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Experimental Investigation on Fire Spalling Behaviour of Concrete: Effect of Biaxial Compressive Loading and Cement Type

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ABSTRACT

Fire spalling of concrete can seriously jeopardise the integrity of the entire structure due to the reduction of the cross-sectional area of the structural elements, which lead to direct exposure of reinforcing bars to flames. In the literature, it is shown that the occurrence of fire spalling is influenced by various parameters, the external compressive load being one of them, which role is not well known in detail. Within this context, an extensive experimental campaign has been conducted to investigate the interaction between pore pressure and thermo-mechanical stresses in triggering spalling. Mid-size concrete slabs (800 x 800 x 100 mm³) were exposed to ISO 834-1 fire curve at the bottom face, while an external membrane biaxial compressive stress was applied before heating parallel to the heated face of the slab. The experimental results have clearly shown that the loaded specimens are more prone to spalling than unloaded specimens, with increasing amounts of spalling for higher values of applied compressive stress. Spalling behaviour of B40-II (12% of calcareous filler and 3% of slag) and B40-III (43% of slag) appear similar.

KEYWORD: standard fire, biaxial loading, spalling, pore pressure, cracking, displacement, cement

INTRODUCTION

Since the safety of people in case of unexpected fire is one of the today's major issues in the design of construction, it is essential to have exhaustive knowledge about the fire spalling behaviour of concrete to guarantee good fire stability of the structural elements. Spalling is a sudden detachment of concrete layers or pieces from the surface of structural element when it is exposed to high and rapid rising temperatures such as those experienced in fires, which could lead to a significant reduction of the section geometry and may lead to the direct exposure of the reinforcing bars to flames (i.e. decay of mechanical properties of steel), with a significant reduction of the load bearing capacity [1-2]. Although numerous experimental and numerical studies have been conducted in order to gain a better understanding of the fundamental physics behind the fire spalling behaviour of concrete, its mechanism is still not yet well understood. Commonly, two physical mechanisms are often associated with this phenomenon, namely: the build-up of pore pressure (the thermo-hydral process [3-4]) and development of thermal stresses (thermo-mechanical process [5-6]) in concrete when exposed to rapid increase in temperature.

According to pioneer investigations in the literature, it has been shown that various factors, such as material factors (moisture content, permeability, aggregate type), geometry factors (section size and shape), and external factors (heating rate and level, applied mechanical loading) influence the

fire spalling behaviour of concrete in different ways [1,7].

Tests carried out by Jansson and Boström 2013 [8], Boström et al. 2007 [9], and Kodur et al. 2007 [10] concluded that the mechanically loaded specimens during heating are more susceptible to spalling than unloaded members. Carré et al. 2013 [11] stated that no spalling was observed in the samples uniaxially loaded at 0, 5 and 10 MPa, while a significant amount of spalling was measured in the 2 samples loaded at 15 MPa.

Despite that, some investigations [8-11] deal with the effect of loading on the fire spalling behaviour of concrete, its role is still not yet well understood. In order to deeper investigate the role of membrane biaxial compressive loading and their levels on the fire spalling of concrete, an extensive experimental campaign has been conducted by means of the test setup developed at the Politecnico di Milano (Italy) [2]. The experimental campaign has been carried out within a research collaboration with the Centre Scientifique et Technique du Bâtiment (CSTB), France and the Université de Pau et des Pays de l'Adour, SIAME, France. The paper describes the test methodology, results including fire spalling depths, temperature, pore pressure, cracking, and displacement.

EXPERIMENTAL INVESTIGATION

Experimental program

The influence of biaxial compressive loading on spalling has been investigated on 15 mid-size concrete slabs (800 x 800 x 100 mm³). The experimental program is given in table 1.

Two ordinary concretes, B40-II and B40-III, made respectively with CEM II and CEM III were tested. Two series of tests have been carried out in 2015 and 2016. Slabs were subjected to ISO 834-1 fire curve at different levels of biaxial compressive loading up to 10 MPa.

Table 1: Summary of the experimental program for the fire spalling test under biaxial compressive loading (Note: / = No test)

Applied stress [MPa]		0	0.5	0.75	1.5	3	5	10
2015	B40-II	1	1	/	/	/	1	1
	B40-III	/	1	/	/	/	1	1
2016	B40-II	1	/	1	1	1	/	/
	B40-III	1	/	1	1	1	/	/

Table 2: Concrete mixture proportions and mechanical properties of hardened concrete

B40 Concrete	Unity	B40-II	B40-III
Cement (C)	kg/m ³		350
Calcareous 8/12.5 gravel	kg/m ³		330
Calcareous 12.5/20 gravel	kg/m ³		720
0/2 siliceous sand	kg/m ³		845
Water (W)	l/m ³		189
Water / cement ratio (w/c)			0.54
fc at 28/90 days (2015)	MPa	43.5 (46.8 – 40.2) / 50.7 (51.0 – 50.4)	41.9 (43.0 – 40.8) / 50.3 (50.4 – 50.1)
fc at 28/90 days (2016)	MPa	39.8 (40.1 – 39.4) / 49.5 (51.5 – 47.9)	40.9 (43.4 – 38.5) / 53.5 (55.3 – 52.1)
ft at 90 days (2015)	MPa	5.1 (5.5 – 4.8)	4.6 (4.7 – 4.5)

