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Reduction of fire spalling in high-performance concrete by means of superabsorbent polymers and polypropylene fibers Small scale fire tests of carbon fiber reinforced plastic-prestressed self-compacting concrete

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ABSTRACT

High-performance concrete (HPC) is prone to explosive spalling when exposed to fire, which may lead to failure of the concrete elements. Polypropylene fibers (PP) are often added to HPC, as upon their melting they create channels through which water vapor is evacuated, preventing the build-up of high vapor pressures. In self-compacting HPC (HPSCC), the amount of PP fibers needs to be limited in order to keep the self-compacting properties, which may reduce the fire resistance.

In this paper, a novel strategy to reduce fire spalling in HPSCC is illustrated, based on adding small particles of superabsorbent polymers (SAP) during mixing. The SAP end up as empty macropores, similar to air voids, in the HPSCC matrix. The PP fibers-SAP voids system percolates at a lower fiber loading than the fibers alone, allowing maintenance of the self-compacting properties while reducing substantially the fire spalling. In particular, in this paper it is shown how addition of SAP is able to reduce fire spalling in thin-walled HPSCC slabs prestressed with carbon fibre reinforced plastic reinforcement.

1. Introduction

Sustainability considerations in precast concrete have led to the development of novel thin-walled concrete structural elements through cautious selection, design, and optimization of both the concrete mixtures and of the reinforcing materials. An example are slender structural elements of high-performance, self-consolidating, fibre-reinforced concrete (HPSCC) reinforced with high-strength, lightweight, and non-corroding prestressed carbon fibre reinforced plastic reinforcement (CFRP) [1].

As for all load-bearing structural members in buildings, the fire performance of these members must be understood to allow their safe use. It is well known that the bond strength between both steel and fibre reinforced plastic (FRP) reinforcing bars and concrete deteriorates at elevated temperature. Moreover, while HPC outperforms conventional concrete in nearly every performance category, one Achilles' heel is its performance when exposed to fire [2]. In particular, HPC is prone to explosive spalling, which decreases the load-carrying capacity and the fire resistance of the concrete elements. The main mechanisms of spalling appear to be pressure build-up of vapor during heating (pore pressure spalling, see e.g. [3]) in the fine pores of the HPC matrix, which cannot be relieved because of its low gas permeability, and different expansion rates between aggregates or reinforcement and mortar (thermal stress spalling). The main factors influencing spalling are [4]: high heating rate (above 3 °C/min), low gas permeability and high moisture content (above 2–3%). It is moreover known (e.g. [5]) that spalling is enhanced by concrete compression, which explains why prestressed concrete is particularly at risk of spalling when service loads are not decompressing the fire-exposed surfaces of a prestressed concrete element [6].

In particular, the spalling behavior of HPSCC subjected to fire has not been extensively studied and thus remains largely unknown. In its fire-resistance chapter, the RILEM TC 205-DSC [7] state-of-the-art report points out the significantly higher spalling tendency for self-compacting concrete (SCC) than for vibrated concrete with the same water-to-binder ratio (w/b) and hardening conditions.

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A well-known method to release the pressure is embedding organic (especially polypropylene, PP) fibers of different lengths into the HPC matrix [2]. The fibers melt and provide channels that allow evacuating the vapor, relieving the internal pressure and avoiding explosive spalling and loss of concrete cross-section in fire [8]. The RILEM TC 205-DSC report [7] confirms that mixing small diameter (<100 μm) polypropylene fibres in SCC is beneficial for increasing the spalling resistance. The amount of fibres needed varies and depends on the type and geometry of the fibres, type of concrete, type of aggregates, loading conditions and moisture content.

To be efficient, the PP fibers need to form a percolated network through the whole microstructure of the HPC, so that once molten they are able to evacuate the water vapor and decrease the gas pressure [4]. Alternatively [2,9], it may be sufficient that the PP fibers form a percolated network with the regions of high porosity in the concrete, which are concentrated in the interfacial transition zone between the cement paste and the aggregates. In both cases, this implies that a high loading of the fibers in the fresh mixtures is needed. In tests on HPSCC, improved resistance against fire spalling has been observed at about 5 kg/m^3 (or 0.5% by volume of concrete) of PP fibers [6]. However, this high volume of fibers causes a loss of the self-compacting properties. At lower loadings (typically 2 kg/m^3, or 0.2% by volume of concrete), the self-compacting properties can be maintained, however the fire spalling resistance is only marginally improved [6].

2. Addition of superabsorbent polymers to reduce fire spalling

In this study, a novel approach allowed reaching percolation of the fibers in a HPC matrix using a low fiber loading, and thereby maintaining the self-compacting properties of HPSCC. This approach consists in including dry superabsorbent polymer (SAP) particles in the mixture composition of HPSCC [10].

