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Effect of polymer fibres inclusion in fire spalling of ultra-high performance concrete

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ABSTRACT: This article presents the first part of a study concerning the behaviour of ultra-high performance fibre concrete (UHPFC) under fire. Four kinds of synthetic fibres were added: polypropylene (PP), acrylic (PMMA), polyvinyl acetate (PVA) and polyethylene (PE). After mechanical and thermal characterizations of the material, blowtorch tests were performed on it. The expected efficiency of PP and PE fibres was observed. Microscopic observations enabled us to put forward a hypothesis regarding the efficiency of fibres in concrete.

1 INTRODUCTION

Explosive spalling of concrete under fire conditions is one of the damage that is the most dangerous for the concrete structure. As Anderberg (1997) & Kalifa (2002) have already shown, the higher the strength of the concrete, the greater the spalling is.

Several hypotheses have been put forward to explain the spalling phenomena in concrete under very high temperature. The first one is that the thermal gradient due to the fire causes a stress gradient in the concrete, which would be responsible for such spalling (Bazant & Kaplan 1997). The second one could be the "moisture clog" effect caused by partial water saturation in the concrete (Anderberg 1997). Indeed the water present in concrete can be free water or bound water which can vaporize due to high temperatures. If the vapour is close to the heated side of the concrete, a part of the vapour drains off through this heated side. The other part goes inside the concrete. This area is then colder, so the vapour condenses and saturates the non-saturated pores. An impermeable barrier obstructing gas is then formed. The pressure of gas rises and weakens the concrete, once the pressure exceeds the tensile strength, the concrete breaks.

However, Jansson & Boström (2007), Mindeguia (2009) show that both phenomena "moisture clog" and high thermal gradient need to be present to rupture the concrete by spalling. Jansson suggests considering the "moisture clog" as a critical area. Indeed he explains that around this area, several mechanisms can cause a spalling: first, the decrease in compression and bending strength as the temperature increases is greater for a saturated concrete than for a non-saturated concrete, then the high thermal dilatation of water (considered as incompressible) can create elevated tension stress in the concrete and finally, the vaporization of water consumes energy that can locally disturb the thermal field and can increase the thermal gradient.

The current solution to improve the behaviour of concrete under high temperature is the addition of polypropylene fibres (Khoury 2008, Bilodeau et al. 2003, Hertz 2003, Chan et al. 2000, Breitenbücker 1996, Harmathy 1965, Malhotra 1956). However, the real mechanisms that play a role in explaining the efficiency of these fibres are not known totally. Moreover it is hard to explain why polymer fibres, other than polypropylene, do not work.

The aim of this article is to test several polymer fibres in ultra-high performance fibre concrete and to understand what mechanisms enable the fibres to be efficient or not. The hypothesis kept there is the "moisture clog" mechanism principally. For that, a very high temperature study with a blowtorch test and microscopic observations have been carried out. After a presentation of the used materials, the experiments are described followed by the results and the conclusion.

2 MATERIALS

2.1 *Concrete specimens*

The minimal expected characteristics for the studied ultra-high performance fibre concrete (UHPFC) as well as its base mix design, are given in Tables 1 and 2.

Table 1. Required mechanical characteristics.

Strength	Minimal value
	MPa
Compressive strength (Rc)	120
Bending strength of binder (Rfb)	10
Bending strength of concrete (Rfc)	30

Table 2. Concrete mixture proportions.

Constituents	Content
	kg/m^3
Premix (silico calcareous sand, fines and cement)	2085.6
Superplasticizer	28.7
Water	194
W/C ratio	0.19

The experiments presented in this paper are performed on 4 x 4 x 16 cm prisms. This size was chosen because of the high temperature setup used in the future part of the study. The dimensions of this press will be only 24 x 24 x 7 cm. Compression tests on small cylinder specimens will be carried out.

Firstly, these specimens were cast in polystyrene moulds to make de-moulding easier. A comparison of specimens made using a steel mould or polystyrene mould has revealed that the surface finish has a large influence on mechanical strength (see paragraph 4.1).

Once the specimens were made they were placed in a wet chamber (20°C and 95% humidity) during 28 days.

For the mechanical tests, the specimens were brought out the day of the tests.

