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Polypropylene Fibers to Resist Concrete Spalling Caused by Fire

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Abstract:
In fast-heated concrete the explosive behavior of concrete is observed in fire. The key factors regulating the spalling phenomenon are attributable to the low porosity and high density of the material, as well as the restricted capacity to move gases and liquids. Therefore the chance of spalling is much higher for high-strength, ultra-high-strength, and reactive powder concrete than for concrete with normal-strength. This paper provides a description of explosive concrete spalling at explosion. An area of engineering design, implementation, and study that produces contradictory theoretical and practical advice is the use of polypropylene fibers in concrete to prevent explosive spalling in the event of an explosion. This study offers a thorough analysis of the many considerations that need to be addressed in the design of a fiber-reinforced shotcrete and in-situ concrete to satisfy not only the customer's requirements for cost-effective construction, but also the requirements of the engineer for guaranteed optimal resistance to explosive spilling and the contractor's all important ability to easily mix and position the concrete, on time and by definition. Fiber forms, dosage, efficiency and safety margins, mixing and distribution are studied, and the impact on concrete properties.

Keywords: *Fire, Temperature, Concrete Spalling, Polypropylene Fiber, Spalling.*

1. Introduction

For several years Concrete has been the main building material and the impact of fire on concrete has been studied for a long time. It is likely that during a explosion, concrete, which is an incombustible material [1], will act explosively due to the spalling phenomenon. Spalling is described a sudden, violent or non-violent loss of concrete cover [2, 3]. Spalling actions can jeopardize concrete components' load-bearing ability due to conservative cross-section loss and reveal steel reinforcement vulnerable to can temperatures [4]. This can lead, in a burn, to a decrease in the ability of the product and even to its collapse [5]. Since the effects of fire in concrete structures can be very serious, a series of studies have been carried out to find ways of minimizing concrete tendency to spall due to exposure to fire [6–9]. It was found that the addition of polypropylene fibers (PP) to the concrete mix would offer positive results. The polypropylene fibers in concrete do not change their mechanical and physical properties at normal temperatures significantly [10]. Nevertheless, as the temperature increases due to heat, the fiber-free concrete permeability increases at 200 C as much as 50 times compared to the fiber-free concrete [11]. A network of pores is formed as fibers melt that increases the permeability of the concrete. This allows the transportation of vapour, reduces the pressure of vapour, and minimizes the risk of concrete spalling in fire.

This severe damage indicated that while the strength and durability of high resistance concrete is considerably higher than that of traditional concrete mixes (offering better mechanical properties, low porosity and chemical resistance), because of its high density and susceptibility to high pore pressures and internal tensile stresses, it is much more prone to fire harm. The severity of this destruction has raised major concerns about the survival and structural stability of tunnel lines following a possible fire and has triggered much field work [12, 13].

Ultra-high-performance concrete is an unnaturally synthetic substance low in water-cement ratio and high in strength, impermeability, density, and fragility. In the event of an explosion, these characteristics make it easy to break, resulting in a decrease in power. The application of polypropylene fibers not only helps increase the strength and elasticity of the concrete, but also creates breathing vessels as the ambient temperature increases. Despite these advantages, ultra-high-performance fiber concrete can withstand heat and pressure for a fairly long period without getting seriously hurt, thereby giving firefighters period to save human lives and property [14 - 16].

To reduce brittleness fiber is added to the concrete [17- 19]. The fibers enhance concrete ductility and mechanical strength [20, 21], minimize plastic shrinking and improve resistance to room temperature effects [22, 23].

2. Spilling into various concrete types

2.1 High performance concrete (HPC)

The high compactness of HPC is the key parameter liable for spalling at high temperatures as per [24]. When contrasting empirically a normal concrete (M30, w / c=0.5) with an HPC concrete (M100, w / c=0.32), both with calcareous aggregates, it could be found that they have a similar thermal activity globally, due to their comparable insulate properties (thermal conductivity and heat). The distinction comes in the calculation of the pore pressure, in the HPC up to 38 bars and in the standard concrete 18 bars; HPC also experienced higher pressure vectors than the standard concrete.

It can be seen that as a result of lower permeability (to vapor and water vapour), there is a substantial difference in the thermodynamic conditions encountered in the transparent system, resulting in a much greater membrane pressure.

2.2 High strength concrete (HSC)

Tests carried out on HSC by [25] were performed on 16 samples, 12 with mixtures of silica fume, and 4 without. It has been noted that all the samples of mixtures heated above 300 C have undergone a form of spalling and lack of mass. In the experiments, spalling varied from negligible aggregate spalling (which induces surface pitting) to, in severe cases, large portions of the samples being burst 800 °C with destructive force that are classified into four types: explosion (parts greater than 1 cm), surface (parts less than 1 cm), aggregate and corner spalling.

