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# ***Experimental discussion on the mechanisms behind the fire spalling of concrete***

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## ***Abstract***

The behaviour of six concretes at high temperature (600 °C) and in particular the risk of fire spalling is studied. Two of the four ordinary concretes are made with calcareous aggregates (including one with polypropylene fibres) and two are made with silico-calcareous aggregates (including one with polypropylene fibres). In complement, tests are also done on two high performance concretes. Tests are performed with two sizes of samples: small samples (300 x 300 x 120 mm<sup>3</sup>) and small slabs (700 x 600 x 150 mm<sup>3</sup>). In addition to the constituents of concrete, other experimental parameters are studied. Different storage conditions (pre-drying at 80 °C, air storing and water storing) are used to highlight the effect of the initial water content. Thanks to different scenarios of heating, the influence of the heating curve and the maximum temperature are studied.

Results obtained enabled to identify parameter that influence highly the risk of fire spalling: initial content of free water and permeability of concrete during the heating. The permeability of concrete can increase during heating due to the melting of the polypropylene fibres or a strong concrete thermal damage. This thermal damage is especially important when heating is violent (ISO 834 or increased hydrocarbon fire), or when concrete is made with silico-calcareous aggregates (in particular flint).

The onset of fire spalling cannot be explained by either the only thermo-mechanical behaviour of concrete, or only by the appearance of high pore gas pressure during heating. Based on the recent theory of the critical zone explaining the occurrence of fire spalling, the formation of a saturated layer of liquid water is consistent with the results obtained.

Keywords: concrete, high temperature, fire, spalling

## ***1 INTRODUCTION***

Channel Tunnel (1996 and 2008), Mont Blanc (1999) and Fr ejus (2005) in France, Storebealt Tunnel (1994) in Denmark, Tauern (1999) in Austria, the Gotthard Tunnel (2001) in Switzerland, all have in common that they suffered a fire which remains in the collective memory for the violent heatings and the significant property damage [1]. All the inspections after fire reported concrete structures badly damaged with in some places (the most severely exposed to fire), parts of concrete detached from the structure. The ejection of concrete during fire is caused by a thermal instability of the

material, a phenomenon commonly called explosion or spalling (depending on the form it takes). In some cases (as in the case of the first fire in the Channel Tunnel), some segments have even experienced a complete ejection of the thickness of concrete [2]. Therefore, we understand the potential risk that such a phenomenon represents for the good behaviour of the structure during and after a fire: by removing the concrete, the load bearing capacity of structures is seriously affected and the thermal insulation function is reduced. In addition, the costs of repair and the costs of stopping the exploitation of the structures damaged by fire spalling of concrete can reach several million Euros.

In laboratories, the risk of fire spalling of concrete has been mainly studied, and some important results have been observed: the high risk of instability of high performance concretes and the positive role of polypropylene fibres on the fire behaviour of concrete were highlighted. Indeed, the addition of a few kilograms of fibres in fresh concrete can reduce or even eliminate the risk of fire spalling of structures [3-5]. Nowadays, taking into account, in the standards, the risks of fire spalling of concrete, and its impact on the stability of a structure during a fire, is mainly based on experimental approaches. Indeed, no predictive calculation of the risk of fire spalling can be correctly achieved. This lack of foresight is due to ignorance, despite numerous experimental and numerical studies, of the physical phenomena that are at the origin of the fire spalling of concrete. Among the hypotheses commonly advanced in the literature, the fire spalling of concrete is based on a thermomechanical process where the matter ejection is caused by high compressive stresses in the first centimeters exposed to fire. This mechanism is closely related to the thermal gradient in the material and the restraining of thermal expansion of the structure [6]. Another possible cause of fire spalling is based on a thermo-hygral process: from complex fluid movement within the concrete, the fire spalling is linked to the generation of high pore fluid pressure compared to the tensile strength of the material [7]. This hypothesis has remained for a long time the most widely accepted by the scientific community. This is particularly the one that is proposed to explain the positive role of polypropylene fibers during a fire: by melting (around 170 °C), fibers create preferential flow paths for fluids within the concrete matrix, thus reducing the fluid pressure. The weak understanding of the physical origins of the fire spalling, which limits predictive calculations and slows the development of technological solutions, has led us to undertake an experimental study whose purpose is to contribute to the study of the fire spalling risk of concrete.

Several sizes of samples were used to evaluate the behaviour of four ordinary concretes (compressive strength of 40 MPa) and two high-performance concretes (compressive strength of 60 MPa). In a previous step, the determination of the evolution of characteristics with temperature such as permeability, porosity, thermal properties and mechanical properties was done in small size samples (at the material level) [8]. This allowed the behaviour of concrete at high temperature to be better understood. These tests are complemented by measurements of pore gas pressure and temperature on intermediate-size samples. Finally, fire tests on small slabs (ISO-834-1 fire and increased hydrocarbon curve HC<sub>inc</sub> fire, [9]) were carried out to study the fire spalling of concrete. The comparison of test results for different sizes allows us to discuss the parameters that appear to be most influential on fire spalling and suggest new paths of investigation.

## 2 Experimental settings

### 2.1 Mixes of studied concretes

Our study is based on six concrete mixes containing the same cement, the same superplasticizer and the same sand. The chosen mixes are assumed to be representative of common civil structures. The first concrete is an ordinary concrete (water / cement ratio = 0.54) with a compressive strength at 28 days of about 40 MPa and it is called B40 in the document. Its composition is given in Table 1. Calcareous aggregates have been used. They are crushed gravel composed with more than 99 % of CaCO<sub>3</sub>.

From the formula of B40, complementary mixes were designed. The concrete called B40SC is made with siliceous-calcareous gravels instead of purely calcareous gravels. The siliceous-calcareous gravels are alluvial semi-crushed gravel. They contain a high amount of flint, a mineral known to strongly modify the properties of concrete at high temperature [10] and to be unstable at a temperature higher than 150 °C. Another important parameter in the study of concrete spalling is the compactness of concrete. Indeed, a high compactness increases the risk of fire spalling. This is particularly the case for high performance concretes (HPC), self-compacting concrete (SCC) and fiber-reinforced ultra-high performance concrete (UHPC) [11-12]. By reducing the W / C ratio of the B40 formula, a concrete reaching a compressive strength of 60 MPa was made and called B60. Finally, it is now widely accepted that the addition of polypropylene fibres to the fresh concrete mix reduces, or eliminates, the risk of fire spalling of the material [3-5]. One aim of this study is to confirm the positive role of polypropylene fibres during fire exposure. The used fibres were monofilament fibres and their melting point is around 170 °C. Two kg/m<sup>3</sup> of polypropylene fibres were added in the B40, B60 and B40SC mixes, creating the concretes named B40F2, B60F2 and B40SCF2. Table 1 presents the different concrete mixes of the study, as well as some of their mechanical properties.

|  | Unity          | B40  | B40F2 | B40SC | B40SCF2 | B60  | B60F2 |
|--|----------------|------|-------|-------|---------|------|-------|
| Cement CEM II/A-LL 42.5 R PM-CP2 (C)                     | kg             | 350  | 350   | 350   | 350     | 550  | 550   |
| 8/12.5 calcareous gravel (Chalonnnes sur Loire)          | kg             | 330  | 330   |       |         | 330  | 330   |
| 12.5/20 calcareous gravel (Chalonnnes sur Loire)         | kg             | 720  | 720   |       |         | 720  | 720   |
| 4/20 siliceous-calcareous gravel (Montereau-Fault-Yonne) | kg             |      |       | 1050  | 1050    |      |       |
| 0/2 siliceous sand (Chazé)                               | kg             | 845  | 845   | 845   | 845     | 845  | 845   |
| Water (W)  | kg             | 188  | 188   | 188   | 188     | 165  | 165   |
| Superplasticizer   | % by mass of C | 1    | 1.4   | 1.5   | 2       | 3    | 2     |
| Polypropylene fibres                                     | kg             |      | 2     |       | 2       |      | 2     |
| W/C ratio  |                | 0.54 | 0.54  | 0.54  | 0.54    | 0.30 | 0.30  |
| 28 days compressive strength                             | MPa            | 37   | 29    | 43    | 46      | 61   | 70    |
| 28 days modulus of elasticity                            | GPa            | 36   | 26    | 31    | 30      | 40   | 41    |
| 28 days tensile strength                                 | MPa            | 2.4  | 2.5   | 3.1   | 3.2     | 3.8  | 4.2   |

Table 1: mixes of the studied concretes

Different types of samples have been casted: prismatic samples for small scale heating test, small slabs for ISO-834-1 and increased hydrocarbon (HC<sub>inc</sub>) fire tests. The dimensions of the samples are given in paragraph 2.2. The samples were stored in two conditions of temperature and humidity, or subjected to thermal treatment prior to testing:

- storage in air ("Air" in Table 2 and 3): 20 °C, 50 % R.H.
- storage in water ("Water" in Table 2 and 3): storage at 20 °C and 50 % R.H. for 28 days, then immersion in water at 20 °C until saturation and date of test
- preheating at 80 °C ("Dry" in Table 3): storage at 20 °C and 50 % R.H. for at least 90 days, then preheating at 80 °C until the weight is stabilized

Table 2 gives the water content of the different samples for the air and water storage conditions. We assume that the (free) water content of the preheated samples is null.

| Storage | Sample                         | B40   | B40F2 | B40SC | B40SCF2 | B60   | B60F2 |
|---------|--------------------------------|-------|-------|-------|---------|-------|-------|
| Air     | small samples                  | 2.6 % | 2.2 % | 2.8 % | 3.0 %   | 3.5 % | 2.9 % |
|         | small slabs - ISO-834-1 fire   | 4.0 % | 2.8 % | 3.9 % | 3.7 %   | 3.4 % | 3.5 % |
|         | slabs - HC <sub>inc</sub> fire | 4.5 % | 4.1 % | 4.4 % |         | 3.3 % | 3.4 % |
| Water   | small samples                  | 5.5 % |       |       |         | 4.6 % |       |
|         | small slabs - ISO-834-1 fire   | 5.3 % | 6.1 % |       |         | 4.2 % |       |
|         | slabs - HC <sub>inc</sub> fire |       | 5.3 % |       |         |       | 4.0 % |

Table 2: water content by weight of the concretes for the different storage conditions

## 2.2 Experimental program

The experimental program is presented in table 3.

Concrete spalling was studied on samples with several sizes and with different heating scenarios. First, tests have been carried out on prismatic samples (300 x 300 x 120 mm<sup>3</sup>), by adopting "laboratory heatings", i.e. less severe than could be a real fire. Then fire tests have been carried out on unrestrained concrete slabs. Different fire curves have been applied. The most severe were: ISO-834-1 and HC<sub>inc</sub>. Except in the case of HC<sub>inc</sub> fire, pore gas pressures were measured into concrete, leading to a better analysis of the thermo-hygral behaviour of concrete under heating. The observation and the characterization of spalling (depth of spalling, ejected volume...) allowed us to analyze the influence of the different parameters (nature of the aggregates, fibre content, concrete compactness, initial water content) on the fire spalling risk.

The Figure 1 shows the different fire curves. They correspond to the evolution of the temperature in concrete at 1 cm from the heated surface.

| Type          | samples (mm)    | heating rate                | Concrete (number of samples - conditions of storage*)  | Measurements during heating |
|---------------|-----------------|-----------------------------|--|-----------------------------|
| small samples | 300 x 300 x 120 | slow 1                      | B40 (2A)   | Temperature and pressure    |
|               |                 | moderate                    | B40 (2A - 2D - 2W)<br>B60 (2A - 2D - 2W)   |                             |
|               |                 | high                        | B40 (2A)<br>B60 (2A)   |                             |
| small slabs   | 700 x 600 x 150 | slow 2                      | B40 (2A)<br>B60 (1A)   | Temperature and pressure    |
|               |                 | ISO 834-1                   | B40 (2A - 2D - 2W)<br>B40F2 (2A)<br>B40SC (2A)<br>B40SCF2 (2A)<br>B60 (2A - 2D - 2W)<br>B60F2 (2A) | Temperature and pressure    |
|               |                 | HC <sub>inc</sub> fire-test | B40 (2A)<br>B40SC (1A)<br>B40F2 (2A - 2D - 2W)<br>B60 (2A - 2D - 2W)<br>B60F2 (2A - 2D - 2W)       | -                           |

\* A = Air - D = Dry - W = Water

Table 3: experimental program

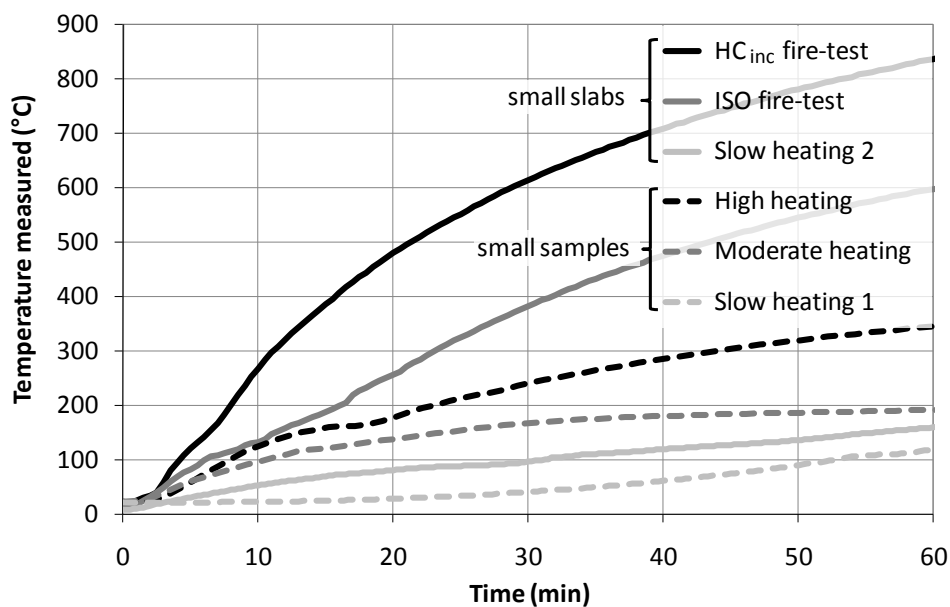


Figure 1: concrete temperature at 10 mm from the heated surface for the different scenario.

## 2.2.1 Tests on small samples

The tests on small samples were carried out on prismatic samples ( $300 \times 300 \times 120 \text{ mm}^3$ ) heated on one side. The experimental device, developed at CSTB [5], allows temperature and pore gas pressure to be measured in a concrete specimen during a transient heating (see Figure 2). Before concrete casting, five metallic tubes (inner diameter of 1.6 mm) are placed in the molds. A sintered metal round plate (diameter 12 mm, thickness 1 mm) is wedged to the extremity of the tube that is placed into concrete. Just prior to tests, type K thermocouples (diameter 1.5 mm) are put in these tubes. It is worth noting that the free volume between the tube and the thermocouple ( $130 \text{ mm}^3$ ) were not filled with any sort of fluid, which can be different than other similar studies [13-14]. The gas pressure in concrete is first transmitted via the metallic tubes to an external "T-junction", and then to an external pressure transducer (piezo-electrical transducer) via plastic tubes filled with silicon oil. By this way, temperature and pore gas pressure are simultaneously measured at the same location. Measurements are done at 2, 10, 20, 30, 40, and 50 mm from the heated surface. The thermal loading is ensured by a ceramic radiant panel (5 kW), covering the entire surface of the specimen and located 3 cm above it. The four sides of the concrete specimen are insulated by porous ceramic blocks. The heat flow can be then considered as unidimensional.

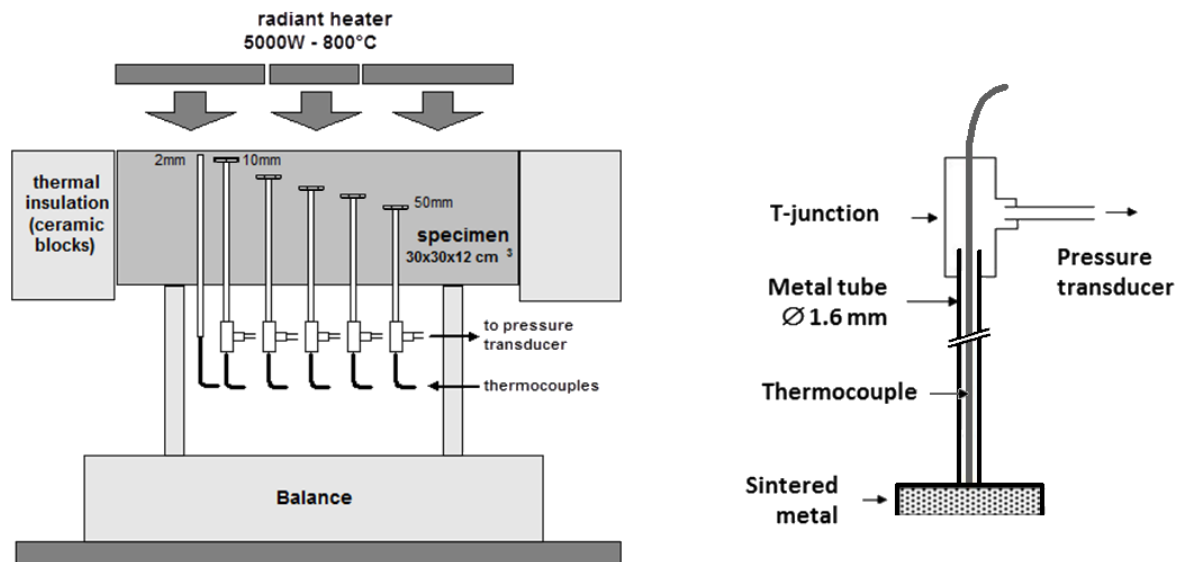


Figure 2: Scheme of the experimental set-up for small-scale tests (left). Right: detail of a metal tube filled with a thermocouple and connected to a "T-junction".

