SPALLING TEST ON CONCRETE SLABS UNDER BIAXIAL MEMBRANE LOADING

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Abstract

Concrete spalling is a rather complex phenomenon ensuing from the interaction of different aspects – often hard to be monitored – namely, temperature, pressure in the pores and stress. It is, in fact, commonly agreed that spalling is triggered by the mutual influence of hygro-thermal and thermo-mechanical processes.

Aimed at investigating these two critical issues, an ad hoc test setup was developed at the Politecnico di Milano, based on in plane-loaded slabs. Concrete specimens of dimensions 800x800x100 mm were subjected to the Standard Fire at the intrados, while a constant biaxial compressive load was applied. Pore pressure and temperature at 6 different depths, as well as the flexural behaviour, were continuously monitored during the test.

Taking advantage of this facility, an experimental campaign was carried out on one High-Performance Concrete ($f_c \geq 60$ MPa with silico-calcareous aggregate), without or with one among 3 different fibre types (steel fibre, monofilament or fibrillated polypropylene fibre). So far, tests on concrete without and with polypropylene fibre were carried out. Explosive spalling was observed in plain concrete only, with a remarkably homogeneous spalled layer. In all cases, the mechanical response was characterized by sagging deflection due to thermal strain followed by hogging deformation due to creep and plastic strain.

Keywords

Biaxial loading, concrete slab, fibre, flexural behaviour, pore pressure, spalling test.

1. INTRODUCTION

Explosive spalling results in the more or less violent expulsion of concrete pieces from the surface of R/C members, when exposed to fire. Such phenomenon can be particularly detrimental to the fire resistance of R/C structures, since it leads to a reduction of the sectional geometry and to the possible direct exposure of the reinforcing bars to the flames (so dramatically speeding up the mechanical decay of steel).

Despite the exact mechanisms behind spalling are still not completely clear, it is commonly agreed that it comes from the interaction of: (a) stress induced by thermal gradients and external loads and (b) pore pressure rise caused by water saturation and vaporization.

As is well-known, the thermal gradients induced in concrete by heating lead to compressive stress in the hot layers and tensile stress in the inner core. The former favours the formation of cracks parallel to the hot face (or more in general to the isothermal surfaces) and a consequent decrease of the local mechanical stability. Concrete cracking is also fostered by kinematic incompatibility between aggregate and cement paste, release of absorbed and chemically bound water and cement dehydration [1].

Another detrimental action is represented by pressure in the pores due to the dilation of dry air and liquid water (if saturation occurs) and to the vaporization process. Pressure and concentration gradients cause moisture migration towards both the hot face and the inner core. In the latter case, the new incoming of liquid water and the possible condensation of vapour [2] favour the formation of a quasi-saturated layer. In dense materials, such as High-Performance Concrete (HPC), saturation can be attained, leading to the so-called moisture clog. Due to the reduced permeability, pressure build-ups are enhanced and values up to 5 MPa [3] were observed. This is the reason why HPC is more prone to spalling than Normal-Strength Concrete (NSC) [2,3].

A clear evidence that pore pressure plays an important role on concrete spalling is given by the beneficial effect brought in by the addition of polypropylene (pp) fibre. Limited amounts of pp fibre (1-2 kg/m^3) are sufficient to dramatically reduce the likelihood of spalling, probably thanks to three main processes: (a) further porosity because of fibre melting at 160-170°C [4], additional microcracking in the cement paste due to (b) the thermal dilation of melting fibre [4] and (c) to the stress intensification around the edges of the channels left free by melted fibre [5,6].

It is worth noting that a critical point is represented by the understanding of the real effect of pore pressure, namely to quantify the tensile load acting on concrete skeleton because of the pressure exerted by the hot fluids in the pores. Within this context, two recent studies were carried out at the Politecnico di Milano, showing that the decay of the “apparent” indirect tensile strength due to pore pressure can be equal to the value of pressure itself [7,8] and depends on the main constituents of mix design (first of all aggregate and fibre [8]).

