

Behaviour of UHPFRC at High Temperatures

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Summary

This paper presents the results of an experimental study carried out at high temperatures on two industrial Ultra High Performance Fibre Reinforced Concrete (UHPFRC) containing polypropylene fibres: Ductal[®]-AF and BSI[®]-“fire”. Hot and residual compression tests with and without preload were carried out from 90°C to 700°C. We present the evolution of the stress/strain curves, the compressive strength and the modulus of elasticity with temperature. Moreover, we observed an unusual thermal dilatation of concrete, i.e. non monotonic. Several fire resistance tests on large scale elements (slabs, columns and beams) and smaller samples are presented. Applied fire scenarios were ISO 834 and Modified Hydrocarbon curves. In most cases no spalling was observed. Comparison with results obtained on reference UHPFRC without polypropylene fibres shows the effectiveness of these fibres for these material and these geometries in reducing the spalling risk.

Keywords: Ultra High Performance Concrete, high temperature, mechanical behaviour, compressive strength, modulus of elasticity, thermal strain, fire resistance, ISO curve, Modified HydroCarbon Curve, Spalling, Polypropylene fibres

1. Introduction

Sudden exposure to high temperatures strongly modifies the behaviour of concrete. To increase the level of safety for concrete structures in the event of fire, design calculations have to take the dependence of the thermo-mechanical properties with temperature into account. Furthermore, a lot of researches have shown that concrete could present a risk of thermal instability with fast rise in temperatures. This phenomenon is commonly called spalling. Moreover, high strength concretes seem to have an increased susceptibility to this instability [1]. Nowadays, big scale fire tests are still the most reliable way to predict the risk of spalling.

Fire resistance is determined both by the choice of materials used and by the structure's design. It has been shown that original UHPFRC as Ductal[®]-FM and BSI[®] present high risk of spalling. To address this issue, manufacturers have then developed special formulas, Ductal[®]-AF and BSI[®]-“fire” consisting in a hybrid mixture of steel fibres and polypropylene fibres [2, 3].

Several researches based overall on experiments but also on modelling have been already done and published on both materials [2, 4, 5, 6, 7, 8, 9]. These researches include study on thermal and mechanical properties at high temperature and fire resistance tests on large scale elements.

This paper aims to present, compare and analyze together mechanical properties and fire resistance behaviour (ISO and Modified Hydrocarbon curves) of both materials in order to better understand the high temperature behaviour of UHPFRC.

2. Concrete mixes and main properties

Tested materials are derived from the original formulas Ductal[®]-FM and BSI[®] by incorporating polypropylene fibres to resist to severe thermal solicitations as ISO, HC, HCM, RWS fires. These formulas are called Ductal[®]-AF and BSI[®]-"fire".

We present in table 1 the mechanical characteristics of the 2 UHPFRC.

BSI[®]-"fire" compressive strengths were determined on cylindrical samples of dimensions 110 x 220 mm and 104 x 300 mm and on cubic samples of 100 x 100 x 100 mm. The modulus of elasticity was only determined on the cylindrical samples [7]. Ductal[®]-FM properties were determined on cylindrical samples of dimensions 70 x 140 mm [2]. Heat treatments shall be described later in the paper.

Table 1 BSI[®]-"fire" and Ductal[®]-AF mechanical characteristics

	BSI [®] -"fire"	Ductal [®] -AF	
	Without heat treatment	With heat treatment	Without heat treatment
Mean compressive strength (MPa)	148 – 164.5	200	160
Mean modulus of elasticity (GPa)	50 – 55	50	45

3. Experimental program

Table 2 summarizes the experimental program presented in this paper. Tests procedures and experimental settings will be presented in the next paragraph.

Table 2 Experimental program presented in this paper

	BSI [®] -"fire"	Ductal [®] -AF
Mechanical properties		
Compressive strength	No heat treatment	Heat treatment
Modulus of elasticity	No heat treatment	Heat treatment
Thermal strain	No heat treatment	Heat treatment
Fire resistance tests	HCM curve	ISO 834 curve
	Cubes and cylinders	Slabs, columns and beams
	Heat treatment/No treatment	Heat treatment/No treatment

4. Tests procedure and experimental settings

4.1. Mechanical properties

4.1.1. Tests on BSI[®] - "fire"

Compression tests at high temperature have been carried out on 12 cylindrical samples of Ø10.4 cm x 30 cm, stored at 20°C and 50%HR.

Tests are inspired by the RILEM recommendations [10]. The testing apparatus is composed of a cylindrical electric furnace which can contain cylindrical samples of 104 mm x 600 mm (Fig. 1). The heating is ensured by 3 radiant rings laid out along the longitudinal axis of the furnace. These rings are controlled independently by means of 3 thermocouples (type K) in order to reduce as well as possible the heat gradient inside the furnace. The unit is controlled electronically, which makes it possible to fix the heating rate of the samples.

The longitudinal strains of the sample are determined thanks to an extensometer equipped with three LVDT sensors.