The influence of various parameters (compactness of the concrete, nature of the aggregates, presence of polypropylene fibres) on thermo-hygral transfers within the concrete, and in particular the generation of pore gas pressure, were analyzed in [8].

The effect of the thermal loading is studied for B40 and B60. A reference thermal loading, called "moderate heating", is defined as following: the radiant panel is controlled in such a way that the temperature measured inside the panel reaches 600 °C as fast as possible (cf. Figure 3). The power of the panel is then kept constant in order to maintain this temperature of 600 °C during 5 hours. The sample is finally naturally cooled down. A second heating scenario, called "high heating", consists in

controlling the radiant panel in such a way that its temperature reaches 800 °C as fast as possible (cf. Figure 3). Temperature is then maintained at 800 °C during 5 hours, after which the sample naturally cools down. Other tests are carried out on the B40 with a thermal scenario called "slow heating 1": temperature in the radiant panel gradually increases up to 600 °C, with a heating rate of 10 °C/min. Temperature is then maintained at 600 °C during at least 5 hours, after which the sample naturally cools down. Figure 3 shows the evolution of the temperature that is measured: i) inside the radiant panel, ii) in the sample (B40), at 10 mm from the exposed surface for the different scenarii.

For B40 and B60, the effect of water content before test is studied. Three storage conditions are used as explained in paragraph 2.1: "Dry", "Air" and "Water". The water contents of the different samples are given in table 2. These samples are heated with the moderate heating rate.

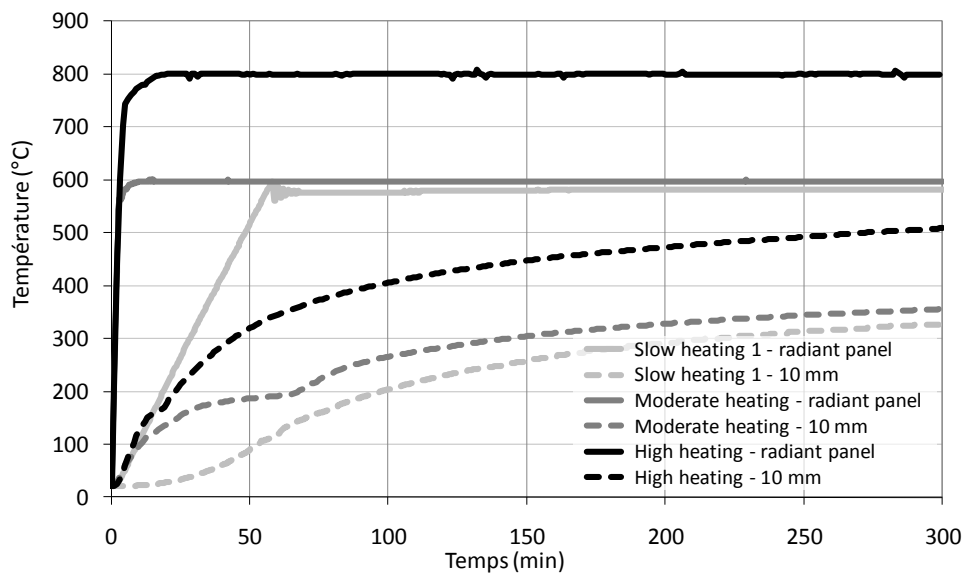


Figure 3: evolution of the temperature measured in the radiant panel and in the concrete (at 10 mm from the exposed surface) for the different thermal scenarii.

## 2.2.2 Fire tests on slabs

Small concrete slabs (700 x 600 x 150 mm<sup>3</sup>) are placed on a horizontal gas-burners furnace (gas used: propane) (see Figure 3). The fire-exposed surface of the slabs is 600 x 420 mm<sup>2</sup>. The slabs are simply laid on two of their sides, the other two sides being not in contact with the furnace. Side faces of the slabs are insulated by rock wool (thickness 50 mm) in order to obtain the most unidimensional heating possible. Slabs are free to expand during the test. It is worth noting that mechanically restraining, or loading, the specimen during a fire test can influence the spalling behaviour. In particular, it has been observed that restraining or loading a slab increases the risk and/or amount of spalling [15]. Finally, even if spalling may be underestimated in our study, the test results we present allow different concrete/testing parameters regarding to the spalling risk to be compared.



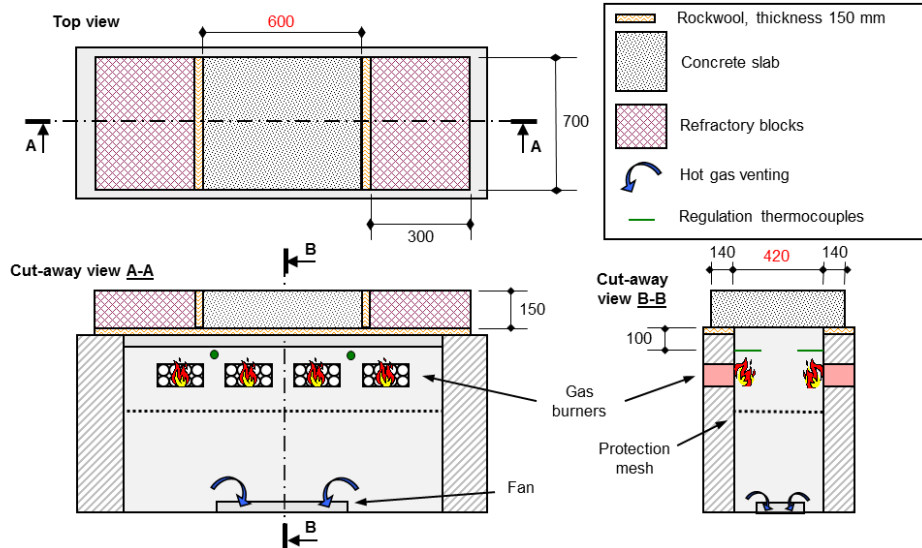


Figure 3: Scheme of the experimental set-up for ISO 834-1 fire tests.

Small slabs are exposed to ISO 834-1 fire during one hour. Probes for measuring pore gas pressure and temperature are implemented in the formwork before casting. The probes are the same as those used in the tests on small samples (see paragraph 2.2.1). Three probes are placed into concrete at 10, 20 and 30 mm from the exposed surface. The thermal scenario for ISO 834-1 fire is defined by the expression:

$$T_{ISO}(t) = 345 \log(8t + 1) + T_0 \quad \text{eq. 1}$$

With  $T_{ISO}$  the air temperature in the furnace (°C),  $T_0$  the initial temperature in the furnace (°C) and  $t$  the time in (min).

For each concrete of the study (B40, B40F2, B40SC, B40SCF2, B60, B60F2), two slabs were exposed to ISO 834-1 fire. For B40 and B60, two extra tests were carried out, consisting in heating the slabs with a slower rate. This slower rate heating called "slow heating 2" correspond to an evolution of temperature in the sample between the slow heating 1 and the moderate heating used for the tests on small samples (see Figure 1).

With the aim of testing the slabs with a more severe heating, fire tests were carried out in a bigger furnace with the  $HC_{inc}$  fire (see Figure 1). Several slabs were grouped for each test. The thermal scenario for the HCM curve is defined by the expression:

$$T_{HC_{inc}}(t) = 1280 (1 - 0.325 e^{-0.167t} - 0.675 e^{-2.5t}) + T_0 \quad \text{eq. 2}$$

With  $T_{HC_{inc}}$  the gas temperature in the furnace (°C),  $T_0$  the initial temperature in the furnace (°C) and  $t$  the time in (min).