New investigations, however, are needed focusing on the effect of pore pressure and loading under realistic conditions of heating. For instance, in Mindeguia et al., (2010) [9], pressure was monitored investigating its development in plain and/or fibre concretes, though no external load was considered. On the other hand, Sjöström et al., (2012) [10] studied concrete sensitivity to spalling 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, since the thermal strain affects both the slab and the tendons.

Trying to cast some light in the above-discussed direction, a new experimental campaign was launched at the Politecnico di Milano in collaboration with CTG-Italcementi Group (Bergamo, Italy) on the behaviour of concrete slabs subjected to Standard Fire under biaxial loading. The test programme includes four concrete mixes ($f_c \geq 60$ MPa, with silico-calcareous aggregates): a reference mix without fibre (1), and the same matrix with 40 kg/m^3 of steel fibre (2), or with 2 kg/m^3 of monofilament (3) or fibrillated (4) polypropylene fibres.

Two slabs were cast for each concrete mix, for a total of 8 specimens (further details on mix designs are given in [11]).

The aim of the present study is to investigate the interaction between the main factors involved in spalling, trying to emphasize the role played by fibres.

2. TEST SETUP

Concrete slabs (800x800x100 mm, Fig.1a) were subjected to Standard Fire (ISO 834) at the intrados under biaxial membrane loading applied via 8 hydraulic jacks (Fig.1b,c). Membrane load was designed in order to instate a constant mean compressive stress of 10 MPa aimed at preventing the onset of tensile stress.

The whole loading system, consisting in a welded steel frame restraining the hydraulic jacks, was placed above an horizontal furnace in which heat was generated by means of a propane burner.

During the test, pressure and temperature were monitored through the thickness via embedded sensors placed at the distances of 10, 20, 30, 40, 50 and 60 mm from the exposed face, while the flexural behaviour was monitored through 6 Linear Voltage Displacement Transducers (LVDTs) measuring the vertical displacements at the extrados (Fig.1a). The control system of the burner allowed to strictly follow the ISO 834 curve.

It is worth noting that the external concrete perimeter in contact with the hydraulic jacks should remain colder to keep low the temperature. Thus, the slab was heated only on its central part of dimensions 600x600 mm. The confining effect provided by the surrounding cold belt was limited by 16 radial cuts whose objective was interrupting its mechanical continuity (Fig.1a).