For the blowtorch tests the specimens were brought out at room temperature (23°C, 60% humidity) one week before the test day.

2.2 *Fibres*

2.2.1 *Characteristics*

Breitenbücker (1996), Anderberg (1997), Kalifa et al. (2002) clearly show the efficiency of polypropylene fibres in the behaviour of high-performance fibre concrete under fire conditions. In this study various polymer fibres that exist on the market were tested. The following fibres were selected: polypropylene (PP), polyvinyl acetate (PVA), acrylic (PMMA), polyethylene (PE).

Literature recommends using a fibre length between 6 and 12 mm.

The selected fibres are given in Table 3.

Table 3. Selected fibres.

Fibre type	Length	Diameter	Melting temperature
	mm	µm	°C
PP fibre	12	50	171
PP fibre	6	18	171
PE fibre	4.6	20	146
PVA fibre	8	40	240
PMMA fibre	6	14	120

2.2.2 *Amount of fibres*

In order to determine the amount of fibres to put in the mix design, our study was based on existing literature. Usually the recommended amounts of PP fibres vary from 1 kg/m^3 to 3 kg/m^3 (Kützling 1999, Bilodeau et al. 2003, Alonso & Rodriguez 2000, Chan et al. 2000, Khoury & Willoughby 2008). For other polymer fibres, Han et al. 2009, Arisoy & Wu 2008 show that the quantity of fibres used is between 1 kg/m^3 and 4 kg/m^3.

A criterion concerning this amount was created so as to compare the fibres. Our idea was based on Khoury (2008) who developed a theory related to specific surfaces. G.A. Khoury shows the development of a specific surface in relation to different dimensions and quantity of fibres. The role of fibres is to reduce gas pressure in the material by creating channel voids when melting. In order to release the pressure the gas reaches the voids through micro-cracks.

And one can then assume, the higher the specific surface of the fibres and thus the voids, the greater the accessibility to the gas.

Our reference fibre is the PP fibre so the specific surfaces corresponding to quantities from 1 to 3 kg/m^3 were calculated. For simplicity reasons, values of these surfaces were rounded up and used for all the fibres.

The quantity of fibres used is given in Table 4. The table shows that the bigger fibres cannot reach the specific surface of 600 m^2 without exceeding the amount of 5 kg/m^3. For these fibres the specific surface was restricted to 200, 300 and 400 m^2.

2.3 *Name of the specimens*

The specimen without any fibres is called CC. The summary of the names is given in Table 5.

3 EXPERIMENTAL TESTS

3.1 *Mechanical tests*

The aim of the mechanical tests is to determine the influence of the polymer fibres in the concrete behaviour. They are carried out on specimens on the 7th day and then again on the 28th day.

Two types of tests have been performed: a 3-point bending test on a 4 x 4 x 16 (cm) prism which is then broken into two 4 x 4 x 8 (cm) prisms, and a compression test which is carried out on these 4 x 4 x 8 (cm) prisms. The compression is supposed tooccur on a 4 x 4 (cm) square. Both test configurations are represented in Figure 1. Results are calculated using standard "strength of materials" equations.

Table 4. Quantity of fibres.

Type	Density	Length	Diameter	Quantity	Theoretical specific surface	Aimed specific surface
		mm	µm	kg/m^3	m^2/m^3	m^2/m^3
PP	0.91	6	18	0.82	200	200
				1.64	401	400
				2.46	602	600
				3.27	800	800
PP	0.91	12	50	2.3	203	200
				3.4	300	300
				4.5	396	400
PMMA	1.12	6	14	0.81	201	200
				1.61	400	400
				2.42	601	600
				3.22	800	800
PVA	1.3	8	40	2.6	201	200
				3.9	301	300
				5.2	400	400
PE	0.93	4.6	20	0.94	201	200
				1.87	399	400
				2.81	600	600
				3.75	800	800

Table 4. Names of the specimens.

