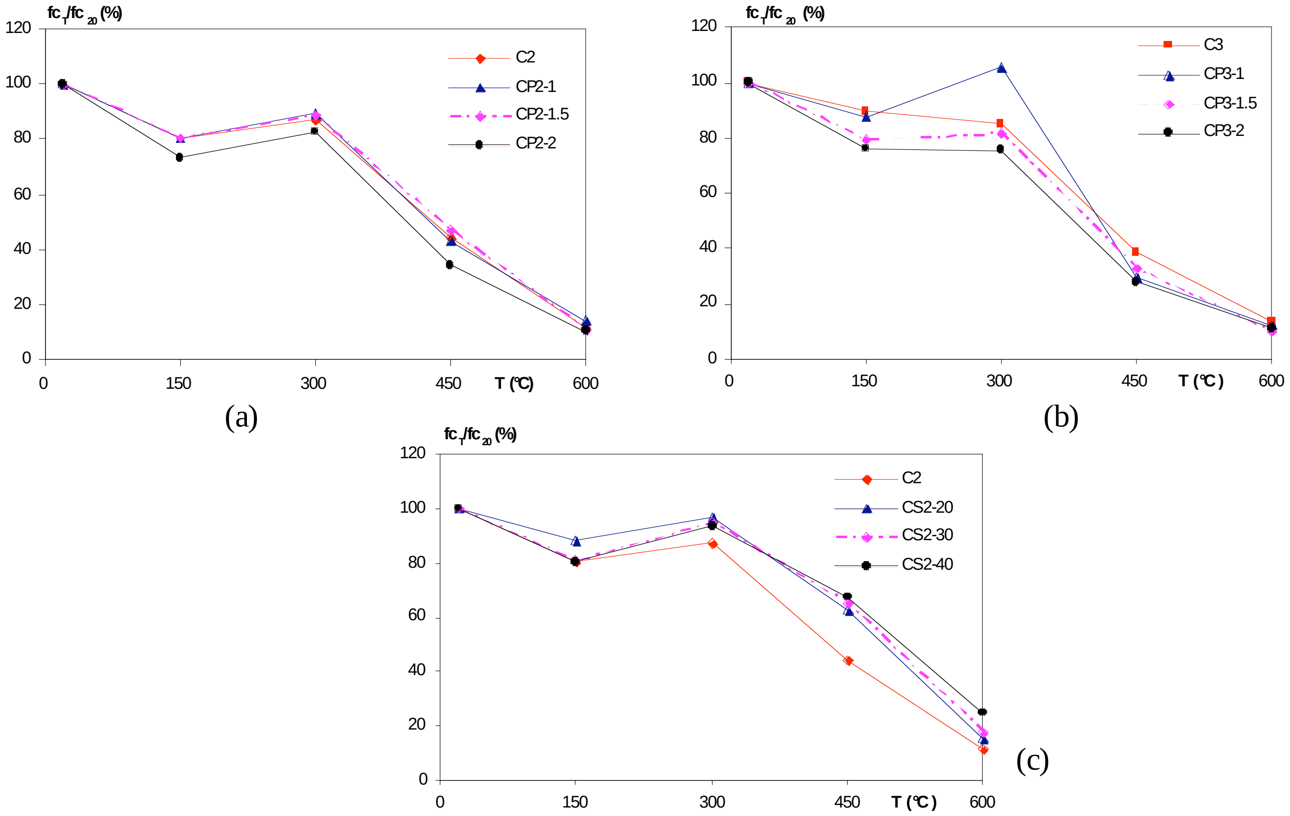
(c)

Figure 2. Water porosity of the polypropylene (a and b) and steel (c) fibres concretes as a function of the temperature.

Steel fibres concretes (figure 2c) showed a weak porosity increase compared to the polypropylene fibres concretes. At the temperature of 300°C, CP2 concrete porosity (18.6% for CP2-2) was higher than that of CS2 (16% for CS2-20). The modification of the microstructure of the polypropylene fibres concretes was more noticeable than that of the steel fibres concretes. Beyond the temperature of 300°C, there was a large increase of porosity for all the tested concretes (with and without fibres). At 450°C, the porosity of polypropylene concretes remained higher than that of concretes with and without steel fibres.