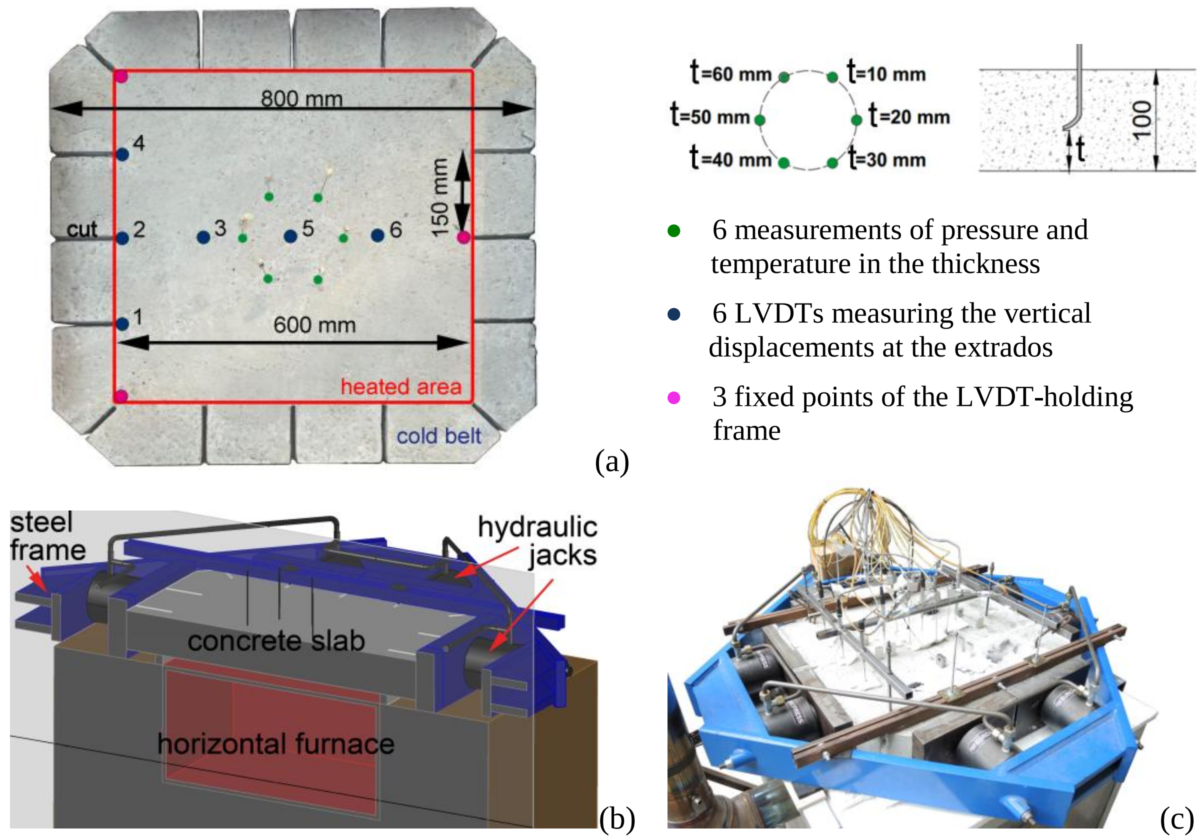

Figure 1: (a) Concrete slab and measurement points; (b) concrete slab within the loading system (steel frame + hydraulic jacks) positioned on the horizontal furnace; and (c) picture of the instrumented slab, ready for the test.

3. RESULTS AND DISCUSSION

3.1 Spalling

So far 3 slabs were tested, namely, concrete without fibre, and with 2 kg/m^3 of monofilament or fibrillated pp fibre. Spalling occurred only in plain concrete slab, after 19.3 min of heating (Fig.2a), while in the other specimens the presence of pp fibre allowed to avoid any form of spalling during the whole fire duration (120 min), with only a slight superficial scaling observed after cooling (Fig.2b).

It is worth noting that spalling process in plain concrete began with a severe event involving all the heated area for a depth of 10-13 mm. Afterwards, many minor events followed, each one taking place in smaller parts of the heated area (up to about 30%). After cooling, the spalled layer appeared rather homogeneous with a maximum depth of 60 mm.

The regularity of the spalled surface is very interesting, since it can be inferred that, in substantially uniform heating and loading conditions, the size of spalled splinters is mainly linked to the gradients of pressure and stress along the depth.

3.2 Temperature

In Fig.3 temperatures of oven, hot and cold faces, and both temperature and pressure at the 6 internal measurement points (10, 20, 30, 40, 50 and 60 mm from the heated face) are shown for the 3 slabs, as functions of time.

The fire duration in the tests was 120 min, except for plain concrete. In this latter case, in fact, the test was stopped after 33 min, since severe cracking involved the cold face (extrados), jeopardizing the test setup.

Unfortunately, in the sensors of plain concrete slab at the depths of 20 and 60 mm, the pipes were partly clogged, this leading to measure lower values of temperature.

No relevant difference, however, was observed among the specimens in terms of temperature development. Obviously, after the first spalling event, the measurements in the layers involved by the detachments were no more reliable.

Figure 2: Slab intrados after cooling: plain (left) and typical pp fibre (right) concretes.

It is worth noting that, despite Standard Fire curve was satisfactorily followed according to the feedback provided by a plate thermometer, temperatures experienced by concrete were lower than expected. This outcome is still under scrutiny, but preliminary evaluations let think that it can be ascribed to: (a) low emissivity of clear smoke produced by propane and (b) low radiant temperature in the bottom part of the horizontal furnace.

3.3 Pore pressure

In Figs.3 and 4 pressure is reported as a function of time and temperature, respectively (in the latter case the saturation vapour pressure curve, P_{SV}, is also shown).