Type	Length mm	200 m² specific surface	300 m² specific surface	400 m² specific surface	600 m² specific surface	800 m² specific surface
PP	6	CPP6_200		CPP6_400	CPP6_600	CPP6_800
PP	12	CPP12_200	CPP12_300	CPP12_400		
PVA	8	CPVA8_200	CPVA8_300	CPVA8_400		
PE	4	CPE4_200		CPE4_400	CPE4_600	CPE4_8200
PMMA	6	CPMMA6_200		CPMMA6_400	CPMMA6_600	CPMMA6_800

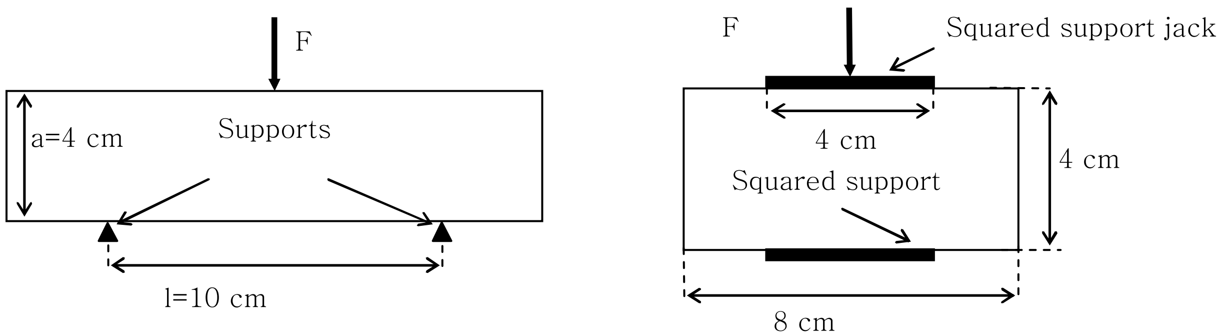

Figure 1. Three points bending test and simple compression test.

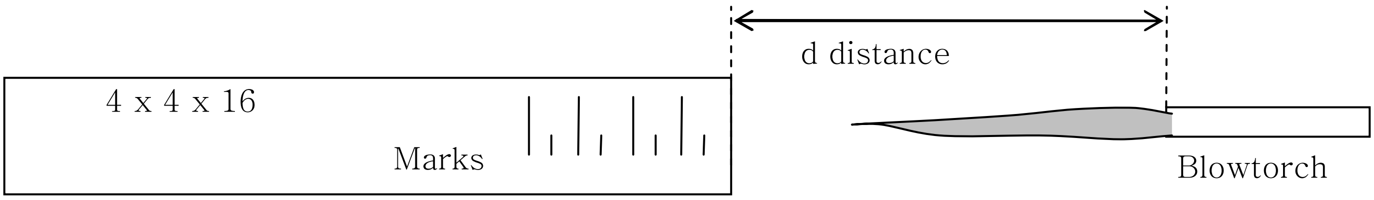

Figure 2. Scheme of the blowtorch test's installation.

3.2 *Blowtorch test*

The blowtorch test is performed on a specimen of 28 days. Its aim is qualitative and it is intended to compare the efficiency of each fibre. One of the 4 x 4 (cm) sides of the prism is heated with a blowtorch while the specimen is placed at distance “d” from the origin of the flame. Lateral marks at each centimetre are intended to estimate the depth of the spalling (see Fig. 2 for details).

The test lasts 5 minutes and the two values 10 and 15 cm are considered for the distance parameter. The drawback is that both maximal temperature and heat rate are impacted when there is a change in distance. Thus, only a qualitative comparison between the specimens is made.

The temperature curves (d=10 cm and d=15 cm) for each test were determined experimentally with an infrared thermometer and they are given in Figure 3. They are compared to the French “building” (ISO 834) and HCM standards.

The heating rate is higher than the standard curves

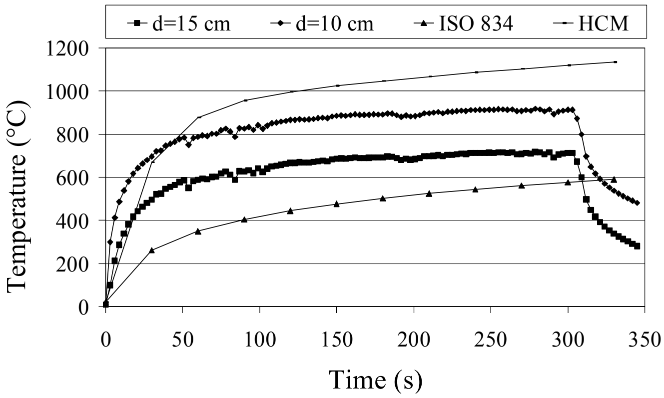

Figure 1. Time-temperature curves of thermal stress.

and that the maximal temperature is above the ISO834 curve.