Materials and mix design

Concrete mixture proportions and mechanical properties of the two concretes are given in Table 2. The same mix design was used for both concretes. The only difference is the cement type. The CEM II (CEM II/A-LL 42.5 R CE CP2 NF) cement contains 85% of clinker, 12% of calcareous fillers and 3% of slag. The CEM III (CEM III/A 42.5 N CE CP1 NF) cement contains 54% of clinker and 43% of slag, and 3% of limestone. The compressive (f_c) and splitting tensile (f_t) strengths were measured on cylinders (\varnothing 160 mm x h 320 mm).

Apparatus and test procedures

Sample geometry and instrumentation and equipment are presented in Figure 1. There have been described more extensively by Lo Monte and Felicetti 2017 [2].

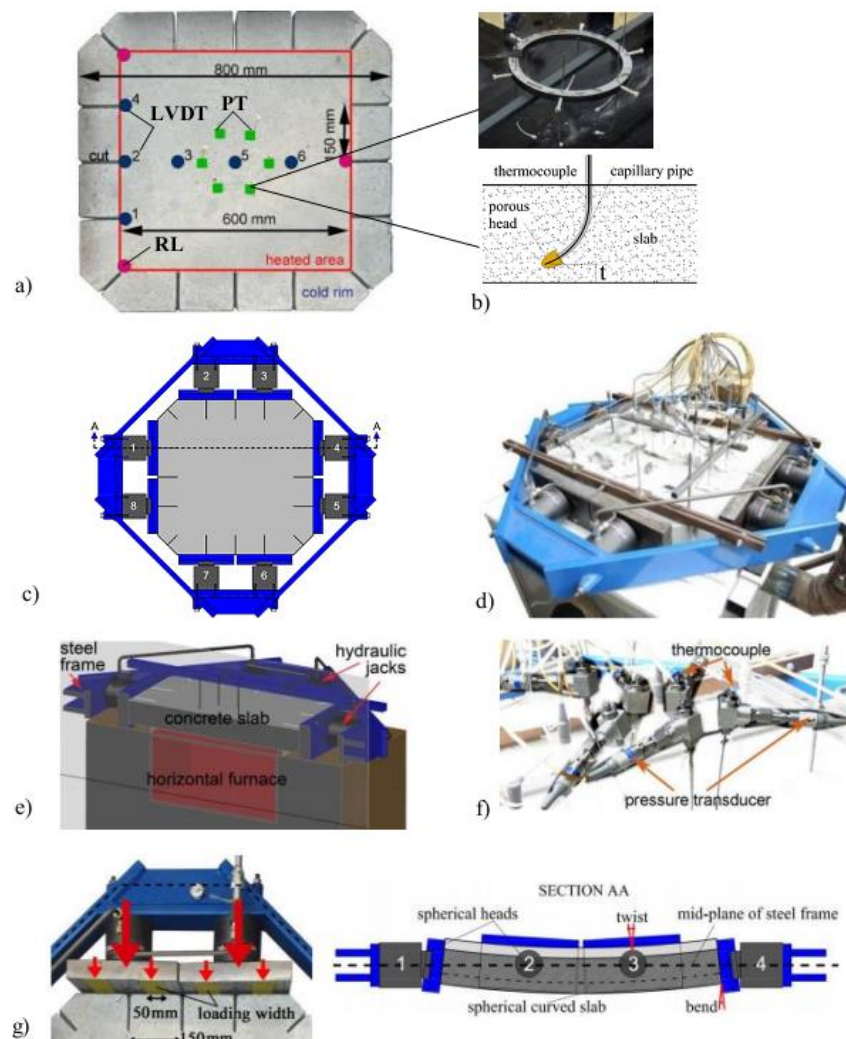


Figure 1 (a-b) Concrete slab and measurement points of pressure-temperature and displacements, (c-d) concrete slab within the loading system, (e) section of the specimen positioned on the horizontal furnace, (f) pressure-temperature sensors, and (g) concrete slab within the loading system and section AA (see Fig. 1c) in deformed configuration. (PT= pressure-temperature sensors, LVDT = displacement transducers measuring the deflection, RL= 3 rigid legs of the LVDT-holding frame).