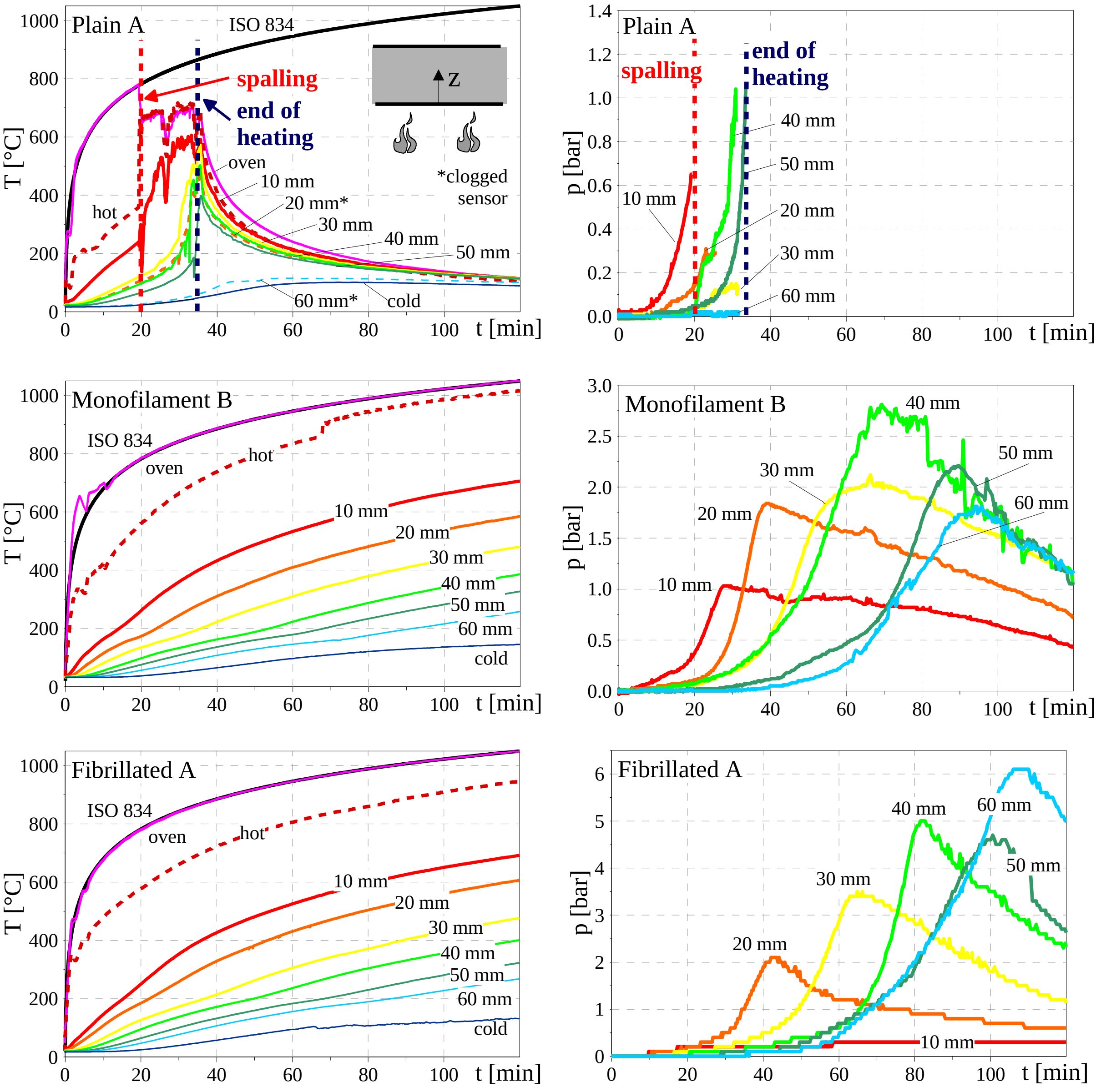

Figure 3: Plots of temperature of oven, hot and cold concrete faces, and of temperature and pressure at the 6 depths in the three slabs as a function of time.