4 RESULTS, ANALYSIS AND DISCUSSION

4.1 *Mechanical results*

The obtained results are represented in Figures 4 to 7.

From the obtain results the general observed trends are the following:
- the bending strength is influenced by the amount of fibres
- the bending strengths are higher than 10 MPa, except for two cases (CPP12_400 and CPVA8_200)
- the compressive strength decreases when the quantity of fibres increases
- the compressive strengths are lower than 120 MPa

This last trend can be explained by the fact that the higher the amount of fibres, the harder the workability is. Thus the bond between fibres and the binder can get worse.

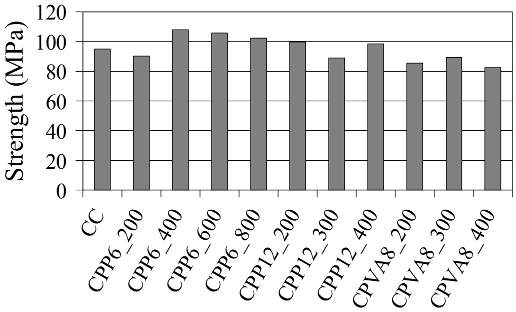

Figure 2. Compression test results : set 1.

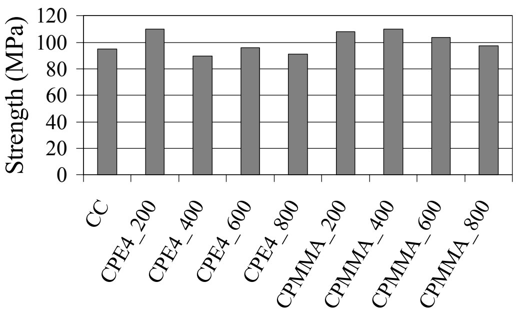

Figure 3. Compression test results : set 2.

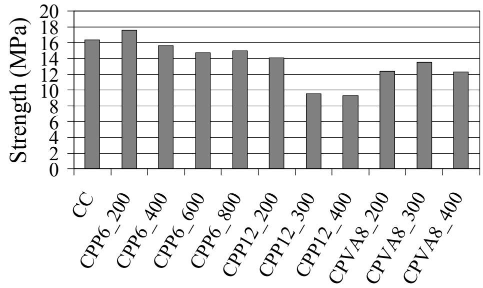

Figure 4. Bending test results : set 1.

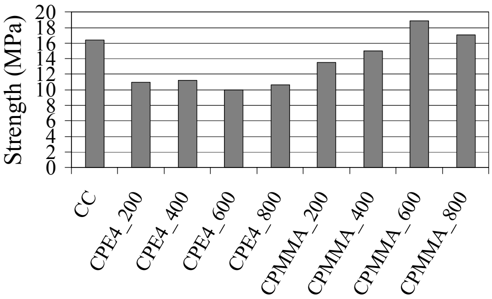

Figure 5. Bending test results : set 2.

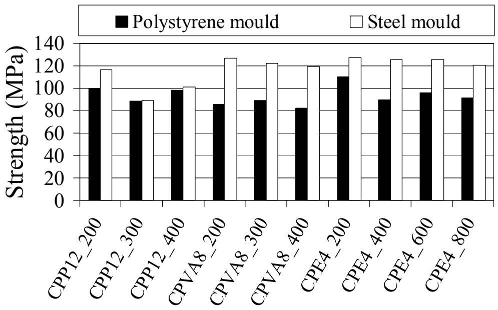

Figure 6. Comparison of compressive strength between polystyrene mould specimen and steel mould specimen.