The concrete slabs were placed on top of the horizontal furnace, within a loading system consisting of a welded steel restraining frame fitted with hydraulic jacks. The thrust is exerted via spherical heads and thick steel plates working as load dividers (see Figure 1g). The spherical heads allow following

the rotation of the slab edges induced by thermal curvature. In order to limit the temperature in the hydraulic jacks, only the central part of the slab (600 x 600 mm²) was heated to keep the external concrete rim colder (100 mm from each side). To reduce the confining effect exerted by this colder rim, 16 radial cuts (around 5 mm thick) were performed, aimed at breaking its mechanical continuity (see Figure 1 a). The furnace was heated by a propane burner with a control system able to strictly follow the ISO 834-1 fire curve. A constant biaxial membrane compressive load was applied before heating (parallel to the heated face of the slab, 300 mm wide and 100 mm thickness on each side) with 8 hydraulic jacks (2 per side, see Figure 1 c-d) and then the load was kept constant throughout the fire test. Seven different levels of biaxial compressive stress (0, 0.5, 0.75, 1.5, 3, 5 and 10 MPa) have been investigated on both concretes (B40-II and B40-III). During the fire tests, temperature, pore pressure (through the thickness, see Figure 1b), and the out of plane displacements (at the cold face) of the slabs were monitored. In order to compare the amount of spalling at different levels of biaxial compressive loading, tests were stopped after 30 minutes. However, collapse of the slab occurred for 3 slabs loaded at 5 and 10 MPa before 30 minutes. Tests were then stopped. Spalling depths fields in the exposed section were measured for all the slabs after the tests. Mean spalling depths were determined.

EXPERIMENTAL RESULTS

Observations and spalling depths

Figures 2 and 3 present the pictures of the exposed face of B40-II and B40-III concrete slabs exposed to ISO 834-1 fire curve at the 7 different levels of biaxial compressive loading. In order to minimise the cold rim effect on the spalling depth, the mean spalling depths were calculated in the area of 500 x 500 mm². Mean spalling depths versus the biaxial applied loads are represented in Figure 4.

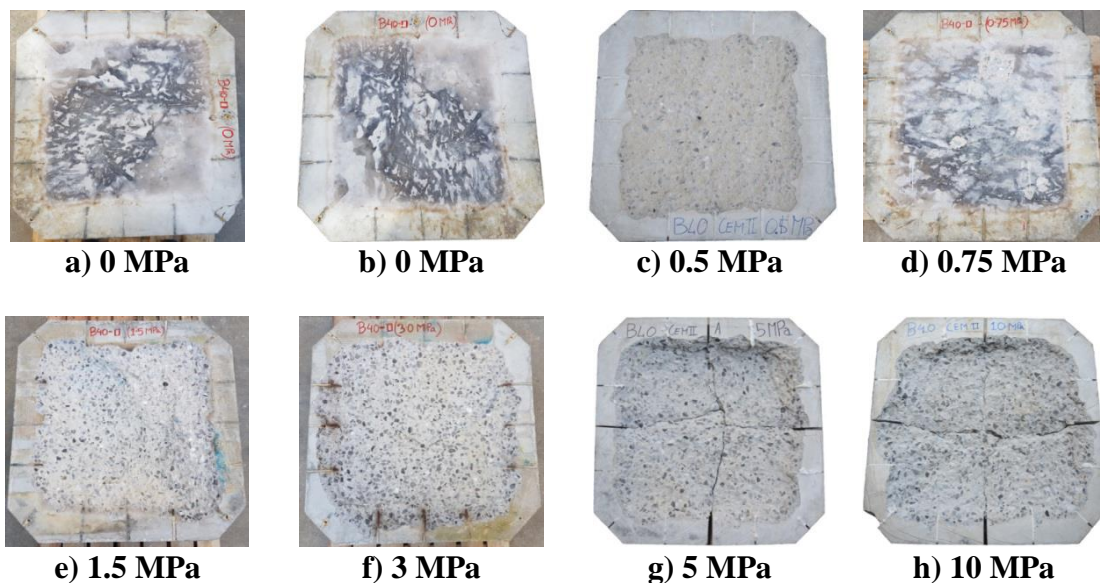


Figure 2 Exposed faces of the B40-II slabs after ISO 834-1 fire curve.

The experimental results show that the loaded specimens are more prone to spalling than unloaded specimens. Similar behaviour has been observed in the uniaxially loaded concrete cubes during ISO 834-1 fire curve tests [12]. Spalling was accompanied by a loud “popping” sound as concrete fragments were released layer-by-layer from the concrete surface. The time of the first spall was in the range from 6 to 10 minutes of fire and the spalling events increased with the increased applied compressive stress. A similar observation was observed in [12].

In Figure 4, the effect of compressive loading on the spalling behaviour of concrete can be defined in three stages: effect of limited load (0 to 0.75 MPa), moderate load (1.5 to 5 MPa), and higher load (5 to 10 MPa).

