Effect of Biaxial Mechanical Loading and Cement Type on the Fire Spalling Behaviour of Concrete

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ABSTRACT

Fire spalling of concrete is a complex phenomenon, which might occur due to pressure build-up in the pores, thermal- and load-induced stresses. In this context, eight mid-size ordinary concrete slabs (4of B40-II and 4 of B40-III concrete: fc28 ≈ 40 MPa) were heated at the bottom face according to Standard Fire curve (ISO 834-1), while a constant biaxial compressive load was applied. Four different levels of biaxial mechanical loading have been investigated on both concretes. The test results showed that the loaded specimens are more prone to spalling than unloaded specimens, with increasing amount of spalling for higher values of applied load. Concrete made with CEM III cement (B40-III: 43 % of slag) exhibited less spalling than CEM II cement concrete (B40-II: 3 % of slag).

INTRODUCTION

Thermal spalling is a sudden and violent breaking away of a surface layer of heated concrete. Fire spalling reduces the cross-sectional area and may lead to the direct exposure of rebars to flame, with a significant reduction of the load bearing capacity [1-2]. Two physical mechanisms are often associated with this phenomenon, namely: the build-up of pore pressure and thermal stresses in the concrete when exposed to a rapidly increasing temperature [1-2]. Despite a large body of literature, controversial opinions exist about the causes of spalling. It is worth noting, however, that a huge number of experimental studies have been reported in the literature on unloaded specimens [1-3], while very limited experimental studies are available on the fire spalling behaviour of concrete under mechanical loading condition [4-9].

Kodur et al. 2007 [4] and Boström et al. 2007 [5] concluded that the type of loading and its intensity have significant influence on fire spalling behaviour of concrete.

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of concrete.

Mechanically loaded specimens during heating are more susceptible to spalling than unloaded members [4-5]. Numerical and experimental investigations by Ali et al. 2010 [6] have shown that increasing loading levels enhance the probability of concrete spalling, particularly under low heating regimes. Miah et al. 2015 [7] investigation on uniaxially loaded cubes have shown that the amount of spalling increases with the applied compressive load. The above reported studies clearly proved that the mechanical loading during fire is a key parameter influencing spalling behaviour of concrete. Within this context, a novel test procedure has been design at the Politecnico di Milano to perform fire spalling test under a constant biaxial membrane loading and ISO 834-1 standard fire curve. In a previous experimental campaign on High-Performance Concrete, explosive spalling was observed in plain concrete slab loaded at 10 MPa and the process involved the whole heated area of the specimen [8-9].

The cement industry has recently shown a significant interest in blast furnace slag based cement because of its very good durability performance as low chloride diffusion and lower carbon footprint. The existing literature does not provide detailed investigation of the fire behaviour of concrete made with blast furnace slag based cement (CEM III in Europe), especially spalling process of concrete in fire.

The lack of published test results on the role of mechanical loading and cement type on fire spalling behaviour of concrete provides the motivation for the experimental program in this paper. The test results including spalling volume, pore pressure, and displacements are presented.

EXPERIMENTAL SETUP AND PROGRAM

To investigate the interaction between pore pressure and thermo-mechanical stresses in triggering spalling, mid-size concrete slabs (800 x 800 x 100 mm^3) were subjected to ISO 834-1fire curve at different levels of biaxial membrane loading. Two ordinary concretes (B40-II and B40-III) made respectively with CEM II (CEM II/A-LL 42.5 R CE CP2 NF) and CEM III (CEM III/A 42.5 N CE CP1 NF) cements have been investigated. The CEM II cement contains 85% of clinker, 12% of calcareous fillers and 3% of slag, while the CEM III cement contains 54% of clinker and 43% of slag. The concrete slabs were placed on top of the horizontal furnace, within a loading system consisting in a welded steel frame fitted with hydraulic jacks. Eight mid-size concrete slabs (4 of B40-II and 4 of B40-III) were heated at the bottom face according to ISO 834-1fire curve. In order to limit the temperature in the hydraulic jacks, only the central part of the slab (600 x 600 mm^2) was heated to keep the external concrete rim colder. 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). 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 compressive load was applied with 8 hydraulic jacks (see figure 1) before heating and then the load was kept constant throughout the fire test. Four different levels of biaxial loading (0, 0.5, 5 and 10 MPa for B40-II and 0.5, 1.5, 5 and 10 MPa for B40-III) have been investigated. In order to avoid complete collapse of the specimen and to compare the amount of spalling at different levels of biaxial loading, the tests were stopped after thirty minutes of fire for spalled specimens, while no spall specimen was heated for 1 hour to monitor the flexural behaviour of heated concrete.