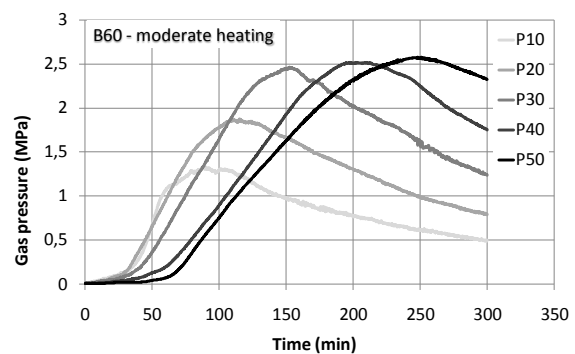
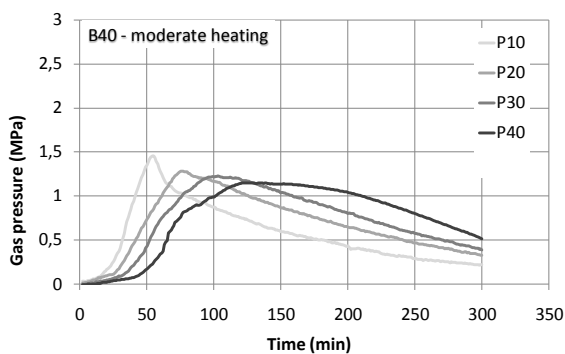
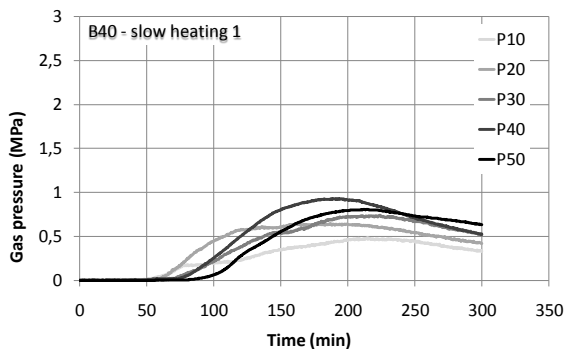
Several concretes were tested: B40, B40SC, B40F2, B60, B60F2. The samples were not equipped with devices. Observations were done during and after heating.

### 3 Results

#### 3.1 Pore gas pressure: effect of thermal loading on small samples

Figure 4 shows the evolution of the measured pore gas pressure in the B40 and B60 (curves corresponding to one of two tests) depending on applied heating temperature curve: slow heating 1 (only for B40), moderate or high heating.

The pressures measured in B40 for the slow heating 1 were lower than in the test carried out with moderate heating (see Figure 4). This observation is attributed to the fact that, under slow heating conditions heat diffusion is slow enough to allow the drying of the material without causing significant pore gas pressures. In the case of high heating, and for both concretes, very low pressures were measured comparing to moderate heating (see Figure 4). We observed after testing a network of cracks on the exposed surface of the specimen as well as large vertical cracks (opening of the order of 1 mm) on the side faces (see Figure 5). Significant traces of moisture were also observed around cracks, showing the creation of preferential flow paths of fluids during high heating. It is important to note that after the tests under relatively moderate and slow heating 1, no cracking of this type were observed on the specimen. Under the effect of rapid heating, the permeability of the sample is greatly increased, thereby facilitating the transport of fluids and then reducing pore gas pressures. The increase in the permeability of the material is attributed to substantial damage of the specimen when it is subjected to rapid heating: higher thermal gradients involve higher compressive stresses in the first centimeters of exposed surface [2] and higher temperatures involve a thermal degradation of the cement paste [12], accompanied by an important thermal mismatch between cement paste and aggregates [16]



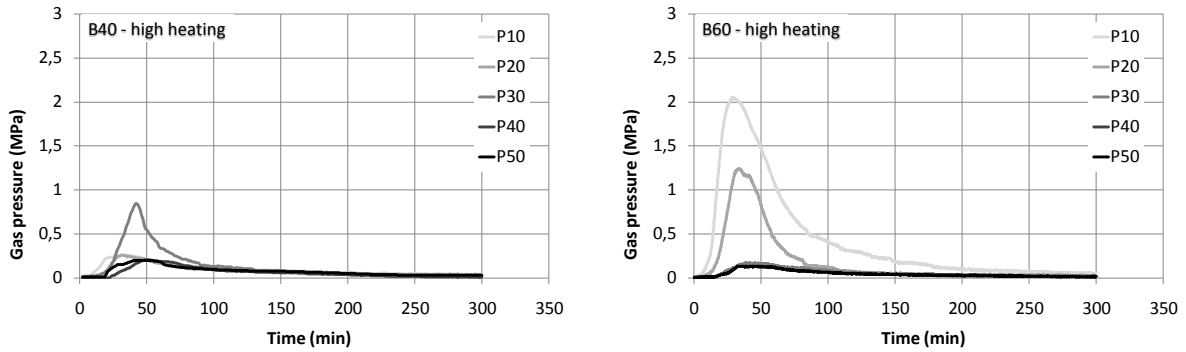


Figure 4: left: Evolution with time of the gas pressure in B40 for different thermal loading Right: Evolution with time of the pore gas pressure in B60 for different thermal loading.

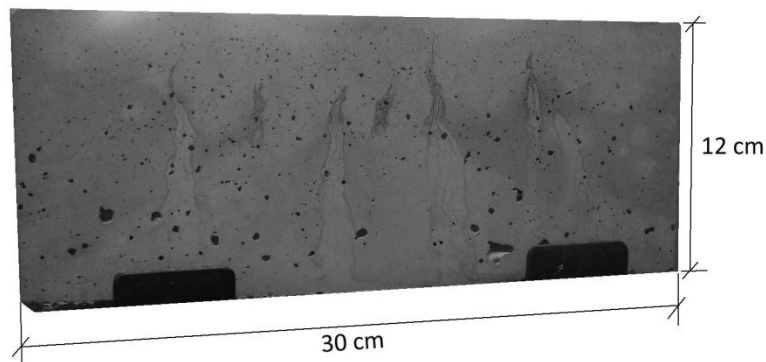


Figure 5: picture of the specimen B40 after high heating - lateral faces with cracks and traces of moisture.

### 3.2 Pore gas pressure: effect of water content on small samples

Figure 6 shows the evolution of the pore gas pressure measured in B40 and B60 under moderate heating, depending on storage conditions of specimens: pre-dried at 80 °C ("Dry"), in air ("Air") or kept in the water ("Water").

For both concretes, the pre-drying at 80 °C greatly reduces the pore gas pressures. The effect is particularly noticeable for the B40 for which the pressures measured on pre-dried test are almost null. This shows that in the case of B40, free water in the material, i.e. the evaporable water at 80 °C, is mainly responsible for the generation of pore gas pressures. In this concrete, water that is released by CSH or Portlandite dehydration does not seem to contribute to the generation of pore gas pressures. In the case of B60, the decrease of pore gas pressure by pre-drying the specimen is less pronounced than in the B40. This can be explained by the lower permeability of the B60, which slows down the movement of water coming from CSH dehydration. Nevertheless, the decrease of pressure remains important. Finally, thanks to continuous measurement of weight loss achieved during testing, we can quantify the amount of free water and bound water released during heating: respectively 4.2 % and 0.6 % for B40, 3.0 % and 0.8 % for B60. The free water content of B40 is higher due to the greater amount of water added in the casting ( $188 \text{ kg.m}^{-3}$  for B40 and  $165 \text{ kg.m}^{-3}$  for B60).

In contrast, the bound water content is greater in the B60, probably because of its greater amount of cement ( $350 \text{ kg}\cdot\text{m}^{-3}$  for B40 and  $550 \text{ kg}\cdot\text{m}^{-3}$  for B60).

For specimens stored in water, it is surprising to note that for both concretes, pore gas pressures are generally lower than those measured in samples stored in air. This phenomenon can be attributed to a possible surface damage of the material due to the water saturation of the pores which are directly exposed to heating. This surface damage may facilitate the transport of fluids and thus may lead to lower gas pressures. This hypothesis is supported by a particular behaviour observed during the tests on water-stored samples: crackles are audible between the tenth and the twentieth minute of the test. Such sounds are not audible in all other tests (air storing and drying at  $80 \text{ }^\circ\text{C}$ ). These sounds certainly correspond to the opening of many micro-cracks close to the exposed surface.

