IFireSS – International Fire Safety Symposium
Coimbra, Portugal, 20th-23rd April 2015

IN-PLANE LOADED CONCRETE SLABS SUBJECTED TO FIRE: A NOVEL TEST SET-UP TO INVESTIGATE SPALLING

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ABSTRACT

Despite the rather good knowledge on the mechanical behaviour of High-Performance Concrete at high temperature, further investigations are still needed, particularly as concerns spalling (to which High-Performance Concrete is very sensitive). Spalling is a complex issue, being the result of the interaction among concrete mechanical decay with temperature, pore pressure build-up due to water vaporization, and stress induced by thermal gradients and external loads. How these aspects influence each other, however, is not completely clear. Within this context, an experimental campaign has been launched at the Politecnico di Milano in collaboration with CTG-Italcementi Group (Bergamo, Italy), focusing on 4 concrete mixes ($f_{cm} \approx 60$ MPa; silico-calcareous aggregate), namely without or with one of 3 different fibre types (steel fibre and monofilament or fibrillated polypropylene fibres). The main goals of the study are: (a) to investigate the interaction between pore pressure and stress in triggering spalling, and (b) to understand the role played by fibre. To this aim, a novel test procedure has been designed, consisting on concrete slabs exposed to fire at the intrados and subjected to compressive load via hydraulic jacks.

Keywords: concrete, fibre, pore pressure, spalling, standard fire.

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1. INTRODUCTION

Explosive spalling is the more or less violent expulsion of concrete layers or pieces from the surface of R/C members, when exposed to fast heating or fire. Concrete spalling is the result of the interaction among: (a) stress induced by thermal gradients and external loads, (b) cracking favoured by dehydration, moisture vaporization and thermal incompatibility between aggregate and cement paste, and (c) pore pressure build-up caused by water vaporization.

Low concrete thermal diffusivity and high heating rates occurring in fire lead to sizable thermal gradients in R/C members. Such thermal gradients induce compressive stress in the layers next to the heated face and tensile stress in the inner core. Compressive stress causes cracking and a consequent decrease of the stability in the external layers, both aspects favouring spalling. Cracking in heated concrete is also fostered by material heterogeneity and chemo-physical reactions. Factors influencing concrete cracking during heating are: the release of absorbed and chemically bound water, thermal kinematic incompatibility between aggregates and cement paste, and cement dehydration [1].

On the other hand, pressure gradients cause the transport of liquid water and vapour towards both the hot face and the inner and cooler core; in the latter case, vapour may condensate leading to the formation of a quasi-saturated layer. The quasi-saturated layer is a critical zone, since in low-porosity material (such as High-Performance Concrete – HPC), full saturation can be attained, leading to the so-called moisture clog. Due to the reduced permeability, pressure build-ups are enhanced and high values of pressure can be obtained (up to 5 MPa [2]). This is the reason why HPC is more prone to explosive spalling than Normal-Strength Concrete – NSC [2,3].

An effective way to reduce concrete spalling sensitivity is to add polypropylene (pp) fibre, even though a debate is still open on the mechanisms behind this beneficial effect. They seem to be mostly related to an increase of concrete permeability induced by three main processes: (a) fibre melting at 160-170°C, which leaves free channels for vapour release [4], (b) thermal dilation of melting fibre, that favours cement paste microcracking and the ensuing interconnection among the pores [4], and (c) further microcracking in the cement matrix due to stress intensification around the edges of the channels left free by fibre melting (notch-effect, sizable mainly at $T \geq 250$-300°C) [5,6].

The influence of pore pressure on the fracture behaviour of concrete has been studied in a few recent studies, showing that the decay of the “apparent” indirect tensile strength due to pore pressure can be equal to the value of the pressure itself [7,8]. Moreover, the role played by the main constituents of the mix design (first of all aggregate and fibre) on the tensile strength versus pore pressure relation was tackled [8].

