Flash vaporization next to an opening crack: a possible explanation of the explosive nature of concrete spalling

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ABSTRACT

In this paper the very quick vaporization of water in the pores of hot concrete next to an opening crack is regarded as way to convert the considerable amount of thermal energy stored in the material into kinetic energy of the fractured splinters. To this purpose, a special setup has been developed in order to suddenly release the vapor pressure accumulated at a sealed edge of a heated sample. The quick local cooling observed confirmed that a sizeable loss of thermal energy occurs in a rather thin layer of concrete facing the depressurized surface. Fast sequences of Neutron Radiographic images allowed to recognize that the influenced zone doesn't exceed 1mm thickness. This has a direct impact on the time scale of thermal and hygral transients and corroborates the idea that a significant contribution to the explosive nature of spalling may be provided by water vaporization.

KEYWORD: neutron radiography, thermal energy, water vaporization

INTRODUCTION

In spite of the number of studies conducted in the field, explosive spalling of concrete in fire keeps being a complex phenomenon that can hardly be governed by the structural designer, since the influence of fire scenario, applied loads, moisture content and inherent permeability of the material has not yet formalized in the shape of a practical spalling criterion. Nonetheless, it is generally agreed that the combined effect of pore pressure and high compressive stress ensuing from restrained thermal dilation is required to produce this critical instability within the exposed concrete cover [1]. Some recent studies allowed to corroborate this perspective.

The potential of pore pressure in promoting the fracturing process was ascertained by testing the splitting tensile strength of small concrete cubes (100mm side) under transient thermo-hygral conditions [2]. The linear decrease of apparent tensile strength with pore pressure confirmed the significant role of this variable. However, the systematic analysis of a series of concrete mixes [3] showed that in High-Performance concrete just a minor share of pore pressure (about 25%) translates into an effective tensile stress borne by the solid skeleton, due to the poorly interconnected porosity. Since pore pressure not exceeding 5MPa is generally measured in the temperature range at which the phenomenon takes place (250-300°C), it turns out that pore pressure can just promote the onset of cracks rather than overcome alone the tensile strength of concrete. In fact, under the minor thermal stress experienced by slowly heated small cubic samples, none of the tested specimens broke before the implementation of the splitting test, though a remarkably violent failure was observed at testing. Similar conclusions were drawn from compressive tests on 150mm cubes heated at 230°C for 2-3 hours [4].

The twofold contribution of compressive stress due to thermal gradients and external loads consists in triggering cracks parallel to the heated face and reducing moisture leakage by preventing orthogonal cracks. This was investigated by testing square slabs under strictly controlled biaxial compressive loading [5]. While ordinary concrete was able to switch from no effects to substantial spalling upon application of just 5MPa compression, Ultra High-Performance steel fibre reinforced concrete exhibited sizeable spalling regardless of the external load, possibly because of the inherently lower permeability and higher thermal stress. The benefits brought in by monofilament polypropylene fibre (lower pore pressure and faster drying of the cover) confirmed the synergistic role of the hygral transient.

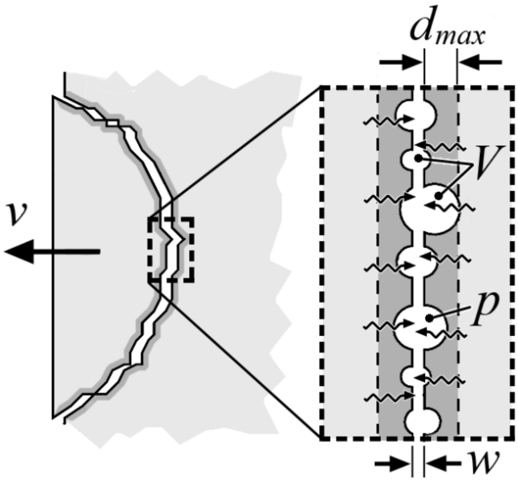
Many numerical models have been developed over the past four decades aimed at assessing the mutual interaction between mechanical and hygral effects of concrete heating [6]. A general result in lightly loaded elements (e.g. concrete tunnel linings) is that the thermally induced compressive stress doesn't exceed 50-60% of the material strength [7], which seems not sufficient to trigger microcracks in High-Performance concrete. This drew more attention to the meso-scale heterogeneity [4, 8], since the higher local stress peaks occur at the interface between coarse aggregate and mortar are likely to originate scattered cracks. Coarse aggregate and microcracks have a sizeable impact also on the penetration of the drying front from the heated surface, as highlighted by Neutron Tomography [9] and confirmed by 3D modelling [10].