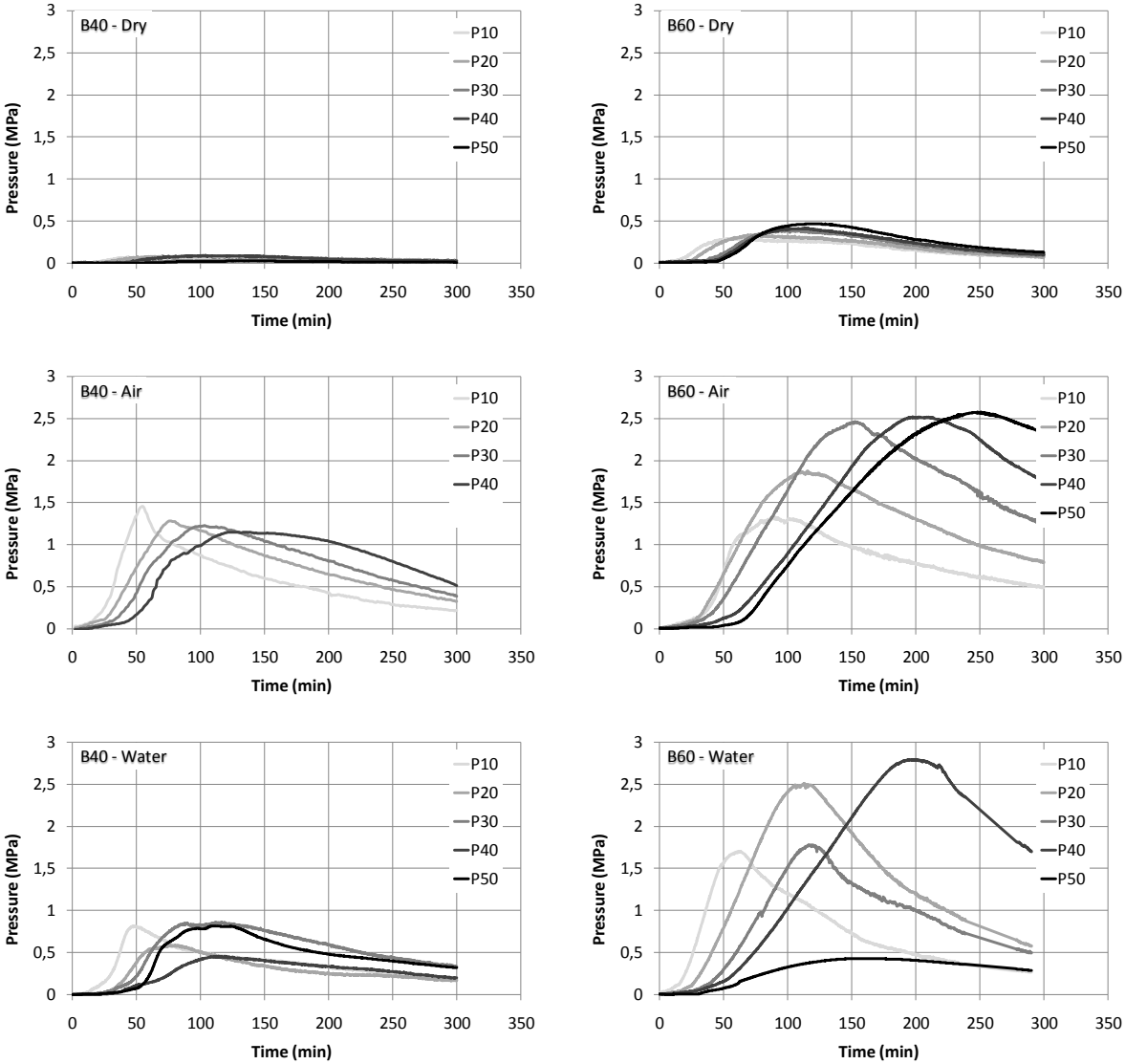


Figure 6: evolution with time of the pore gas pressure in B40 and B60 for different storage conditions (preheated at  $80 \text{ }^\circ\text{C}$ , air, water).

### 3.3 Pore gas pressure: ISO-834-1 fire tests

Figure 7 shows the profile of the maximum gas pressure in the concrete measured during all ISO-834-1 fire tests performed on small slabs. For all tests under ISO-834-1 fire, maximum pressures do not exceed 0.60 MPa in the first three centimeters of the slabs, zone directly affected by the fire spalling of the concrete. These pressures are relatively low compared to the results obtained on tests on small samples (paragraphs 3.1 and 3.2). The huge difference in pressure can be explained by the high heating rate induced in concrete by the ISO-834-1 fire curve. For the same reasons discussed in paragraph 3.1 to explain the influence of thermal loading on the thermo-hygral behaviour of concrete, if the heating is more severe, the concrete is more damaged. Therefore, the permeability of the material is greatly increased, thus facilitating the transport of fluids. This behaviour induces low pore gas pressures. This is confirmed by the great pressure values obtained during the tests on slab with slow heating.

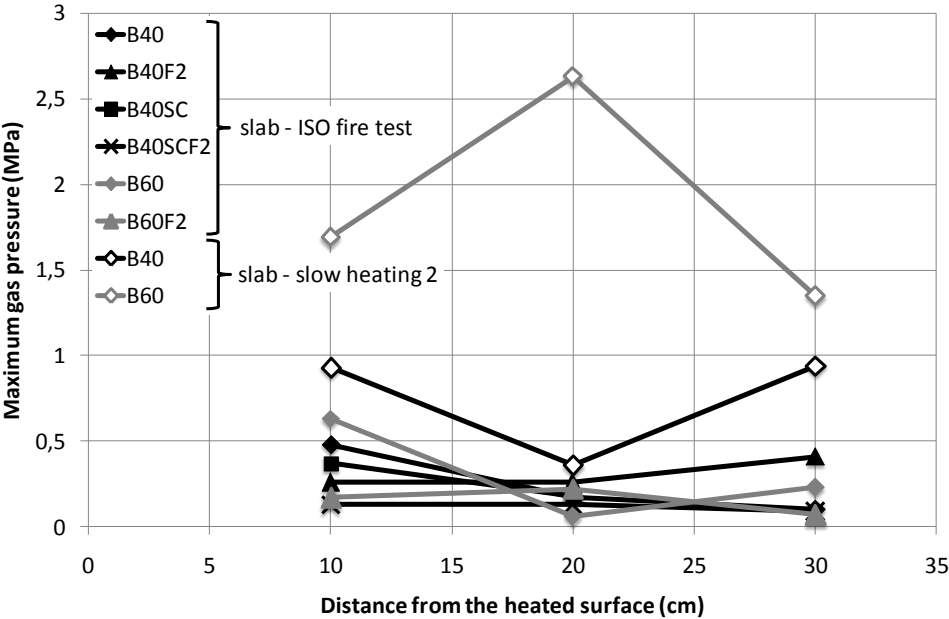


Figure 7: maximum pore gas pressures measured in concrete during ISO-834-1 fire tests.

### 3.4 Concrete spalling under ISO 834-1 fire tests

The analysis of the behaviour of concrete under ISO 834-1 allows characterizing the risk of fire spalling of the material. Two tests have been done for each configuration (see Table 3). In addition to the ISO-834-1 fire curve, B40 and B60 slabs have been exposed to a slow heating rate (slow heating 2 in Table 3 and Figure 1).

Spalling depth is measured a few days after the cooling of the slabs. The thickness of the ejected concrete from the exposed surface is measured along a grid, with a mesh size of 4 cm. The total volume of ejected concrete, the maximum thickness of ejected concrete ( $z_{max}$ ), the average thickness of ejected concrete on the entire surface of the sample ( $z_{mean}^{total}$ ) and the average thickness of ejected concrete on the spalling surface ( $z_{mean}^{spalling}$ ) are calculated. Figure 8 shows a comparison of these different indicators normalized by their maximum value. The maximum value of each indicator is obtained on a slab of B60 exposed to slow heating. Values obtained with the different indicators are consistent. For the rest of the study, we chose to present the results of the average thickness of ejected concrete on the spalling surface ( $z_{mean}^{spalling}$ ). This indicator is assumed to be the most reliable for an engineering calculation of the fire resistance of a concrete structure.

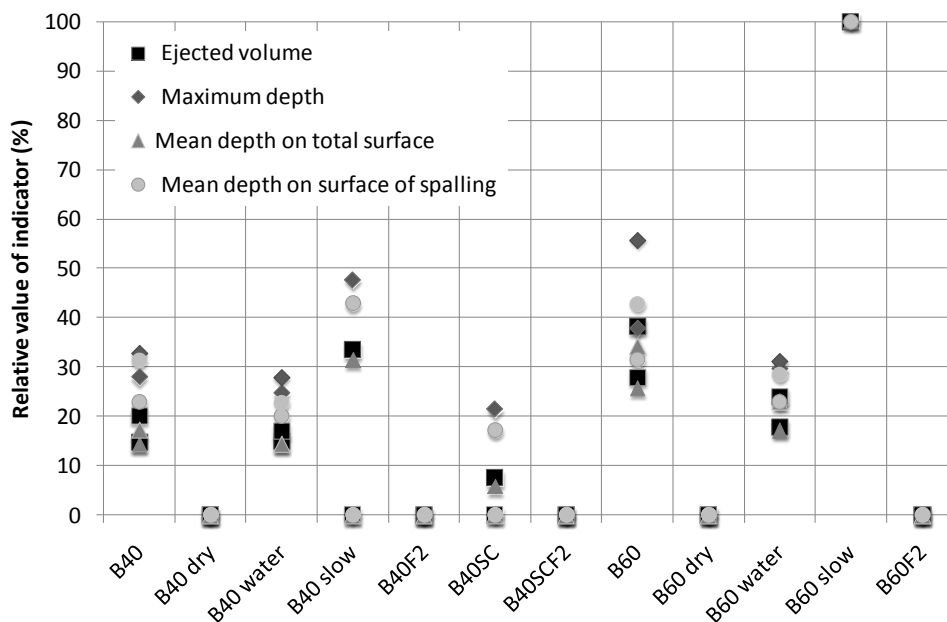


Figure 8: relative values of several indicators of spalling for ISO-834-1 fire tests.

