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An experimental method for assessing the spalling sensitivity of concrete mixture submitted to high temperature

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ABSTRACT

In concrete exposed to high temperatures, two inseparable processes arise: a "thermo-mechanical" process in which the gradient of thermal deformation generates stresses and a "thermo-hydrous" process that generates a driving force for flow of vapour and liquid water. Explosive spalling, especially caused by the latter process, can appear for some kinds of concrete under some heating circumstances, including exposure to fire. To detect the explosive spalling sensitivity of a concrete mixture, a simple test on spherical specimens is proposed and justified.

The studied mixtures are high performance concrete with or without polypropylene fibres. Two different curing methods are used and the size effect is analysed. The data recorded are the specimen mass, the temperatures on the surface and in the centre, and the pressure. This exploratory work provides the following elements: a critical percentage of polypropylene fibre avoids spalling with little scattering and smaller sphere diameters accentuate the thermo-hydrous process.

1. Introduction

This research investigates the explosive spalling of different types of concrete under heating to a high temperature. Explosive spalling is a brittle failure and occurs suddenly and violently. This is caused by the stresses and strains imposed on the gel structure creating high strain energies within the structure [1]. Much later in the fire exposure period, the ultimate tensile strength of concrete can be reached, involving concrete cracks and the fall off of pieces of material.

The main factors affecting the susceptibility to explosive spalling of different kinds of plain concrete, according to previous studies [2,3], include (1) the curing regime prior to heat testing (this is connected to the volume of free water and moisture gradients), (2) rate of heating, (3) porosity or permeability of the concrete (this is linked to the water cement ratio and/or densified concrete) and (4) presence or not of a notable volume of polypropylene fibres. Other factors were reported: type of aggregate and loading prior to or during heating.

To investigate sensitivity to explosive spalling, the traditional method of testing is to put concrete specimens or structural elements in an oven under fire conditions and to quantify the volume or the depth of loosened material or to realize tests in situ, but these experiments are quite expensive. To simplify the investigation, Hertz and Sorensen [4] proposed a material test for determining whether or not concrete may suffer from explosive spalling at a specified moisture level. The test specimen is a concrete cylinder of 150 mm in diameter and 300 mm in height, placed in a steel mantle. One end of the cylinder is suddenly exposed, through a 100 mm diameter hole, to heat from an oven at 1000 °C, resulting in a temperature of 800 °C within 20 min at the surface of the cylinder. Sullivan, taking into account the fact that the sudden violent failure was a stochastic process [1], investigated a probabilistic method of testing for the assessment of explosive spalling of high strength concrete. The specimens were tests by flexure. Other researchers measured the pore pressure in materials, but its level is not the only cause of the concrete spalling risk [5] and its measurement remains a complex experimental problem.

Cementitious materials may undergo explosive spalling at temperatures as low as 200 °C [6,7]. Other researchers noted a higher temperature: 200–350 °C [4]. In all cases, Gawin et al. [8] note that the heating rate has an effect on this reference temperature value.

This paper investigates a test method to try to establish reliable procedures for evaluating the spalling behaviour of specific concrete materials, taking the effects of thermal stresses into account. The observations made by means of the test method extend knowledge of the nature of explosive spalling. This method can be a step towards establishing a standard test for determining the sensitivity to spalling of concrete mixtures.

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2. Importance of a spherical specimen

Transient thermal modelling with the finite element software “Abaqus” was carried out in order to obtain the temperature distribution inside concrete elements of various shapes:

– a sphere of 0.18 m in diameter,
– a cylinder of 0.18 m in diameter and 0.36 m in height,
– a wall of 0.09 m in thickness.

The boundary conditions were an initial temperature of 20 °C, then a temperature increase of 3 °C/min up to 600 °C on the cylinder and sphere surfaces and only on one face for the wall. For experimental tests on materials used, the following thermal properties were used:

– thermal conductivity evolves linearly from 2.4 W m^{-1} K^{-1} at 20 °C to 1 W m^{-1} K^{-1} at 600 °C,
– a density and a mass specific heat according to Eurocode 2 [9].

An axisymmetric model was used for the sphere and the cylinder and a two-dimensional model for the wall.