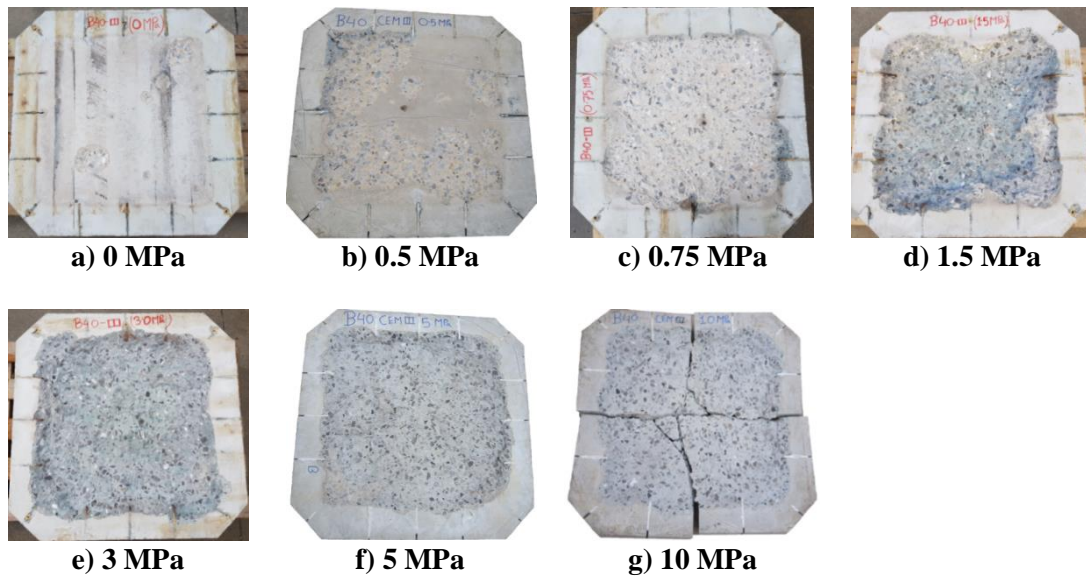


Figure 3 Exposed faces of the B40-III slabs after ISO 834-1 fire curve.

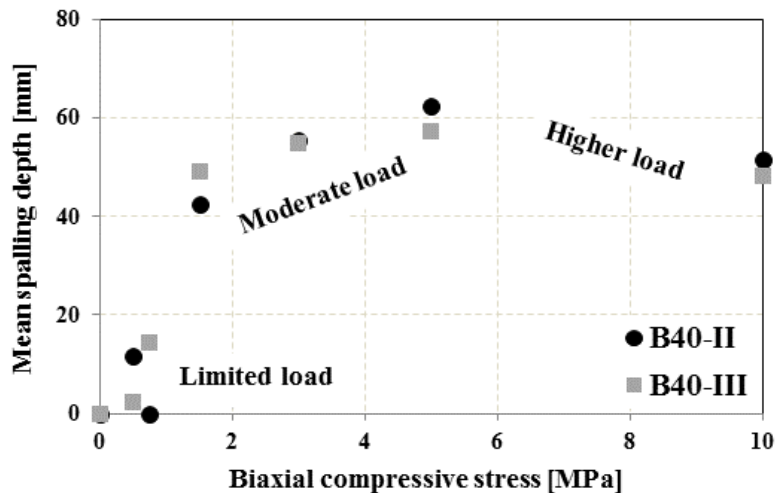


Figure 4 Mean spalling depth as a function of applied compressive stress.

No spalling was observed in unloaded tests of both concretes and on B40-II loaded at 0.75 MPa. Very limited spalling was observed on B40-III at 0.5 MPa. On another hand, a uniform erosion extended to the whole heated area has been observed at 0.5 MPa for B40-II and 0.75 MPa for B40-III. The determined average spalling depths for these 2 last tests were respectively 12 mm and 14 mm.

The observed spalling depth decrease on B40-II from 0.5 to 0.75 MPa may appear inconsistent with the other tests results. The exact reason for this behaviour is not known.

A large increase of spalling depths is observed when the applied load increased from 0.75 MPa (higher than 40 mm) to 1.5, 3 and 5 MPa (close to 60 mm over the 100 mm slab thickness).

As can be seen in Figure 4, the mean spalling depth of both concretes decreased from 5 to 10 MPa. However, the collapse of the 3 slabs occurred when the bending bearing capacity of the slabs was reached: 29 min for B40-II at 5 MPa, 25 min for B40-II at 10 MPa and 24 min for B40-III at 10 MPa, see Figure 2 g, h and 3 g. The spalling depth at 10 MPa could then be equal or higher than at 5 MPa if the collapse had not occurred and the tests could have continued for the same fire duration (30 min).

From these results, spalling behaviour of B40-II and B40-III appear similar. This result is opposite

than the one we observed by carrying out spalling test on the same concrete under uniaxial load. This difference have been discussed by Miah et al. 2016 [13].

Temperature curves versus time

Temperature curves at different depths are plotted in Figure 5.

