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Influence of aggregate size and inclusion of polypropylene and steel fibers on the hot permeability of ultra-high performance concrete (UHPC) at elevated temperature

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HIGHLIGHTS

- PP fibers and larger aggregates show synergistic effect on increasing permeability.
- The addition of steel fibers does not increase permeability at elevated temperature.
- Melting of PP fiber and formation of micro-cracks help to increase permeability.
- PP fibers activated at the onset of melting, which is lower than the melting point.

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ABSTRACT

Explosive spalling is one of the most detrimental problems for ultra-high performance concrete (UHPC) in fire condition due to the risks of breaching the integrity of concrete structures. This paper investigates the influence of aggregate size and inclusion of PP and steel fibers on the intrinsic permeability of UHPC at elevated temperature. Hot permeability measurements were performed on UHPCs subjected to elevated temperature up to 300 °C. Microstructure of UHPC samples before and after the exposure to elevated temperature was studied to reveal potential mechanisms responsible for the change of permeability. Results showed that the inclusion of PP fibers or larger aggregates significantly increases the hot permeability while the addition of steel fiber does not contribute to the enhancement of the permeability of UHPC at elevated temperature. The combined use of PP fibers and larger aggregates in UHPC showed synergistic effect and resulted in the significant increase of permeability at elevated temperature, which is mainly attributed to the formation of interconnected micro-crack networks at elevated temperature due to the melting of PP fiber and thermal expansion and mismatch between the aggregate/fiber and matrix.

1. Introduction

Ultra-high performance concrete (UHPC) is generally defined as a cement-based material with compressive strength beyond 150 MPa. UHPC has been gradually adopted in civil engineering structures such as high-rise buildings [1], industrial construction [2], and bridges [3,4]. The high performance of UHPC is a result of densely packed microstructure which greatly reduces the porosity and permeability of the cement matrix leading to high strength, excellent abrasion resistance and enhanced durability [5,6]. Nevertheless, UHPC is more vulnerable to explosive spalling under fire condition [7,8]. It causes loss of concrete cover and subsequent exposure of steel reinforcements to fire, which significantly compromise the load-carrying capacity of structures [9,10].

Explosive spalling is a complicated phenomenon caused by a combination of thermal, hydral, and mechanical degradation process [11]. One of the main sources of explosive spalling is the build-up of pore pressure due to migration of water vapor towards concrete interior at elevated temperature [12,13]. If concrete is sufficiently permeable, pore pressure can be released and thus mitigating explosive spalling. In the case of UHPC, however, the very dense microstructure and low permeability hinder the release of pore pressure, which in combination with thermal stresses lead to severe explosive spalling [14].

Permeability is a measure of the ability of a porous material to transfer fluids under pressure gradient. It has been reported that

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high temperature can strongly modify the transport properties of concrete [15]. Permeability of concrete at elevated temperature is therefore one of the most important characteristics controlling moisture transport and pore pressure build-up inside concrete [9,10,16,17] and is accepted as a reliable indicator of the risk of explosive spalling.

Previous studies are mainly focused on the effect of high temperature on permeability of normal concrete and high strength concrete [18–21]. Investigation on intrinsic permeability of UHPC at elevated temperature was rather limited. Besides, most of the permeability measurement were performed at residual state, i.e. the permeability was measured after the heated specimens were cooled down to ambient temperature from heating [11,12,18,19,22,23], which may not be the same as the permeability at hot state due to the changes in microstructure after cooling.

Several strategies have been proposed to mitigate explosive spalling of concrete at elevated temperature. The addition of polypropylene (PP) fibers in high strength concrete to mitigate explosive spalling has been reported [24–27]. The inclusion of steel fibers [24–28] and larger aggregates [10,13,17,29] were also shown to have significant effects on explosive spalling. It was generally believed that PP fibers melt at elevated temperature, which leave behind empty fiber tunnels and create pathways by connecting the porous interface transition zone (ITZ) between the aggregate and the matrix, and thus increasing the permeability of concrete. In UHPC, however, no significant porous ITZ was observed between the aggregate and the matrix interface or the fiber and the matrix interface [6,30]. Therefore, the effectiveness of using fibers and aggregates to mitigate explosive spalling in UHPC is still questionable and the mechanisms are not get understood [17,22].