Fig. 1 shows the thermal field inside the different samples at 600 °C. The sphere enables a symmetrical temperature distribution to be obtained involving a perfect symmetrical distribution of thermal stresses. On the cylinder, singular zones appear on the corners which can cause an unpredictable cracking. The formation of these cracks can involve a decrease in the vapour pressure inside the sample, avoiding any spalling. A spherical sample avoids this problem and minimises the scattering of results. Fig. 2 shows the thermal gradient following the axis plotted in Fig. 1 at 600 °C. The thermal gradient in the sphere is more than half as steep as in the wall; consequently, the thermal stresses are lower. In the sphere, the increase in moisture inside the material can be more efficient because of the specimen shape, so the hydric phenomena are emphasized. The hydric transfer depends on the concrete mixture properties (porosity, permeability), therefore the spalling sensitivity of concrete mixture could be better estimated. Furthermore, with the sphere, the modelling can be carried out in one dimension (in spherical coordinates), without any singular point.

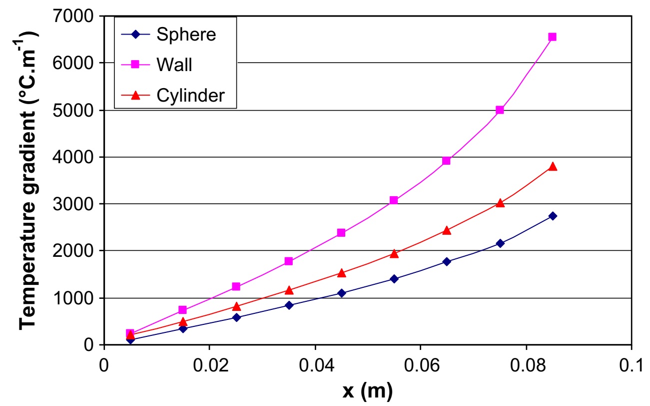

Fig. 2. Thermal gradient, when surface temperature reached 600 °C for the different samples.

To investigate the influence of the heating rate and the sphere diameter, a thermomechanical analysis was carried out. The same parameters as previously delineated were used and an elastic behaviour of concrete was considered. The effect of the transient creep was taken into account, according to Eurocode 2, with a linear decrease of the Young modulus: 35,000 MPa at 20 °C to 5000 MPa at 600 °C. Two sphere diameters were modelled: 0.12 m and 0.24 m. In Fig. 3, the radial tensile stress within the sphere was plotted against time for a heating rate of 3 °C/min. Different positions along a sphere radius are given: 0.5, 1.5, 3.5 and 5.5 cm from the sphere surface. In the sphere of 0.24 m diameter, the radial stress at 5.5 cm from the sphere surface is 2.5 times higher than in the sphere of 0.12 m diameter. This increase is