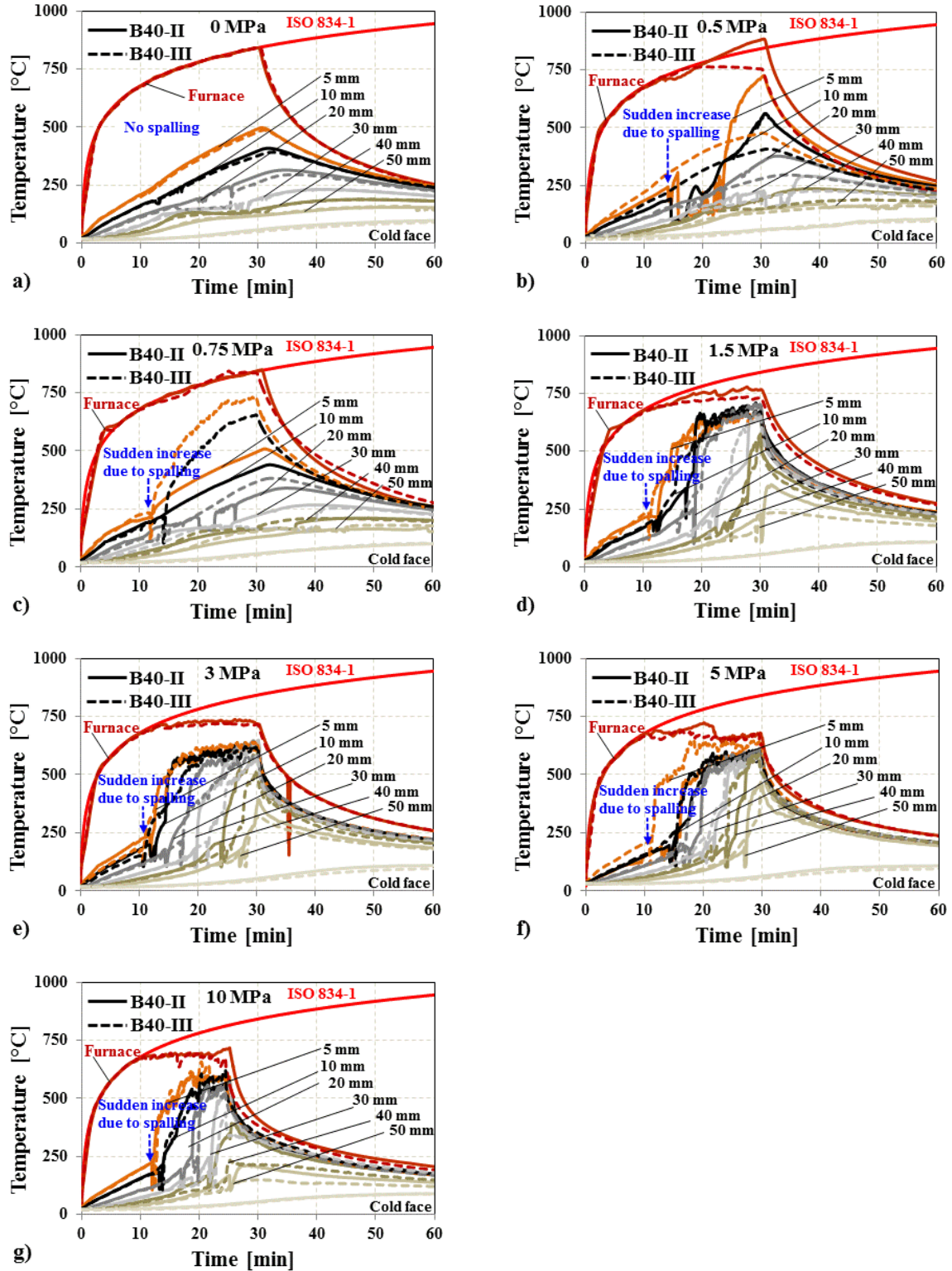


Figure 5 Development of temperature in B40-II and B40-III as a function of time.

The sudden large temperature increases due to spalling can be observed in the graphs. The other possible effect of the biaxial load on temperature induced by the effect on the cracks formation and then fluid transport should be very low and possibly negligible.

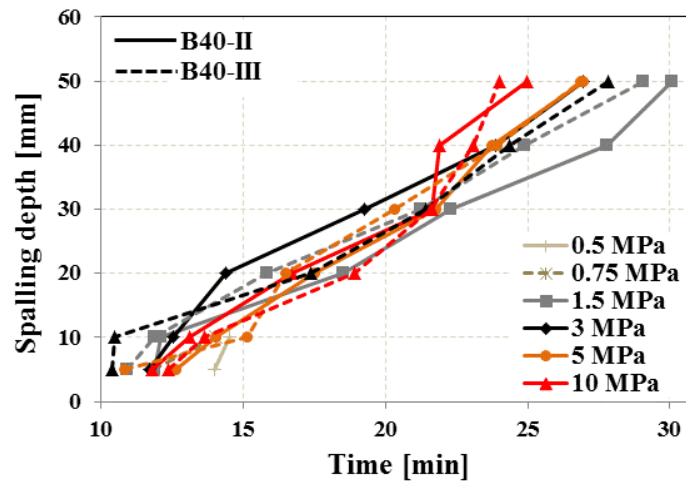


Figure 6 Determined spalling kinetics based on observed sudden temperature increase caused by thermocouples exposition to fire.