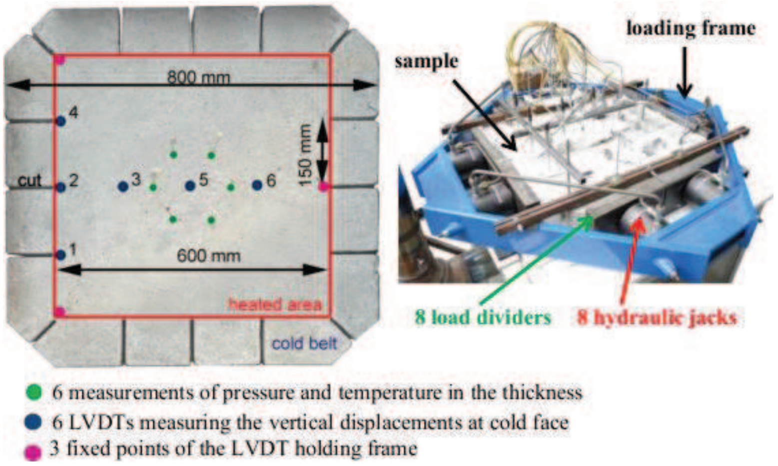

Figure 1. Concrete slab and measuring points (left); biaxial membrane loading system (right).

During the fire tests, both pore pressure and temperature were monitored (according to the system described by Felicetti et al. 2012 [10]) at 6 different depths of 5, 10, 20, 30, 40 and 50 mm from the exposed face of the slab. The flexural behaviour was monitored through 6 Linear Voltage Displacement Transducers (LVDT) placed on one center line and on one edge of the slab to measure the out of plane displacements at the top (cold) face. A more detailed description about the test set-up and the test method is given by Lo Monte et al. 2015 [8-9]. After each test, the thickness profile of the spalled area was measured at room temperature by using a laser profilometer. The compressive strength of both concretes measured on cylinder (Ø 160 mm x h 320 mm) at 28 days and 90 days are 40 MPa and 51 MPa, respectively. Further details about mix design and mechanical properties of these concretes are presented in Miah et al. 2015 [7, 11]. The initial water content of B40-II and B4-III concretes after drying at 80 °C was 4.0% and 5.3 %, respectively. This water content refers to the initial free water of the fire test specimens.