Superabsorbent polymers (SAP) have recently found application in concrete technology, thanks to their ability to absorb amounts of water many times their own mass, retain it in the fresh concrete and release it at a later time [11–14]. A primary application of SAP has been in internal curing of low *w*/*b* concrete, especially to reduce autogenous shrinkage [11–16] and more recently to control the coefficient of thermal expansion [17]. In most applications, SAP have been added in the dry state to the concrete mixture. When dry SAP particles come into contact with water during mixing of concrete, they rapidly absorb it and form water-filled cavities. The kinetics of absorption and the amount of fluid absorbed by the SAP depend both on the nature of the SAP [18] and of the cement paste or concrete, in particular on the pore solution composition. Once the SAP have reached their final size, they form stable, water-filled inclusions, from which the water is subsequently sucked into smaller capillary pores and consumed by hydration of cement [19]. After being emptied of the pore solution, the water-filled inclusions end up as small (ideally about 100–300 μm across), empty pores in the HPC matrix [11,12].

The novel approach for reducing the spalling of HPC described in this paper is schematically shown in Fig. 1. It consists in creating a system of 100–300 μm diameter voids in the cement paste that are able to bridge the channels created by molten PP fibers in HPSCC subjected to fire and allow their percolation at lower fiber loading (e.g. at 2 kg/m^3 instead of 5 kg/m^3). This reduces the likelihood of fire spalling and improves the fire resistance of the HPSCC mixtures, without losing the self-compacting properties. In particular, according to Bentz [2], at the typical PP fiber loadings used in HPC, the fibers are not percolated through the whole microstructure. However, the system formed by the channels left by the molten fibers at high temperatures and the porous interfacial transition zone (ITZ) around the largest aggregate is percolated, which allows releasing the water vapor at comparatively lower pressures and avoiding spalling [2]. The addition of small-size SAP particles would form a system of pores, similar to air-entrainment, which would allow percolation of the interfaces-fibers-voids system at lower PP fiber loading (Fig. 1).

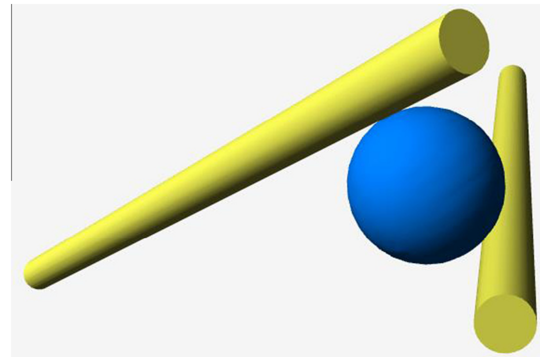

Fig. 1. Schematic representation of PP fibers (yellow) in the microstructure of a HPC, which come into contact through a void created by an empty SAP particle (blue). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Previous researchers have observed a reduction of fire spalling in HPC mixtures with air entrainment and PP fibers ([20] cited in [2]). In these air-entrained mixtures, the air voids may have played the same role as the SAP in the approach followed in the present study. Moreover, Bentz [2] points out that air voids are also surrounded by ITZ, which would facilitate percolation of the fibers-voids-aggregate ITZ systems. A clear advantage of employing SAP instead of air entrainment would be the stability of the pore system that is created after the SAP are emptied of pore solution. On the contrary, air entrainers have problems of compatibility with e.g. superplasticizers [21] and fly-ash [22]. Another advantage would be the possibility of precisely designing both the amount of pores and the pore size distribution [12,23,24] with the aim of improving the percolation of the systems comprising SAP and PP fibers.

More in detail, the SAP (typically, 0.2–0.6% by mass of cement) can be added as a dry powder to the concrete mixture. During mixing and casting, the SAP absorb a part of the mixing water and create water-filled inclusions in the concrete matrix. It is remarked that a small amount of SAP does not influence the fresh concrete properties as much as a high loading of fibers does. In particular, by either adjusting the amount of water in the mixture or increasing the amount of superplasticizer, or both, it is possible to maintain the self-compacting properties of HPC and UHPC mixtures with fibers [25]. After setting and during hardening of the concrete, the water contained in the SAP is sucked into the concrete matrix by capillary forces, which are particularly high in HPC due to its low w/b and fine pore structure. The SAP end up as empty macropores in the hardened concrete, which are uniformly distributed in the HPC matrix. The size distribution of the voids left by the SAP can be tailored to the application by choosing opportune absorption properties and particle size distribution of the dry SAP [23].

This paper presents the results of an experimental study on 6 small-scale thin-walled slabs subjected to central precompression by CFRP tendons in a standard fire following ISO 834. In particular, an attempt is made to improve the spalling behavior of a previously studied PP fibre-modified HPSCC [26] by the addition of SAP. The results elucidate the performance of precast CFRP pretensioned HPSCC elements in fire and show the effectiveness of SAP in reducing the spalling tendency of HPSCC.