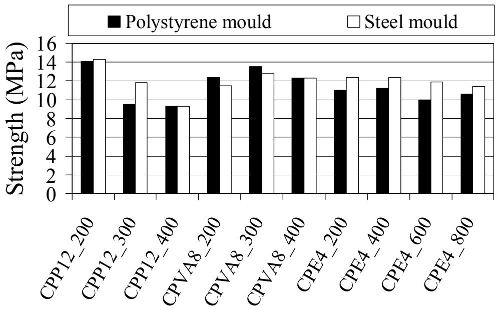

Figure 7. Comparison of bending strength between polystyrene mould specimen and steel mould specimen.

Let us note that the previous values are taken from tests performed on specimens cast in polystyrene moulds. To compare, the Figures 8 and 9 shows the different results obtained on specimens from polystyrene and steel moulds.

From the figure the conclusions are:
- the flexural strength is slightly influenced by the type of mould (0 % to 16 %)
- the compression strength is more influenced by the type of mould (0 % to 32.5 %)

The influence of the surface roughness can be observed more easily with the compression test because the contact surface for this test is larger than for the "3-point bending test".

Table 5. Results of blowtorch test.

Name	d=15 cm	d=10 cm	Name	d=15 cm	d=10 cm
CC	S	S	CPMMA_200	S	---
CPP6_200	S	---	CPMMA_400	S	---
CPP6_400	NS	---	CPMMA_600	S	---
CPP6_600	NS	NS	CPMMA_800	S	---
CPP6_800	NS	NS	CPE_200	S	---
CPP12_200	S	---	CPE_400	NS	S
CPP12_300	NS	NS	CPE_600	NS	NS
CPP12_400	NS	NS	CPE_800	NS	NS
CPVA_200	---	---			
CPVA_300	---	---			
CPVA_400	S	---			

4.2 *Blowtorch results*

The summary of the tested specimens is given in Table 6. The following lines explicit the alphanumeric parameters appearing in Table 6.

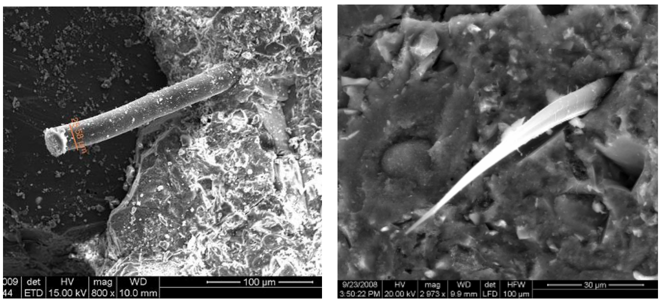

Figure 8. PP (left) and PMMA (right) fibre at 25°C.

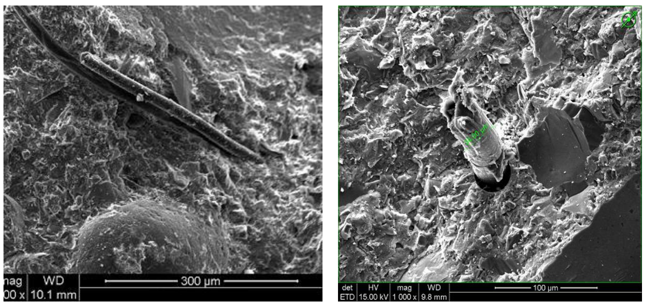

Figure 9. PE (left) and PVA (right) fibre at 25°C.

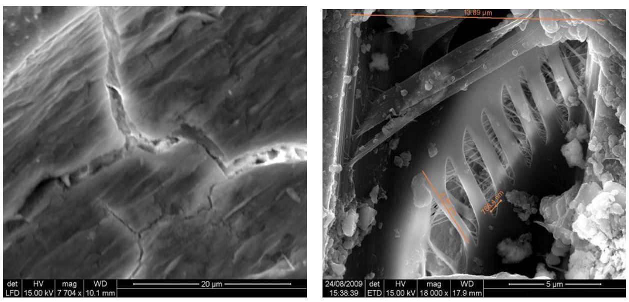

Figure 10. Bed of PP (left), PMMA (right) melted fibre.