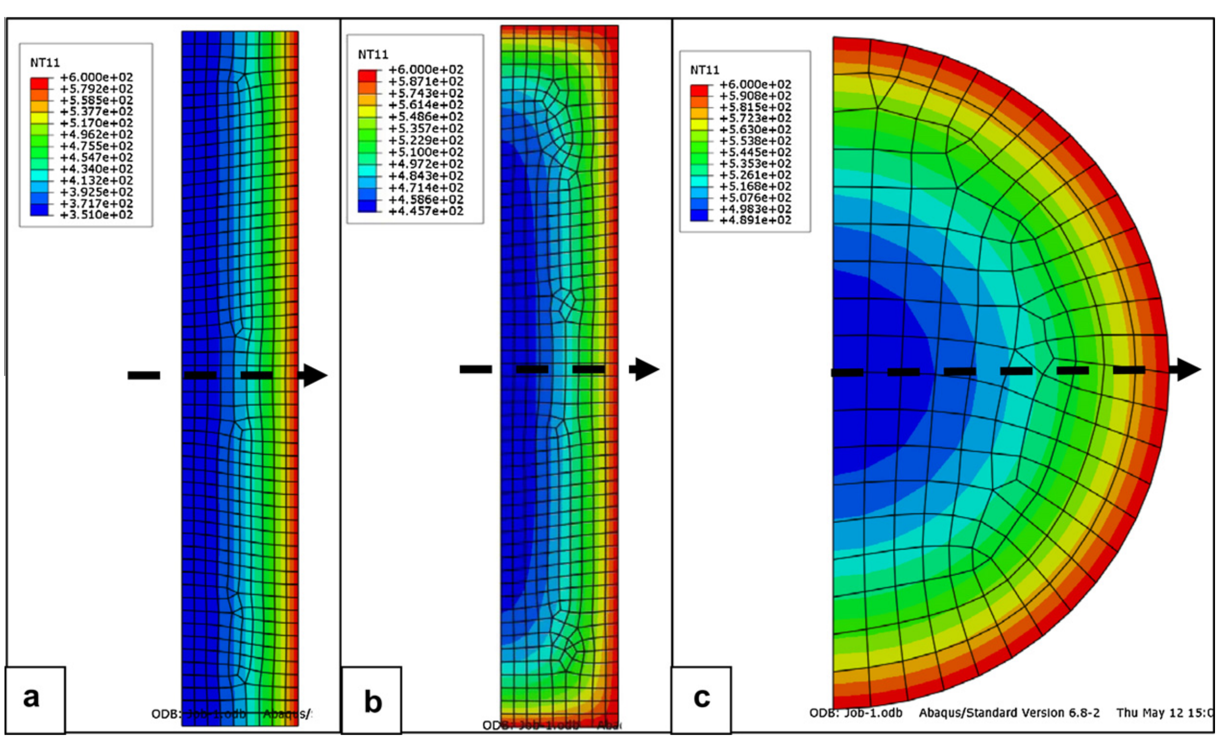

Fig. 1. Thermal field at 600 °C for (a) the wall, (b) the cylinder and (c) the sphere.

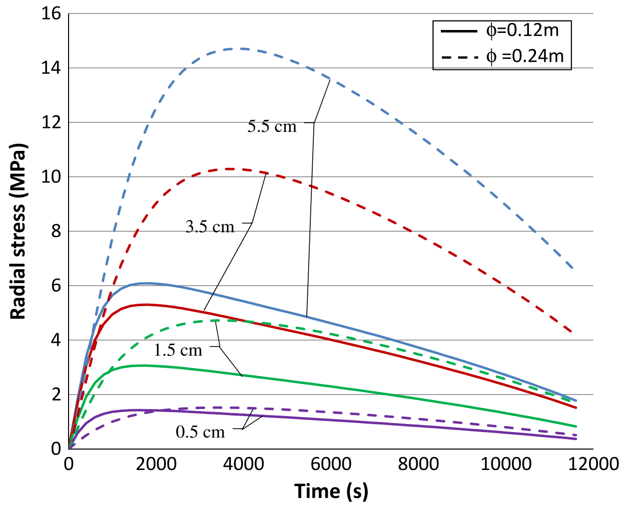

Fig. 3. Radial stress – Heating rate: 3 °C min^{-1} – Positions: 0.5, 1.5, 3.5, 5.5 cm from the sphere surface – Sphere diameters: 0.12 or 0.24 m.

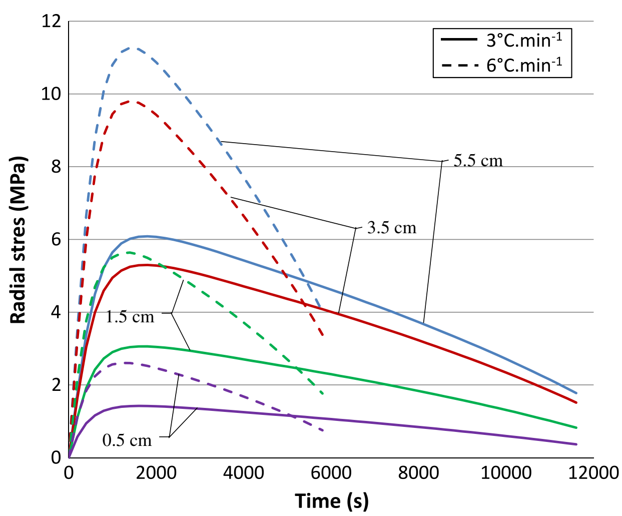

Fig. 4. Radial stress – Heating rates: 3 and 6 °C min^{-1} – Positions: 0.5, 1.5, 3.5, 5.5 cm from the sphere surface – Sphere diameter = 0.12 m.

due to a temperature gradient that is more significant in the sphere of 0.24 m diameter. The possible formation of delaminated cracks is more significant for the spheres of higher diameter. Fig. 4 shows the radial stress for a sphere of 0.12 m diameter heated at 3 or 6 °C/min. For the same reasons as previously mentioned, an increasing of the heating rate causes also a higher tensile radial stress.