The cited developments allowed an important progress in the recognition of the causes for the onset of spalling, which is generally denoted by a combination of mechanical stress, pore pressure and damage which cannot be anymore be borne by the material. However, it is not yet fully understood why in many cases the fractured cover remains in place [11], with little detriment to fire safety, while in other situations concrete splinters are thrown many meters away, with possible direct exposure of rebars to the flames.

Some Authors [12] proved to be sceptical about the role of pore pressure in accelerating the fractured shards, because crack opening implies a huge increase of the initial pore volume and, in their opinion, no significant amount of water could flow into this gap from the surrounding concrete in the very short duration of the explosive spall. Then a sudden pressure drop is expected and just the elastic strain energy due to thermal stress would be converted into fracture and kinetic energy. This point of view was partly corroborated by the energy balances proposed in [13], though the contribution from pore pressure was recognized necessary when the splinter velocity exceeds 5m/s, which is often the case [14]. Involving in the energy balance the adiabatic expansion of an initial volume of pressurized vapor required considering an already widely open crack (0.5mm) filled with gas at significant pressure (4MPa), a steady condition which looks not realistic to reach, since concrete loses most of tensile strength already with a tenfold thinner crack [15].

An alternative to account for the mechanical work developed by pressurized fluids was the definition of the "influencing region" [14], namely the domain around the crack contributing to the inflow of water vapor into the opening gap (Figure 1). Unfortunately, no indication was provided in this study about the thickness d_{max} of this band of moist concrete facing the opening crack, though this is a crucial parameter to determine the rate of moisture migration and then to rebut the original arguments against this perspective [12].

The focus of this paper is to gain a deeper insight into the intriguing concept of the influencing region. Direct observation by means of Neutron Radiography (NR) during fast thermo-hygral transients is the key objective of the research project. The background idea, the test setup and some first results are illustrated in the following sections.



spall of a 20mm layer [13]	kJ/m^2
elastic strain energy	1
fracture energy	0.5
kinetic energy (v=12m/s)	3
1 mm thick layer at 250°C, 4.0MPa	
sensible heat for 1°C temperature variation *0.001m · 2350kg/m^3 ·1kJ/kg°C*	2.4
latent heat of vaporization of 1% moisture b.w. *0.001m · 2350kg/m^3 · 0.01 · 1715kJ/kg*	40
adiabatic expansion work of 1% vapour b.w. *from 40bar to 1.013 bar, c_p/c_v = 1.48, V_2/V_1 = 12*	6.8

Figure 1 The influencing region next to an opening crack [14] and magnitudes of energy contributions involved in the spalling phenomenon.

TEST PRINCIPLE AND FIRST VALIDATION

As discussed, the magnitude of the different energy shares governing the sudden separation of concrete fragments from the exposed cover was the object of former studies available in the literature [13, 14]. Some indicative figures per unit spalled area are reported in Figure 1, together with the terms entailed by unit temperature and moisture content variations within a unit thickness layer under typical conditions for incipient spalling. These latter values should be doubled, since both faces of the opening crack are influenced by the surrounding concrete.

What stands out is the dominant role of thermal energy and latent heat of vaporization compared to what is demanded for fracturing and accelerating the surface splinters. Cooling a thin layer of hot concrete by a few tens of degrees provides far more energy than required for vaporizing water and pressurizing the opening crack. If one considers that the heat flux entering the exposed face of a concrete member during the first ten minutes of severe fire scenarios (from standard to RWS fires) can be as high as 25-50kW/m^2, the energy mobilized by explosive spalling corresponds to the thermal flux accumulated by the concrete cover in less than one second.

Another important outcome of the cited figures is that the amount of water which should be quickly vaporized to accelerate the fractured shards to their maximum observed velocity can be taken from a layer much thinner than 1mm. Reducing the size of the involved region has a significant impact on the time scale of thermal and hygral transients. Heat conduction transients are ruled by Fourier's dimensionless time, which goes with 1/d^2 (where d is the distance through which conduction occurs). While heating rebars across a 30mm cover may take one hour, moving heat within the influencing region would take a fraction of a second. Water movement is also expected to be considerably faster, because of both the reduced path distance and the steeper pressure gradients (i.e. higher fluid velocity according to Darcy's law).

In order to confirm the ability of the influencing region to exhibit a fast thermal response under a sudden drop of pore pressure, a simple test setup was devised (Figure 2). One face of a concrete cylinder was sealed by gluing the rim of an aluminium plate with heat resistant silicon (OTTOSEAL S17 by Otto Chemical). A small gap was left between the concrete face and the plate by inserting a spacer (1mm). A blind central hole and two radial ducts drilled in the plate allowed connecting the gap to a pressure sensor and a solenoid valve. The plate was packed with threaded ties to balance the thrust produced by vapour pressure. The temperature of the concrete face was monitored with a thin shielded thermocouple (1mm diameter) inserted in a sub-surface hole.