5.3 Compressive strength (fc)

Figure 3 shows the relative residual compressive strength as a function of the temperature. The behaviours of the concretes without fibres, with polypropylene fibres or steel fibres were identical. The fibres don't influence the shape of the curve. Two parts can be distinguished in the curves [Diederichs et al. (1992), Phan et al. (2001), Kanéma (2007)]. The first one, from the ambient temperature to 300°C, was characterized by a weak loss and/or an improvement of strength. The second part, beyond the temperature of 300°C, marked a sharp decline of strength. The fast increase in porosity (figure 2) beyond 300°C could contribute to the sharp decline of strength. Polypropylene fibres concretes (figure 3a and 3b) were damaged more quickly than the steel fibres concretes (figure 3c). CP2-2 concrete lost 65% of its compressive strength at 450°C while CS2-40 concrete lost about 33%. The strength loss increased with polypropylene fibres content. For the amount of 2 kg of polypropylene fibres, CP2 and CP3 concretes lost an average of 90% of their initial strength. The concretes with and without polypropylene fibres had almost the same strength after the heating at 600°C. The strength loss is more noticeable beyond 300°C for C3 than C2 concretes. By incorporating steel fibres in C2 concrete, the relative residual strength (figure 3c) was improved. The increase of the amount of steel fibres contributed to the improvement of the residual strength beyond 300°C. At 600°C, the strength decrease at was 85% for CS2-20 concrete while it was 75% for CS2-40 concrete.



(a)

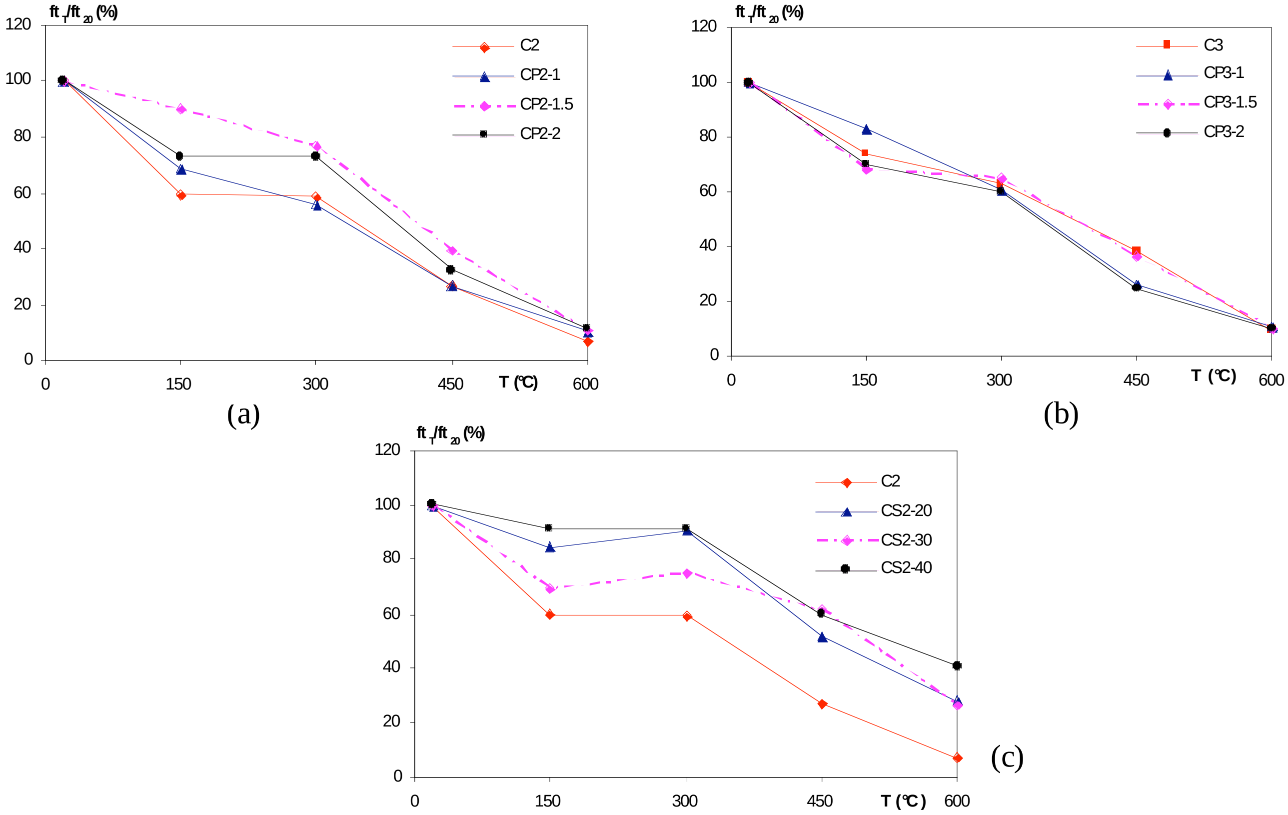
(b)