3. Test set-up and testing procedure

The spalling tests were carried out on four concrete mixtures (HPC0, HPC0.5, HPC1, and HPC2) with different amounts of fibres (Table 1). The polypropylene fibres used are 15 μm in cross section diameter and 6 mm in length [10]. Their melting temperature is 165 °C. To study the size effect, three sphere diameters were used: 0.12 m, 0.18 m and 0.24 m. After casting and removal, the samples were cured in water or placed into sealed plastic bags, so no additional water gain was possible during hydration. The specimens were tested at least 28 days after casting and the heating rate was 5 °C/min. For each set of parameters at least two specimens were tested.

Table 1
Mixture proportions and some properties of concrete mixtures.

	HPC0	HPC0.5	HPC1	HPC2
CEM I 52.5 (kg m^{-3})	450	450	450	450
Water (kg m^{-3})	160	160	160	160
Sand (kg m^{-3})	840	840	840	840
Gravel 0–10 mm (kg.m^{-3})	960	960	960	960
Silica fume (kg m^{-3})	22	22	22	22
Water reducer (kg.m^{-3})	3.5	7	7	7
Polypropylene fibre (kg.m^{-3})	0	0.5	1	2
Air entrained (%)	2.9	2.4	2.4	2.4
Slump (cm)	16.2	26.3	25.5	24
Water porosity (%)	10.0	–	11.0	10.9
28 day compressive strength (MPa)	88.2	86.7	80.1	86.4

The measurements taken during the heating (Fig. 5) were the temperature in the center of the sphere with one thermocouple, the temperature on the surface with two thermocouples and the mass of the specimen. The pressure at the sphere center was also recorded. The measurement device was composed of a pipe of 2 mm in inner diameter installed during the concreting of the sample, but filled with a bar of 1.5 mm diameter, so that the air section was about 1.37 mm^2. This pipe led from the oven to a pressure sensor. This device carried out a local measurement of the pressure.

4. Results and discussion

Table 2 presents all the tests carried out, indicating the mixture, the curing mode, the total weight loss or the weight loss up to spalling, and the percentage of spalled samples. In these tests, the curing mode (in water or in sealed bag) has no influence on the spalling sensitivity of the spheres. Fig. 6 shows that the curing mode does not affect the total weight loss of specimens because of the low permeability of high performance concretes. For spheres with no spalling, the weight loss when the temperature is uniform (i.e. when the center temperature reaches the surface temperature) is around 7%, but only 4% for the spalling samples during heating.

Fig. 7 presents the percentage of spalled specimens for the different mixtures plotted against the sphere diameter without taking into account the curing mode. For no fibre concrete (HPC0), all of the samples spalled with a 100% result repeatability. For a fibre content of 1 kg m^{-3}, spalling of the spheres is avoided, whatever the diameter. For a fibre content of 0.5 kg m^{-3}, no sphere of 0.12 m in diameter spalled, while 50% of the spheres of 0.24 m in diameter and 100% of the spheres of 0.18 m in diameter spalled. Consequently, for the mixtures containing a very low amount of fibre, the specimens of small diameter are less sensitive to spalling.

Fig. 8 shows that the spalling of the samples occurs around 400 °C heating temperature, whatever the sphere diameter. Moreover, for the same heating rate, at spalling, the weight loss is four times as high for a sphere of 0.12 m in diameter (4%) as for a sphere of 0.24 m in diameter (1%). In Fig. 9, with the same sphere diameter, the weight loss for no-fibre mixtures is slower than for fibre mixtures. This indicates clearly that the polypropylene fibre melting improves the hydric transfers and the vapourization rate of the water from the heart of the specimen to the sphere surface.

Fig. 10 gives the average temperature gradient between the sphere centre and its surface (Eq. (1)) plotted against the heating temperature. The specimen size has no influence and spalling takes place at an average temperature gradient of approximately 8 °C/cm. On the contrary, spalling occurs for different center and surface temperatures depending on the sphere diameter. The surface temperatures for the spheres of 0.12, 0.18, and 0.24 m in diameter are 250 °C, 280 °C and 330 °C, respectively.