After insulating the sample with ceramic fibre, one end of the concrete cylinder was heated by means of a ceramic radiator. Both configurations in Figure 2 were checked. In principle, heating the sealing plate has the pros of a faster response and no risk of vapour condensation in the ducts within the aluminium plate. On the other hand, a significant temperature difference develops between the plate and the sample (due to high thermal flux), the concrete face has a higher tendency to dry and the silicon undergoes more demanding operational conditions. In summary, the reversed layout with the sealed gap opposite to the heater proved more effective and reliable and was preferred thereafter.

The samples were some spare cylinders of ordinary concrete kept for several years in the laboratory environment. Despite of the relatively low saturation and the lack of any lateral sealing, a significant pressure was produced in the gap (≈ 1MPa). Upon opening the solenoid valve the gauge pressure dropped to zero and a sudden vaporization of moisture at the sealed surface was made possible (Figure 3). At the same time, a remarkable drop of temperature was observed (-90°C), confirming that vaporization occurs at the price of a loss of thermal energy stored in the material. It has to be remarked that the response time of isolated shielded thermocouples to step temperature variations is not very fast (in the magnitude of some seconds). Then, the recorded rate of temperature change may have been partly reduced by the thermal inertia of the sensor. Nonetheless, the observed initial cooling rate was as high as 120°C/s.