In all the tests, it was observed that spalling behaviour was homogeneous all over the central part of the exposed section (50 cm x 50 cm) and for all the samples. Then interestingly, spalling kinetics could be reasonably determined from the sudden temperature increase determined on the different thermocouples (Figure 6). We can observe that for most of the tests, spalling rates were almost constant and very close to each other (parallel curves). The spalling rate is approximately 100 mm/h. A particular trend is observed on tests loaded at 10 MPa. Spalling rate increased after 22 min in both samples. This have led to the collapse of the 2 slabs at 24 and 25 min.

Pore pressure curves versus the time

Pore pressure curves at different depths are plotted in Figure 7. Two curve shapes have been observed. Curves have a bell-shape when no spalling occurred. This can be observed on unloaded tests, at 0.5 MPa on B40-III and at 0.75 MPa on B40-II. Very sudden decrease of pore pressure is observed when concrete spalls. This is very well observed on the tests at 1.5 MPa to 10 MPa.

In the limited load zone, maximum pore pressure increases when biaxial applied stress increases. In unloaded samples, maximum pore pressures of both concretes (B40-II and B40-III) are almost same, which is 1.2 MPa (see Figure 7a) and no spalling was observed. At 1.5 MPa, the same values are 2.0 and 2.2 MPa respectively (see Figure 7d). Spalling was then observed.

It can be deduced from these observations that membrane compressive loading can affect the build-up of pore pressure during heating. Following explanation is proposed.

In unloaded situation, the permeability close to the exposed surface increases with temperature because of the cracks and micro cracks development due thermal incompatibility between the cement pastes and aggregates [14]. As a result, vapour and liquid water can escape more easily from the specimen since the cracks are free to open in all directions. This higher permeability significantly affects the build-up of pore pressure.

On the contrary, when the specimens are heated under a constant biaxial compressive loading, the applied load tends to close the cracks perpendicular to the loading direction [15]. Felicetti and Lo Monte 2016 [16], by implementing on the same biaxial fire tests an innovative technique based on ultrasonic pulse-echo have shown that damage is significantly reduced when samples are loaded, even at a very low stress (0.5 MPa). As a result, the presence of load limits the moisture transport inside the concrete by decreasing permeability which induces the higher value of measured pore pressure (see Figure 7c-e).