This paper reports the influence of aggregate size and inclusion of PP and steel fibers on the intrinsic permeability of UHPC at elevated temperature. The general principle of the experimental setup followed the RILEM-CEMBUREAU method [31] and the intrinsic gas permeability was calculated by adopting Klinkenberg method [32]. Hot permeability measurements were performed on five UHPC samples subjected to elevated temperature in the range between ambient temperature and 300 °C. Microscopic investigations were performed on UHPC samples before and after the exposure to elevated temperature to reveal potential mechanisms responsible for the increase in permeability.

2. Experimental program

2.1. Materials and mix design

A UHPC matrix with compressive strength of 150 MPa was formulated and used as the control mix shown in Table 1. The control mix consisted of cement, fine aggregates (less than 600 μm), micro silica sand, and silica fume and had a water-to-cement ratio of 0.22 to realize dense packing and high strength. Superplasticizers were used in the mix to achieve sufficient consistency and workability. To investigate the influence of fiber addition, 3.0 kg/m^3 of PP fibers were added in the UHPC-PP mix, while UHPC-S mix had 196.3 kg/m^3 (2.5% by volume) of steel fibers. Larger aggregates with the maximum size of 5 mm were used in the UHPC-AG mix to study the effect of aggregate size. UHPC-PPAG mix contained both PP fibers and larger aggregates of 5 mm to investigate the combined effects of the two factors.

The cement used in this research was ASIA® CEM I 52.5 N. The silica fume used was Grade 940 from Elkem Microsilica®, which is a high reactive pozzolan. Natural river sands were used as aggregate in the concrete mixtures. For UHPC mixes with fine aggregates, the aggregates were sieved to 600 μm. The silica sand used had a median particle size of 130 μm. Steel fibers with a length of 13 mm and a diameter of 160 μm were supplied from Dramix®. The tensile strength of the steel fibers is about 2000 MPa. Monofilament PP fibers with a length of 12 mm and a diameter of 40 to 60 μm were supplied by DFL. The tensile strength of the PP fibers is about 550–600 MPa. A third generation polycarboxylate-based superplasticizer Sika® ViscoCrete®-2044 was used in all UHPC mixtures to increase workability in the fresh state.

2.2. Specimen preparation

The UHPC mixes were prepared using a Hobart® planetary mixer. Cement, silica fume, silica sand, and aggregates were dry-mixed for 2 min. Thereafter, premixed water and superplasticizer were added and mixed for another 3–5 min until the fresh mortar is homogenous and consistent. Fibers were then added into the mixture and mixed for another 2 min. The fresh UHPC mixtures were then cast into cube (50 × 50 × 50 mm^3) and cylindrical disc (∅150 mm × 48 mm) molds for the compressive strength and hot permeability tests, respectively. During casting, the molds were placed on a vibration table to remove entrapped air for better consistency. The specimens were demolded after 24 h and stored in lime-saturated water at ambient temperature for another 27 days before testing. After curing, the surfaces of cylindrical discs were smoothened by grinding from two ends to 40 mm thick to ensure good contact with the permeability measurement device and to eliminate possible effects from the mold.

2.3. Hot permeability test

Apparent gas permeability was determined by means of the RILEM-CEMBUREAU method, which is easy to perform and reasonably accurate at the same time [31]. The apparent gas permeability was determined based on the Darcy's law which was later modified by the Hagen-Poiseuille relationship [33]:

$$k_a = \frac{Q}{A}\frac{2\mu L p_{atm}}{(p_i^2 - p_{atm}^2)} \quad (1)$$

Table 1
Mix proportions and compressive strength of UHPCs.

Mix design	Relative weight ratio to cement						PP fiber (kg/m^3)	Steel fiber (kg/m^3)	f_c (MPa)
	C	AG	SS	SF	SP	W/B			
UHPC-C	1.0	1.1^	0.25	0.25	0.03	0.22	0.0	0.0	149.6 ± 4.78
UHPC-PP	1.0	1.1^	0.25	0.25	0.03	0.22	**3.0**	0.0	159.7 ± 5.70
UHPC-S	1.0	1.1^	0.25	0.25	0.03	0.22	0.0	**196.3**	172.1 ± 3.66
UHPC-AG	1.0	**1.1***	0.25	0.25	0.03	0.22	0.0	0.0	145.0 ± 4.14
UHPC-PPAG	1.0	**1.1***	0.25	0.25	0.03	0.22	**3.0**	0.0	147.7 ± 1.49

C: cement, AG: aggregates, SS: silica sand, SF: silica Fume, SP: superplasticizer, W/B: water-to-binder ratio, f_c: Compressive strength at age of 28 days.
The bold values are variables in each mix design.
^ Denotes aggregates with the maximum size of 600 μm.
* Denotes aggregates with the maximum size of 5 mm.