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A new test method to study the influence of pore pressure on fracture behaviour of concrete during heating

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ABSTRACT

Fracture behaviour of concrete at high temperature is one of the factors governing explosive spalling, namely the expulsion of chunks due to both pressure build-up in the pores and stress induced by thermal gradients and external loads. In this context, a special experimental setup has been developed aimed at performing simple indirect-tension tests under different levels of sustained pore pressure. A cubic specimen is heated on two opposite faces, whereas the lateral sides are sealed and thermally insulated, so as to instate a mono-dimensional thermo-hygral transient field. In the splitting test, fracture develops along the symmetry plane, where both temperature and pressure are monitored by means of a customized probe. The results show that pore pressure has a significant influence on the mechanical response of heated concrete, though the concurrent contribution of external load and thermal strain is required for triggering explosive spalling.

1. Introduction

Concrete tensile behaviour in reinforced concrete (R/C) members exposed to fire is made important by the tricky phenomenon of spalling, namely the – more or less – violent expulsion of chips and shards from the hot layers due to the interaction between (a) rising pressure in the pores due to water vaporization and (b) the stress induced by both thermal gradients and external loads. Explosive spalling is a still hot issue in structural design, since it may lead to a sizable reduction of the cross-sectional area and to the direct exposure of rebars to flames, dramatically speeding up the decrease in the load-bearing capacity of R/C members.

A number of studies have been conducted on this topic [1,2] stressing the influence of both internal material factors (moisture content, porosity, tensile strength, fibre content) and external structural factors (heating rate, applied loads and constraints). These aspects control the relative roles of the two main mechanisms to which spalling can be ascribed [3,4] (Fig. 1). First, the restrained thermal dilation of the exposed concrete leads to compressive stress parallel to the surface (Fig. 1b) and to radial tensile stress in curved elements and corners, which favour cracking and a local loss of material stability. Second, vapour pressure build-up in the pores due to water vaporization and moisture flow (Fig. 1c) substantially contributes to the explosive nature of spalling, with violent bursting of thin splinters in High-Performance Concrete (HPC).

Based on high speed camera recording, a clear relationship between gas pressure in the pores and velocity of spalled-off pieces has been shown by Zeiml et al. [5]. This evidence justifies the increasing attention to the thermo-hygral behaviour of concrete exposed to fire.

From the experimental point of view, several authors [5–8] have directly measured local gas pressure in concrete specimens subjected to thermal transients. In most cases, this was done by embedding thin stainless steel pipes fitted with external pressure sensors. The setup normally includes a porous sensing head – to measure the mean pressure of larger volumes – and thermally stable silicon oil filling the pipe [9] – to improve the stiffness of the measuring chain. It has to be noted that the pressure measured in this way results from the equilibrium reached by the probe and the hot fluids (water, vapour, air) inside a limited volume of the cement matrix around the sensor head [10]. Nonetheless, consistent results have been obtained under different test conditions (concrete grade, moisture content, heating rate). Values as high as 5 MPa have been reported in the case of HPC [9], while lower values are reported for Normal-Strength Concrete – NSC [7] and polypropylene fibre concrete [6,11].

A number of authors have investigated the influence of several parameters on both pore pressure and spalling depth [7,8,12]. Their studies cover a wide range of experimental results, from low to high values of pressure and from no spalling to large amounts of spalling. Though pore pressure is definitely a driving force in spalling, the authors concluded that no direct relationship was evident, in the cases considered, between severity of spalling and measured pore pressure values. Some

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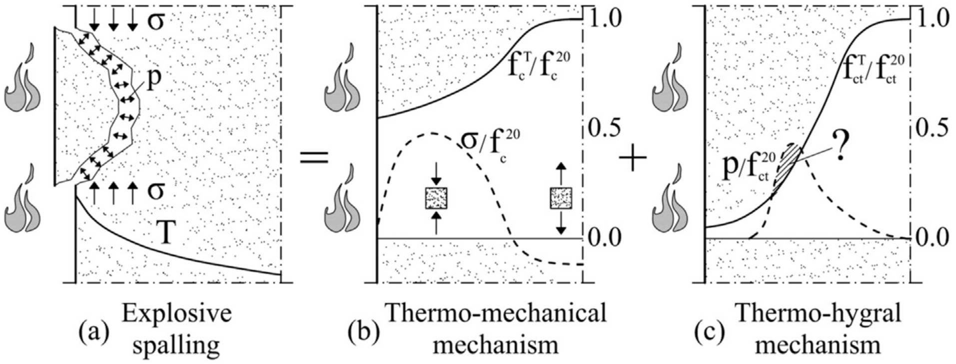

(a) Explosive spalling (b) Thermo-mechanical mechanism (c) Thermo-hygral mechanism

Fig. 1. Explosive spalling in an unloaded thick concrete wall heated on one side; qualitative plots of: (a) temperature T, (b) relative thermal stress σ/f_c^{20} and compressive strength f_c^T/f_c^{20}, and (c) relative pore pressure p/f_{ct}^{20} and tensile strength f_{ct}^T/f_{ct}^{20}.

specimens spalled with measured pore pressures lower than 0.5 MPa, while other specimens didn't spall even at pressures exceeding 3 MPa. Hence, Jansson and Boström [8] proposed a new spalling mechanism based on the concept of moisture clog: spalling is fostered by pore liquid pressure and by the lower strength of the hot, water-saturated concrete layer. Thermal dilation of liquid water inside the fully saturated pores may also initiate microcracking in the cement paste [13].