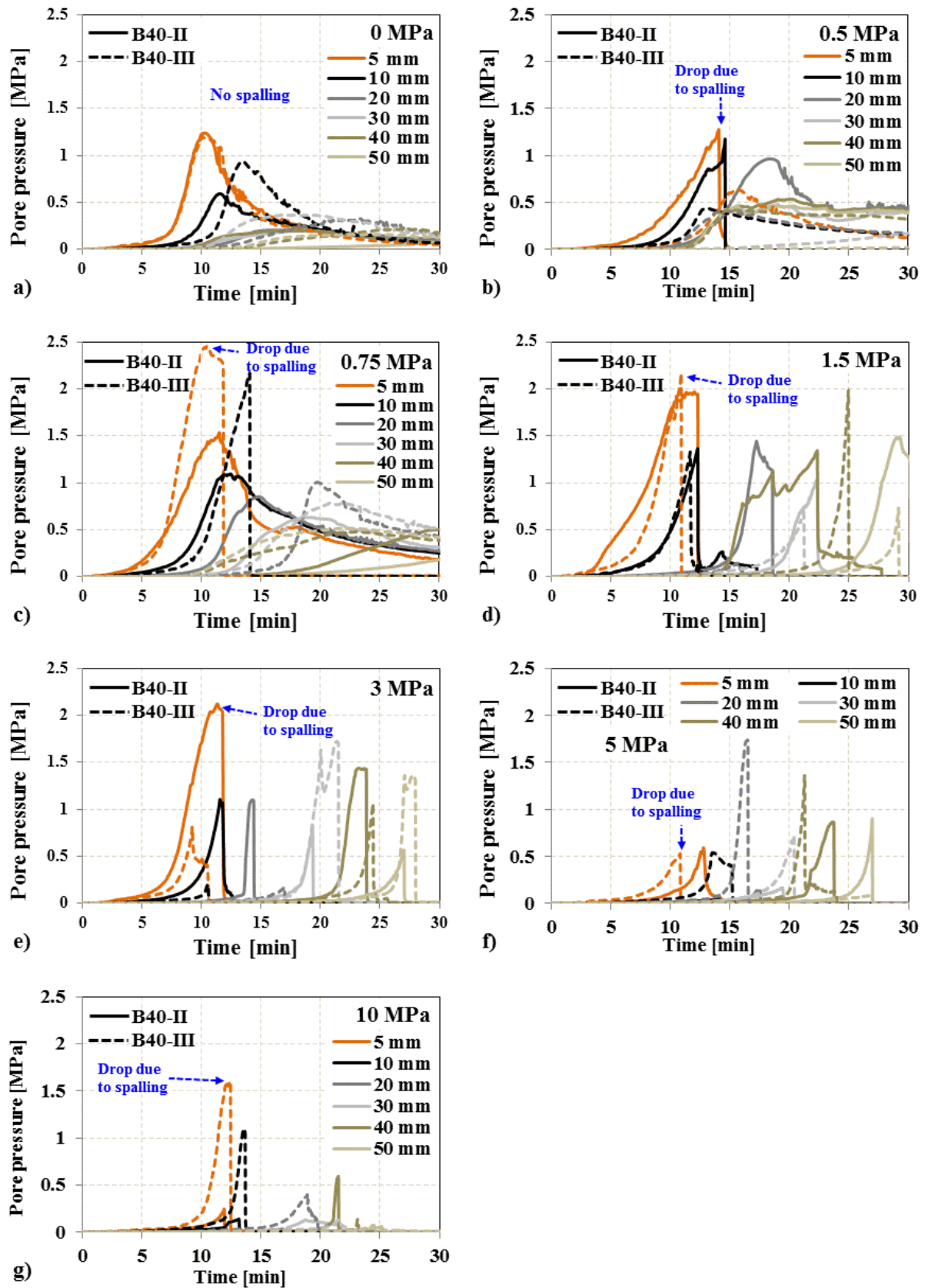


Figure 7 Development of pore pressure in B40-II and B40-III versus time at different depths.

Maximum measured pore pressures as a function of applied compressive stress are plotted in Figure 8. From this graph we can observe the following trends.

Under low stress, maximum pore pressure tends to increase with the applied stress. This can be due to, as explained earlier to the permeability decrease when applied stress increase.

In the higher stresses range where spalling occurs, maximum pore pressure tends to decrease when applied stress increases. This can be explained by the fact that spalling can occur when the state of stresses combining thermal stresses, applied stresses and pore pressure reaches a given threshold. Then to reach this threshold, higher is the applied stresses lower will be the pore pressure.

From this graph, we can observe that, except at 5 and 10 MPa, maximum pore pressures are globally in the same range for B40-II and B40-III.

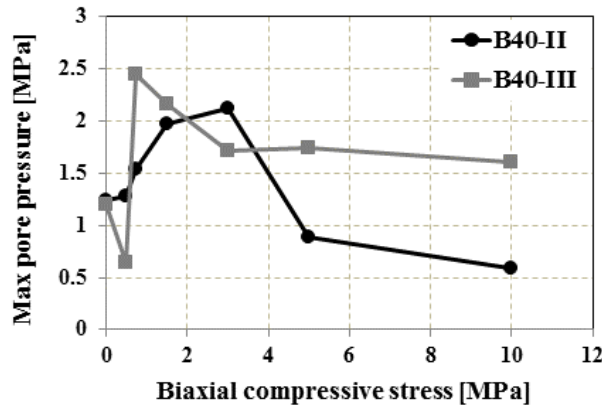


Figure 8 Maximum measured pore pressure as a function of applied compressive stress.

Out of plane displacement versus the time

Figure 9_left presents the positions of the LVDTs on the concrete slab specimens in the direction of X and Y, while Figure 9_right presents the calculation method of the displacement of LVDT3, LVDT5 and LVDT6. The modified displacements are as follows:

$$LVDT3^* = LVDT3 - 0.75 * LVDT2$$

$$LVDT5^* = LVDT5 - 0.50 * LVDT2$$

$$LVDT6^* = LVDT6 - 0.25 * LVDT2$$

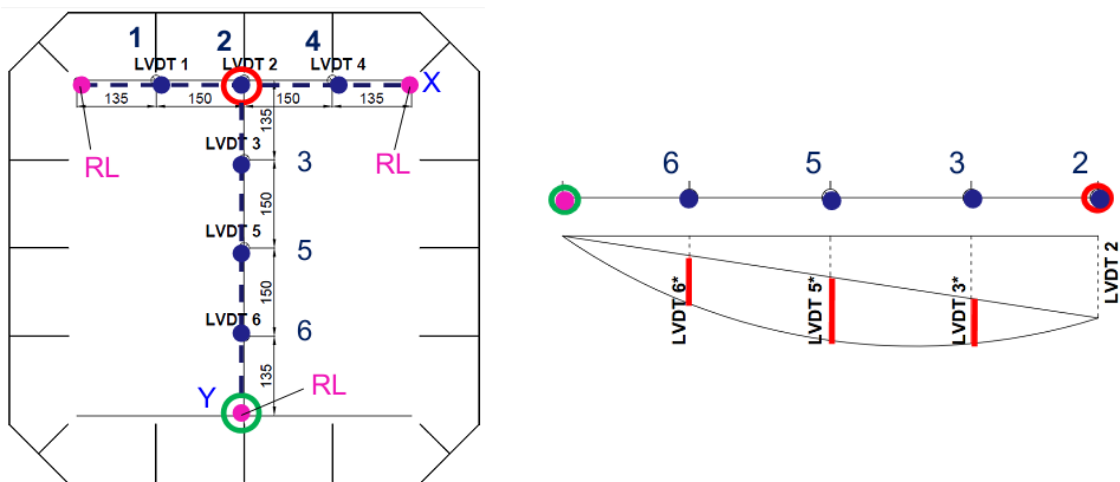


Figure 9 Schematic diagram of the measurement points of displacements (left) and an explanation of the displacement calculations for LVDT3, LVDT5 and LVDT6 (right) (RL= 3 rigid legs of the LVDT-holding frame).

