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# MULTI-PHYSICS APPROACH TO MODELLING CONCRETE AT HIGH TEMPERATURE

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## 1 INTRODUCTION

During heating of concrete, one observes several complex, interacting physical and chemical phenomena resulting in significant changes of the material inner structure and properties [1]. It is commonly known that these changes can lead to a decline of load-bearing capacity or other important service features of concrete structures, especially during a rapid or/and prolonged, increase of ambient temperature, like for example during a fire or a nuclear accident. An interesting phenomenon, very specific for concrete and of a great practical importance, is the so called thermal spalling which can sometimes be explosive in nature. This has been studied, both experimentally and theoretically, for many years but it’s physical causes are still not fully understood and their relative significance is controversial. Within the recent years the authors of the paper have developed a mathematical model and a computer code based on it [1-6]. In section 2 we will present a brief analysis of physical processes in a heated concrete element, which can lead to thermal spalling of an external concrete layer, using results obtained with the above mentioned model.

## 2 PHYSICAL PHENOMENA LEADING TO THERMAL SPALLING IN HEATED CONCRETE

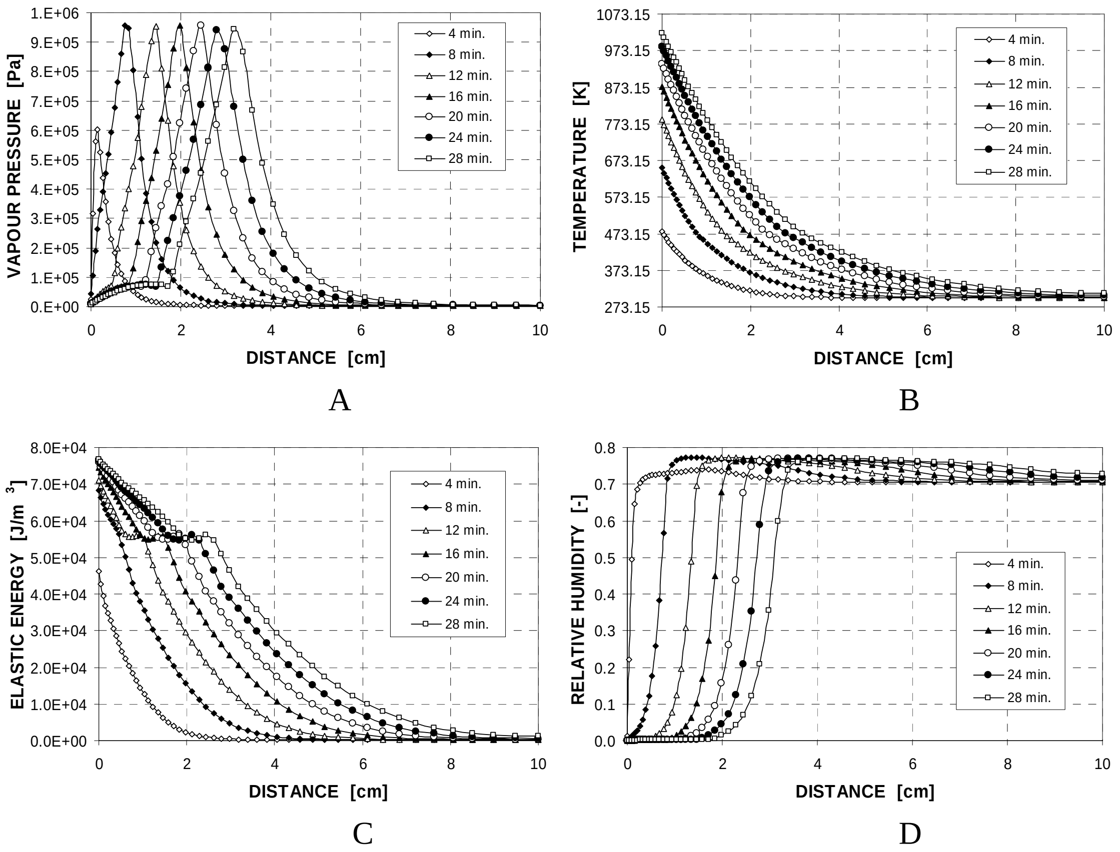
A complete description of physical phenomena in heated concrete based on the available literature, concerning high temperature tests of concrete elements, performed over years, as well as the results and interpretation of our own computer simulations, can be found in [1]. For clarity, our considerations are illustrated (Figure 1) by the results of simulations concerning a 10-cm wall, made of a C-60 concrete (see [1]), exposed on one side to the standard ISO fire, i.e. a rather fast heating.