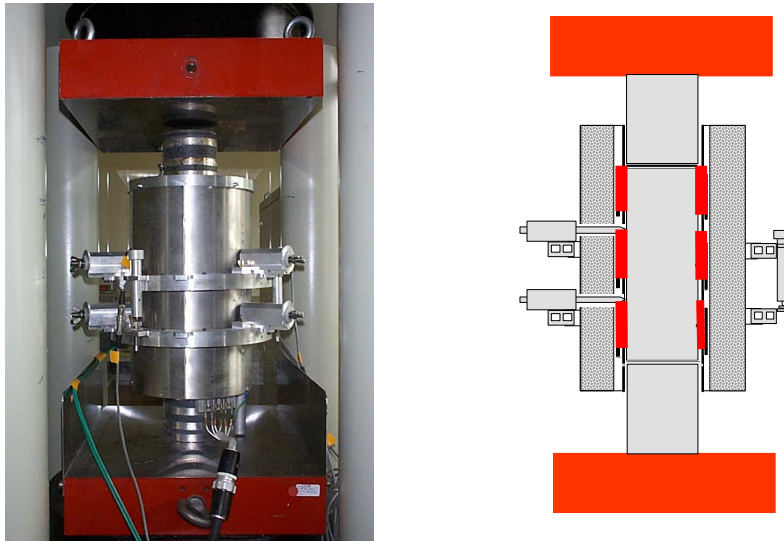


Fig. 1 – Hot mechanical tests apparatus used for tests on BSI[®] - "fire"

Samples were heated at a rate of 1°C/min until the following temperatures: 90°C, 150°C, 300°C, 450°C and 600°C. Once the test temperature reached, samples were maintained at this temperature during one hour (2 hours for 90°C) in order to insure a good homogeneity of the thermal field in the sample. During the heating phase, the thermal strain of the samples was measured.

At the end of the stabilization stage of temperature, the samples were compressed until rupture by the plates of the press. We deduced from these tests the stress/strain curves and the compressive strength of material according to the temperature.

From the curves presented in Fig. 3, we calculated the modulus of elasticity of material at the different temperatures. We defined the modulus of elasticity as the ratio between the stress and the strain of the sample, for a load corresponding to 30% of the hot compressive strength. It is to note that this ratio can only be considered as an "apparent" modulus of elasticity because the mechanical

behaviour of the concrete at high temperature is not elastic linear and preloads have not been applied previously to the compressive tests.

4.1.2. Tests on Ductal®-AF

These experiments are part of the European HITECO project. Cylindrical samples were cured. Their dimensions were 60 mm x 180 mm. Samples were heated at a rate of 2°C/min up to the following temperatures: 100°C, 200°C, 300°C, 400°C, 500°C, 600°C and 700°C. Once the test temperature were reached, samples were maintained at this temperature for one hour. From experiments done on Ductal®-AF, the influence of preload and of cooling phase on the compressive strength can be observed. Four tests conditions have been compared. Half of the samples have been subjected to a preload during the heating phase. The preload corresponds to 20 % of the room temperature strength. The rest of the samples have been tested without preload as the tests carried out on the BSI®-"fire". In the same way, half of the samples have been tested at hot temperature and the other half after cooling. More details on experimental conditions are given in [2, 4].

Tests conditions for the 2 series of tests are summarised in table 2.

Table 2 Mechanical tests conditions

	BSI®-"fire"	Ductal®-AF
Cylinders size (mm)	104 x 300	60 x 180
Heating rate (°C/min)	1	2
Tests temperatures (°C)	90, 150, 300, 450 and 600	100, 200, 300, 400, 500, 600 and 700
With/without preload	Without	With (20 %) and without
Hot/residual	Hot	Hot and residual
Plateau duration	1 h (2h at 90 °C 2h)	1 h

4.2. ISO and Modified Hydrocarbon Curves Fire tests

4.2.1. ISO Curve Fire tests on Ductal®-AF

Slabs, columns and beams were submitted to an ISO 834 fire. The tests were performed at CSTB laboratory [11] and at VTT laboratory [12].

The ISO 834 fire temperature-time relationship is defined by the equation (1). It reaches the temperatures of 600, 800 and 1000°C respectively after 6, 24 and 90 minutes (Fig. 2).

$$T = 345 \cdot \log(8t+1) + 20 \quad (1)$$

T: temperature in °C.
t: time in min.

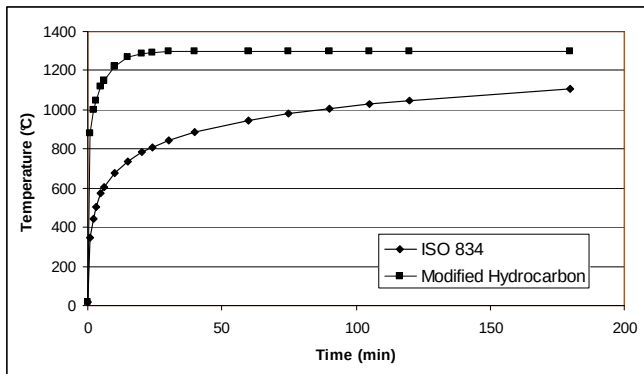


Fig. 2 ISO 834 and HCM curves and global view of the gas-burners furnace

Tests on slabs

Two slabs 400 x 300 x 25 mm³ made with Ductal[®]-AF were tested at CSTB laboratory. One was heat treated at 90°C for 48 hours with steam. The other one was not thermal treated. The 2 side lateral surfaces of each slab were thermally insulated.