From Fig.4, looking at the results of the slabs with fibre and at those of plain concrete (disregarding, in this latter case, the depths of 20 and 60 mm, since thermocouples gave no reliable values due to cement clogging of the tubes), it seems clear that increasing the depth, the pressure-temperature curve slope increased (pressure-temperature curves are closer to the saturation vapour pressure curve). This was probably caused by the increase of the saturation degree with depth and to the slower temperature increase.

From Fig.3 it should be noted that the highest peak pressures were reached in the case of fibrillated pp fibre concrete, while plain mix experienced the lowest values, even lower than monofilament pp fibre concrete (though in the slabs with pp fibre, the peaks were measured for long fire durations). As already observed in [8], monofilament pp fibre are more effective than fibrillated pp fibre in reducing pore pressure.

In Fig.5 the pressure profiles through the thickness are shown for the three specimens at different time steps for the whole fire duration, and in Fig.6 the same profiles are shown only for the earlier 19.3 min of heating, time at which spalling occurred in plain concrete slab.

In the first 10 min the different slabs showed very similar pressure profiles (since fibre were not melted yet), while just before spalling occurred in plain concrete (about 20 min of heating), pressure in the slab without fibre was significantly higher.

Moreover, in plain concrete, pressure profiles were characterized by sharp gradients. This was probably caused by the lower permeability, which limited 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 observed in [12].