$$gradT = \frac{Tsurface - Tcentre}{R} \tag{1}$$

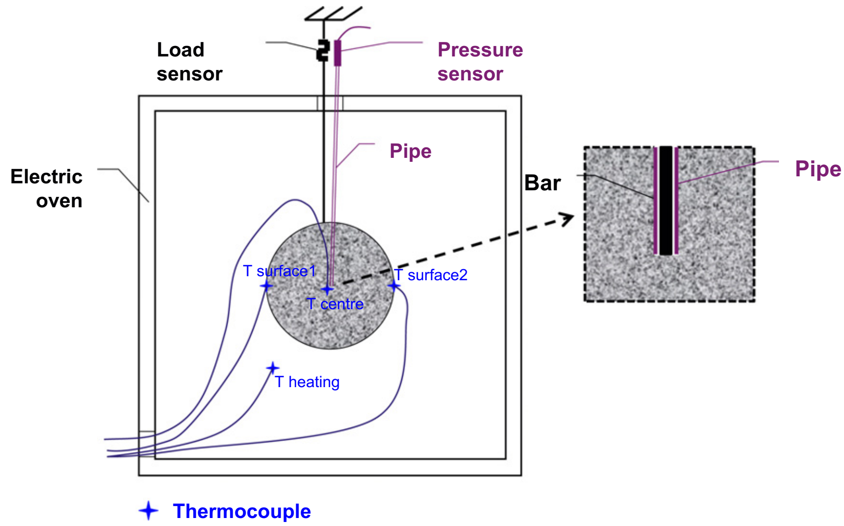

Fig. 5. Test set-up.

Table 2
Results of spalling tests.

Mixture	Diameter (m)	Cure	Weight loss (%)	Percentage of spalled samples (%)
HPC0	0.12	Water	3.9[a]	**100**
		Sealed bag	4[a]	**100**
	0.18	Water	–	**100**
		Sealed bag	2.5[a]	**100**
	0.24	Water	–	**100**
		Sealed bag	1.5[a]	**100**
HPC0.5	0.12	Water	7.2	0
		Sealed bag	5.5	0
	0.18	Water	3.8[a]	**100**
		Sealed bag	3.6[a]	**100**
	0.24	Water		-
		Sealed bag	1.5[a]–6.6	**50**
HPC1	0.12	Water	7.2	0
		Sealed bag	6.7	0
	0.18	Water	–	–
		Sealed bag	–	–
	0.24	Water	–	–
		Sealed bag	–	0
HPC2	0.12	Water	7	0
		Sealed bag	7	0
	0.18	Water	–	0
		Sealed bag	6	0
	0.24	Water	–	0
		Sealed bag	6.7	0

[a] Spalling specimen.

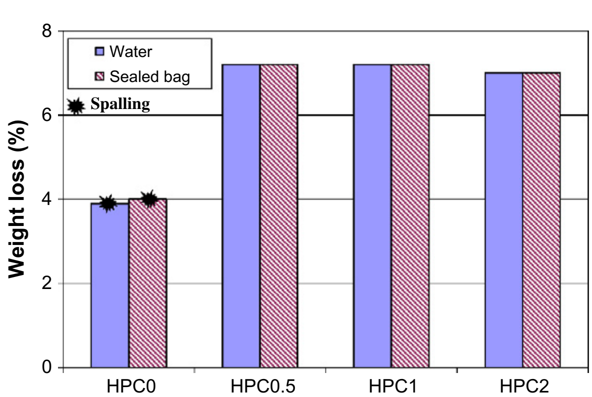

Fig. 6. Weight loss for 0.12 m diameter spheres.

With grad T = average temperature gradient, *Tsurface* = surface temperature, *Tcenter* = center temperature, R = sphere radius.

Fig. 11 demonstrates a slower heating of the sphere centre for the HPC2 mixtures despite the same conductivity of the specimens. In fact, several authors [11,12] have shown that the thermal properties of concrete are principally influenced by the aggregate constitution (the same for all the mixtures) and the water content. The fibre percentage has no impact, because of its low level in the mixtures (below 2 $kg\,m^{-3}$). Nonetheless, the extra diffusion of vapour, allowed by the fibres melting, has an influence on transport phenomena and vapourization rate which can explain this slower heating for the specimens with polypropylene fibres.

For the no-spalling mixture (HPC2), Fig. 11 shows a strong fall in temperature in the sphere center. This drop is caused by water vapourization which is a strongly endothermic reaction. Table 3 compares the maximum pressure measured and the saturating vapour pressure corresponding to the temperature fall in the sphere center. A relatively high scattering of pressure measurements was found, therefore only the maximum peak value was kept.