Further investigations, however, are needed to cast some light on the interaction between pore pressure and stress, under realistic conditions of loading and heating. In a few works [2,9], pressure has been measured, investigating its development in plain and/or fibre concretes, but without considering external loads. On the contrary, a few authors studied concrete spalling sensitivity in heat-exposed slabs subjected to membrane load applied by means of post-tensioning (which has the disadvantage to make difficult the application of a constant load, once the thermal strain affects both the slab and the tendons) [10].

Within this context, a new experimental campaign has been launched at the Politecnico di Milano in collaboration with CTG-Italcementi Group (Bergamo, Italy) on the study of concrete slabs subjected to heating. Four concrete mixes ($f_c \approx 60$ MPa, with silico-calcareous aggregates) have been designed: without fibres – reference mix (1), with 2 kg/m^3 of monofilament (2) or fibrillated (3) polypropylene fibres and with 40 kg/m^3 of steel fibres (4). (For further details on the mix design see [11]). Two slabs of dimensions 800x800x100 mm were cast for each concrete mix.

The aim of the present study is to investigate the interaction between the main actors involved in spalling, trying to emphasize the role played by fibres. To this end, a novel experimental set-up was designed, as described in the following Sections.

2. TEST SET-UP

In order to investigate the interaction between pore pressure and stress in triggering explosive spalling, concrete slabs (800x800x100 mm, Fig.1a) are subjected to Standard Fire (ISO 834) at the intrados, while an external membrane load is applied before heating via 8 hydraulic jacks (Fig.1b,c). Membrane load induces a mean compressive stress of 10 MPa, kept constant during the fire exposure, with the aim of limiting the onset of tensile stress (which may lead to cracking and to the consequent release of vapour).

A steel frame restrains the hydraulic jacks and the whole loading system is placed above a small horizontal furnace. During the test, pressure and temperature are monitored at 6 different depths of the slab, while the flexural behaviour is monitored through 6 Linear Voltage Displacement Transducers (LVDTs) measuring the vertical displacements (see Fig.1a). The furnace is heated by a propane burner with a control system able to strictly follow the ISO 834 curve.

It is worth noting that to limit the temperature reached in the hydraulic jacks, the external concrete belt, in contact with the loading system, should remain colder. Then, only the central part of slabs was heated (600x600 mm). This cold belt, however, would provide a confinement to the heated part. In order to limit as possible this effect, 16 radial cuts were made (Fig.1a).

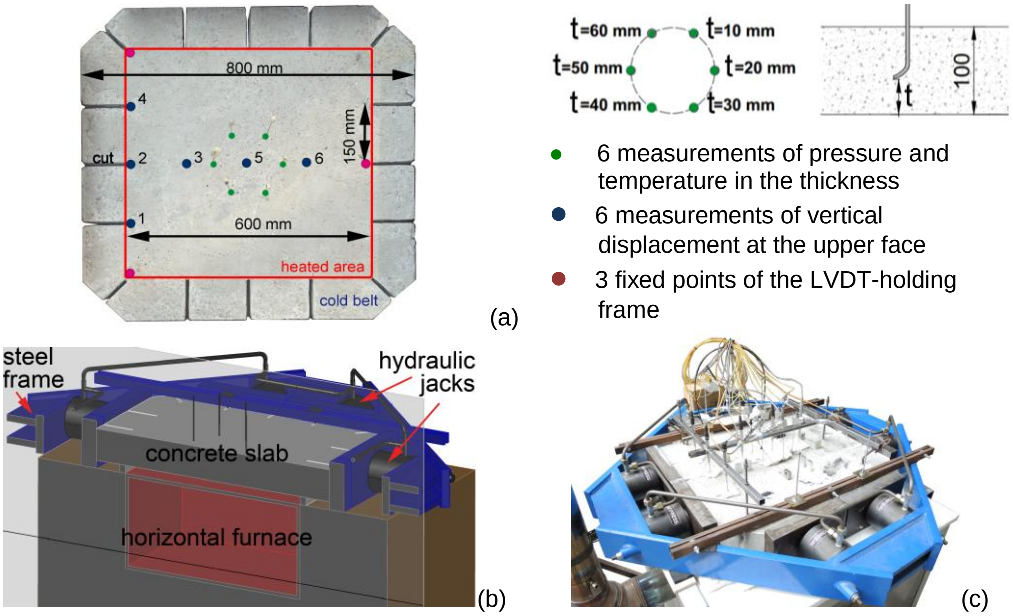


Figure 1: (a) Concrete slab and measurement points; (b) concrete slab within the loading system (steel frame + hydraulic jacks) positioned on the horizontal furnace; and (c) picture of the instrumented slab, ready for the test.