Two other slabs made with Ductal[®]-FM (metallic fibres) and Ductal[®]-FO (organic fibres) but without polypropylene fibres were tested in the same period. They were both heat treated. One was 200 x 200 x 900 mm and the other one 300 x 300 x 700 mm.

Tests on columns

Four columns made with Ductal[®]-AF (with polypropylene fibres) were tested. Two columns were 200 x 200 x 900 mm and 300 x 300 x 700 mm. One column of each size was heat treated at 90°C for 48 hours with steam. The other one was not thermal treated. The tests were performed at CSTB laboratory.

The columns do not include any reinforcement. Each column was instrumented with 21 thermocouples. The extremities are protected against high temperatures using rock wool.

Two other columns made with Ductal[®]-FO with organic fibres but without polypropylene fibres were tested in the same period. They were both heat treated. One was 200 x 200 x 900 mm and the other one 300 x 300 x 700 mm. As for the slabs, results determined on these two other columns are presented in this paper in order to show the obtained results on the influence of the polypropylene fibres on this UHPFRC.

Tests on beams

Three prestressed beams were fabricated. The length of the beams was 6.15 m. The transversal section has an I-shaped form. The height of the transversal section was 24 cm and the width of the flanges was 15 cm. The beams were prestressed by 2 0.6-inch tendons positioned at the lower part. The initial force in each tendon was 18.1 tons.

The first beam was heat treated at 90°C for 48 hours with steam. It was tested unloaded under ISO fire in CSTB laboratory.

The two other beams were tested in VTT laboratory. The second was tested loaded under ISO fire. The third one was tested at room temperature to determine the ultimate capacity.

For the second beam, two jacks located 1.5 m from the bearing points each applied a 25 kN downward force. The maximum bending moment was 42 kN.m. This value includes the applied

load (37.5 kN.m) and the moment generated by the beam's own weight. The breaking strain measured at room temperature was 89 kN.m: the loading rate applied during the fire test was therefore 47%. During the test, the top of the beam was protected, and the other faces were exposed to ISO fire conditions.

4.2.2. Modified HydroCarbon Curve Fire tests on BSI® - "fire"

Preliminary Modified HydroCarbon curve (HCM) tests were applied on small samples in a gas-burners furnace of the CSTB. This furnace, of dimensions 3 m x 4 m x 2 m, makes it possible to reproduce the HCM curve of rise in temperature. This thermal scenario, fixed by the equation (2), reaches the temperature of 1000°C in only 2 minutes (Fig. 2).

$$T = 1280(1 - 0,325e^{(-0,167t)} - 0,675e^{(-2,5t)}) + 20 \quad (2)$$

Eight cylindrical samples of Ø11 cm x 22 cm and 12 cubic samples of 10x10x10 cm³ were tested. Half of each type of samples were placed in a tight envelope just after the demoulding and stored at 20°C. The other half samples were stored at 20°C and 50%HR and subjected to a heat treatment.

The heat treatment is divided in three stages: a first stage of rise in temperature of 20°C until 80°C at a heating rate of 20°C/h, a second stage of maintain at 80°C during 48h and finally a natural cooling until 20°C. During these three stages the samples are maintained in a wet envelope in order to avoid their natural desiccation with 20°C. At the end of cooling the samples are stored again at 20°C and 50%HR. The pre-heating aims to accelerate the maturation of the concrete. Fire tests on the dried and wet samples allowed us to study the fire behaviour of concrete structure in different conditions of humidity.

The 20 samples were divided in two identical series and each one was exposed to a Modified HydroCarbon Curve during 180 min fire (HCM180), with an 8 days interval. This measure was adopted in order to check the repeatability of the results.

5. Results and discussion

5.1. Mechanical properties

5.1.1. Stress strain curves

Examples of measured stress strain curves are given in Fig 3. Results correspond to the hot compression tests carried out on the 104 x 300 mm BSI® - "fire" cylinders. Two samples were tested at each temperature. The figure shows the curves presenting the evolution of the strains according to the stress applied to the sample for the various temperatures.

We can observe a weak dispersion of the results. The strength of material at 20°C is about 150 MPa, which is a main property of the UHPFRC. We can observe that the rigidity of material decreases with the rise in temperature. However, at 150°C, the material is as rigid as at 90°C. In addition, we note that the strain reached at rupture grows with the rise in temperature. This can be explained by additional induced strain by crack closing. These cracks are generated during the heating phase because of the thermal incompatibilities between the cement paste and the aggregates. From these curves are deduced the compressive strength (maximum stress) and the apparent modulus of elasticity (slope of the initial straight part of the curves). Evolution of strength and modulus of elasticity with temperature will be analyzed on the next paragraph.