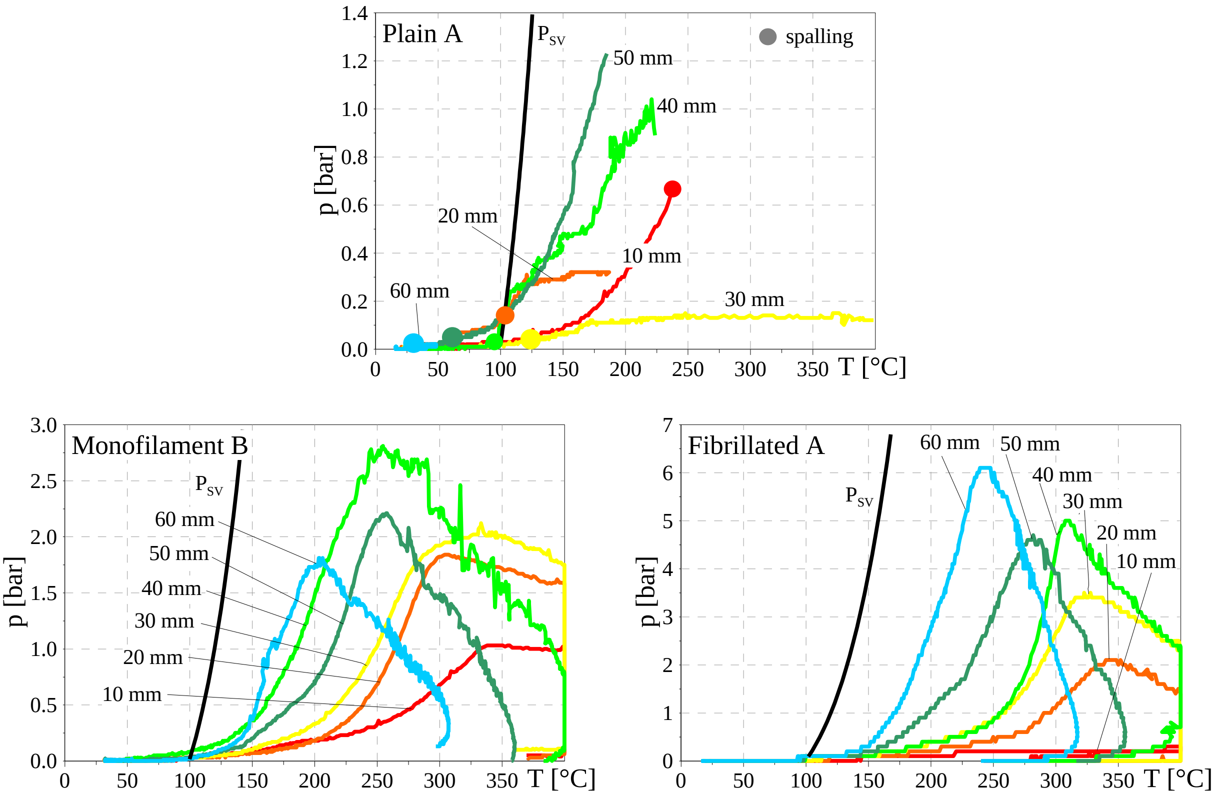

Figure 4: Pressure as a function of temperature at the 6 measuring depths for plain and pp fibre concretes, together with the vapour saturation pressure curve, P_{SV}.

3.4 Flexural behaviour

In Fig.5, the deformed shape of the axes x and y are shown for different fire durations for the three specimens (the two axes are depicted in the insert of the top-right plot of Fig.5).

The flexural behaviour can be subdivided into two parts:

- First phase: the curvature was positive (sagging) and increased with time, because of the higher thermal dilation of the bottom heated face.
- Second phase: when the decay of concrete stiffness in the hot layer became sizeable, a strong increase of strain at the intrados took place, this leading to hogging deflection.