The vapourization center temperature (T_{vap}) in HPC2 mixtures indicates the pressure peak reached in the sphere center and corresponding to the spalling center temperature of HCP0 mixtures for spheres 0.12 m in diameter. Several authors [10,13,14] have shown that the spalling occurs in a saturated zone (so-called moisture clog) situated around 1–6 cm from the exposed surface. For spheres of 0.12 m in diameter, the moisture clog is close to the center, therefore the maximum pressure peak is close to the center. In fact, the vapourization center temperature of the HPC2 concrete mixtures corresponds to the spalling center temperature of the concrete mixture without fibres (HPC0).

For spheres of 0.24 m in diameter, the moisture clog is closer to surface than to the center. For the HPC0 concrete mixtures, the maximum pressure peak is not in the sphere center and the spalling occurs before the water vapourization in the center. Consequently, the spalling center temperature of the HPC0 mixtures is lower than the vapourization center temperature of the HPC2 mixtures. The increasing of the measurement distance from the moisture clog involves a decrease in the center pressure peak with the increase in sphere diameter. The latter explains the state of the specimens after spalling (Fig. 12). The spheres of 0.12 m are completely disintegrated whereas the spheres of 0.24 m in diameter

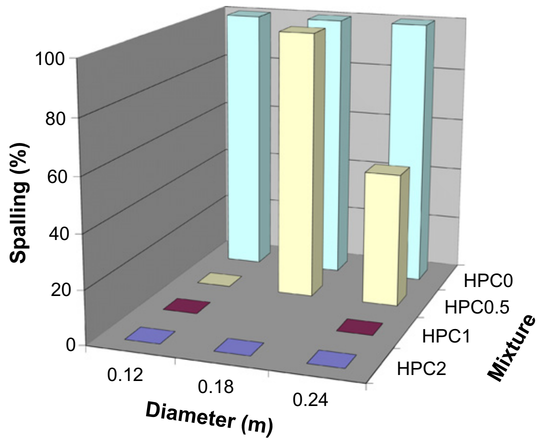

Fig. 7. Percentage of spalled specimens according to sphere diameter and amount of fibre.

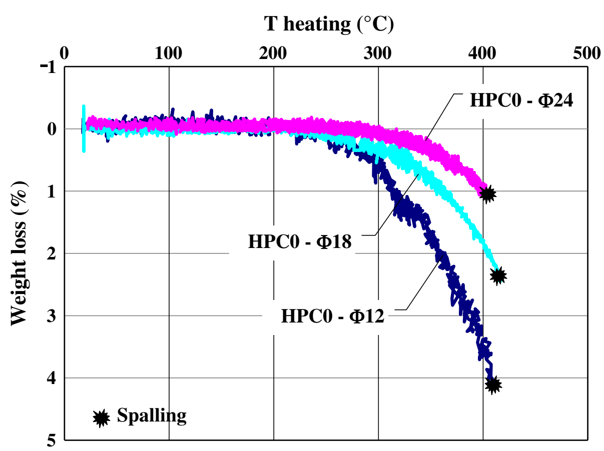

Fig. 8. Weight loss against heating temperature for the HPC0 mixtures.

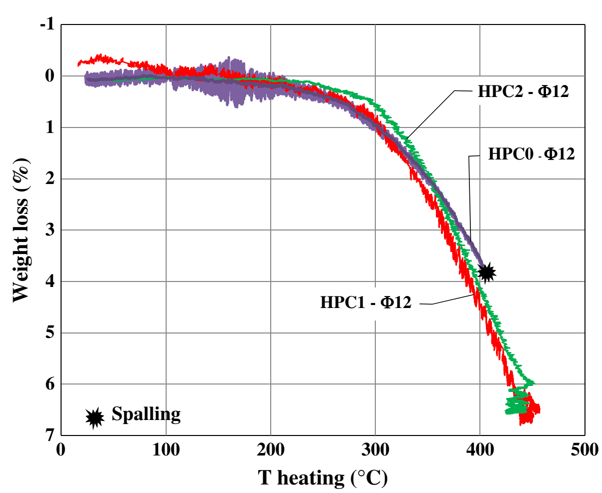

Fig. 9. Weight loss against heating temperature for the 0.12 m sphere diameter.