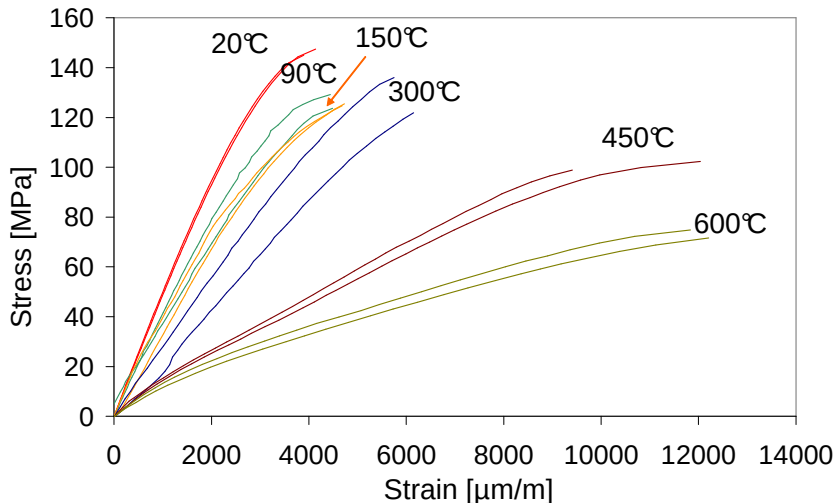


Fig. 3 Stress/strain curves for the different temperatures determined on BSI®-"fire" at hot temperature without preload.

5.1.2. Compressive strength

Evolutions of the relative compressive strength versus temperature for the 2 UHPFRC are presented in Fig 4. Relative compressive strength is defined as the ratio between the value obtained at the test temperature and the initial value (20°C).

We first focus on results obtained at hot temperature without preload on the 2 UHPFRC (hot – 0 %). Strength determined on BSI®-"fire" presents a 15% decrease at 90°C. Between 90°C and 300°C, compressive strength does not decrease and presents even a light increase of about 5%. From 300°C, compressive strength decreases in a linear way with the rise in temperature. At 600°C, the material lost half (50%) of its initial compressive strength. When comparing the obtained results on Ductal®-AF and BSI®-"fire" at hot temperature without preload, one must consider that tests procedures are slightly different (tests temperature, samples size ...). Obtained results on the 2 UHPFRC are however relatively close. It is to note that, in the case of Ductal®-AF no values have been determined between 100 and 500°C. It would be interesting to determine the strength evolution between these two temperatures.

The evolution of strength with temperature can be compared with what is observed on High Performance Concrete (HPC). Results obtained by some authors, as for example by Castillo and Durrani [13] and Hager and Pimienta [14], allow to propose a division of the evolution of strength into three main phases. The compressive strength of concretes decreases during the first stage of heating, reaching a local minimum at a temperature of around 100°C. This first phase was related by different authors to the presence of water [15]. During the second stage, between about 100-300°C, the strength is partially restored. This can be explained by the migration of water from the material. The lower water permeability of UHPFRC could explain its delayed strength increase. This is in accordance with observation done on the influence of decreasing water on cement (W/C) ratio [14, 16]. Further heating causes a continuous, quasi-linear strength decrease. This can be mainly explained by the generated cracks because of the thermal incompatibilities between the cement paste and the aggregates.

Lea et Stradling have predicted since 1922 the existence of a relaxing phenomena allowing to explain the non cracking of ordinary concrete at temperature as low as 100 °C. It is only 40 years later that transient thermal creep was experimentally observed [17, 18]. It is interesting to mention that more recently it was found, on the base of several experiments on one side [18] and modelling on the other side [20, 21], that relaxing phenomena that takes place in cement paste should mainly be effective at temperatures lower than around 400°C. At higher temperatures the large thermal

strains measured under load and increasing temperature is mainly considered to be due to cracking. Even if these observations have been made on ordinary concrete and HPC, they are in good agreement with the measured evolution of strength on BSI®-"fire" and Ductal®-AF: low variation of strength between 20 and 300-500°C and quasi linear decrease of strength at higher temperatures.