Let us assume that a 2-cm layer of the wall spalls after 16 minutes, that is at the position where at this time instant the vapour pressure has reached its maximum value (Fig.1a) and the temperature is equal to ~200°C (Fig.1b) what corresponds to the situation often observed during experiments [1]. The total kinetic energy of the concrete pieces spalled from 1 $m^2$ of the heated surface may be estimated as ~550 $J/m^2$. This is the difference between the elastic strain energy, released after spalling of the 2-cm layer, equal to ~1150 $J/m^2$ (i.e. the area under the graph of elastic energy, Fig. 1c, between x=0 and x=0.02 m) and the energy consumed for fracturing, equal to ~600 $J/m^2$, if one assumes the specific fracture energy of $G_f \cong 200$ $J/m^2$ [1] and the total fracture surface $A_f \cong 3$ $m^2$ (i.e. an average piece of concrete has dimensions 0.02m x 0.02m x 0.02m). For a smaller value of the total surface of all cracks created during concrete fracturing, i.e. for larger dimensions of the spalled material pieces, their kinetic energy would be even higher. The kinetic energy of 550 $J/m^2$ corresponds to the average velocity of the concrete pieces of ~4.7 m/s, if one assumes the concrete density of $\rho$=2500 $kg/m^3$ and hence the total mass of the spalled concrete equal to $m$=2500$kg/m^3$ x 0.02m x 1$m^2$=50kg. Such a high value of the velocity indicates that the analysed phenomenon can be of explosive nature. Some contribution to the concrete fracturing and then increase the kinetic energy of the spalled material pieces has also the compressed gas. Assuming that it has initially a pressure of $p_1 \cong 0.95$ MPa (Fig. 1a) and that during spalling it expands adiabatically (what is a good approximation for very quick processes) to the atmospheric pressure ($p_2 \cong 0.1$ MPa), the work performed by the gas, $W$, can be estimated from the well known relationships valid for ideal gases:

$$W = \frac{p_1 V_1 - p_2 V_2}{k-1}; \qquad p_2 (V_2)^k = p_1 (V_1)^k \tag{1}$$

where $k=c_p/c_v$ is the specific heat ratio characteristic for a given gas, $c_p$ and $c_v$ are the isobaric and isochoric specific heats of a gas, and $V_1$ and $V_2$ are the initial and final gas volumes. Let us assume that $k \cong 1.39$, i.e. the value for air at T=200°C, and that the crack has initially a width of ~0.5 mm. This value seems to be reasonable and has been only used to estimate the order of magnitude for the work $W$ performed by gas. The higher the initial crack width, the higher would be the $W$ value. For 1 $m^2$ surface one obtains: $V_1$=0.0005 $m^3$, $V_2 \cong 0.0025$ $m^3$, and $W \cong 570.3$ $J/m^2$, what is the value comparable to the released elastic strain energy and to the fracturing energy. Taking into account the work $W$ performed by the pressure, the total energy of the concrete pieces spalled from 1 $m^2$ will be equal to ~1120 $J/m^2$, what corresponds to the average velocity of the concrete pieces of ~6.7 m/s. For the initial gas pressure as high as 4 MPa, i.e. measured for a heated HPC concrete by Kalifa et al. [7], one obtains $W \cong 3306.5$ $J/m^2$, what is a visibly higher value than the elastic strain energy and the energy necessary for development of fractures. In such a case the kinetic energy of the concrete pieces would be ~3856 $J/m^2$, and the average velocity ~12.4 m/s. Of course, the presented quantitative analysis has only a simplified character and is based on several assumptions, e.g. concerning adiabatic character of the gas expansion, as well as geometry and dimensions of the fracture and spalled pieces of concrete. Then, it neglects some physical phenomena, like for example energy dissipation, more complex behaviour of the water vapour - air mixture, different from a perfect gas, rapid evaporation of water after crack opening and resulting decrease of the water pressure, etc. Nevertheless, it clearly shows that the constrained elastic energy in a heated concrete element may be sufficient for development of cracks and to give a considerable kinetic energy to the pieces of spalled concrete. The gas pressure may contribute mainly to an increase of the kinetic energy, which in the case of higher gas pressures can be high enough to consider thermal spalling as an explosive phenomenon. However, the necessary condition for this is previous existence of cracks – the higher is their initial width, the higher the velocity which can be reached by the pieces of spalled concrete. Some researchers, hold view that the cause of explosive thermal spalling, especially after prolonged heating of concrete elements, may be formation of the so called "moisture clog" or "saturation plug" zone, Fig. 1d, and simultaneous thermal dilatation of liquid water what in the fully saturated pores may result in a rapid increase of the water pressure. Such a situation is more probable in concrete elements, with higher initial moisture contents, after prolonged heating. Simplified calculations done for a non-deformable skeleton show, that a temperature increase of 50 K in the pores fully filled with liquid water is sufficient to increase the water pressure by $\Delta p^w$=~75.9 MPa (assuming for water that the thermal volumetric expansion coefficient $\beta_T$= 6.95•$10^{-4}$ $K^{-1}$ and the compressibility coefficient $c_w$= 4.58•10-10 $Pa^{-1}$). If this pressure occurred at the distance $\Delta x$= 5 cm from the heated concrete surface (after longer heating the high pressure zone usually occupies the central part of the element, see e.g. [4]), and the temperature there was equal to about 200°C, at which the explosive spalling is often observed, e.g. [1], the mass flux of liquid water for the concrete with a porosity $n$=0.095 and an average permeability $k$=3•10-15 $m^2$ (these are possible properties of the C-90 concrete at $T$=200°C, [1]) would exceed 72 kg/$m^2$•s (assuming the average water pressure gradient equal to $\Delta p^w/\Delta x$). This estimation gives the lower limit of the possible water flux, because in reality the outer layer of concrete would have higher temperature and hence higher permeability, and the pressure gradient would be higher because the layer close to the heated surface is usually almost dry at temperatures exceeding 200°C, see Fig. 1b. In these conditions, the total mass of the water inside the pores may be of ~82 kg/$m^3$, what means that all the mass from the "moisture clog" zone would outflow within a fraction of second. Even if the analysed process had started at lower water pressure, let us say 10-15 times, i.e. comparable to the tensile strength of concrete, this pressure would be still high enough to cause water outflow from the zone in a couple of seconds. It seems rather impossible that the rate of temperature increase and resulting increase of the water volume would be able to compensate the water outflow and maintain its' pressure at high level, even for a short period of time. This shows that the pressure increase due to thermal dilatation of the liquid water, fully saturating the concrete pores, cannot be considered as a cause of the thermal spalling.

Considering physics of the phenomena in heated concrete presented in this section, it is quite obvious that a high initial moisture content, a high heating rate, a low concrete porosity (hence also permeability), an additional compressive load parallel to the heated surface, and use of aggregates with high thermal expansion are factors favouring thermal spalling. This also explains why application of the PP-fibres considerably decreases thermal spalling risk.



A B

C D

Fig.1. Results of computer simulations concerning the first 28 minutes of ISO 834 fire in a 10-cm concrete wall made of C-60 concrete. Evolution of the space distribution of the following fields: a) vapour pressure; b) temperature; c) elastic strain energy; d) relative humidity.

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