Numerical simulation of polypropylene fibres in concrete materials under fire conditions

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ARTICLE INFO

ABSTRACT

In recent years experimental investigations have demonstrated that the risk of spalling for a concrete material under fire conditions is drastically reduced by using a low dosage of polypropylene fibres in the mix design. This effect can be explained by considering the increase in voids connectivity within the cement paste and in concrete porosity due to polypropylene evaporation above certain temperatures.

In this work the complex mechanism of polypropylene contribution on concrete behaviour under thermal conditions has been numerically evaluated through a coupled hygro-thermal–mechanical finite element formulation.

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1. Introduction

The role of polypropylene (PP) fibres into concrete mix design to prevent the spalling phenomena, when concrete structures are subjected to elevated temperatures, is largely recognised. Explosive spalling can be explained by taking into account two main contributions: a thermal stress, generated by a thermal gradient between the heated surface and the internal concrete zone; and the pore pressure increments in concrete that occurs when the internal water evaporates [1].

Studies from different researchers have proved that PP fibres reduce pore pressure in the cement paste so decreasing the risk of explosive spalling [2–4].

At high temperatures PP fibres' evaporation creates voids channels in the cement paste so increasing the connections between the pore network in the matrix and consequently the material permeability and diffusivity [5,6].

The porosity in concrete enriched with fibres can be found by considering different contributions starting from the initial porosity (subdivided into capillary porosity, micro- and macro-porosity), dependent only on mix design such as: w/c ratio, aggregates type, hydration degree etc. [7,8].

Additionally fibres employed in concrete increase the initial porosity at room temperature by increasing the pore connectivity in the ITZ (the interfacial transition zone, a thin layer close to aggregates and fibres [2,6]); at elevated temperatures, after PP melting, a connection of the micro air bubbles trapped in the cement paste [3] occurs as well, and the maximum increment is reached when the fibres change phase, passing from liquid to gas through vaporisation.

In this work an empirical law accounting for porosity variation due to PP fibres is proposed and the whole model is calibrated against numerical and experimental data.

Particularly, a 1D hygro-thermal finite element code has been built to evaluate thermal and humidity variations within concrete subjected to elevated temperatures in agreement with [9–11], where the hydraulic diffusivity relation has been modified by taking into account the porosity variation induced by polypropylene fibres.

A model calibration has been carried out referring to [12] where concrete samples under high thermal conditions have been simulated.

The effect of PP fibres has been compared with experimental evidences obtained from [3] where the inclusion of fibres causes a high reduction of internal pores pressure in concrete samples, so reducing the spalling risk.

2. Polypropylene fibres

The polypropylene fibres generally employed in concrete materials to prevent spalling phenomena are anisotropic monofilaments with diameter d_f between 10 to 100 μm and a length L_f between 3 to 20 mm. It has been experimentally verified that this type of fibres are not able to increase the material stiffness [1], but under high temperatures the explosive spalling risk decreases if the volume content in the mix design is between 1 and 3 kg per m³ of concrete. Below 1 kg/m³ such an effectiveness is reduced.

During concrete cast the hydrophobic condition of PP fibres is such that water is removed generating a thin layer around the fibres themselves, with different characteristics compared to the