RESULTS AND DISCUSSION

SPALLING

Figures 2 presents the image of the exposed face of B40-II and B40-III concretes slabs exposed to ISO 834-1 fire at 4 different levels of biaxial loading. The experimental results have shown that the loaded specimens are more prone to spalling than unloaded specimens. Similar behaviour has been observed in uniaxially loaded concrete cubes during ISO 834-1 fire tests [7]. Spalling was accompanied by a loud "popping" sound as concrete fragments were released layer-by-layer from the concrete surface. The time of first spall is about 6-10 minutes of fire. The oven temperature at the onset of spalling was 600-650°C, whereas the measured temperature at the depth of 5 mm from the exposed surface was about 130-170 °C. The collapse of the slabs occurred at 29.7 min for the specimen loaded at 5 MPa (B40-II only) and 25.1 / 24.4 min for the specimens loaded at 10 MPa (B40-II / B40-III); then the heating was stopped. Spalling leads to a maximum loss of up to 73% and 87% of the total thickness of B40-II concrete loaded at 5 and 10 MPa, respectively, and 76% of the total thickness of B40-III concrete loaded at 10 MPa (Figure 3 right). Due to early failure behaviour of both concretes loaded at 10 MPa, the spalling volumes are decreased at 10 MPa than the specimens loaded at 5 MPa (see figure 3a). After cool down the furnace, the mass of the concrete spalled fragments were weighed. The mass of the concrete spalled fragments loaded at 5 and 10 MPa are respectively 35.3 kg and 33.1 kg for B40-II and 30.9 kg and 28.6 kg for B40-III concrete. It is interesting to see that the whole heated area of the concrete specimen was spalled, except B40-III concrete slabs loaded at 0.5 MPa and 1.5 MPa. Unfortunately, the temperature of the furnace was lower in B40-III concrete loaded at 1.5 MPa than the target temperature due to a problem in the gas supply after 10 minutes of fire duration. Therefore the amount of spalling was lower in B40-III concrete loaded at 1.5 MPa than the expected, see figures 2 and 3.

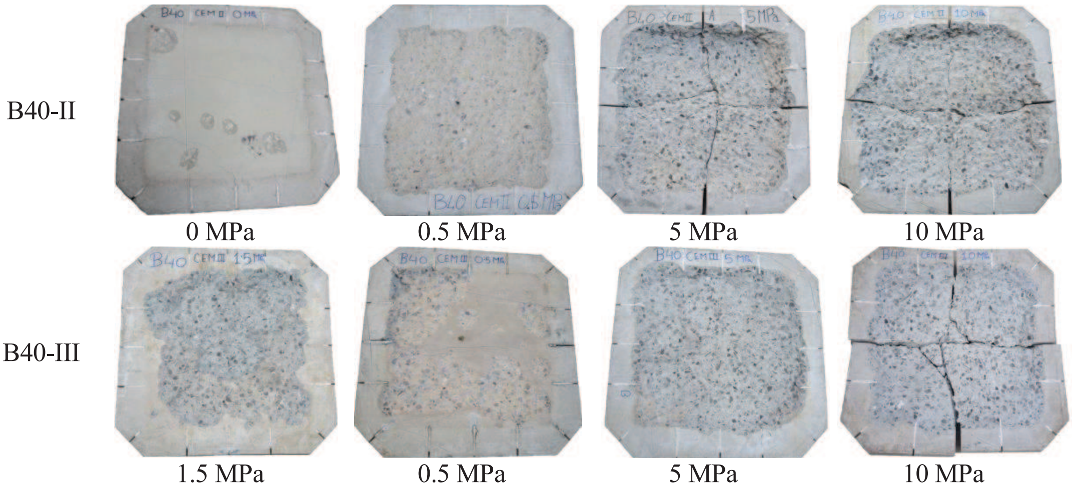

Figure 2. Exposed face of the B40-II and B40-III slabs exposed to ISO 834-1 fire.

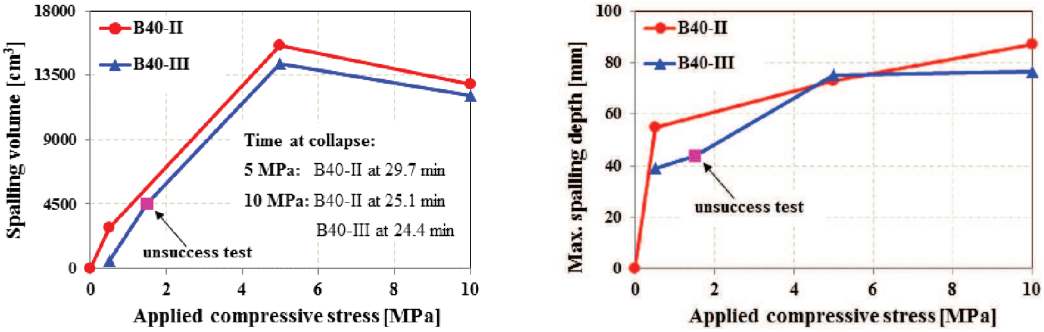

Figure 3. Spalling volume (left) and maximum spalling depth (right) of B40-II and B40-III concretes.