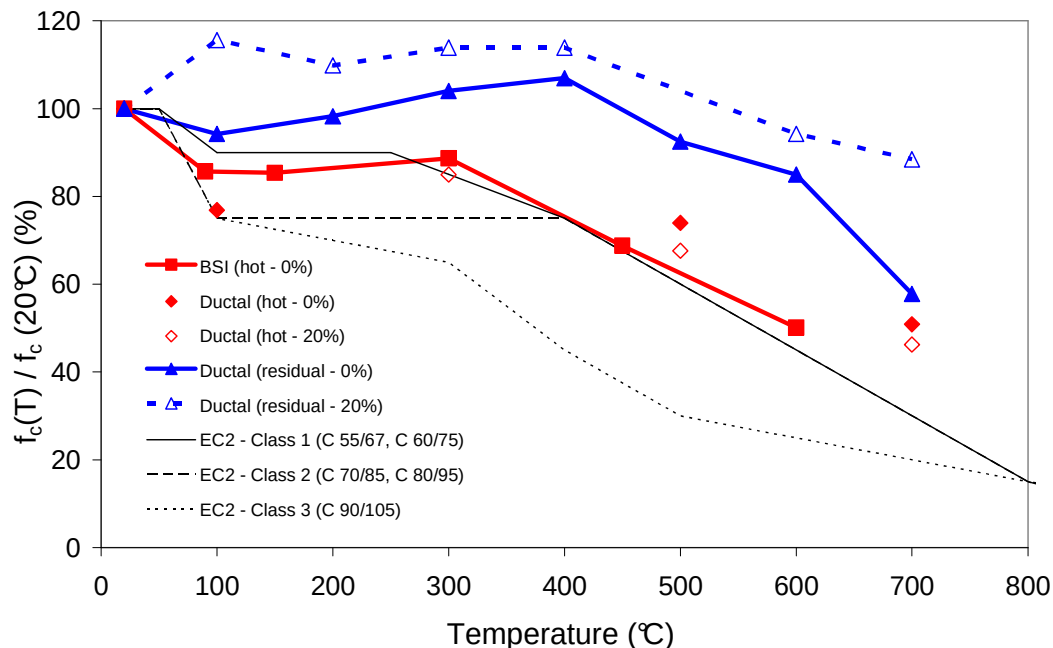


Fig. 4 – Evolution of relative strength as a function of temperature

Fig. 4 allows comparing the results to code 2 values. In spite of their ultra high initial strength, measured curves on the 2 UHPFRC are in good accordance with the values defined by the standard for 3 HPC classes. They are located between the values defined for a class 1 concrete (C 55/67, C 60/75) and a class 2 concrete (C 70/85, C 80/95) until the temperature of 300°C. Beyond 300°C, determined values are even slightly higher.

From experiments done on Ductal®-AF, influence of preload and of cooling phase on the compressive strength can be observed. Residual strengths are, for all temperatures, higher than the ones determined at hot temperature., This result fit with was observed on HPC by Phan and Carino [22] and Hager and Pimienta [14] at temperatures lower than 200 – 300 °C but it does not at higher temperature. Indeed, these authors have found that strengths determined at hot temperature are lower than residual strengths below 200-300 °C. This result is in agreement with what was obtained on Ductal®-AF and this lower compressive strength determined during hot test can be related to the influence of the hot water mentioned above. At higher temperatures however, these authors have found that HPC residual relative strength becomes lower. This can be explained by the additional damage during the cooling phase. As mentioned above, this behaviour was not observed on Ductal®-AF.

Compressive strengths determined after preload during the heating phase at 500 and 700°C are slightly lower than the ones determined without preload. It is to note that in a wider range of temperature an opposite result was found by several authors on ordinary concrete [23] and HPC [22]. The increase of strength due to the preload is generally considered to be due to the densification of the cement matrix during the heating phase. The opposite result obtained on Ductal®-AF could not be explained. At temperature lower than 500°C, the too small number of points does not allow to conclude.

5.1.3. Modulus of elasticity

Evolutions of the relative modulus of elasticity versus temperature for the 2 UHPFRC are presented in Fig. 5. As written above, the calculated modulus is considered to be "apparent" modulus of elasticity.