The tests revealed that the level of spalling significantly decreased when the amount of water to binder ratio rose in mixes including silica fume and also that silica fume could generally regulate destructive spalling caused by increased tensile resistance.

2.3 Self-Compacting concrete (SCC)

Tests performed on SCC by [26] found that destructive spalling exists in both pulsated concrete and SCC at a range of temperatures from 350 ° C to 580 ° C. At the other hand, no spalling was found on any of the specimens examined for LSCC (Laterized Self Compacting Concrete). There was no crack detected at up to 600 ° C in LSCC. Also at 800 ° C surface fractures were observed on the samples, and the amount of cracks in water-cooled samples was greater.

Understanding concrete spalling

Spalling can be divided into four classifications: (1) aggregate spalling; (2) destructive spalling; (3) spalling of surfaces, and (4) spalling of the corners. The first three happen in a fire within the first 20-30 min and are affected by the level of heat, whereas the fourth happens after 30-60 minutes of flame and is affected by the high temperature. It can also be claimed that ground spalling is actually a type of explosive spalling which is the most dangerous spalling type [27].

Concrete spalling could be defined as fracturing off sheets or parts of concrete from a structural element's surface when exposed and rapidly growing fire temperatures [28]. Three different types of spalling concrete are:

Surface spalling: During the early part of the explosion, small pieces of concrete, up to 20 mm in size, are slowly and non-violently dislocated from the earth. This is usually caused by splitting of the composite fragments at high temperatures due to physical or chemical changes. The deterioration of the concrete in surface spalling is fairly slow and requires oxidation of the cement matrix accompanied by the lack of connection among aggregate and matrix. If the temperature increase is slow, there is time for the moisture in the concrete to move from the exposed side to heat, and there is limited pressure build up. In this situation, the presence of moisture will help reduce the impact of the increase in temperature, because much energy is expended in converting moisture into vapour.

Corner break-off: Also recognized as skin peeling off, when the concrete has fractured and collapsed, corner break-off occurs at the edges and corners of concrete structures during the latter phases of the burn.

Explosive spalling: Undoubtedly the most extreme and harmful type of spalling that happens within the first 20–30 min of a flame when the concrete temperature is within 150-250 ° C. Combustible spalling happens as the temperature increases exponentially, such as in fires fueled by hydrocarbons after a traffic crash, where very pieces of concrete can be thrown aggressively for many meters. When a fresh concrete mask is exposed to the flame radical destructive pouring happens deep into the concrete surface, undermining the construction's structural stability.

It is recognized after many decades of study that there is a complex mix of chemical, physical, and thermodynamic factors that affect the spalling of explosives. Which include humidity content, aggregate form and thickness, concrete permeability, warming capacity, reinforcement presence, and exterior loadings. Scientists agree that when high strength, low permeability concrete is specified, there is a substantially higher chance of explosive spalling due to the larger pore pressures that accumulate throughout warming.

The hypotheses about how and why destructive spalling happens are primarily moisture dependent. If the concrete temperature rises, the concrete humidity transitions to steam vapour. This vapor causes a dramatic rise in the pressure within the concrete if it is unable to escape. As this cycle progresses, the strength of the vapor increases to the point that it exceeds the concrete's tensile capacity, causing violent and explosive dislodging of concrete parts. Besides this modern theory of 'moisture movement,' there is an agreement that aggregate contraction induced by thermal stresses often directly affects destructive spalling.

Why polypropylene fibers avoid explosive spills

The application of appropriate polypropylene nylon microfibers (Figure 1) to counteract incendiary spalling in cast concrete [29] and shotcrete [30] has been recognized for several years, but it is important to have an awareness of the thorough mechanism by which these fibers function in order to develop an engineered microfibre to avoid explosive spalling. Because the spalling is induced by pressure caused by a limitation on moisture or steam movement, then the presence of the fibers must alleviate the pressure somehow.

Figure 1. Monofilament polypropylene fibres (PP)

As the heat in reinforced concrete increases in the microfibre, the PP softens and starts to melt due to a gradual phase shift that starts at around 150 ° C where the crystallinity starts to break into an undifferentiated polymer. It rises at 165 ° C (the widely known boiling point), and is full at around 175 ° C. It's this melt that is presumed to promote the decrease in the concrete's internal stresses which cause the destructive spalling. There are two key hypotheses on how these microfibers do it.

Mechanisms: While acknowledging the probability of other processes, Khoury [31] supports what he calls a PITS (Pressure Induced Tangential Space) concept in which the steam supersedes the PP's contraction as it melted, squeezing between the microfiber and the concrete matrix and moving along the fiber duration. He argues that the efficacy of such a system would rely on the microfibre's accumulated land area and fiber communication, and is therefore favored by an ultrafine fiber with a diameter of around 18μm which offers a very large number of fibres. Because microfibers are scattered across the concrete, how the connection of the fibers is generated as well as how the steam pressure is alleviated is not clear. This hypothesis is also unable to understand why microfibers with a diameter of 32μm-which have just one third of the number of fibers relative to 18μm in diameter-have proved to have equivalent and probably slightly superior destructive spalling resistance [32].