It is worth noting that the spalling behaviour of concrete under very small load (0.5 MPa) and no load (0 MPa) has two different scenarios. On the one hand, a uniform erosion extended to the whole heated area has been observed in B40-II concrete loaded at 0.5 MPa, for an average spalling depth of 16 mm. On the other hand, no spalling has been observed in unloaded B40-II specimen. These results tend to show that very small loads can influence the spalling behaviour of concrete, even though 0.5 MPa stress is small compared to the tensile strength of concrete (tensile strength at 28 days = 4 MPa). This implies that the permeability may play an important role during heating, since the development of cracking is more restricted in loaded than in unloaded specimens [12-13].Indeed, lower permeability reduces transport of water vapour inside the concrete and then induces faster build-up of pore pressures. Higher pore pressure was observed in B40-II specimen loaded at 0.5 MPa than the unloaded specimen (see figure 4c). This higher pore pressure of loaded specimen with the combination of stresses (due to thermal gradients and external load) increased the risk of spalling.

Higher spalling has been observed in B40-II than the B40-III (figures 2 and 3). These results are in good agreement with the uniaxially loaded cube test results [7]. Contrary to B40-II, the B40-III specimen loaded at 5 MPa did not collapse after 30 min heating, also less and non-uniform spalling behaviour has been observed in B40-III specimens loaded at 0.5 MPa compared to B40-II at the same loading level.

TEMPERATURE AND PORE PRESSURE

Temperature trends at 6 different depths along the slab thickness (5, 10, 20, 30, 40 and 50 mm) and at the hot and cold faces are shown in figures4a-b as functions of time for B40-II concrete exposed to ISO 834-1 fire curve under mean biaxial compressive stress of 0 and 10 MPa. It can be seen that the measured air temperature in the furnace followed the target ISO 834-1 fire curve, except after the first spalling event. An initial temperature plateau can be seen at around 150 °C (onset of water vaporization which consumes a significant amount of energy). In principle, the development of temperature within a heated concrete specimen is governed by its thermal diffusivity, i.e. thermal conductivity over heat capacity. The imposition of the external mechanical loading should not have any effect on these properties, except for the rate of mass loss at elevated temperatures due to the formation of cracks and release of hot vapour. The experimental results showed that higher temperatures were exhibited by loaded specimen. This is caused by spalling, since thickness reduction leads to the direct exposure of thermocouples to flame, hence to higher temperature rise.

However, it can be seen that the development of pore pressure seems to be different for specimens with no load or limited load (0.5 MPa). Maximum pore pressures was 0.84 MPa and 1.28 MPa in the former and in the latter case, respectively, for B40-II concrete. Even if the temperature of the furnace was lower after 10 min of fire in B40-III loaded at 1.5 MPa, the maximum pore pressure of 2.2 MPa was measured at 10 mm depth after 17 min of fire. From these values, it seems that there was some effect of loading on permeability of hot concrete which can influence the build-up of pore pressure during heating. The permeability increase is favoured by the thermal incompatibility between cement pastes and aggregates, which brings in tensile stresses in the matrix leading to cracking [1]. As a result, vapour and liquid water can escape from the specimen, this affecting the build-up of pore pressure. As mentioned before, the development of cracking is more limited in loaded specimen than in unloaded specimens [12-13]. In the literature, it was found that the permeability of concrete during heating under compressive loading (stress levels lower than 80% of the strength) is smaller than the permeability measured after unloading [14]. It can be seen that higher load (10 MPa) can affect the build-up of pore pressure during heating. In this case, spalling might take place before the pressure peak reaches the sensors; afterwards pressure build-up is impaired by increased permeability because of cracking.