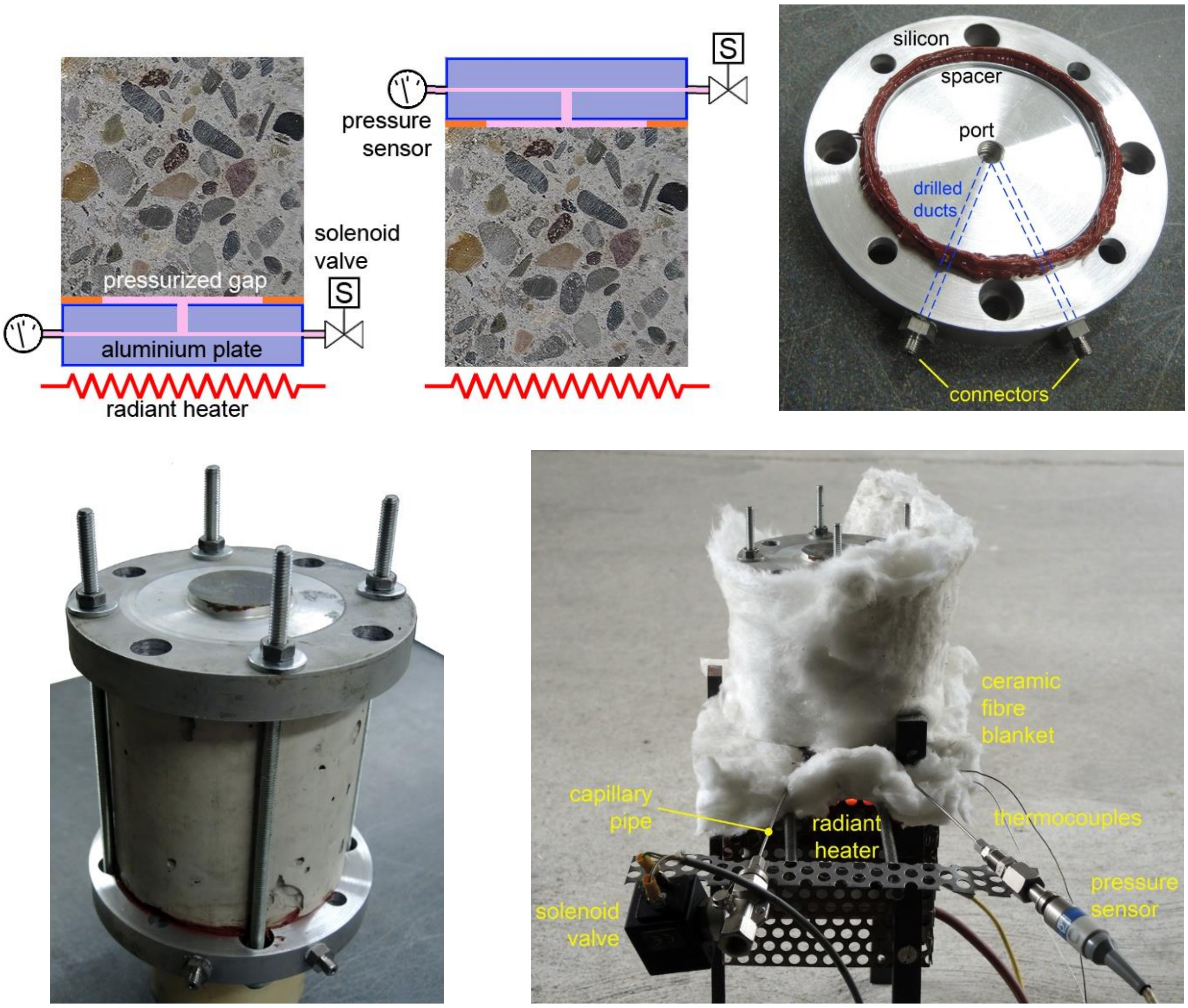


Figure 2 Test schemes for the first trial tests and details of the setup for sealing one face of the concrete sample and then releasing the pressure developed in the gap.

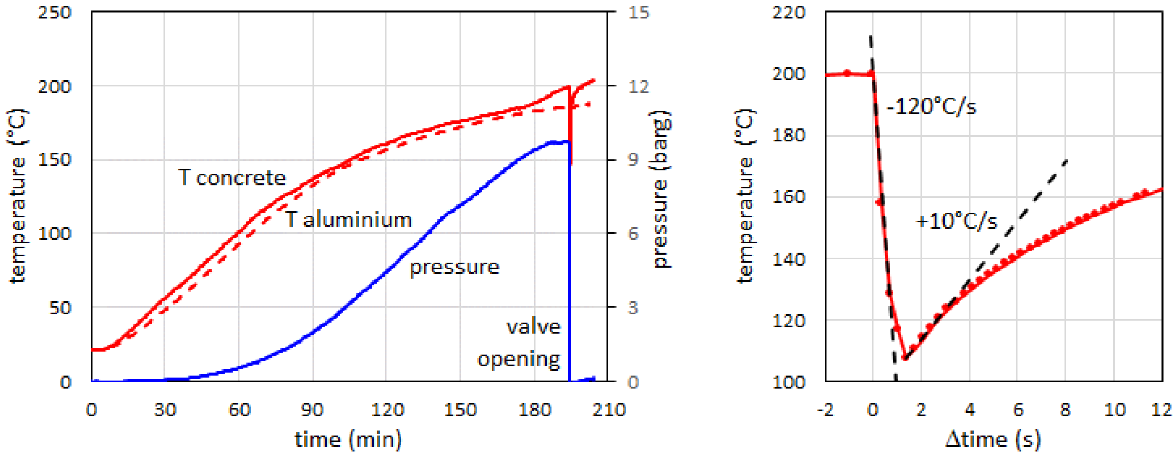


Figure 3 Temperature and pressure trends in a preliminary trial test (sealed face opposite to the heater) and temperature drop at valve opening.

After 1.38s from valve opening, the temperature suddenly stopped decreasing and a sharp inversion of rate was exhibited (from -30°C/s to +10°C/s). This indicates the end of water vaporization and settling of the local thermal disturbance by plain heat conduction. The relatively short time to settle (≈ 30s) denoted a relatively thin disturbed layer and confirmed the above considerations about the expected size of the influencing region. This encouraged the development of a similar setup allowing direct observation of moisture migration by means of Neutron Radiography.

TEST SETUP FOR NEUTRON RADIOGRAPHY

As documented by several references in the literature (see [9]), an effective monitoring of moisture migration in concrete samples can be obtained by exploiting the high penetration capabilities of neutrons into dry cement and aggregates in contrast with the high attenuation produced by the nuclei of hydrogen atoms in water molecules. In case of quick hygral transients, a high neutron flux and a not too thick specimen would allow to perform fast radiographic scans, as required by the thorough monitoring of the process. The first requirement was fulfilled by taking advantage testing facilities available at the Institute Laue Langevin (ILL) in Grenoble, France [16], which currently has the highest neutron flux in the world (about 10^8 neutrons per second per cm^2 at the instrument). Concerning the specimen thickness, based on past experience 30mm was found to be a good compromise between reducing the beam attenuation and averaging the inherent material heterogeneity (Figure 4). A relatively small aggregate size (6mm) was also chosen to this latter purpose.