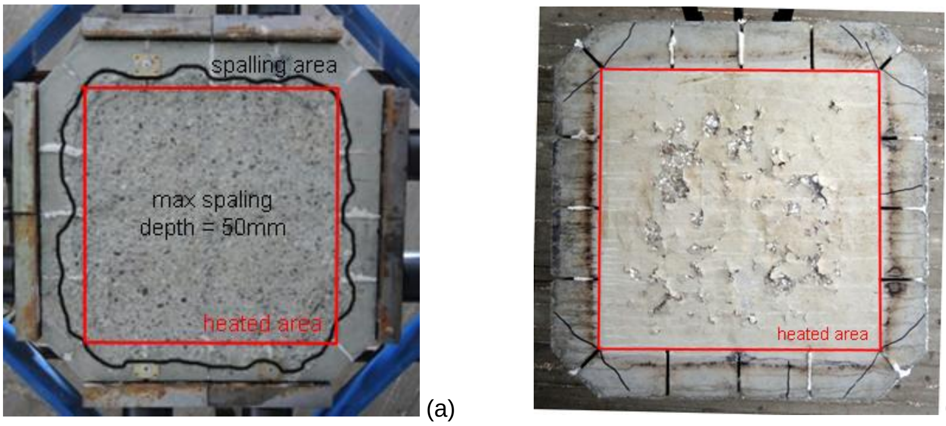
3. RESULTS AND DISCUSSION

3.1 Experimental results

So far, two slabs were tested, the first made of plain concrete and the second including fibrillated pp fibres. In the former test, explosive spalling occurred at the heat-exposed surface after 19.3 min of heating (Fig.2a). On the other hand, the presence of pp fibres allowed to avoid any form of spalling in the second case, for all the fire duration (120 min, Fig.2b). As concerns spalling in plain concrete, it is worth noting that the process was progressive, but rather regular, involving the whole heated area of concrete. The first very violent event occurred at 19.3 min of heating, with the expulsion of an almost constant concrete thickness (≤ 10 mm) in the all heated area (600x600 mm). Then, many minor events followed (characterized by lower energy), each one involving only part of the heated area (up to about 30%). After cooling, the spalled layer appeared rather homogeneous. This is very interesting, since it can be inferred that, in substantially uniform heating and loading conditions, the size of the spalled splinters is not strictly related to local mechanisms involving the meso-scale (aggregate-to-cement past interaction).

3.1.1 Temperature

In Fig.3a temperatures of furnace (“Oven 1” and “Oven 2”), hot face, 6 internal measurement points (10, 20, 30, 40, 50 and 60 mm from the heated face) and cold face are shown for pp fibre concrete slab, as functions of time. The results are shown for pp fibre concrete only, since the differences between the two slabs are negligible before spalling occurs in the plain concrete specimen. It is worth noting that the temperature measured in concrete is sizably lower than that of the furnace. This comes from the low heat flux entering the slab, due to two main reasons: (a) low emissivity of white smokes produced by propane and (b) low radiant temperature in the bottom part of the horizontal furnace.



(a) (b)

Figure 2: Slab intrados after cooling: plain (a) and in pp fibre (b) concretes.

