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# Effects of polypropylene fibre type and dose on the propensity for heat-induced concrete spalling

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ABSTRACT

The term *high-performance* concrete (HPC) is typically used to describe concrete mixes with high workability, strength, and/or durability. While HPC outperforms normal strength concrete in nearly all performance criteria, it also displays a higher propensity for heat-induced concrete spalling when exposed to severe heating or fire. Such spalling presents a serious concern in the context of the historical approach to fire safe design of concrete structures, where structural engineers typically rely on concrete's inherent fire safety characteristics (e.g. non-combustibility, non-flammability, high thermal inertia). It has been widely shown that the inclusion of polypropylene (PP) fibres in concrete mixes reduces the propensity for heat-induced concrete spalling, although considerable disagreement exists around the mechanisms behind the fibres' effectiveness. This paper presents an experimental study on the effects of PP fibre type and dose on the propensity for heat-induced spalling of concrete. A novel testing method and apparatus, the Heat-Transfer Rate Inducing System (H-TRIS) is used to test medium-scale concrete specimens under simulated standard fire exposures. Results show (1) that although the dose of PP fibres (mass of PP per $m^3$ of fresh concrete) is currently the sole parameter prescribed by available design guidelines, both the PP fibre cross-section and individual fibre length may have considerable influences on the effectiveness of PP fibres at reducing the propensity for heat-induced concrete spalling; and (2) that current guidance for spalling mitigation with PP fibres is insufficient to prevent spalling for the HPC mixes tested.


## 1. Introduction and background

Structural engineers have historically relied on concrete's inherent fire safety characteristics (e.g. non-combustibility, non-flammability, high thermal inertia) for the fire safe design of concrete structures [1]. Modern advances in concrete construction have been driven by the need to build faster and higher, to reduce cost, increase sustainability, and increase service lives. The term *high-performance* concrete (HPC) describes concrete mixes with high workability, strength, and durability, and low compressive creep [2,3].

While HPC outperforms normal concrete in nearly all performance criteria, *"its Achilles heel is its performance when exposed to fire"* [4]; it has a high propensity for explosive spalling under severe heating and also experiences more rapid reductions in compressive strength than 'normal' strength concrete at elevated temperature [5]. Given its ever-increasing use in high-rise buildings (particularly for columns), and in tunnel structures and lining segments [6], the heat-induced spalling resistance of HPC is a critical issue for the concrete industry (in-situ and precast).

### 1.1. Spalling

Heat-induced spalling of concrete, which is widely perceived as being a random phenomenon [7], occurs when the exposed surface of heated concrete flakes away in a more or less violent manner (see Fig. 1). As a consequence, the concrete cover to the internal reinforcement is reduced, resulting in more rapid temperature increases of the internal reinforcement and within the core of the structural element, in addition to a direct influence on load bearing capacity due to the loss of physical or effective cross sectional area. Heat-induced concrete spalling presents a potentially serious concern in the context of the historical approach to fire safe structural design of concrete structures, where spalling is less common and presumed as 'implicitly' accounted for in prescriptive, tabulated fire design guidance. The concrete industry is beginning to grapple with the implications of the clearly demonstrated increased propensity for spalling of modern high-performance concrete

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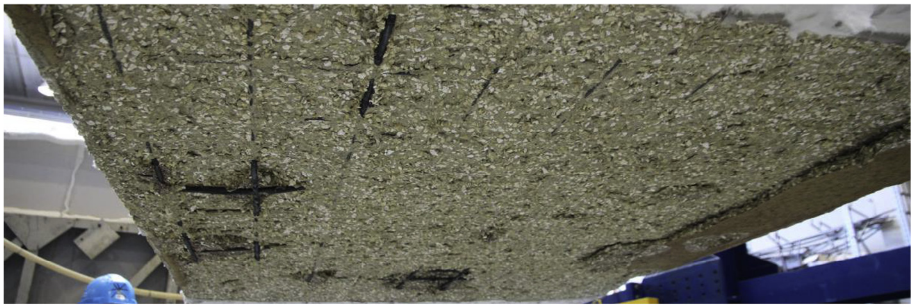

**Fig. 1.** Evidence of the significant extent of spalling on the soffit of a large-scale concrete specimen after a standard fire resistance test (photo courtesy Ieuan Rickard).

mixes [7,8] and its possible effects on the fire resistance of concrete structures.