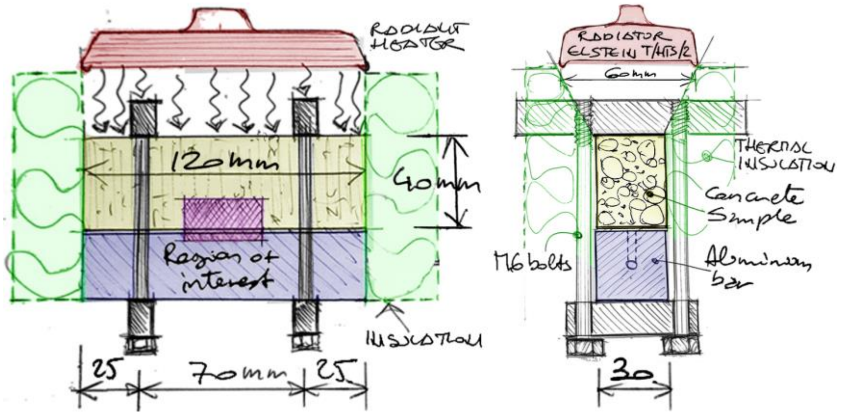


Figure 4 Design sketch of the setup for tests in the Neutron Radiography beam line.

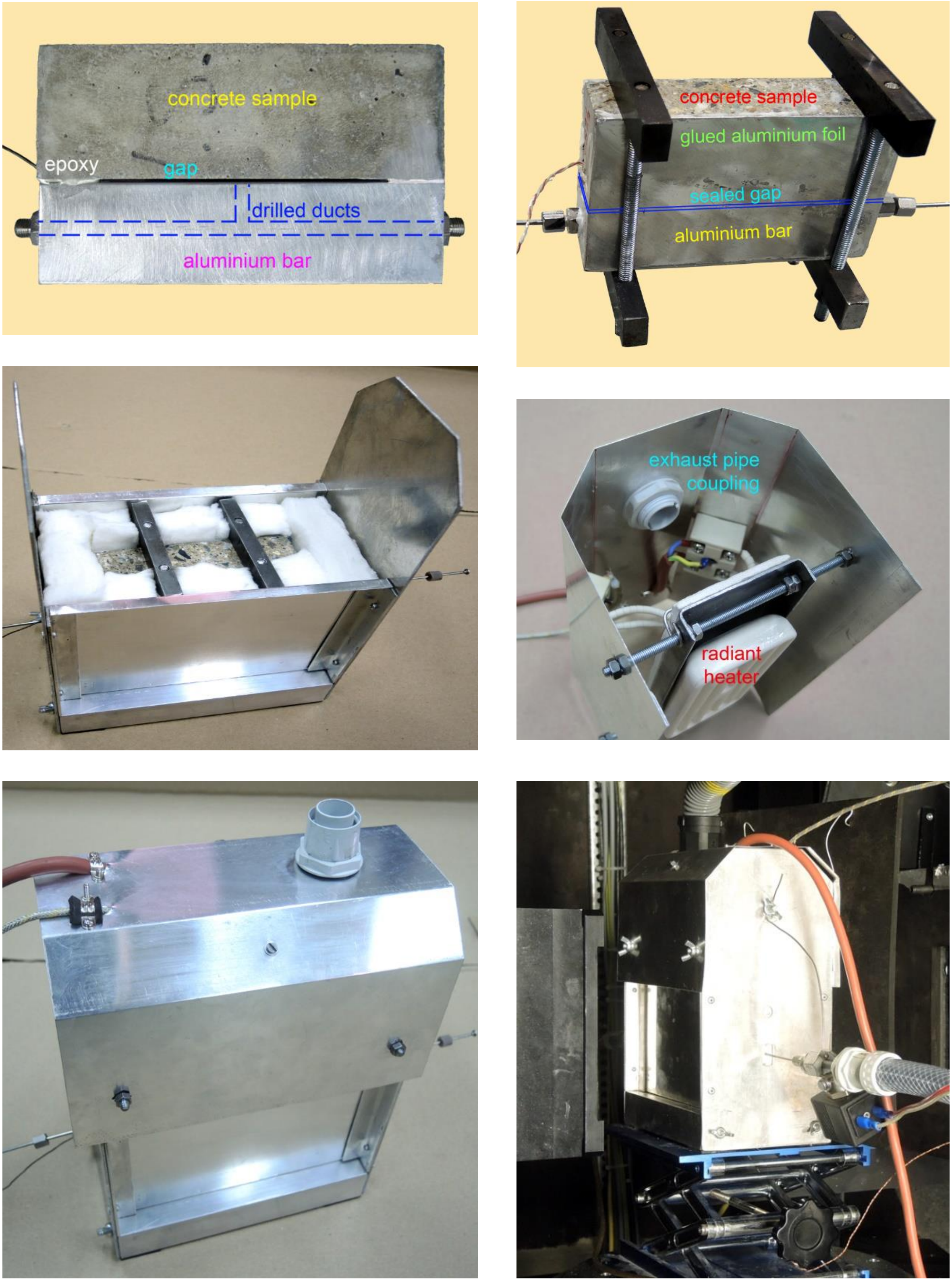


Figure 5 Details of the setup for tests in the Neutron Radiography beam line: thin gap created between the concrete sample and the aluminium bar; sealed and tied sample before and after installation in the insulated aluminium holder; hood fitted with the radiant heater and installation of the complete setup in the beamline.