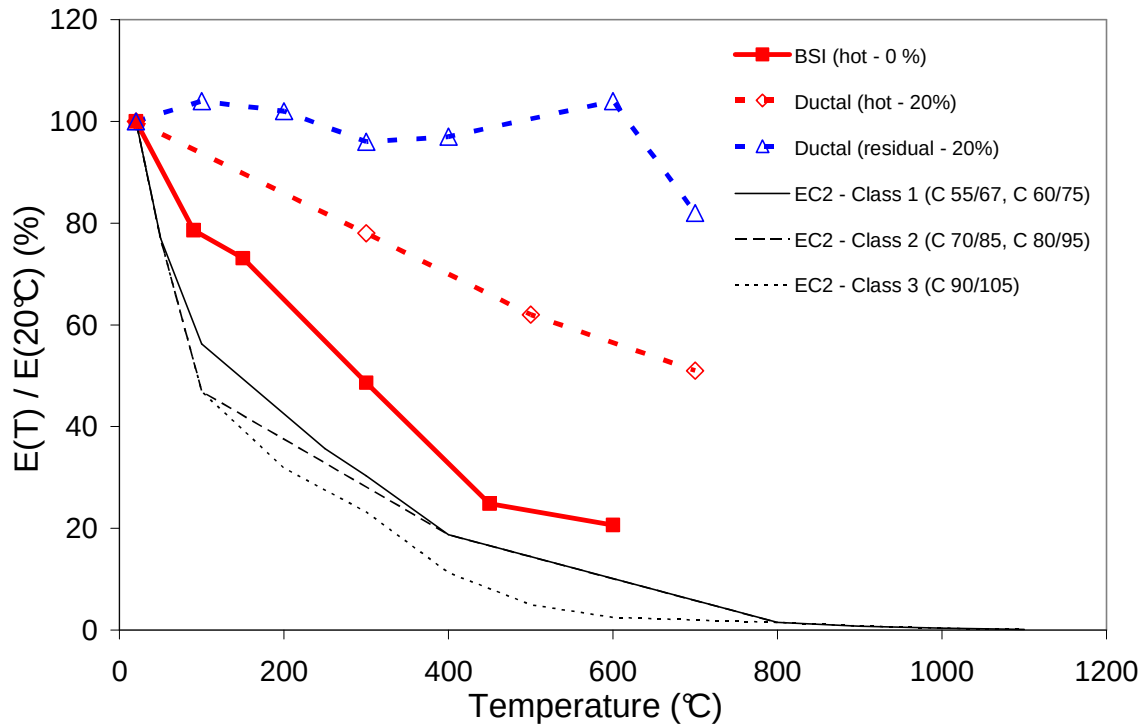


Fig. 5 Evolution of relative modulus of Elasticity as a function of temperature

As for compressive strength, we first focus on results obtained at hot temperature without preload. The modulus of elasticity of BSI[®]-"fire" decreases in a relatively linear way with the rise in temperature. At 20°C, the modulus of elasticity is about 50 GPa and reaches at 600°C the value of 10 GPa, which represents a loss of rigidity of material of about 80%. We also notice that in spite of the ultra high strength of the material, the loss of rigidity with temperature is less important than the loss defined by the equations given by Eurocode 2 for 3 HPC classes. It is interesting to note that experiments made on 3 calcareous aggregate concretes differing only by their W/C ratio have shown that evolution of the relative modulus of elasticity seems to be independent of the W/C ratio [14]. Indeed, no significant differences between those three concretes were observed.

In Fig 5, experiments carried out on Ductal[®]-AF correspond to the ones done with a preload at hot temperature and after cooling.

Modulus of elasticity determined at hot temperature with a 20% preload are, for all the temperatures, higher than the ones determined on BSI[®]-"fire" without preload.

Concerning the effect of the cooling phase, in a similar way than for compressive strength, residual modulus of elasticity are for all temperatures higher than those determined at hot values. As for compressive strength, these results at temperatures higher than 200 – 300 °C do not fit with what was observed on HPC by Hager and Pimienta [14]. These authors have found that modulus of elasticity determined at hot temperatures are lower than residual values below 200-300 °C. This result is in agreement with what was obtained on Ductal[®]-AF. At higher temperatures, however, HPC residual relative modulus of elasticity has been found to become lower.

5.1.4. Thermal strain

Evolutions of the thermal strain versus temperature for the 2 UHPFRC are presented in Fig. 6. They are compared to the curves given by Eurocode 2 for concretes with limestone and siliceous aggregates.

Curve obtained on Ductal®-AF is in good agreement with those given by Eurocode 2. Up to temperatures of about 500°C, extension was essentially linear, representing nothing more than thermal expansion. The slope in this segment was $12.10^{-6} / ^\circ\text{C}$ which corresponds to the thermal expansion coefficient. The extension curves then "bulge" as a direct result of the quartz's highly expansive alpha/beta transformation (at 573°C). It is to note that the trend of the presented experimental curve presented in Fig. 6 was confirmed by a second measurement campaign [2]. This trend is very different to the one observed for the other UHPFRC.

During the heating phase before each compression test carried out on BSI®-"fire" samples, thermal strain was measured. The 9 determined curves were very close [7]. Curve given in Fig. 6 is the calculated mean value.

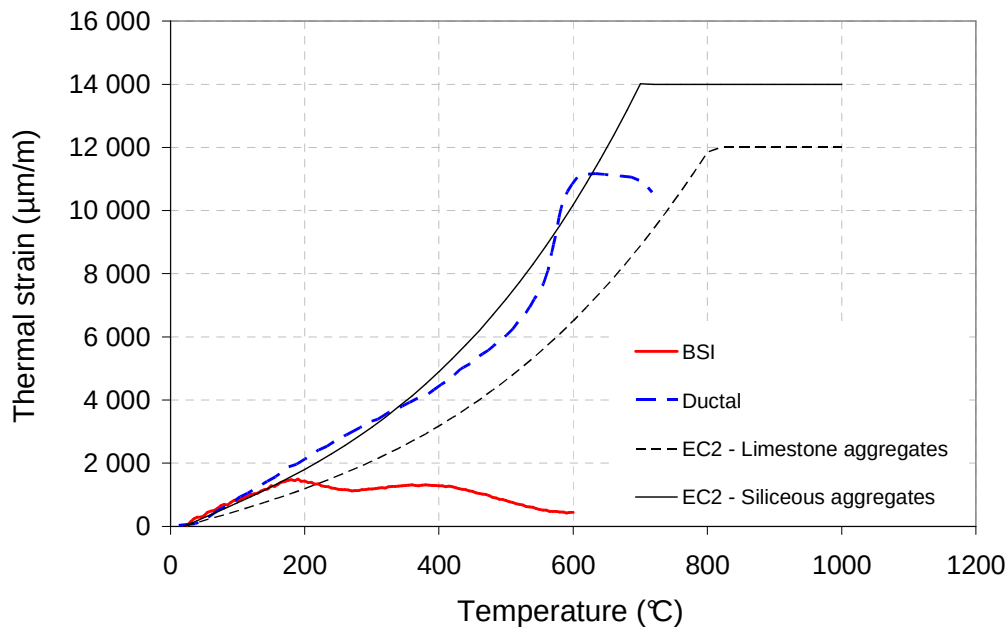


Fig. 6 Thermal strain as a function of temperature

BSI®-"fire" first expands in a relatively linear way until 190°C. Beyond this temperature, the material behaviour brutally changes and the concrete shrinks until 275°C before expanding again between 275°C and 390°C. At last, the material behaviour changes once again and the concrete shrinks until the temperature of 600°C.

This behaviour is in good accordance with thermal strain determined on Ductal®-AF and defined by the standards until the temperature of 190°C. Beyond this temperature, the measured thermal strain strongly deviates from these values. BSI®-"fire" is much more stable. This property could be favourable to the integrity of a structure subjected to fire. Indeed, the zone exposed to the fire will induce smaller strains to the rest of the structure.