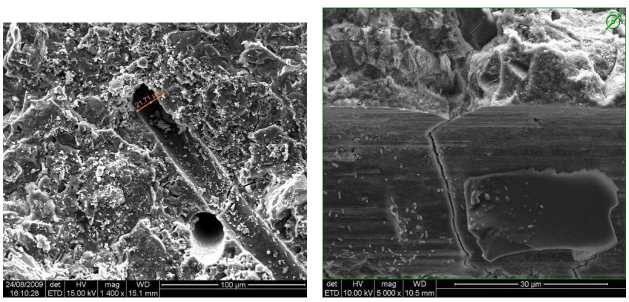

Figure 11. Bed of PE (left) and PVA (right) melted fibre.

"S" means spalling occured.
"NS" means no spalling occured.
"---" means the test had not been done

PP fibres are found to improve significantly the behaviour of the concrete under fire conditions (even a UHPFC).

As far as the PP fibres results are concerned it seems necessary to have a minimum of 300 m² specific surface to resist to the blowtorch test. This result is the same for PE fibres at the distance of 15 cm. This similarity is probably linked with the close (or same) characteristics of these fibres in term of melting temperature and dimensions.

4.3 *Microscopic observations*

In order to understand why only the PP fibres are really efficient in fire resistance, microscopic observations were done on the polymer fibres.

4.3.1 *Room temperature*

A first campaign at room temperature was done to compare the geometry of the different fibres. Views of these observations are given in Figures 10 and 11.

Concerning the geometry, PP, PE and PVA fibres shapes seem similar (cylinder). In a contrast, a typical PMMA fibre is like a spike. So for these fibres the calculated specific surface could be over estimated.

4.3.2 *High temperature*

In order to observe the bed of the melted fibres, specimens were heated at 280°C (for PP, PE and PMMA fibres) and 300°C (for PVA fibres) during 6 hours.

The pictures taken during these observations are given in Figures 12 and 13.

It appears that the beds of the PP, PE and PVA melted fibres have the same appearance. We recognize the initial roughness surface of the fibres (like a bark) with cracks.

On the other hand, the bed of the PMMA fibres has a smooth surface with a few fine cracks. Moreover these cracks are covered by a kind of film. This film could come from:

- either the affinity between the fibre and the binder at the fresh state concrete. Indeed Peled et al

(2008) explain that the behaviour of the polymer fibres with the binder changes in function of the chemical nature.
- either a polymerisation of the melted fibre when the temperature decreases. So once the melting temperature is reached, the fibre is too much viscous to go away and forms this film.

This film left by the PMMA fibres in the bed can block the propagation of the gases and thus facilitates the spalling.

The comparison between the bed of the PP, PE and PVA fibres doesn't show big differences in their appearance.

However the melting temperatures differ from below 200°C (PP and PE fibres) to 240°C (PVA fibres) and can explain the difference of efficiency observed in fire resistance of concrete. Indeed from 100°C where the steam appears to 240°C where the PVA fibres melt, the accumulated inner pressure is high enough to destroy the concrete.

Finally the observations of bed from PE and PP melted fibres explain why they are so close in term of efficiency for the fire behaviour of concrete.

5 CONCLUSION

The first part of the study on the behaviour of ultra-high performance fibre concrete enabled us to confirm the performance of the PP fibres in concrete. The same performance for PE fibres was observed, although these fibres do not figure as much in current literature. This is probably linked to their cost.

The unexpected result observed was the inefficiency of PMMA fibres. They are dimensionally close to PP fibres, but have a lower melting temperature. However, they cannot solve the problem of the fire resistance of concrete.

Microscopic observations enable us to put forward a hypothesis regarding PMMA inefficiency. The bed left by the PMMA fibres, once melted, does not have the same appearance as that left by the PP fibres. For PMMA fibres, the surface of the bed is very smooth with a few fine cracks and is covered by a thin film. This deposit could be either a reaction between the binder and the fibre in fresh state concrete or a polymerisation of the melted fibre once the temperature drops. For PP fibres, the bed surface is rough with numerous cracks. This can explain the ease with which the gas moves within the concrete at high temperatures. The bed left by the PVA fibres has the same appearance as the PP fibres but as their melting temperature is higher than that of PP fibres, voids created appear too late to release inner gas pressure.

With the first part of this study complete, the second one is underway. It consists of measuring the compressive strength of concrete at high temperatures. Indeed, even if there is no spalling of concrete the resistance of this material cannot be as high as expected. The future part of this study will be based on mechanical isothermal tests at high temperatures.

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