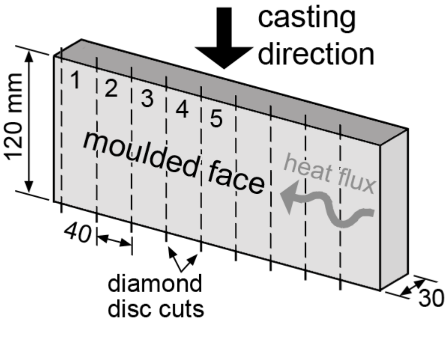
Contrary to tomographic 3D reconstructions [9], a single radiographic image reports the integral of the attenuation along the beam direction and then moisture variations across the specimen thickness should be minimized. For this reason, the opposite faces crossed by the beam were sealed with aluminium foils (0.3mm thickness) glued with heat-resistant epoxy resin (DP760 by 3M). As regards the face to be submitted to pressure transients, a thin thermocouple with exposed junction (0.3mm wires) was glued directly onto the surface with an epoxy droplet. Then, an aluminium bar (30x30mm) provided with drilled ducts and pipe connectors was glued with the same epoxy glue while interposing some spacers so to leave a 1mm gap (Figure 5). The initial idea to leave the gap open (as reported in the picture) and then to seal the sides just with the aluminium foils proved to be prone to blistering effect, due to the remarkable brittleness of the glue and stress concentration at the edges of the concrete prism. Hence, a thin rim of glue (about 3mm) was applied along the major sides of the rod as well.
After mounting of the restraint frames for balancing the pressure developing in the gap, the sealed specimen was insulated with ceramic fibre and installed in the aluminium holder. The upper hood fitted with the radiant heater and the exhaust pipe connector was then mounted on top of the holder. Finally, the whole box containing the sample was positioned in the Neutron and X-Ray imaging beamline D50 at ILL.
The tests were run by switching on the heater at full power until the target temperature 500°C was reached by the built-in control thermocouple of the radiator. Pressure and temperature in the sealed gap opposite to the heated face were continuously monitored and neutron images were taken at regular time steps (about 90s). When a change in the increasing rate of pressure was recognized, denoting the impending attainment of a pressure peak (normally after 30-60min heating), the maximum image acquisition rate was set (33 frames/s) and the solenoid valve was opened, while recording temperature and pressure at the maximum available rate (4 samples/s). At this frame rate the image resolution was 0.09mm/pixel, which is still adequate to monitor the shallow drying process occurring next to the sealed gap.

FIRST RESULTS AND DISCUSSION

A first series of tests was performed on concrete samples of normal strength batched according to the mix design of Table 1. Rectangular slabs were cast parallel to their plane, demoulded after one day and cured in water for one week. Curing continued in the laboratory environment till the time of testing. The samples were 40mm deep prisms obtained by cutting the slabs with the diamond disc. Based on this scheme, the moulded faces were sealed with the aluminium foils whereas the saw-cut faces were the object of the hygral transients, so to better replicate the material texture facing a natural crack. Right before testing, the capillary pipe connecting the pressure sensor was filled with silicon oil and the drilled ducts in the aluminium bar were partly filled with water, so to limit moisture loss from the region of interest during the preliminary heating stage.

Table 1 Mix design and orientation of saw cut samples relative to the casting direction.

cement	500 kg/m^3
water	200 kg/m^3
w/c	0.4
siliceous aggregate (d=6mm) *Bolomey's grading curve, workability A=12*	1693 kg/m^3
plasticizer (% of cement weight)	1%
age at testing	35 days
compressive strength (100mm cubes)	49 MPa



