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On the mechanism of prevention of explosive spalling in ultra-high performance concrete with polymer fibers

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ABSTRACT

It has been a common practice to use polymer fibers to reduce susceptibility of explosive spalling in ultra-high performance concrete (UHPC). However, to-date, despite the proposition of different mechanisms through which polymer fibers enhance gas permeability and reduce explosive spalling, there are many unanswered questions and unjustified claims on the proposed mechanisms. Therefore, the major emphasis of this work is to thoroughly re-examine and understand the exact role of polymer fibers in the prevention of explosive spalling of UHPC. A range of analytical and microscopic tools are used to realize this objective. It is concluded that melting of polymer fibers and creation of empty channels are not required for enhancing the permeability of gases or water vapor through concrete. In fact, it is the thermal mismatch between embedded fibers and matrix that is critical in obtaining an interconnected network of cracks in the matrix. This occurs even before melting of polypropylene (PP) fibers. The network of cracks is responsible for enhancing permeability, thereby reducing the susceptibility of explosive spalling of UHPC.

1. Introduction

Despite the high compressive strength of ultra-high performance concrete (UHPC) (typically > 150 MPa), it is susceptible to explosive spalling when exposed to fire. As a result of explosive spalling, the rate of heat flow to inner layers of member(s) increases, compromising the load-carrying capacity of structures [1]. The mechanisms for explosive spalling have been studied quite extensively for many decades and it is now widely accepted that a combination of build-up of internal pore pressure and thermal stresses is required for spalling to happen. Simply put, the pore pressure build-up, which is a trigger for spalling, is a result of restricted pathways for evaporated free water and physically-bound water [2,3]. In regions closer to the heated surface, due to restriction of thermal dilatation, compressive (thermal) stresses will develop parallel to the heated surface resulting in spalling [4]. Therefore, thermal characteristics like heating rate play an important role in determining the extent of spalling.

For resisting spalling, different approaches have been proposed to tackle both material-scale phenomena/properties of concrete (improving gas permeability and inherent characteristics like initial moisture content) and structural properties such as steel reinforcement, thickness of concrete cover, etc. [5–7]. As there are many studies on these aspects, to avoid duplication, the authors will only present a critical review of widely-used methodologies of preventing explosive spalling with polymer fibers, which is the focus of this work.

Many spalling prevention mechanisms with PP fibers (added to concrete in the range of 1 to 3 kg/m^3) were proposed, although they have not yet been fully validated by actual spalling test results. These include the formation of pressure-induced tangential space (PITS) [8], interfacial transition zones (ITZ) between the fibers and concrete matrix [9–11], and microcracking at higher temperatures of 200 °C [12] and even at 400 °C [16]. Nonetheless, melting of PP fibers and creation of pathways to relieve the vapor pressure built-up in concrete is the most commonly accepted spalling resistance mechanism in the literature [7,13]. Despite the extensive literature on this topic, many aspects of this proposed mechanism are qualitative, and many questions still remain unanswered. For instance:

(i) what is the role of molten polymer in spalling (which generally happens in the temperature range of 200–300 °C [2])?
(ii) How does this polymer melt flow in concrete so as to create empty channels to release trapped vapor pressure as the polymer does not even start to decompose until 265 °C (onset decomposition temperature, $T_{5\%}$, where 5% of mass loss occurs)?

On this aspect, some studies have claimed that PP melt is partially

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Table 1
Mixture compositions of UHPC (unit in kg/m^3).

W/B[a]	Cement[b]	Silica fume	Silica sand	Superplasticizer	Fine aggregate	Water	PP fiber[c]
0.2	830	208	208	33	913	208	3

[a] W/B: water to binder ratio.
[b] Portland cement (ASIA@CEM II 52.5 R).
[c] PP fiber was added only in UHPC/F.

absorbed by cement matrix [14,15]. However, it is difficult to accept this considering the high melt viscosity (600–1000 Pa·s at 250 °C depending on applied shear rate) and size (hydrodynamic volume) of the polymer chains. Another important aspect is the significant increase in permeability of UHPC including high-performance concrete (HPC) even below the melting temperature of PP fibers [16–18]. For example, Bošnjak et al. [18] noted that the permeability of concrete with PP fibers shows a sudden increase of approximately two orders of magnitude (from $\sim 3 \times 10^{-18}$ m^2 to 2×10^{-16} m^2) between 80 °C and 130 °C. In this regard, the major focus of this work is to thoroughly re-examine the exact role of PP fibers in the prevention of explosive spalling of UHPC. For this purpose, a range of analytical, physical and microscopic characterization techniques are used on the concrete samples before and after subjecting to elevated temperature.