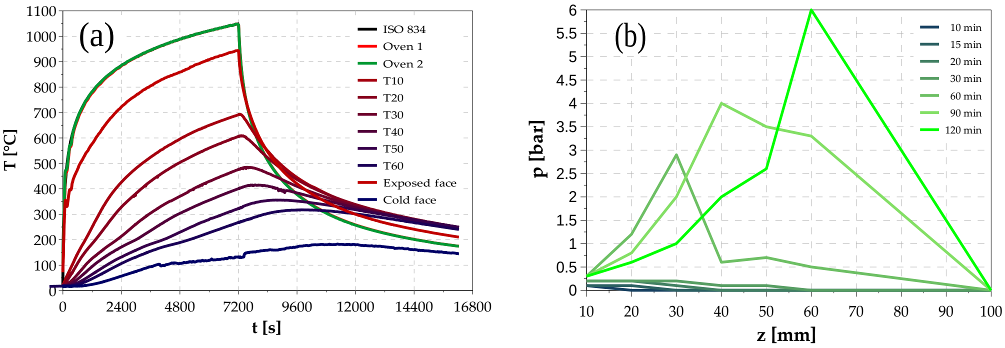


Figure 3: pp fibre concrete slab: temperature as a function of time in the oven (heating for 7200 s and then cooling), at the exposed face of the slab, at the 6 reference depths and at the cold face (a); pore pressure as a function of depth for different fire durations (b).

3.1.2 Pore pressure

In Fig.3b, the pressure measured at 6 different depths (10, 20, 30, 40, 50 and 60 mm from the heated face) is shown as a function of depth, for the pp fibre concrete slab. In Fig.4a,b the same results are shown for the two slabs, respectively, up to 19.3 min of heating, time at which spalling occurred in plain concrete slab. In Fig.4c,d pressure is reported as a function of the temperature measured at the correspondent point, together with the saturation vapour pressure curve. Looking at the results of the slab with pp fibre and at those of plain concrete regarding only the depths of 10, 40 and 50 mm (the other three sensors gave some problems in monitoring the temperature, due to cement clogging of the tubes), it seems clear that increasing the depth, both the peak pressure and the pressure-temperature rate increases (pressure-temperature curve are close to, or even higher than, the saturation vapour pressure curve). This is probably caused by the increase of the saturation degree with depth and to the lower temperature rate. From Figs.3b and 4a, it is interesting to observe that the higher values of peak pressure are reached in the case of pp fibre concrete, even though the peaks are measured for very high fire durations (the highest value, 6 bar, is reached after 120 min).