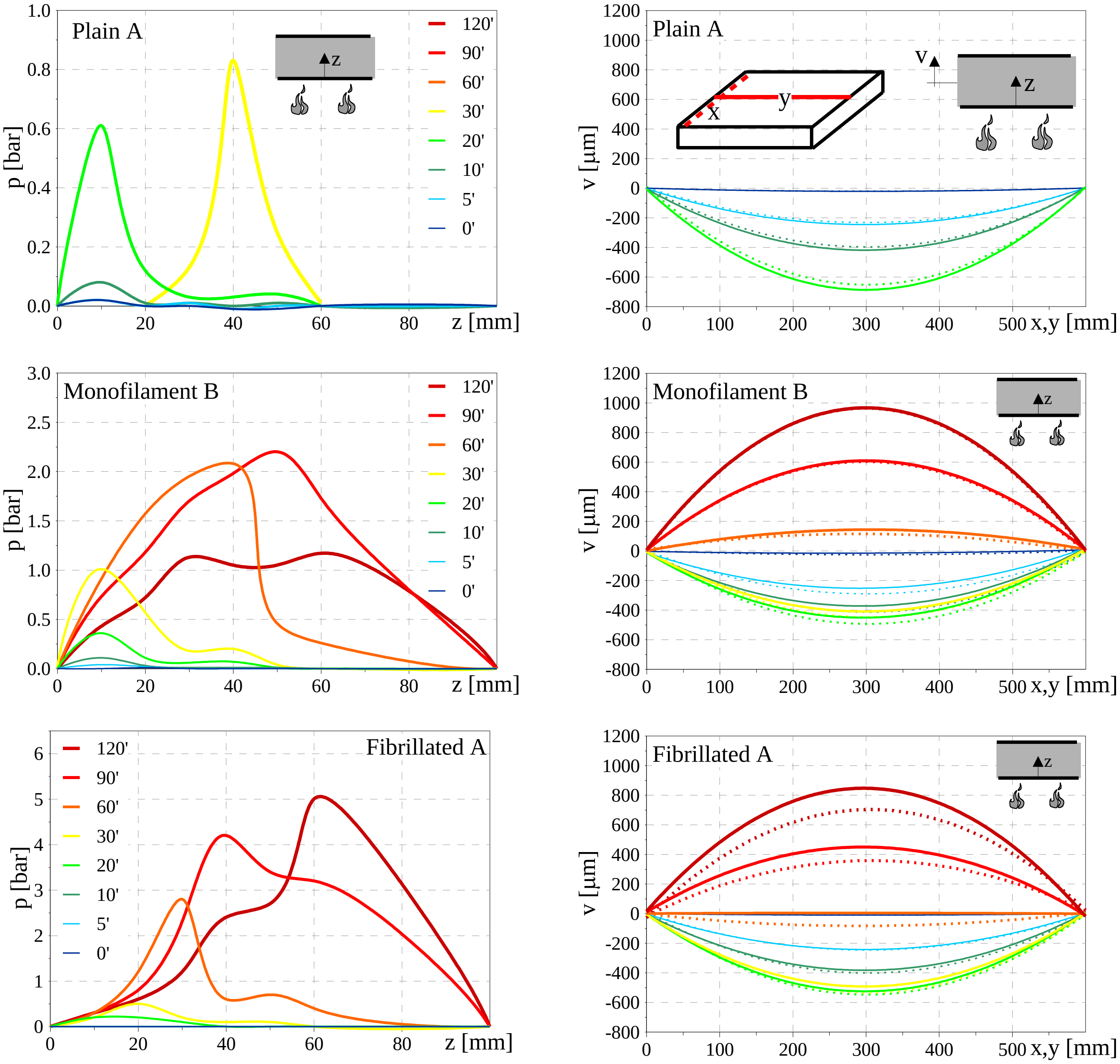

Figure 5: Pressure profiles through slab thickness and deformed shape of the axes x and y (see insert in the top-right plot), for the three mixes for different fire durations.

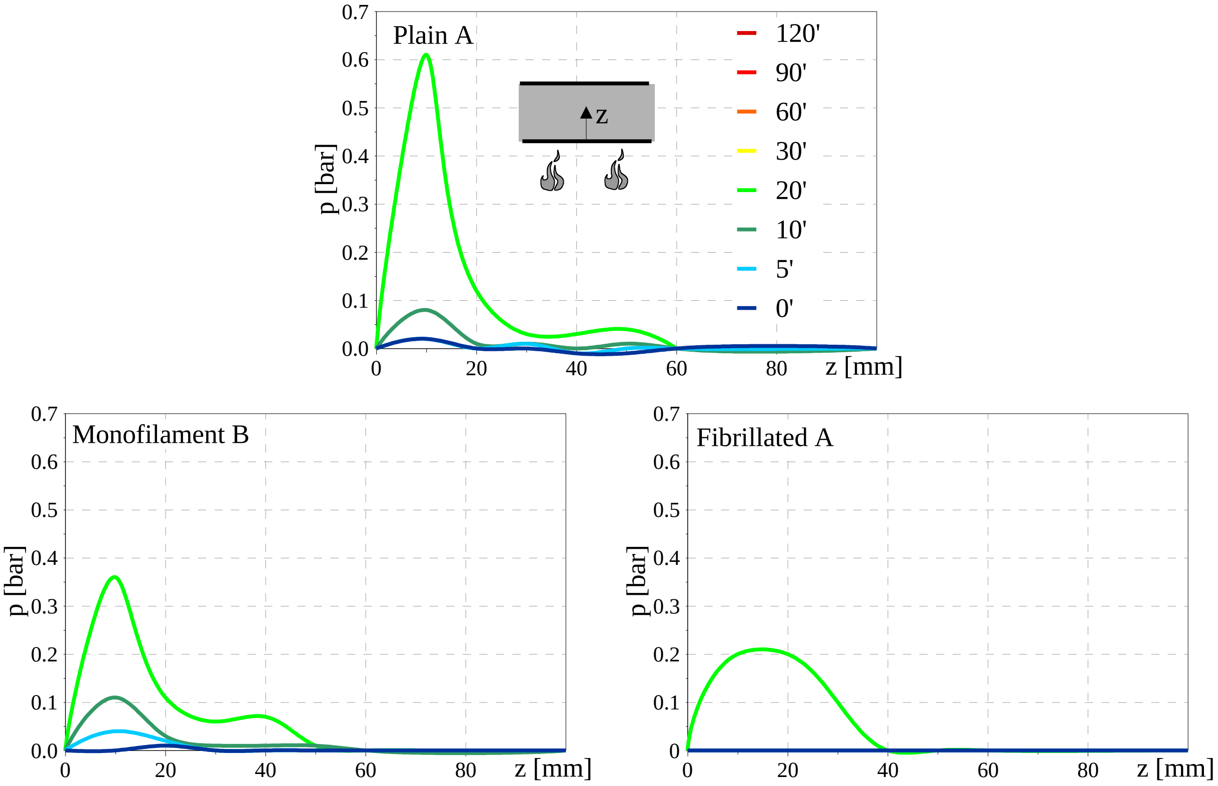

Figure 6: Pressure profiles through slab thickness for the three mixes for different fire durations, before spalling occurred in plain concrete slab (19.3 min of heating).