(c)

Figure 3. Relative residual compressive strength of the polypropylene (a and b) and steel (c) fibres concretes as a function of the surface temperature.

5.4 Tensile strength (ft)

As for the compressive strength, a decrease of tensile strength was observed. Figure 4 shows the evolution of relative residual tensile strength of the concretes without fibres, with polypropylene fibres and with steel fibres. As for the compressive strength, we noticed that the addition of fibres in concrete did not modify the shape of the tensile strength curves. The tensile strength loss was faster than that of the compressive strength. Polypropylene fibres did not have a significant effect on the relative tensile strength (figures 4a and 4b). The addition of steel fibres improved the tensile strength at ambient temperature and improved also the relative ductility. When the steel fibres concrete was exposed to high temperature, a decrease of relative residual tensile strength was also observed (figure 4c). The strength decrease was lower than that of the concrete without fibres. After the heating-cooling cycle at 600°C, a profit of relative residual strength of 33% was observed for CS2-40 concrete. Beyond 300°C, more the amount of steel fibres was important, less the strength loss was. Moreover, the residual ductility of steel fibres concretes was preserved until the temperature of 600°C.



(a)

(b)

(c)

Figure 4. Relative residual tensile strength of the polypropylene (a and b) and steel (c) fibres concretes as a function of the surface temperature.

5.5 Modulus of elasticity (E)

The modulus of elasticity of the concretes with or without fibres (figure 5) decreased under the effect of the heat treatment. As for the compressive strength, the addition of polypropylene or steel fibres did not modify the general evolution of the modulus of elasticity as a function of the temperature. The behaviour remained the same whatever the W/C ratio and the amount of fibres [Noumowé (1995), Gaweska (2004), Kanéma (2007)]. The decrease of the modulus of elasticity of the concrete exposed to high temperature [Tolentino et al. (2002)] was explained by the increase in porous volume and also by the cracking at the interface zone between the paste and the aggregate. The effect of polypropylene fibres (figure 5a and 5b) was not very important. The relative residual modulus of elasticity was almost the same for the temperatures of 450°C and 600°C. By adding steel fibres in the concrete (figure 5c), an improvement of the residual modulus of elasticity was observed until the temperature of 450°C. The profit of relative modulus of elasticity was about 11% at 450°C for CS2-40 concrete. At 600°C, the relative residual modulus of elasticity of concretes with steel fibres was close to that of concrete without steel fibres.