Based on Figure 8, 9, 10 and 11, the main observations of ISO 834-1 fire tests are:

- In the area exposed to thermal loading, the ejected concrete thickness is fairly regular as shown in Figure 9. The potential influence of edges on spalling is limited.
- Little dispersion is observed except on B40 exposed to slow heating 2 ("B40 slow").
- For concrete containing aggregates with flint (B40SC), measured fire spalling is lower than concrete containing only limestone aggregates (B40).
- The efficiency of polypropylene fibres to avoid fire spalling is observed under ISO-834-1 fire. This effectiveness has also been observed for samples stored in water before test

- Spalling of concrete with higher compactness is higher (Figures 9 and 10).
- No spalling was observed on samples dried at 80 °C. This result clearly highlights the role of free water in the fire spalling phenomenon (Figures 10 and 11).
- As for tests on small samples, the effect of water saturation is surprising. Indeed, spalling in the case of saturated slabs is lower than the one of slabs stored in air. This can be explained by a higher amount of damage and higher permeability in sample saturated by water (Figure 11).

The more important information deduced from these tests is that the amount of measured spalling of concrete is closely related to its transfer properties: a temperature-induced increase in the permeability of the material reduces the risk of fire spalling. Permeability of concrete at high temperature can be increased:

- by a thermal damage induced by the mismatch between aggregated and cement paste. This damage is even higher when using unstable and/or quite expandable aggregates (as flint in our study or quartzite [10]),
- by the presence of polypropylene fibres: many assumptions have been proposed intending to explain the mechanisms of polypropylene fibres under fire. One common explanation is that concrete permeability is increased both by fibres melting and by induced micro-cracking [5, 17].
- by a low initial permeability: less compact concretes experiment less spalling.
- by initially saturating pores with water.

Finally, a low free water content of the concrete tends to reduce the risk of fire spalling.

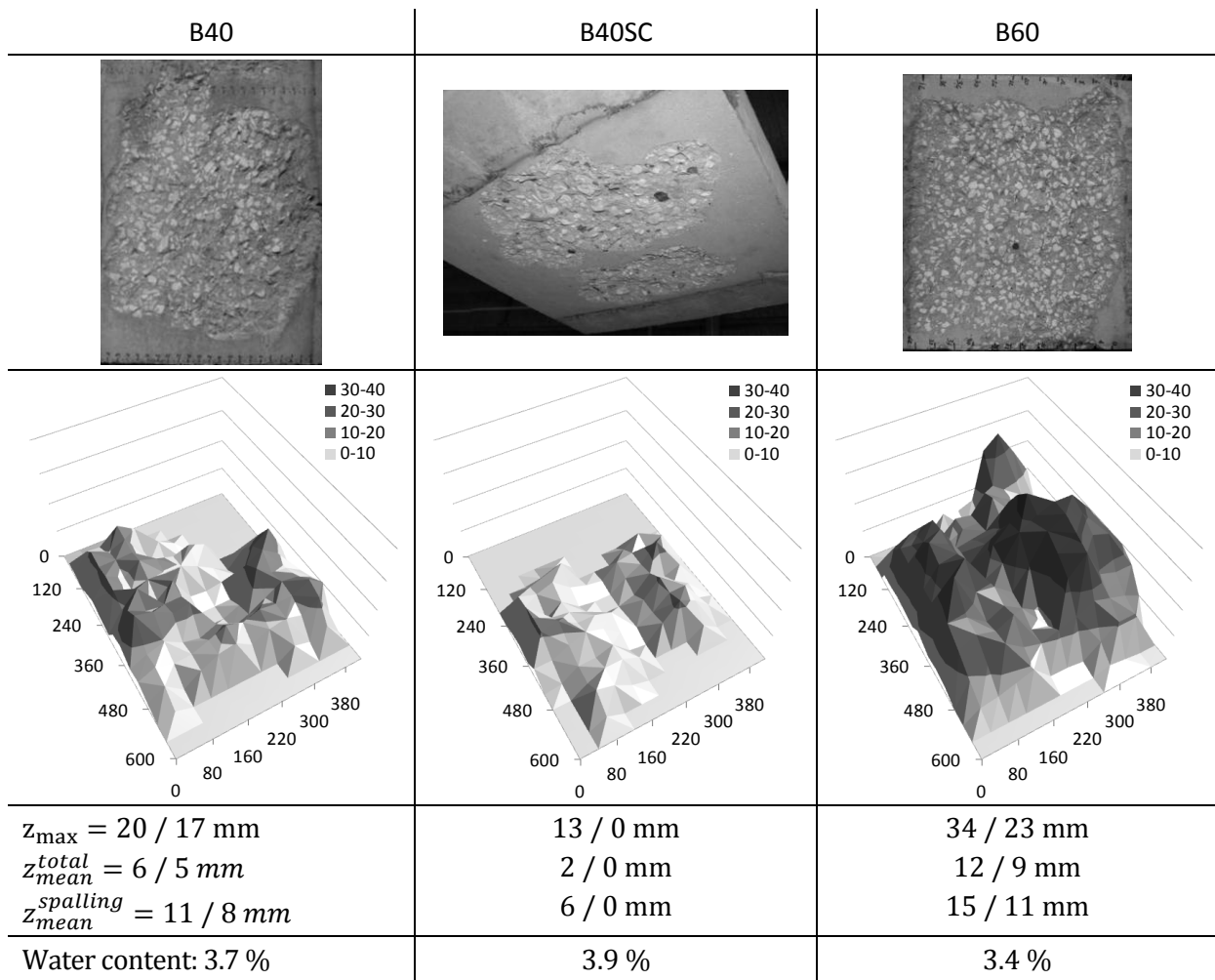


Figure 9: from the top for 3 concretes (B40, B40SC and B60): picture of the exposed surface of concrete slabs after one hour of ISO-834-1 fire test, mapping in mm of measured spalling on exposed faces, measured spalling depths (2 tests per concrete) and initial water content of slabs.



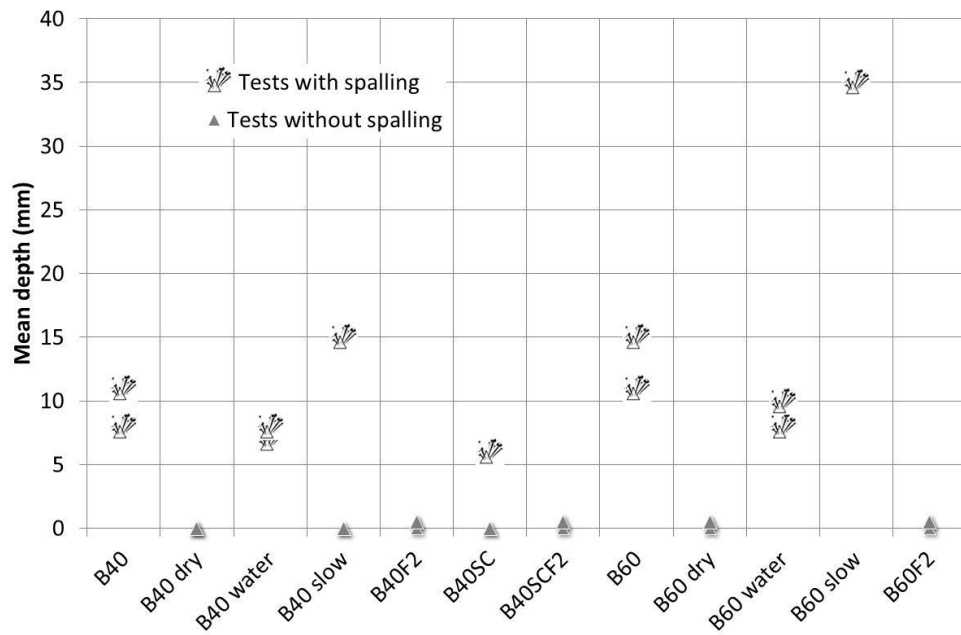


Figure 10: mean depth of spalling for all the configurations.

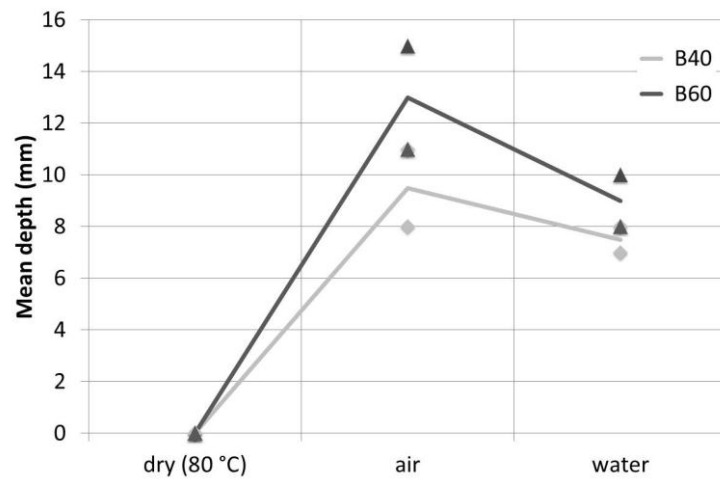


Figure 11: mean depth of spalling depending on the conditions of storage.