2. Experimental work

2.1. Materials and sample preparation

The mix proportion of materials used for UHPC in this study is shown in Table 1. The mean size of silica sand was 110 μm. Natural river sand with the maximum size of 0.6 mm was used as fine aggregate. PP fibers with a density of 910 kg/m^3 and an aspect ratio of ~360 (12 mm length and 33 μm diameter) were obtained commercially. Polycarboxylic type superplasticizer (Sika ViscoCrete-2044) was used in all concrete mixtures. Samples of UHPC with and without PP fibers, were denoted as UHPC/F and UHPC/O, respectively, hereafter. The specimens were demolded after casting for 1 day and stored in lime-saturated water at ambient temperature for 27 days. The compressive strength values of UHPC with and without PP fibers at 28 days were ~148.6 ± 3.0 MPa and 159.9 ± 2.9 MPa, respectively.

The samples for permeability test were cast in disc-shaped molds with 45 mm depth and 150 mm in diameter. After curing, the discs were grinded on both faces and smoothened, with a final thickness of ~40 mm. Cylinder-shaped samples with 50 mm diameter and 100 mm height were also prepared for spalling tests at elevated temperature.

2.2. Thermal analysis

Differential scanning calorimeter (DSC, from TA Instruments, model: Q10) and thermogravimetric analysis (TGA, from TA Instruments, model: Q500) were conducted to understand the melting and decomposition behavior of PP fibers and concrete mix. A constant heating rate of 5 °C/min from room temperature to 400 °C was employed in DSC, while in TGA, a ramp of 5 °C/min was used to heat up to 400 °C in the air atmosphere. The gas flow used in both DSC and TGA was set at 100 ml/min. To understand the dimensional changes and variations in coefficient of thermal expansion (CTE) of fibers, cement paste and aggregates with temperature, thermomechanical analyzer (TMA, from TA Instruments, model: Q400) was employed. The samples were heated in a furnace with a probe in contact that is connected to a strain detector and a force generator. The force was set at 0.01 N. For the cement paste and aggregate, the samples were heated to 300 °C with a heating rate of 5 °C/min, while the maximum temperature of 150 °C was used for PP fibers. All the TMA tests were performed under nitrogen atmosphere.

2.3. X-ray diffraction

X-ray diffraction (XRD) measurements using CuKα radiation were conducted on UHPC/O and UHPC/F to identify the crystal phases. The sample sections were 18 mm in length, 12 mm in width and 3 mm in thickness. Four batches of samples were prepared for each mix for testing at different selected temperatures, i.e., ambient, 105 °C, 150 °C and 250 °C. Since spalling of concrete usually occurs at a temperature ranging from 200 °C to 300 °C [2,19], only behaviors under 300 °C are of interest in this study.

2.4. Microscopic observations and crack quantification

A scanning electron microscope (SEM, JSM 6360) operating at an accelerating voltage of 5 kV was used for observing microstructural changes of UHPC/F and UHPC/O at different temperatures after carefully preparing the samples following a series of grinding and polishing steps. 800, 1200 and 2500 grit sandpapers were used for initial grinding of the samples for 0.5 min, 2 min and 10 min, respectively. Then, the samples were polished on a Buehler TexMet P cloth (hard perforated and non-woven) by using 1 μm diamond paste for 20 min. Afterwards, the samples were rinsed for 5 min with isopropanol in an ultrasonic bath. For each target temperature (chosen as 105 °C, 150 °C, 170 °C, 200 °C and 300 °C), to obtain information before and after melting of fibers, samples were kept in a convection furnace for approximately 30 min. Subsequently, they were allowed to cool down naturally in the furnace.

To observe a representative area/number of fibers at high resolution (for identifying microcracks in samples) in an SEM micrograph, 25 micrographs at a fixed magnification (500×, covering an area of 256 × 192 μm^2) were taken and stitched together. This selection was based on the findings in [26,27] where it was noted that 20 frames of images at a magnification of 500× were necessary for meaningful image analysis. To perform an accurate fully-automated image analysis for quantification of microcracks, it is a requirement that the original image is of exceptional resolution with good contrast and have sharp transitions from white to black (and vice versa). Generally, SEM micrographs of concrete do not possess these qualities, and therefore, automated detection and crack segmentation methods are usually unreliable. Hence, a semi-automated approach was adopted here. The stitched SEM micrograph was converted to a binary image in which the pixels of microcracks were set to 1 (black) and the pixels of background were defined as 0 (white) by using Fuji/ImageJ software, developed by National Institutes of Health (NIH) [20]. This was followed by manual tracing using Photoshop. Finally, image analysis was performed. Based on isotropy hypothesis of crack distribution and statistics for crack length, stereology parameters were extracted from 2D images to describe the networks of cracks [21–23]. In this study, number density of microcracks (total number of microcracks divided by the image area), crack area fraction (% of crack area to the image area) and crack connectivity were quantified. Crack network (connectivity), ϕ, is defined by the following equation [22]:

$$\varnothing = 1 - \sum_{j=1}^{m} l_j^2 / \sum_{k=1}^{n} l_k^2$$

where m and n represent the number of isolated and total number of