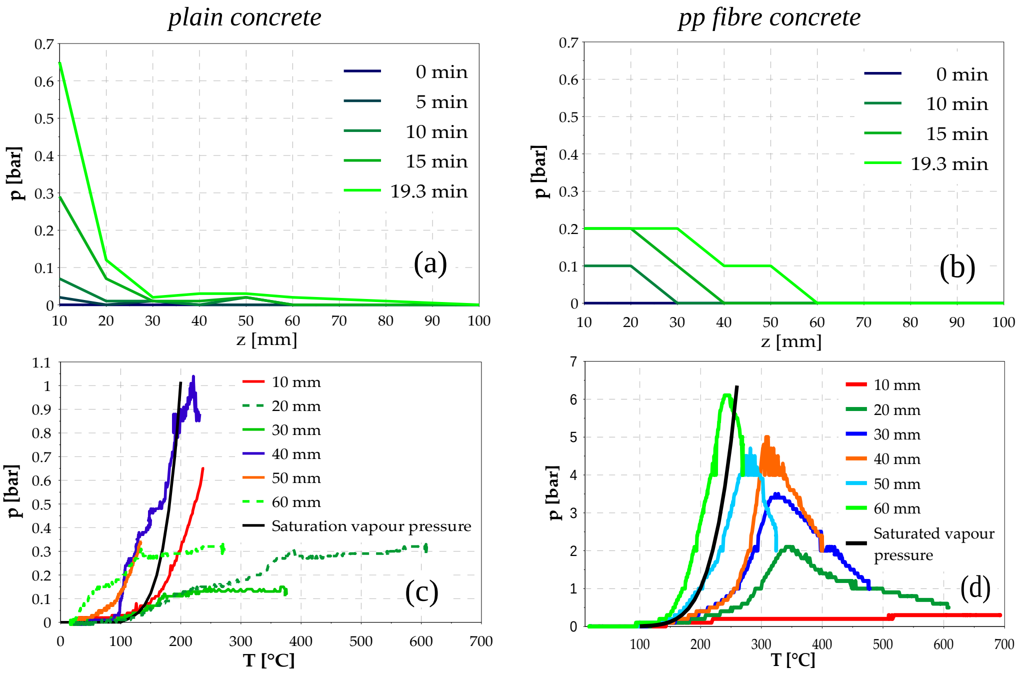


Figure 4: Pore pressure profiles in the early stages of fire tests (a,b) and as a function of temperature at the 6 reference depths (c,d).

In the early minutes, however, plain concrete experiences higher values of pressure, and the gradients are sizable sharper (Fig.4a,b). This is probably caused by its lower permeability, which limits vapour release, forcing the pressure to remain concentrated in the hot layer (in pp fibre concrete permeability is increased by fibre melting). Similar results were obtained in [12].

3.1.3 Flexural behaviour

In Fig.5a, the relative vertical displacements in reference points 2 and 5 of Fig.1a are shown for pp fibre concrete slab, as functions of time. (Up to 19.3 min – spalling time for plain concrete slab –, the flexural behaviour of the two slabs is rather similar). Focusing on the case of pp fibre concrete, for which the measurements were performed up to the end of the test, it is fair to observe that the flexural response can be subdivided into two phases. In the first phase of heating, the curvature is positive, due to the higher thermal dilation of the bottom heated face. When the decay of concrete stiffness in the hot layer becomes sizable, the rise of the sectional stiffness centroid makes the external load (applied on the mid-plane) to have a negative eccentricity, this causing a hogging moment. Hence, in the second phase, the displacement rate changes sign and the curvature becomes negative, after about 75 min.

3.2 Numerical simulation

3.2.1 Stress

Numerical simulations were performed to evaluate the stress induced by thermal gradients and external loads, using the software ABAQUS and its implemented Concrete Damaged Plasticity model. Fig.5b shows the modelled fourth of the slab. The definition of concrete stiffness decay with temperature is a critical issue, since it should take into account instantaneous load-induced strain and transient creep [13]. Concrete hot compressive behaviour was initially defined according to EN1992-1-2:2004 (EC2), while fracture energy was kept constant with temperature (evaluated at T = 20°C according to Model Code, 1990). With these assumptions, however, no sign change in the curvature was numerically observed. Then, a calibration of concrete stiffness decay was performed (see Fig.5c) in order to obtain a satisfactory agreement with the experimental results.

Figs.5a shows the comparison between numerical and experimental results in terms of vertical relative displacements as functions of time. Fig.5d shows the stresses evaluated numerically. The maximum tensile stress develops only in the last minutes of heating; its magnitude is rather limited (≤ 4 MPa) and the concurrent temperature is still low (≤ 140°C): this is instrumental to limit cracking. Compressive stress is also limited, being lower than 30% of hot compressive strength in the first 20 min of the test (spalling occurred in plain concrete after 19.3 min of heating).