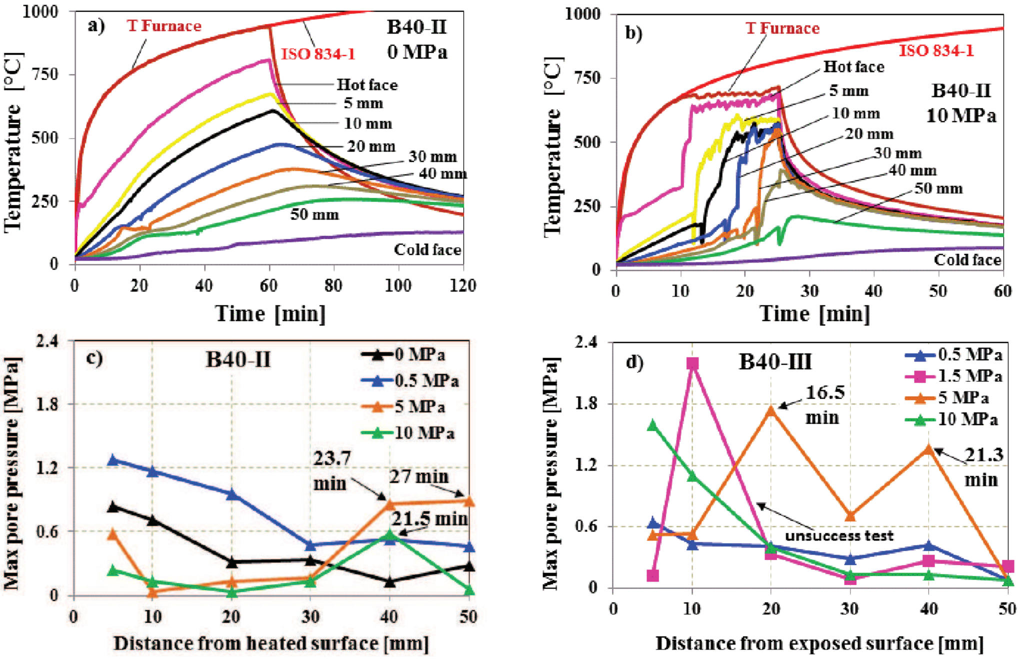

Figure 4. Development of temperature and pore pressure inside the B40-II and B40-III concrete exposed to ISO 834-1 fire at different levels of biaxial compressive loading.

Nevertheless, higher pore pressures were measured in B40-III than B40-II (contrary to 0.5 MPa). Firstly, this could be due to the higher thermal damage of B40-II specimens during heating (higher spalling in B40-II than B40-III), which increase the permeability and then decrease the pore pressure. The second reason is that the initial water content of B40-III concrete is about 1.3 % higher than the B40-II concrete. This higher water content could be leading higher pore pressure in B40-III than the B40-II.

FLEXURAL BEHAVIOUR

Figure 5 presents the deformed shape of the slab specimens in the x and y axes (symbols on each line depict the measurement points). It can be seen that the applied external mechanical loading reduces the displacement of the slabs during heating. When heating concrete, initial sagging curvature towards the fire prevails due to the thermal dilation of the bottom heated face. Afterwards, the decay of concrete stiffness in the hot layers makes the bottom part of the slab more and more deformable. When this layer becomes significantly weaker, a reverse hogging curvature may occur due to the presence of applied external mechanical loading during heating. In fact, the line of action of the applied load remains in the original centre-line of the slab thickness, this resulting in an eccentric force due to the significant degradation of stiffness at the exposed side of the slab. As a consequence, the combined effects (sagging curvature due to thermal loading and hogging curvature due to the presence of mechanical loading caused by eccentric force) lead to lower curvature in the loaded specimen than in unloaded specimens. As a consequence, upward deflections have been observed in the most loaded specimens due to the larger eccentricity caused by the higher reduction of thickness (see figures 5c-d). In the end, a sudden failure was reached in these latter tests due to excessive bending and lack of reinforcement.