In the following paragraph we propose an explanation to this original result based on the high cement paste content of UHPFRC. However, we could not explain why this particular behaviour was observed on BSI®-"fire" and not on Ductal®-AF. Thermal strain of a concrete is a combination of the thermal strain of the cement paste and the aggregates. Most of the aggregates continuously

expand with temperature. In an opposite way cement pastes first expand to reach a maximum at about 150 – 200°C and then shrinks due to its drying and dehydration [24, 25, 16]. Below this temperature range, thermal strain of a concrete can be illustrated by a competition between the expansion of the aggregates and the shrinkage of the cement paste. In most of the concretes, the expansion of the aggregates is predominant and thermal strain is similar to what is proposed in the normative documents. The observed shrinkage of the BSI®-"fire" above 190°C could be explained by its much more important volume of cement paste compare to ordinary concrete. This important volume of paste should lead to a predominance of the cement paste shrinkage on the aggregates expansion. The expansion observed on BSI®-"fire" between 275°C and 390°C has not been explained. Further study on thermal properties of pure aggregates should provide answers.

5.2. ISO and Modified HydroCarbon Curves Fire tests

5.2.1. ISO Curve Fire tests carried out on Ductal®-AF

Unloaded slabs test

The 2 slabs made with Ductal®-AF remained intact until the end of the test after 132 minutes exposure. No spalling was observed (Fig 7).

The non exposed surface of the heat treated 25 mm thickness slab reached 140°C after 11 min 30. Some small cracks appeared after 43 min. One longitudinal crack already existing before the test has developed. After cooling, the surface appeared whitened.

The non exposed surface of the non heat treated slab reached 140°C after 13 min. After cooling, the surface presented a pink coloration. The fibres were apparent and brown.

On the 2 other slabs made with Ductal®-FM (metallic fibres) and Ductal®-FO (organic fibres) but without polypropylene fibres, spalling was observed and started after 8 min. Phenomenon was during part of the test violent.

This result shows the effectiveness of adding polypropylene fibres for this material and this geometry in reducing the spalling risk.

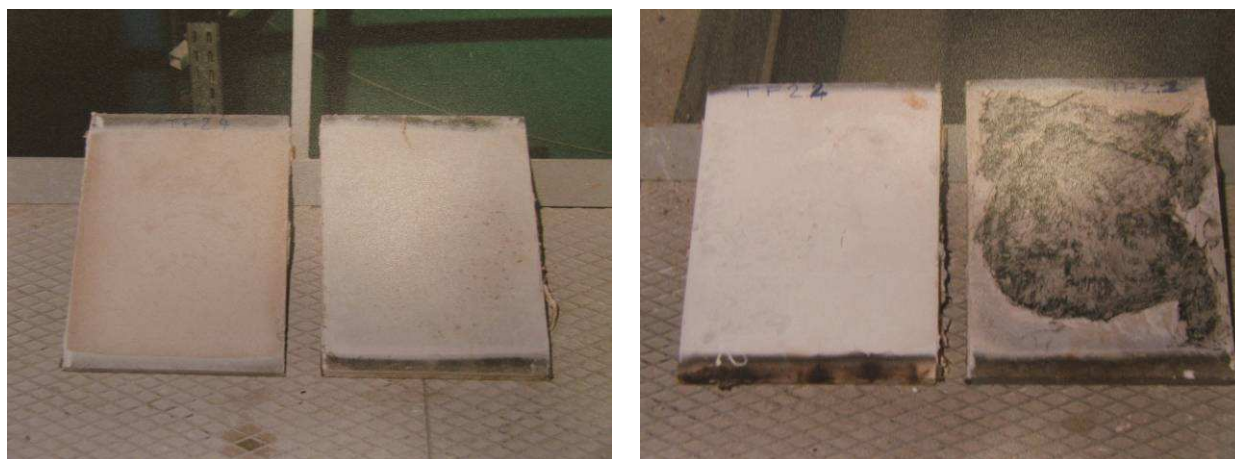


Fig. 7 Exposed surface of the 4 tested slabs; from left to right: Ductal®-AF heat treated, Ductal®-AF not heat treated, Ductal®-FO and Ductal®-FM

Unloaded column test

The columns remained intact until the end of the test after 132 minutes exposure. No spalling was observed on the heat-treated columns (Fig. 8). Slight spalling was observed in places on the untreated columns. After cooling, the vertical surfaces were crazed and fibres near the surface were blackened.

The edges remained well-defined. A few minor edge cracks were visible.

The 2 other columns made Ductal®-FO with organic fibres but without polypropylene fibres were completely destroyed and fell down.

This result shows again the effectiveness of adding polypropylene fibres for this material and this geometry in reducing the spalling risk.



Fig. 8 The 6 columns made with Ductal® after ISO Curve Fire tests; the picture clearly shows that no spalling or slight spalling was observed on the columns made with Ductal® -AF, the 2 other columns made with Ductal®-FO were completely destroyed and fell down

Tests on unloaded beam

The first beam tested unloaded remained intact throughout the test (Fig. 9). No significant material loss was observed during the 134 min hours test duration. It was only observed a slight spalling in the centre on the bottom surface after 5 min. A few horizontal and vertical cracks appear between 18 and 46 min. There were visible on the surface after cooling.