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Nomenclature

$A_{a,1}$	aggregate surface	t	time
c	permeability	T	temperatures
C	hydraulic diffusivity	$t_{a,ITZ}$	ITZ thickness around aggregates
$\mathbf{C}$	capacity matrix	t_e	concrete age
d_i	diameter of ($i = a$ aggregates; $i = f$ fibres)	$t_{f,ITZ}$	ITZ thickness around fibres
$\mathbf{F}$	flux vector	T_{PPi}	characteristic i-temperatures for PP fibres
G_c	cement dosage	T_0	absolute temperature
h	humidity	$\mathbf{u}$	variables vector
h_c	critical humidity	V	reference volume
$\mathbf{J}$	moisture flux	V_a	aggregates volume
k_d	cotangent of the slope of the desorption isotherm	$V_{a,1}$	single aggregate volume
k_i	hygrometric coefficient	V_c	cement volume
$\mathbf{K}$	diffusivity matrix	V_f	fibres volume
m_a	average aggregates number	V_{ITZ}	ITZ volume around aggregates
n	porosity	v_p	capillary pore volume (in [l])
$n_{a,ITZ}$	porosity part related to aggregates ITZ connected by fibres	V_p	capillary pore volume (in [m³])
n_c	capillary porosity	$V_{va,ITZ}$	total voids volume in ITZ around aggregates
n_{cls}	initial porosity in concrete	V_v	voids volume
n_m	micro porosity	V_w	water volume
n_M	macro porosity	w	water content
n_f	porosity part due to fibres evaporation	w/c	water cement ratio
$n_{f,ITZ}$	porosity part due to fibres ITZ	α_i	hydration degree
p_{gw}	water vapour pressure	ρ_c	cement density
p_{gws}	water vapour saturation pressure	ρc_p	thermal capacity
p_{gws0}	water vapour saturation pressure at T_0	ρ_f	fibres density
q	heat flux	Δn	porosity increment

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cement paste and a greater initial porosity (this zone is named ITZ of the fibres). Additionally during concrete mixing, fibres make a network that increases pores connection in concrete, so connecting even the ITZ around aggregates and the micro air bubbles trapped in concrete during mixing. The sum of these effects increases the initial porosity at low temperatures.

Polypropylene at room temperature is a material in solid state with a low density (about 0.85–0.95 g/cm³) and a low elastic modulus (about 0.5–2.4 GPa). When PP is heated, two phase changes occur at certain fixed temperatures [2]:

1. $T_{PP0} \approx 165\ °C$ temperature of melting.
2. $T_{PP1} \approx 200\ °C$ end of melting.
3. $T_{PP2} \approx 325\ °C$ temperature of evaporation.
4. $T_{PP3} \approx 475\ °C$ end of evaporation.

At room temperature PP is in a solid state with a molecular structure about 55% crystalline and 45% amorphous. When temperature increases to the melting phase (between T_{PP0} and T_{PP1}) PP chains loose the crystal conditions and become amorphous with increasing viscosity. In this phase the elastic properties of PP decrease and a relaxation of the cement matrix occurs [13].

When temperatures increase over T_{PP3}, the PP vaporisation process finishes and the connected voids channels appear increasing the water vapour diffusivity of concrete.

3. Concrete porosity without fibres

Porosity n in a concrete material is the part of voids, connected among themselves, that can permit the transport of gases and water. By considering the total reference volume V, n can be evaluated with the relation:

$$n = \frac{V_v}{V} \tag{1}$$

where V_v is the connected void volume in concrete.

The initial porosity in the concrete paste, without fibres, can be subdivided into three main parts: 1) the capillary porosity n_c dependent on water cement ratio w/c and mix design of concrete [8]. Capillary pore volume can be evaluated following Power's [14] equation:

$$V_p = 0.1w/c - 0.03615\alpha_i \tag{2}$$

where V_p is the volume of the capillary pores (in [m³]) and α_i is the hydration degree.

2) The macro porosity n_M, dependent on the micro air bubbles trapped during concrete mixture, generally assumed between 1 to 2%; and 3) a micro porosity (gel pore) n_m, assumed around 6%.

$$n_{cls} = n_c + n_M + n_m \tag{3}$$

The initial porosity in a concrete material with a water cement ratio $w/c = 0.5$ and with $\alpha_i = 1$ varies, e.g. from $n_{cls} = 0.15$ to $n_{cls} = 0.25$.

4. Porosity variation with polypropylene fibres

Experimental tests [3] have evidenced that the presence of polypropylene fibres in the mix design of concrete causes a little increment of initial porosity at lower temperatures (room temperature) which can increase further when concrete is exposed to elevated temperatures. This behaviour can be explained considering different effects that the presence of polypropylene fibres cause in concrete, among which:

1. Connection of the ITZ pores around aggregates. This effect causes a porosity increment $n_{a,ITZ}$ compared to the initial concrete porosity n_{cls}.
2. Porosity increment near fibres caused by ITZ formation around fibres $n_{f,ITZ}$.
3. Voids variation due to relaxation of PP fibres n_{relax}.