### 3.5 Experimental dependence between spalling and pore gas pressure

The fact that the fire spalling of concrete is observed despite relatively low pore gas pressures (see paragraphs 3.3 and 3.4) may indicate that gas pore pressure is not the unique mechanism that should be considered when analyzing the spalling risk of concrete. As a summary of the different heating tests carried out in this study, Figure 12 presents the evolution of the measured spalling depth versus the maximum measured pore gas pressure. The following observations can be made:

- No dependence is clearly observed between the amplitude of gas pressure and the depth of concrete ejected (Figure 12): for the same level of gas pressure, maximum ejected thickness varies from 0 to 30 mm. In parallel, for many tests with a pressure lower than 0.5 MPa, spalling has been observed whereas for other tests with a pressure higher than 0.5 MPa, no spalling has been observed.
- The pressures measured in compact concrete (B60), for which the fire spalling is more pronounced, are in the same range of values than in concrete less damaged by fire spalling (B40), (Figures 7 and 12).
- Under ISO-834-1 fire, the pore gas pressures measured in the concrete does not seem to depend on the nature of the aggregates. On the other hand, fire spalling is itself quite dependent on the nature of the aggregates (paragraph 3.4, Figures 7 and 10).
- The presence of polypropylene fibers does not induce visible reduction of gas pressure under ISO-834-1 fire.

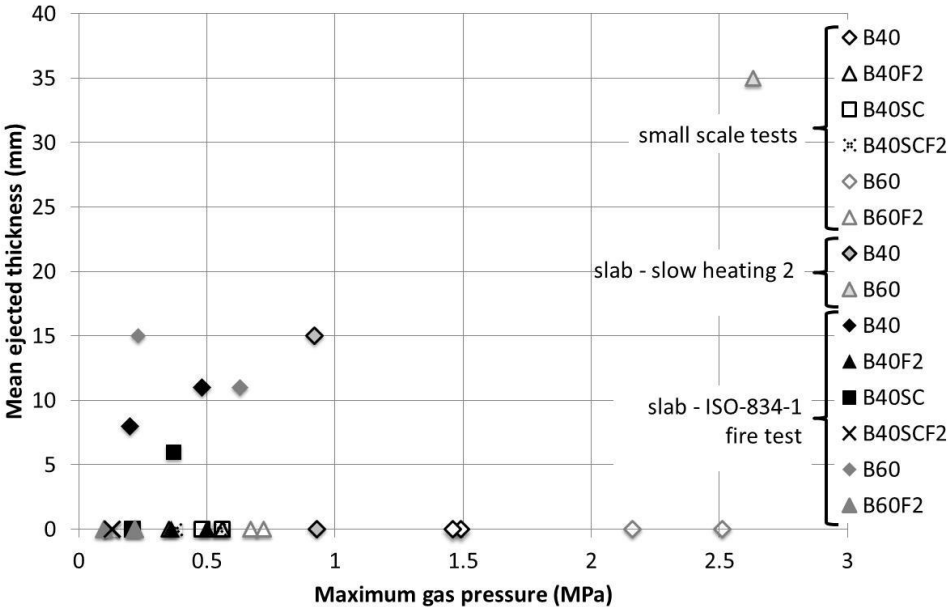


Figure 12: relation between maximum pore gas pressures measured in concrete during different heating tests and mean depth of spalling.

### **3.6 Behaviour of concrete exposed to HC<sub>inc</sub> fire**

Generally, the results from ISO-834-1 and HC<sub>inc</sub> fire tests are quite different. This is the case in our study where around 10 mm of concrete progressively fell from the exposed surface of the slabs during the cooling phase (mostly one day after the test) after one hour of HC<sub>inc</sub> fire test. This loss of matter, commonly called "sloughing off", is non-violent regarding to the fire spalling of concrete [18]. Sloughing off is often explained by a possible re-hydration of cement paste which results in a swelling of the damaged paste. Sloughing off can be more severe for concrete containing calcareous aggregates (as for B40 and B60 in our study): the limestone dehydration product (CaO, quick lime) first reacts with water in ambient air to product slaked lime (Ca(OH)<sub>2</sub>) and then becomes again limestone on contact with the carbon dioxide of the ambient air. These chemical reactions are associated with a swelling of the material, which first results in a cracking, then a fall-down of the thermally-damaged cement matrix. Sloughing off can affect both durability and mechanical properties of a concrete structure after a fire.

Due to this sloughing off, it was not possible to distinguish the part of concrete that just fell during the HC<sub>inc</sub> fire from the part of concrete that fell at soon as the slab cooled down. Therefore, the comparison with the ISO-834-1 fire tests, where no sloughing off was observed, would not be reliable. As a consequence, only visual observations were made during and after the HC<sub>inc</sub> tests. The main findings of these tests are as follows:

- No fire spalling of concrete with polypropylene fibres was observed during heating, even when the samples were stored in water before testing. The positive role of polypropylene fibres on the risk of fire spalling is then also observed under HC<sub>inc</sub> fire. However, it is worth noting that despite the good behaviour during heating, sloughing off was anyway observed for concretes containing polypropylene fibres (Figures 13-a and 13-b). Durability and mechanical properties of concrete containing pp fibres after HC<sub>inc</sub> fire can then be affected.
- No spalling was observed for B40 and B60 slabs that were pre dried at 80 °C before HC<sub>inc</sub> test. As for ISO-834-1 fire, this seems to demonstrate the decisive role of the free water content on the fire spalling risk. Interestingly, no sloughing off at all was observed for pre-dried concretes (Figure 13-c). No clear explanation is given for this observation.

Finally, an interesting observation of HC<sub>inc</sub> fire tests is the formation of a 1 cm-thick particular layer on the exposed side of slabs (Figures 13-b). This layer seems like a mineral "crust" and its thickness is relatively constant regardless of the test configuration. This layer was observed after HC<sub>inc</sub> test in exposed parts of slabs where no concrete fell during the cooling phase (sloughing off). The fire-exposed side of the crust clearly shows a vitrification of the concrete (melting of the siliceous compounds of concrete). Since no sloughing off was observed for pre dried slabs, the exposed side vitrification was quite well observed on these slabs (Figures 13-c).

As a complement to these results, the behaviour of B40 under HC<sub>inc</sub> fire curve has been studied under different testing conditions (bigger slabs, longer fire exposure, mechanical loading of slabs, and thermal protection with various thicknesses). Those results indicate a more important amount of spalling during fire comparing to the ISO-834-1 tests [19, 20].

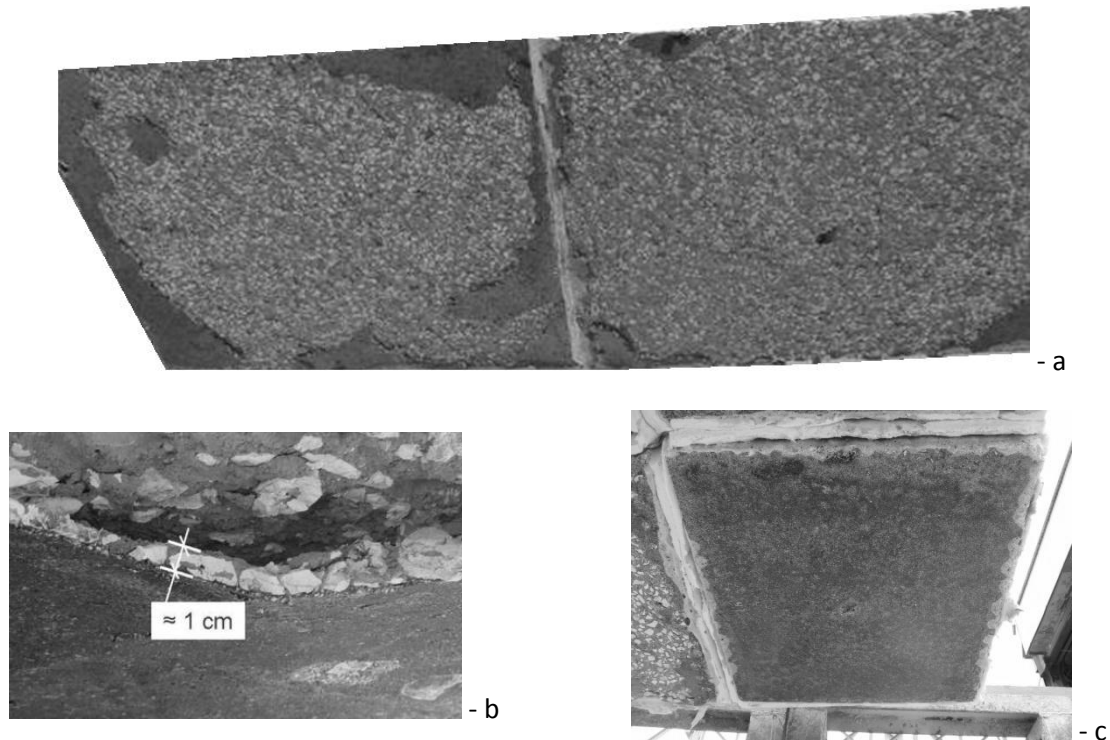


Figure 13: a: picture of the B40F2 slabs after HC<sub>inc</sub> fire test and cooling (one day);  
 b: zoom on the concrete layer being detached during cooling (one day);  
 c: picture of the exposed surface of the pre-dried slab of B60 after fire test and cooling (one day).