Tests on loaded beam

The test on the loaded beam lasted 36 minutes. The right hand side picture of Fig. 9 shows the state of the beam after the test, during which a bending failure occurred. No spalling was observed. The failure was caused by the pre-stressing cables: the crack was straight and the upper part of the beam was undamaged.

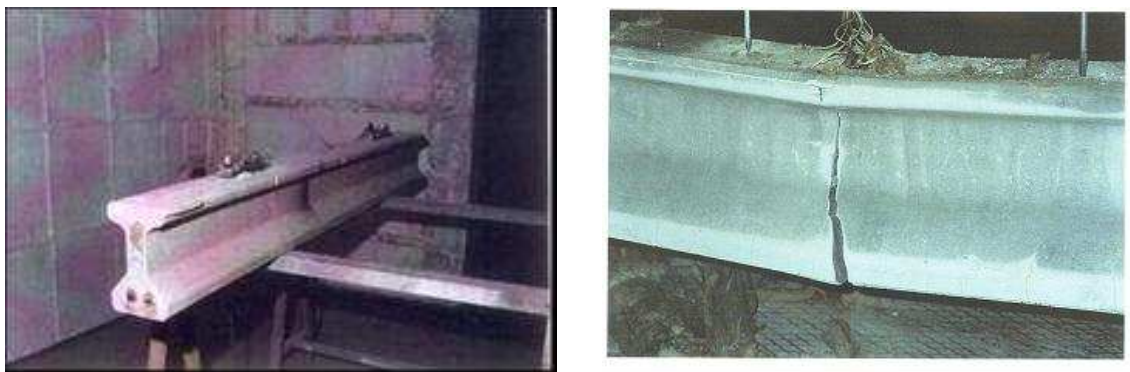


Figure 9. Beams made with Ductal® -AF after ISO Curve Fire tests; on the left, unloaded beam, on the right loaded beam

5.2.2. Modified Hydrocarbon Curve Fire tests carried out on BSI® - "fire"

On Fig. 10, we present the visual aspect of one of the samples tested with HCM180 fire. Visual observations of the samples after HCM180 tests bring the following remarks.

All the samples surfaces present a very marked brown colouration (Fig. 10). This colouration appears at a temperature near 950°C,

None of the samples that were pre-heated in oven for accelerated maturation showed any effect of spalling,

Some local fractures appear on certain 28 days samples which were stored in water,

A great majority of steel fibres disappeared from the surface of the samples leaving only the print of their volume (Fig. 10).



Fig. 10 On the left, global view of a sample after HCM test. On the right, zoom on the sample surface



Fig. 11 View of half of a vertically sawn sample

To try to understand the origin of the surface colouration, which closely looks like corrosion, a cylinder was sawn vertically (Fig. 11). We could observe that this colouration appears only at the sample surface, that the steel fibres had disappeared on a depth from approximately 20mm and that on this same layer the concrete had a similar porous morphology as a volcanic rock.

Beyond this superficial layer, the concrete keeps a dense structure and fibres are always present. It should be noted that the colouration of fibres is here undoubtedly the fact of sawing under water.

All the samples were weighed before and after the fire test. This reveals that on average, an 11x22 cm cylinder with accelerated maturation loses 9.10% of its mass during HCM180 fire. After the period of maturation, this cylinder had already lost 0.45% of its mass. Those stored in water lost on average 10.7% of their mass after HCM180 test.

6. Conclusions

Mechanical tests results present a weak dispersion. Compressive strengths determined at hot temperature without preload on the 2 UHPFRC are relatively close. In spite of their ultra high initial strength, compressive strength and modulus of elasticity are in good accordance with the values defined by the Eurocode 2 for HPC. Influence of the cooling phase seems to be different than what was observed on HPC at temperatures higher than 200-300°C. Results obtained on Ductal®-AF show that residual compressive strength and modulus of elasticity remain higher than hot values in the higher range of temperature.

Contrary to Ductal®-AF and traditional concretes, the free thermal strain determined on BSI®-"fire" is non monotonous and presents sudden changes of behaviour according to the temperature. This property could be favourable to the integrity of a structure subjected to fire.

Several large scale fire resistance tests results have been presented. ISO 834 curve have been applied to slabs, columns and beams made by Ductal®-AF. In most cases no spalling was observed. Only slight spalling was observed in places on the untreated columns.

Some tests have been carried out on Ductal® formulas without polypropylene fibres. Important spalling was then observed.

Preliminary Modified HydroCarbon curve (HCM) tests were applied on small cylinders and cubes made by BSI®-"fire". Again, no spalling was observed. The samples stored in water presented some local fractures. Analyzing the samples exposed to 1 300°C, have shown that fibres close to the surface melt and steel migrate to the surface and become corroded inducing a very marked brown colouration.

All the results have then shown the effectiveness of adding polypropylene fibres for these material and these geometries in reducing the spalling risk.

7. Acknowledgements

The authors want to thank the Fire Resistance Laboratory of CSTB for carrying out fire tests presented in this paper and M Philippe Rivillon for helping in setting up the hot temperature compressive tests equipment.

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