Heat-induced concrete spalling is by no means a new phenomenon (e.g. [9–18]), although as noted it is increasingly a concern for modern HPC mixes. Numerous past researchers have studied heat-induced concrete spalling, mainly focusing their efforts on:

- understanding the thermo-physical mechanisms leading to spalling, thus studying the factors which influence its occurrence [11,12,17–19];
- modelling (analytically or numerically) the occurrence of spalling [20,21];
- modelling of the potential impacts of spalling on the load bearing capacity of structural systems [22,23]; and
- defining techniques to diminish and/or avoid the occurrence of spalling [13,24].

### 1.2. Polypropylene fibres

More than three decades of experimental studies have convincingly shown that polypropylene (PP) fibres' (see Fig. 2) inclusion in fresh concrete can considerably reduce the propensity for heat-induced spalling of concrete (e.g. [13,17,25]). Polypropylene fibres are theorised to alter the transient moisture migration and/or evaporation processes within heated concrete, thus reducing the propensity for spalling (particularly when a thermo-hydraulic spalling mechanism is dominant). While the mechanisms behind PP fibres' effectiveness remain poorly understood, three potential mechanisms are widely quoted involving the PP fibres generating: (1) discontinuous reservoirs, (2) continuous channels, and/or (3) vacated channels [26].

During heating, rapid volumetric changes of the PP fibres may cause micro-cracks within the concrete matrix surrounding the fibres, thus creating *discontinuous reservoirs* that enhance moisture migration within concrete. Polypropylene fibre inclusion may also promote the formation of discrete reservoirs by inherently increasing air entrainment within the concrete matrix during mixing and casting.

*Continuous channels* may also be formed at the interfaces between the PP fibres and the concrete matrix due to poor interfacial adhesion and/or a relatively more porous transition zone at the interface. This phenomenon, called *Pressure-Induced Tangential Space (PITS)* theory [26], is postulated as enhancing concrete moisture migration during heating.

Enhanced moisture transport may also be driven by the formation of *vacated channels* left behind by pyrolized (or melted) PP fibres during heating. This is the most widely quoted mechanism used to describe the effect of PP fibres in heated concrete [26], however there is little direct experimental evidence for it [7].

Polypropylene fibres used in concrete applications are commercially available in a range of types and sizes. The most common are monofilament, multifilament, and fibrillated (see Fig. 2). Monofilament and multifilament fibres are both manufactured through an extrusion process, with nominal diameters in the range of 10–40 μm. Monofilament fibres are manufactured from a single strand of fibre, while multifilament fibres are made from multiple, combined strands. While the diameter of fibrillated fibres is in the range of monofilament and multifilament fibres, these are manufactured in the form of films that are slit in such a way that they can be expanded into an open network [27] (see Fig. 2). Fibres of

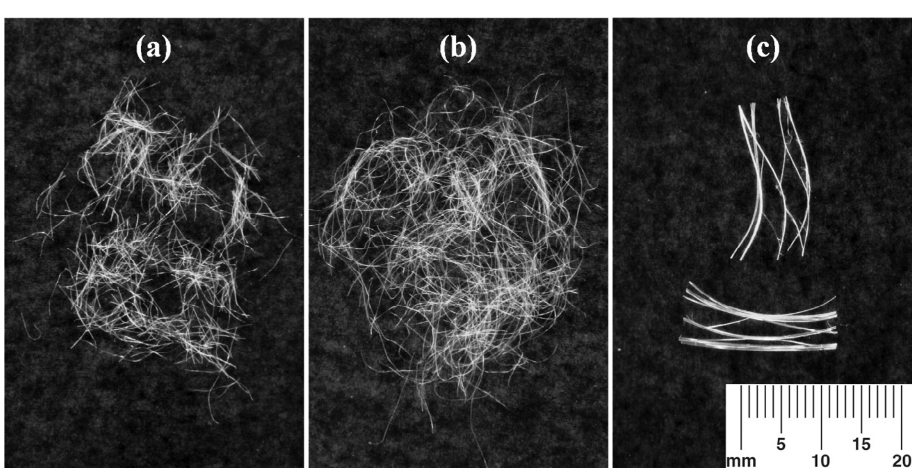


**Fig. 2.** Photographs of (a) 6 mm monofilament (32 μm diameter), (b) 12 mm multifilament (32 μm diameter), and (c) 20 mm fibrillated ($37 \times 200$ μm$^2$) PP fibres.