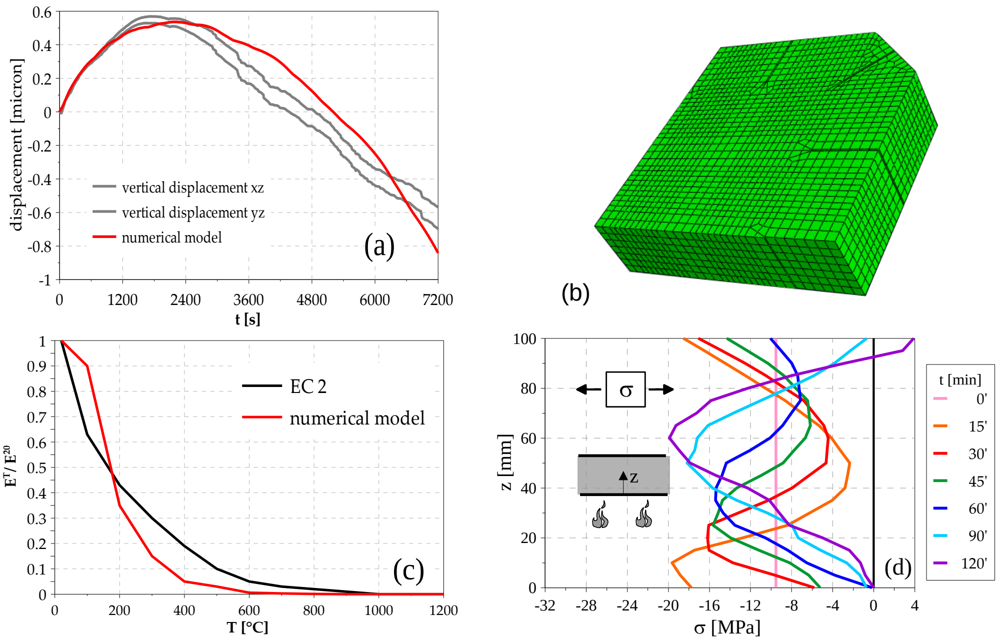


Figure 5: pp fibre concrete slab: (a) relative vertical displacements in reference points 2 and 5 of Fig.1a; (b) fourth of the slab modelled in ABAQUS; (c) concrete stiffness decay with temperature after calibration (red curve) and according to EC2 (black curve); and (d) numerically-evaluated stress along the depth in the central segment of the slab for different fire durations.

4. CONCLUSIONS

A novel experimental set-up has been designed at the Politecnico di Milano consisting in concrete slabs subjected to compressive membrane load and exposed to Standard Fire. Two slabs have been tested, the first made of plain concrete and the second including fibrillated polypropylene fibres. Thanks to the continuous measurement of pressure, temperature and displacements, together with numerical simulations, the following considerations can be made.

4.1 Spalling

In plain concrete slab, explosive spalling occurred at the heat-exposed surface after 19.3 min of heating, while the presence of pp fibres allowed to avoid spalling in the second slab, for the whole fire duration (120 min).

The spalling process in plain concrete started with a severe event followed by progressive detachments, involving the whole heated area of concrete. The first violent event occurred at 19.3 min of heating, with the expulsion of an almost constant concrete thickness (≤ 10 mm) in the all heated area (600x600 mm). After heating and cooling, the spalled layer appeared rather homogeneous.

4.2 Temperature

The temperature development in the two slabs is practically coincident, showing the limited influence in concrete thermal behaviour of transport phenomena occurring during heating. (The two concretes have different permeability due to fibre, but similar thermal diffusivity).

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4.3 Pore pressure

Experimental results showed that for increasing values of depth, both the peak pressure and the pressure-temperature rate increase. This is probably caused by the rise of the saturation degree with depth and to the lower temperature rate.

The higher values of peak pressure are reached in the case of pp fibre concrete for very high fire durations and in the inner layers, where the quite low temperature little affects mechanical properties. On the other hand, in the early minutes, plain concrete experiences higher values of pressure, characterized by sharper gradients. This can be ascribed to the lower permeability in plain concrete, which limits the vapour release, forcing the pressure to remain concentrated in the hot layer (while in pp fibre concrete permeability is increased due to fibre melting).

4.4 Stress

As regards stress, numerical investigations showed that the maximum tensile stress develops only in the last minutes of heating with values lower than the hot tensile strength. Also compressive stress was limited, being lower than 30% of hot compressive strength before spalling (which occurred 19.3 min after heating).

5. AKNOWLEDGMENTS

The Authors are grateful to CTG-Italcementi (Bergamo, Italy) for the design of the concrete mixes and the useful contribution in preparing the specimens. Fondazione Lombardi Ingegneria (Minusio, Switzerland) is also thanked for the financial support given to this research project.

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