#### ***4 Experimental discussion on fire spalling mechanisms***

Figure 14 is a synthesis of the measured pore gas pressures of the study (maximal values are given). Tests for which the fire spalling of concrete has been observed are highlighted. Globally, pressures are slightly scattered (most configurations being tested twice). When concrete spalling has been observed, the measured pore gas pressures were relatively low. In contrast, significant pore gas pressures were measured for some test configurations for which the fire spalling was not observed. In addition, we have clearly demonstrated a lack of correlation between the spalling depth and the level of measured pore gas pressures. For all these reasons, it appears that pore gas pressures does not seem to be the sole cause for fire spalling of concrete. On the other hand, the thermomechanical process does not allow taking into account the influence of the water content on the risk of fire spalling: for instance it is insufficient to explain why spalling was not observed on pre-dried slabs at 80°C, i.e. slabs without free water. In another words, not only the thermal gradient is crucial for explaining fire spalling, but also the water field in the first exposed centimeters of concrete. Finally, the thermomechanical process does not explain the efficiency of polypropylene fibres to avoid fire spalling.

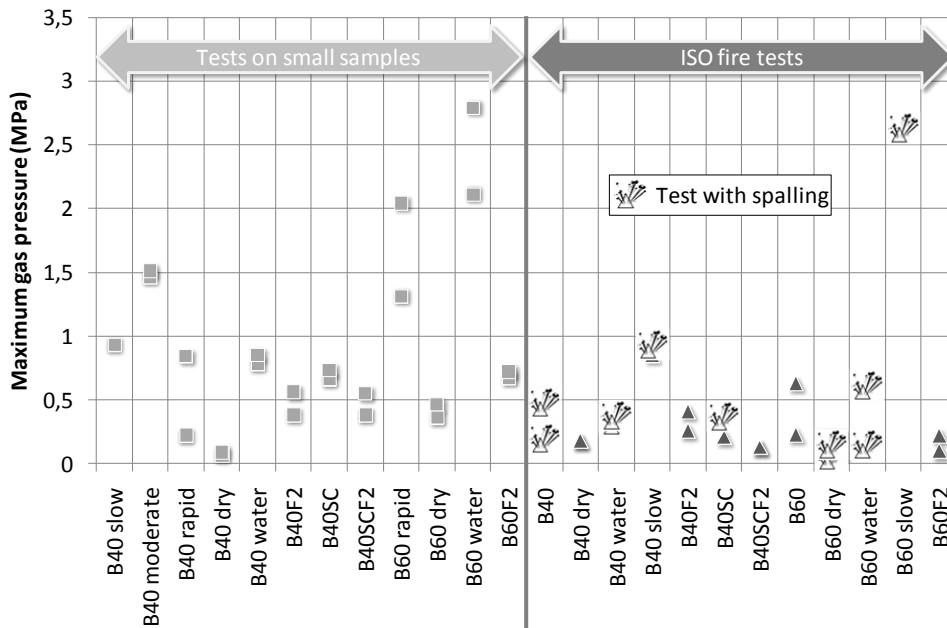


Figure 14: summary of maximum pore gas pressures measured during the various tests of the study (small scale tests and ISO-834-1 fire tests).

The hypothesis formulated by [21] seems to be a relevant basis for the analysis of fire spalling of concrete. According to this author, the fire spalling of a concrete element depends on the existence of a “critical zone”. The critical zone is an area of concrete with a water saturated zone, which would be located a few centimeters from the fire exposed surface of concrete, i.e. in the area commonly affected by the risk of fire spalling. According to [21], the fire spalling of concrete close to this critical zone is not due to the generation of gas vapor pressure (unlike the initial idea of [7]) but could be caused by a sharp deterioration of mechanical properties of concrete saturated with water [21, 22]. According to the “critical zone” hypothesis, no spalling can be observed for configurations where the creation of a water saturated layer is avoided. This could explain why we did not observe spalling for the following test configurations:

- concrete with polypropylene fibres,
- concrete with siliceous calcareous aggregates, and flints in particular (and the thermo-mechanical damage they induce),
- pre-dried concrete (no free water),

For these test configurations, the conditions necessary for the creation of the “critical zone”, i.e. a water saturated layer, are not met. In the case of pre-dried concrete, it seems that the initial water content in the pores is not sufficient to saturate the material, even if water can move during heating. In the case of concrete containing polypropylene fibres and siliceous calcareous aggregates (flint in particular), the sharp increase in permeability avoid the creation of the “critical zone”. These assumptions are schematically shown in Figure 15.

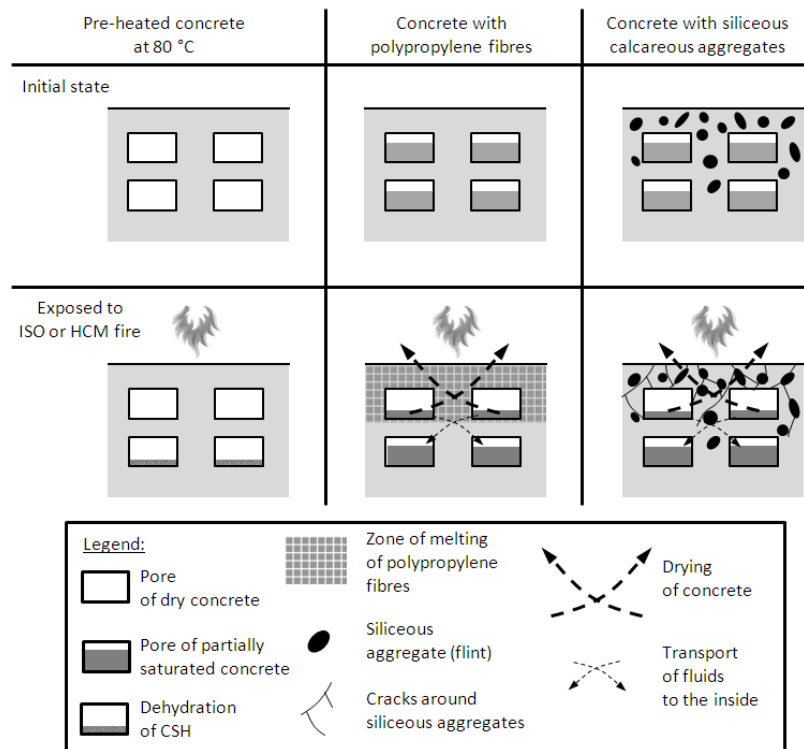


Figure 15: schematic representation of the lack of critical zone in pre-dried concretes at 80 °C, in the concretes containing polypropylene fibres and in concretes containing siliceous calcareous aggregates.

## 5 CONCLUSIONS

The analysis of the tests presented in this study allows a contribution to the physical explanation of the risk of concrete spalling due to fire exposure:

- Fire spalling cannot be only explained through the built-up of too high pore gas pressure. During ISO-834-1 fire tests, spalling was observed on slabs despite low pore gas pressure. At the opposite, during slow heating tests, high pore gas pressures were generated without causing any spalling (tests on small samples). Just considering a thermomechanical process is also insufficient to explain the fire spalling of concrete. It was observed that for a same thermal gradient, the water content and/or the order of gas permeability play a crucial role for fire spalling. In particular, a simple thermomechanical model cannot explain why no spalling was observed on pre dried slabs and in slabs containing polypropylene fibres. If the pore gas pressure does not appear to be the direct cause of fire spalling, the hygral state of concrete has a decisive role. The water content of the concrete during heating and movement of water seem to be able to explain the risk of fire spalling. This is the idea proposed by [21], with the “critical zone” hypothesis, i.e. a water saturated area that could trigger concrete spalling.

Finally, in agreement with the “critical zone” hypothesis, if water can escape quickly from the first exposed centimeters of concrete, the risk of fire spalling is greatly reduced, or in the best cases, no spalling is observed. Efficiency of polypropylene fibers to reduce the risk of concrete fire spalling can be explained by a highly increased permeability of the first centimeters of exposed concrete: melting of fibres allows “draining” water out of the first centimeters of concrete, avoiding by this way the creation of the “critical zone”. More widely, finding technological solutions (except thermal protection layers) that reduce the fire spalling of concrete consists in finding solutions that induce a rapid departure of water from the first centimeters of exposed concrete.

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