An example of out of plane displacement measured at different times and along X and Y directions is given in the Figure 10a. Values along the X axis and Y axis are given in dashed and solid lines respectively. Deflections at the centre of the sample (LVDT n° 5) versus the time and for all the tests are plotted in Figure 10b. From this graph, it can be seen that the applied external membrane compressive loading reduces the displacement of the slabs.

During heating of concrete, initial sagging curvature towards the fire is due to the higher thermal dilation of the bottom heated face than the top colder face.

At the same time, because of the decay of concrete stiffness in the hot layers (corresponding to the decrease of the modulus of elasticity (E) with temperature, i.e. $E_{hot} < E_{cold}$) and because of the spalling phenomena, the stiffness centre rises. As the external load is continuously applied at the mid-plane, this turns into the upward eccentricity (hogging bending moment) and the displacement trend is reversed.

As a consequence, the combined effects (sagging curvature due to thermal loading and hogging curvature due to the presence of compressive loading caused by eccentric force) lead to lower curvature in the loaded specimen than in unloaded specimens. As a result, upward deflections increases when applied load increases. This trend is enhanced with spalling kinetics increase.

The increasing rate of the upward displacement of both concretes was much higher than the downward displacement, especially after 20 minutes of fire test loaded at 10 MPa.

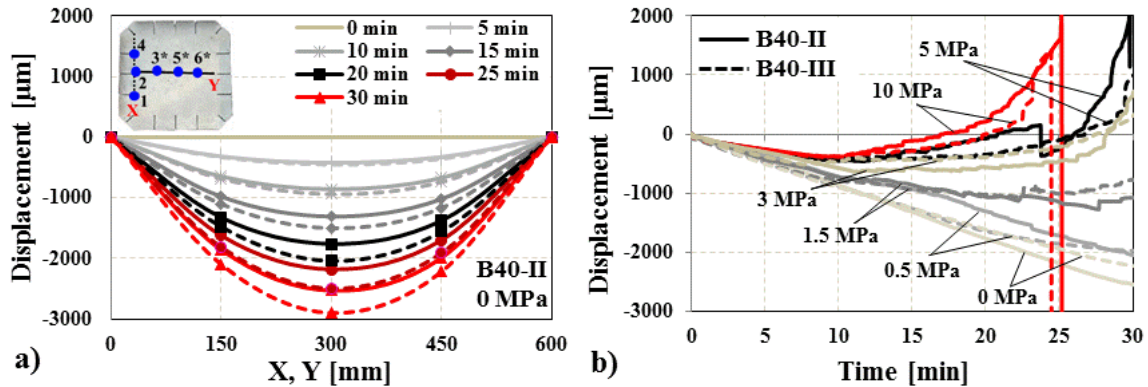


Figure 10 (a) Deformed shape of the B40-II slab at unloaded condition in the X and Y axes (symbols on each line depict the measurement points) and (b) vertical displacement of the concretes (B40-II and B40-III) as a function of time subjected to different levels of compressive loading (comparison of the top-mid displacements, i.e. LVDT 5).

CONCLUSIONS

The following conclusions can be drawn based on the results presented in this research work.

- The experimental test results have clearly shown that the biaxial compressive loading and their levels have a significant influence on the fire spalling of concrete. Loaded specimens are more prone to spalling than unloaded specimens, even if the load is very small (0.5 MPa) compared to the compressive strength. It is worth to note, that unloaded samples made with the 2 concretes did not spalled. On the contrary, intense spalling was observed on the same slabs under membrane biaxial load during the 30 minutes tests.
- Significant higher spalling depths were observed when the specimens were loaded in the range of 1.5 MPa to 5 MPa.
- From the sudden temperature increase related to spalling, we have been able to determine the spalling kinetics for all the tests. It appears that the spalling rate is almost constant during all the

tests and very close to one test to the other. In our tests, spalling rate was approximately 100 mm/h.

- It was found that under low stress, maximum pore pressure tends to increase with the applied stress. In the higher stresses range where spalling occurs, maximum pore pressure tends to decrease when applied stress increases. Possible mechanism to explain these trends have been given. The amount of pore pressure, is well known as a key parameter that influences spalling risk.
- From these results, spalling behaviour of B40-II and B40-III appear similar. This result is opposite than the one we observed by carrying out spalling test on the same concrete under uniaxial load.
- During a real fire, concrete structural members are always loaded or restrained. The presence of compressive loading during heating significantly increases the compressive stresses. We have shown that membrane compressive load in addition to increase the compressive stresses, can increase the pore pressure too and consequently increase the risk of fire spalling. Then, the applied compressive stress is a very important key factor that the fire resistance design of concrete structures should take into account when considering spalling. Hence, it is recommended that the fire spalling test should not be carried out only on unloaded specimens, especially for the ordinary concrete.

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