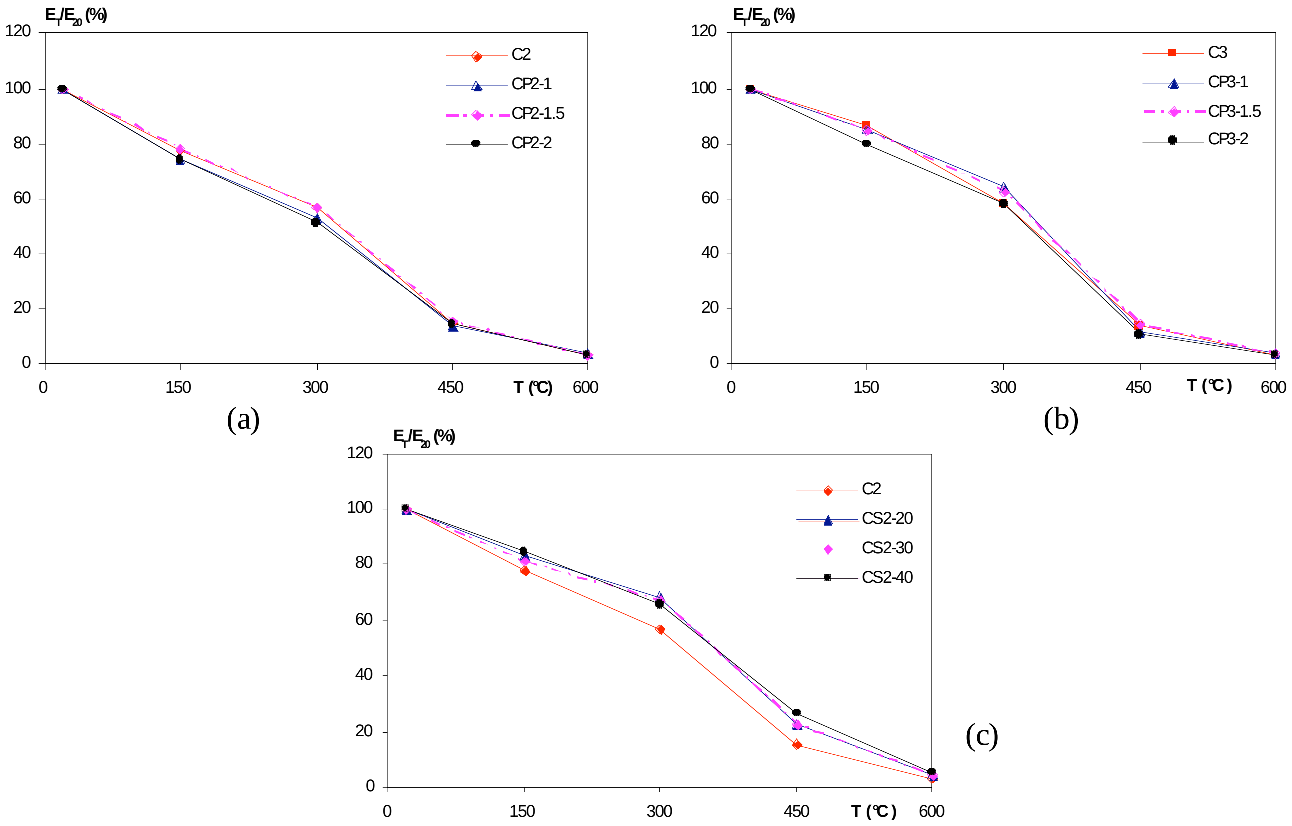


Figure 5. Relative residual modulus of elasticity of the polypropylene (a and b) and steel (c) fibres concretes as a function of the surface temperature.

6 CONCLUSION

The study of concrete with and without polypropylene or steel fibres showed a modification of the microstructure and the mechanical properties of the concrete at high temperature. The high temperature caused a concrete mass loss. The mass loss varied with the W/C ratio: C3 concrete (W/C = 0.3) lost 7.2% of its initial weight when heated at the temperature of 600°C while C2 concrete (W/C = 0.45) lost 8.1%. An additional mass loss was observed when adding polypropylene fibres to concrete as well as a high increase in porosity as a function of the temperature. The porosity increase was more important for the C3 concrete. Porosity increase was less for steel fibres concrete than for polypropylene fibres concrete. At 450°C, porosity of C2 concrete was 19.4% while it was 20.8% for CS2-30 concrete. The increase of porosity lead to a decrease of strength.

At 450°C, the relative residual compressive strength showed respectively a decrease of 56%, 65% and 35% for C2, CP2-2 and CS2-30 concretes while the porosity increase was respectively 5%, 7% and 6%. Until the temperature of 450°C, slight strength decrease was noticed when using polypropylene fibres (10% in compression for CP2-2). Relative residual strength of the concretes with or without polypropylene fibres were almost the same at the temperature of 600°C. The polypropylene fibres did not improve the residual mechanical properties of the concrete exposed to high temperature. The addition of steel fibres in the concrete limited the strength loss. The profit of relative residual strength was more important in tension. At 600°C, the profit of residual tensile strength was more than 30% for the CS2-40 concrete. In compression, the profit was 14%. For all the heating-cooling cycles, an improvement of relative residual strength in compression and tension was observed. An improvement was also noticed when studying the relative modulus of elasticity until the temperature of 450°C. At a minimum amount of 20 kg, the steel fibres improved the concrete residual mechanical properties. A conservation of the concrete residual ductility was also noticed.

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