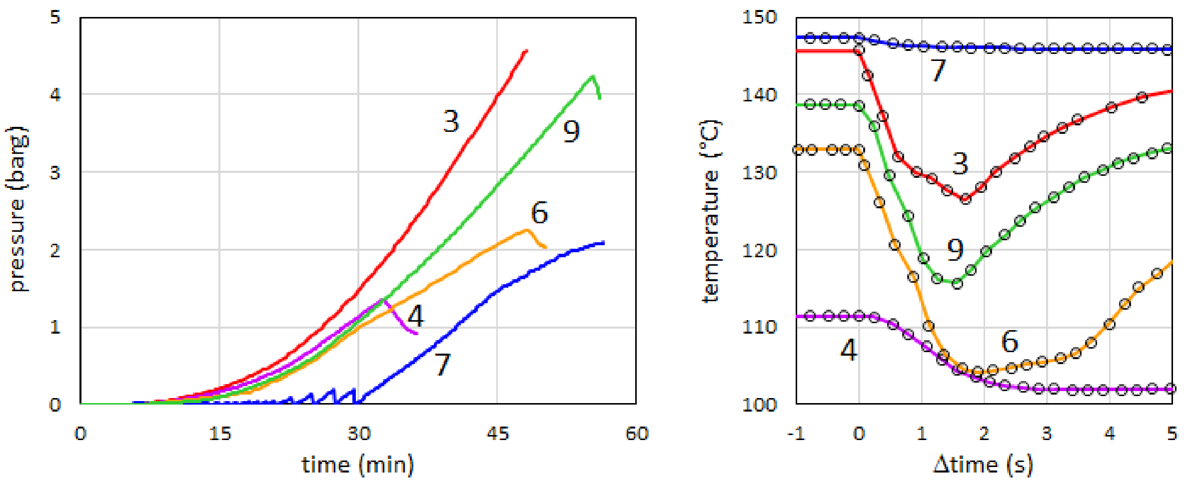


Figure 6   Pressure trends until the opening of the valve and following temperature drops in the first tests performed in the Neutron Radiography beamline.

The pressure and temperature plots obtained (Figure 6) were similar to the above discussed preliminary trial test (see Figure 3). However, lower pressure peaks (1-5 barg) occurring at lower temperature were observed, probably because of the more critical sealing conditions and possible vapour leakage in the preliminary stage of the test (see sample #4). The temperature drops at the valve opening were of lower magnitude as well (up to -30°C) according to the milder transient induced in these tests. In most cases an almost linear trend could be recognized (-20°C/s) and the minimum temperature was reached in about 2s. In these tests the results should not have been affected by the response time of the exposed junction thermocouples, thanks to their faster response. In one case (sample #7) the valve was opened several times during the heating stage, so to allow some drying of the sample. Despite of the sizeable pressure reached afterward, a very weak thermal transient was produced by the valve opening. Also in tests on samples #4 and #9 it was possible to re-pressurize the gap (1.0-1.5 barg pressure) in the same test run, but no thermal perturbation was induced by the second valve aperture.

As concerns NR images, the drying front penetration from the upper side of the samples during preliminary heating (10-15mm) was denoted by a lighter grey tone (Figure 7).

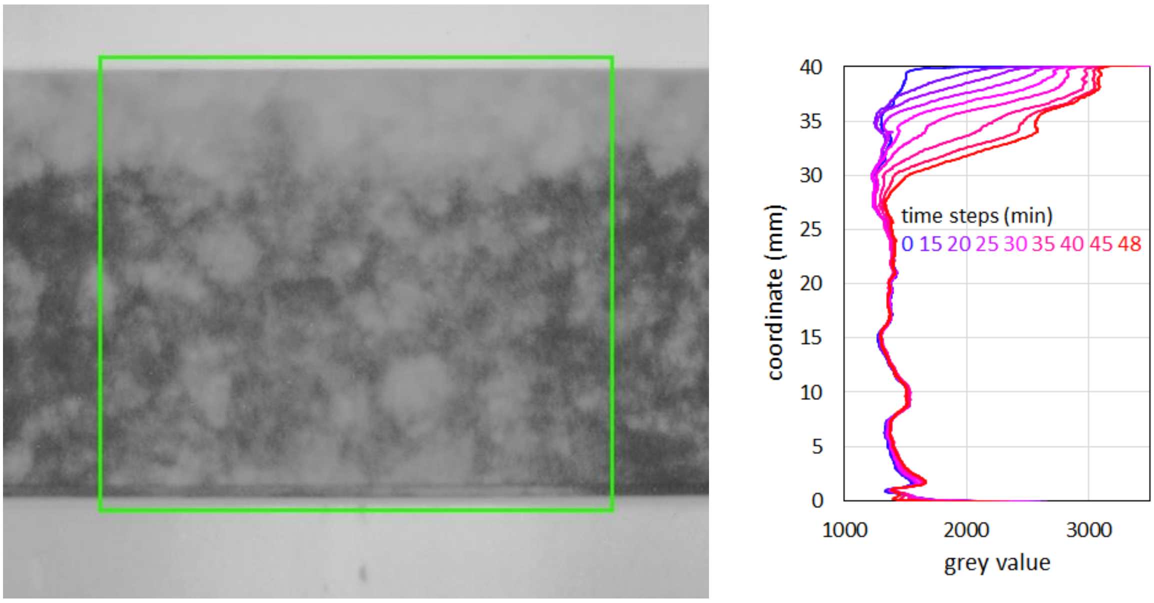


Figure 7   NR image of sample #6 right before valve opening and profiles of the grey value averaged along horizontal lines in the highlighted region of interest.