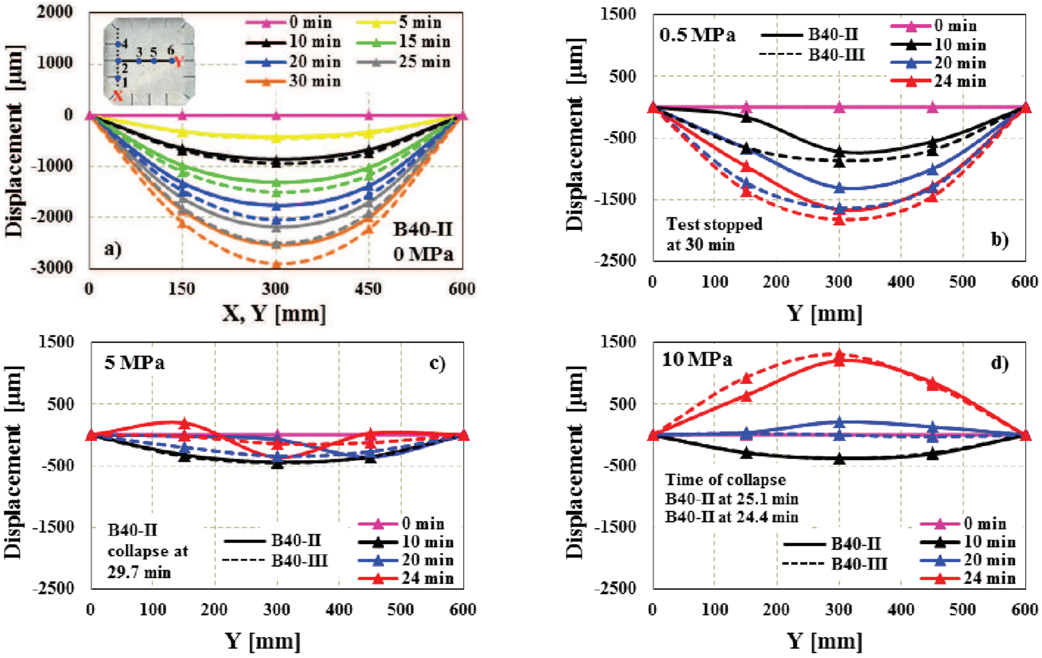

Figure 5. Deformed shape of B40-II slabs in the x and y axes (see top-left plot). Almost similar displacements have been observed in B40-III concrete slabs.

When curvature sign changes in loaded specimens, namely from sagging to hogging, concrete is pressed at the bottom side, this probably closing macro-cracks and then fostering the increase of pore pressure (see figures 4c-d and 5c-d). Due to higher reduction of the slab thickness caused by spalling, higher bending moment could develop due to higher eccentric force. Furthermore, lower displacements have been observed in B40-II than B40-III, see figures 5b-d. Due to higher reduction of thickness caused by spalling, a higher load eccentricity was introduced in B40-II, resulting in lower deflections.

CONCLUSIONS

The fire spalling behaviour of concrete exposed to ISO 834-1 fire under different levels of biaxial loading has been documented. Two ordinary concretes (B40-II and B40-III) made respectively with CEM II and CEM III cements have been investigated. The following conclusions can be drawn based on the results presented in this study.

The experimental test results have clearly shown that the mechanical loading and loading levels have significant influence on the fire spalling behaviour of concrete. Loaded specimens are more susceptible to spalling than unloaded specimens. The amount of spalling was increased by higher values of applied compressive load.

It was found that the stresses due to both thermal gradients and external load in combination with pore pressures can increase the risk of spalling. These results show that the compressive stress is one of the most important parameters that fire resistant design of concrete structures should take into account when considering spalling.

Concrete made with CEM III cement (B40-III: 43 % of slag) exhibited less spalling than CEM II cement concrete (B40-II: 3 % of slag). These results tend to show that the studied B40-III concrete could be less sensitive to fire spalling.

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