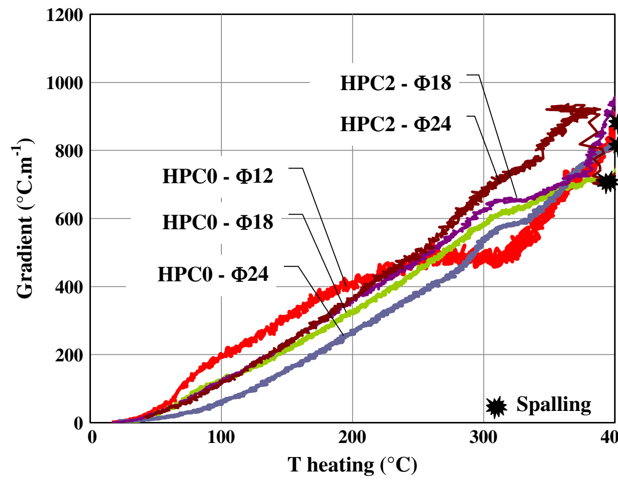

Fig. 10. Temperature gradient between the surface and the center against the heating temperature for the HPC0 and HPC2 concrete mixtures.

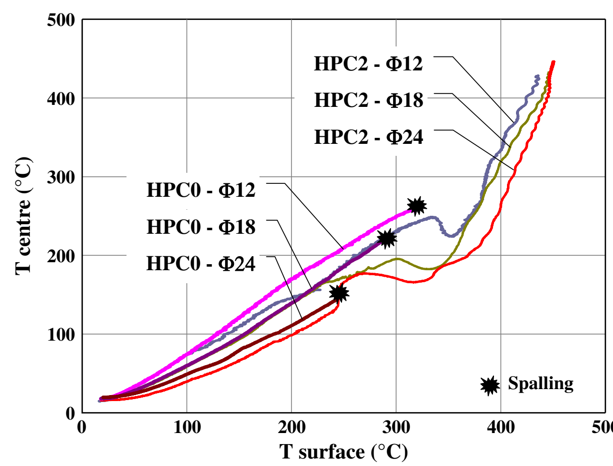

Fig. 11. Center temperature against surface temperature for the HPC0 and HPC2 concrete mixtures.

Table 3
Pressures measured and calculated at the sphere centre.

Sphere diameter (m)		0.12		0.18		0.24	
Mixture		HPC0	HPC2	HPC0	HPC2	HPC0	HPC2
Spalling specimens	Heating temperature (°C)	405	–	410	–	410	–
	Center temperature (°C)	250	–	210	–	150	–
No spalling specimens	Vapourization center temperature (Tvap) (°C)	–	250	–	200	–	180
	Pressure corresponding to Tvap (MPa)		4		1.6		1
	Max measured pressure (MPa)		3.5		2.4		1.4

break into a few pieces and the central part is unchanged. The spheres of 0.18 m in diameter are an intermediate case.

The achieved pore pressure is lower than the tensile strength of the investigated concretes. The spalling is also due to thermo-mechanical stresses induced by the temperature gradient between the surface and the center. Nevertheless, the pore pressure increase in the saturated zone seems to be the governing phenomenon in the spalling of the specimens.

Fig. 12. Samples after spalling for a sphere diameter of (a) 0.12 m, (b) 0.18 m and (c) 0.24 m – No fibre concrete mixtures (HPC0).

5. Conclusions

This experimental method, using specimens of spherical shape, enables the sensitivity to spalling of concrete mixtures to be characterized. The tests are simple to carry out in the laboratory and limit the scattering of results.

With the concrete mixtures tested, a fibre content of 1 kg m^{-3} is sufficient to prevent spalling. The curing mode, in water or in sealed bag, does not seem to influence the risk of spalling for the concretes investigated. The total weight loss and the temperature evolution at the sphere center is similar whatever the curing mode and the amount of polypropylene fibres. The specimen size influences the spalling mechanism. For spheres of 0.12 m in diameter, the saturated zone is close to the center, involving a total and explosive spalling of specimens. For spheres of 0.24 m in diameter, the pressure peak seems to be situated between the center and the surface, involving a spalling of the specimen into several parts.

To complete this first study, other parameters will be tested. The effect of the hydric state has to be investigated with dried specimens. The heating rate can also influence the spalling sensitivity of concrete mixtures. Pressure measurement devices have to be improved and completed in order to obtain pressure values at different radii of the sphere. From the data recorded during a test, numerical modelling can be carried out in order to study the influence of these parameters more precisely.

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