A second research line is focused on numerical models simulating the heat and mass transfer taking place in concrete when exposed to high temperatures. This involves the solution of a complex set of coupled differential equations and several approaches, based on different simplifying assumptions, have been proposed over the past thirty years [14]. Their consistency is often checked against the ability to fit temperature and pressure obtained in experimental tests. In these models, however, the mutual interaction between pore pressure and the mechanical response of the material is a critical problem, for which no experimental evidence is so far available in the literature.

As commonly done in multi-phase porous media, the total stress $\boldsymbol{\sigma}^{\text{tot}}$ sustained by the material is split into the effective stress $\boldsymbol{\sigma}^{\text{eff}}$, borne by the solid skeleton, and the solid phase pressure p^s exerted by pore fluids [15]:

$$\boldsymbol{\sigma}^{tot} = \boldsymbol{\sigma}^{eff} - p^s \cdot \mathbf{I} \tag{1}$$

where **I** is the unit tensor (tensile stress and pressure are assumed to be positive).

The main point is to understand how solid phase pressure p^s is related to the pressure in the pores, in order to define the hydrostatic tensile stress in the solid skeleton required to balance the pressure rising in the porous network. Solid phase pressure can be expressed as a combination of the gas and capillary pressures according to different expressions that have been proposed in the literature [16], as summarized in Table 1. In some models only the gas phase is considered, with different weight coefficients.

According to Biot's theory, one option for compressible fluids inside a not-well cemented stiff skeleton, is to introduce bare gas pressure into the equilibrium equations [17]. Another – and opposite – option is to assume that gas pressure is exerted just inside the pores and should be then multiplied by the material porosity [4], according to Biot's model for well cemented sedimentary rocks. An intermediate value is obtained by considering the elastic solution for intensification of stress around a spherical cavity [18]. More sophisticated models also take capillary pressure into account, multiplied by the fraction of skeleton area in contact with liquid water [14,16,19]. Nonetheless, the role of capillary pressure does not seem critical, either in modelling fast heating and moisture transients [20], or in determining mechanical damage [21].

Table 1
Definition of solid phase pressure p^s according to different authors. p^{gas}, p^c = gas, capillary pressure, χ = meniscus curvature.

$p^s = p^{gas} - \chi \cdot p^c$	Gawin et al. [14]
$p^s = p^{gas}$	Tenchev and Purnell [17]
$p^s \approx 0.8 \cdot p^{gas}$	Ichikawa and England [18]
$p^s = \text{porosity} \cdot p^{gas}$	Dwaikat and Kodur [4]

One general remark about the models cited is that they consider concrete as a porous solid in flow analysis of fluid phases, whereas the material is assumed to be a homogeneous continuum in mechanical analysis of the solid skeleton. However, exceeding "tensile strength" is the macroscopic result of unstable crack propagation through the same porous network where fluid pressure is exerted. Considering the influence of pressure on this internal instability would be a more consistent way of understanding the role played by water (liquid and vapour) in fostering the spalling phenomenon.

In order to substantiate this viewpoint, this study tackles the problem of designing a novel test setup aimed at performing a fracture test under different levels of sustained pore pressure. Contrary to most experimental techniques for material characterization at high temperature, requiring uniform steady-state temperature and not well known hygral conditions, here the test is carried out during a controlled transient. The objective is to clarify whether pore pressure may in itself – even without any significant contribution from thermal stress – be a sufficient driving force to exceed the mechanical strength and trigger explosive spalling in R/C members exposed to fire.

2. Test principle and setup

Concrete members in fire undergo high thermal gradients (due to low thermal diffusivity) and pressure build-ups (because of water vaporization in the pores). The latter is the main driving force of mass transfer, leading to both progressive drying close to the exposed surface and vapour migration toward the cold core of the structure, where water content may be increased due to vapour condensation. As a result, a quasi-saturated layer with reduced gas permeability can form, this fostering the development of high pressure peaks [3]. This phenomenon is even more severe along symmetry planes, where no moisture transport occurs. Examples are concrete cylinders and spheres, whose higher sensitivity to spalling also comes from the radial tensile stress due to their curved shape [22]. Another example is the thin web of precast I-beams (Fig. 2), which may exhibit delamination and even through holes after a fire, in spite of the shorter time they require to dry.

This latter example inspired the experimental method proposed herein: the mono-dimensional thermo-hygral transient occurring in a thin web (Fig. 2b) can be recreated by heating two opposite faces of a concrete cube. A splitting test is then performed along the mid-plane, in order to investigate the influence of pore pressure on the fracture response [11]. As will be discussed, this scheme involves the problem of preventing any thermal and mass flow through the lateral faces. On the contrary, the role of thermal stress parallel to the heated surface is