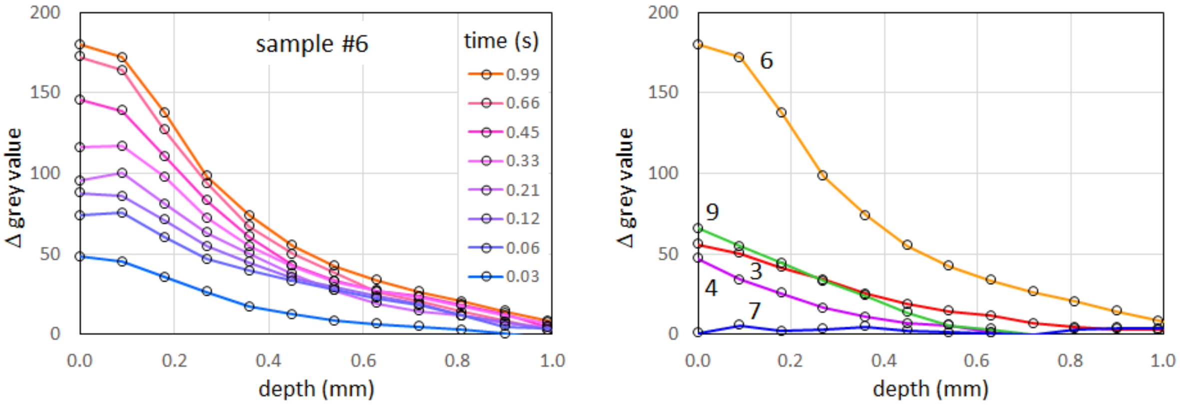


Figure 8 Evolution of grey value profiles during the fast transient following the valve opening and final profiles observed in the first 5 tests performed in this project.

In order to highlight the local perturbation caused by pressure transients, the last 10 images acquired prior to valve opening were averaged and subtracted from the following frames. The results show that within one second a local increase of grey value occurred in the first millimetre from the drying face (Figure 8). Nonetheless, some disturbance can be recognized already in the first frames, namely after a few hundredths of second from the valve opening. The final magnitude of grey value variations was within 10% of the total change induced by substantial drying at the heated face of the samples.

This preliminary analysis of raw data seems to corroborate the idea that the quick temperature drop following the sudden depressurization of an interface in hot moist concrete is caused by quick vaporization of a share of the water available in the pores.

CONCLUDING REMARKS

In this paper the quick thermal and hygral transients occurring upon depressurization of an internal interface in hot moist concrete have been addressed as a possible explanation of the explosive nature of spalling in fire. A special test setup was developed for taking fast Neutron Radiography images during this kind of transients. The first results allow drawing the following conclusions.

A sudden temperature drop is caused by depressurization of pores. A decrease by 30-90°C and a cooling rate of 20-120°C/s were observed in laboratory tests starting from relatively low initial pressure and temperature (up to 10barg at 200°C). Higher figures are expected in realistic fire conditions.

Fast NR images confirm that during these transients a relatively small share of the available moisture content was quickly vaporized within a thin layer facing the depressurized interface (about 1mm thickness). In this region a first decrease of neutron absorption could be recognized already after 0.03s.

It is worth mentioning that the sensible heat mobilized by cooling a unit volume of concrete by 100°C is three orders of magnitude higher than the expected elastic energy due to thermal strain [13]. This thermal energy would be sufficient to vaporize 6% of liquid water by weight within the same unit volume (see Figure 1). If such free moisture content were available, the work of adiabatic expansion of vaporized water coming from just a 0.05mm thick layer of concrete on both sides of an opening crack would be able to accelerate the fractured splinter to the maximum velocity documented in real fire tests. This tiny thickness would imply a very fast development of transients, as required by the highly dynamic instability involved by explosive spalling.

These early results and the connected considerations ask for a renewed attention to the role of the thermo-hygral transient on the possible ejection of the fractured concrete cover exposed to fire. The development of more realistic experiments and of numerical models adapted to the unusually short time scale at issue are the current tasks in this project.

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