Thus, in the second phase, the sign of displacement rate was reversed (after about 25 min of fire duration) and the curvature became negative after 50 and 69 min for monofilament and fibrillated pp fibre concretes, respectively.

It is interesting to observe that the maximum downward displacement was reached at about 25 min for all specimens, and was close to 700 μm for plain concrete and 400-500 μm in the case of pp fibre concretes. After 120 min of heating, the maximum upward displacement was 750-950 μm for pp fibre concretes.

The lower curvature in the first phase of heating for pp fibre concretes can be ascribed to a faster stiffness decrease with temperature, this leading to a greater effect of the external load. This evidence may come from both a higher heat-sensitivity or a more relevant transient creep. These results, however, need to be confirmed by the next tests. Moreover, investigations on hot compression behaviour are still in progress and they, hopefully, will cast some light on this aspect.

4. CONCLUSIONS

A novel experimental setup was designed at the Politecnico di Milano based on concrete slabs heated at the intrados according to the Standard Fire curve, while subjected to membrane biaxial loading.

Three slabs were tested, made of High-Performance Concrete ($f_c \geq 60$ MPa, with silico-calcareous aggregate) with/without monofilament or fibrillated polypropylene fibres.

Thanks to the continuous measurement of pressure, temperature and displacements, the following considerations can be drawn.

4.1 Spalling

In the plain concrete slab, explosive spalling occurred at the heat-exposed surface, while the addition of polypropylene fibres allowed to avoid such phenomenon, for the whole fire duration (120 min).

The spalling process in plain concrete started after 19.3 min of heating with a severe event, characterized by the expulsion of a uniform concrete thickness (≈ 10-13 mm) in the whole heated area (600x600 mm); then it was followed by progressive detachments involving smaller parts of the intrados (thickness ≈ 8-10 mm).

After heating and cooling, the spalled layer, however, appeared rather homogeneous. Such evidence corroborates the idea that, under substantially uniform heating and loading conditions, spalling phenomenon is mainly driven by pressure and stress gradients along the depth.

4.2 Temperature

The development of the thermal field was rather similar for all the slabs, showing the quite limited role played in concrete thermal behaviour by transport phenomena occurring during heating. (Polypropylene fibre concretes have higher permeability than plain concrete due to fibre, but similar thermal diffusion).

4.3 Pore pressure

Experimental results showed that for increasing depths, the pressure-temperature curve slope increases. This is probably caused by the rise of the saturation degree with depth and to the slower temperature increase.

The highest values of peak pressure were reached in fibrillated polypropylene fibre concrete, while in plain concrete the values were even lower than those in monofilament polypropylene fibre mix. This is caused by the fact that, once spalling occurred, pressure was significantly influenced by severe cracking.

On the other hand, in the early minutes (before spalling occurrence), plain concrete experienced the highest values of pressure, whose profiles were characterized by sharp gradients. This can be ascribed to the lower permeability, this limiting the vapour release and forcing the pressure to remain concentrated next to the hot layer (while in polypropylene fibre concrete permeability is increased due to fibre melting).

4.4 Flexural behaviour

In the first part of heating, slab curvature is positive (sagging) since deformation is driven by thermal dilation at the bottom heated face. When concrete stiffness decay in the hot layer becomes sizable, the kinematic behaviour is driven by external load and the displacement rate changes sign leading to negative curvature (hogging).

The higher values of downward displacement reached in plain concrete in the first phase of heating, suggest that stiffness decay due to high temperature is lower with respect to concrete with polypropylene fibre.

This can be ascribed to a less pronounced heat-induced damage or transient creep effect. Such result, however, still needs further investigations.

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