Microcracking mechanism: An alternative hypothesis proposed by [33] argues that its much higher frictional heating coefficient compared with that of concrete (8.5x) produces a huge number of microcracks when an individual PP fiber melts. Such newly formed microcracks will then attach to the microcracks formed by the thermal expansion of adjacent microfibers, or by heat triggered stresses, to form an interlinking system that can promote the flow of steam through concrete. It was this permeability that is only generated if a fire event happens, which relieves the stresses generated by the steam generator and mitigates the risk of destructive spalling.

Liu et al [34] discovered from back scattering electron microscopy (BSE) and gas permeability monitoring that the melt of PP fibers improved the functionality of the insular pores resulting in increased permeability, with maximum permeability happening at roughly 200 ° C or shortly after polypropylene boiling point. It was established that the formation of microcracks and their access to a system (Figure 2) are important determinants concrete's permeability when exposed temperatures.

Figure 2. Microcracking network

Saka et al [35] notes from preliminary finite element analysis experiments that a single PP fiber inserted in a mortar matrix and subject to an increase in temperature of 140 ° C induces considerable stress on the framework because of disparity in the frictional heating coefficients. Khoury [31] also suggests that the large gap in thermal expansion among concrete and PP polymer leading to the creation of microcracks exerts a substantial tensile stress on the underlying matrix.

In concrete, microcracks are often formed by thermal gradients such as aggregate contraction, drying shrinkage and producing steam. But, it is the additional development of microcracks created by the melt of the PP microfibers that occurs with these holes and interfacial transition zones in a habitual / national system [36], which offers the highest degree of concrete security towards destructive spalling.

The greater the weight of the single fibre, the greater the tension that the melted polymer will produce and the enhanced propensity to form microcracks as a consequence of that tension. However, very large a single fiber results in a smaller number of fibers spread in the ground, which limits the possibility of channel creation. Likewise, at other end, so tiny an actual fiber increases the potential for microcracks to form, limiting the system that can be generated, thus reducing the overall fiber's ability to avoid destructive spread. [37]. Between such two poles exists the optimum fiber size for the most effective explosives resistance to spalling.

Optimum fibre dimensions: Jansson and Boström's research [37] contrasted the output of 12 mm long PP microfibers of two specific diameters (32 μm and 18 μm) in test boards made from concrete commonly used during tunnel building in Sweden. The experiments were performed under circumstances designed to promote a propensity for destructive spalling, like: using a more intense Rijkswaterstatt (RWS) fire curve of 2 hours at a peak temperature of 1.350 ° C against the regular Eurocode 1 fire curve of 1.100 ° C for 2 hours (Efnarc, 2006), use large panels of 1.200 mm x 1.700 mm x 300 mm instead of small panels of 500 mm x 600 mm x 300 mm, using large aggregate versus smaller aggregate, and testing panels with high moisture content under compressive load and with low fibre dosages (Figure 3).

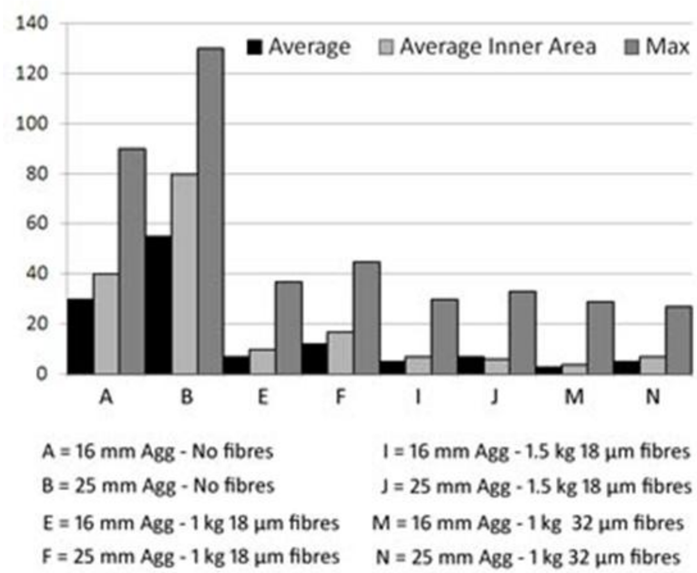

Figure 3. Spalling depths (mm) of large scale slabs after 30 minute fire exposure to RWS fire curve.

The figure 3 clearly, evidence invalidates the idea that it is actually the amount of fibers in the concrete that defines the efficacy of the fiber provide destructive resistance to spalling. Because it is seen that the PP fibers with a diameter of 32μm have at least comparable output to 18μm diameter fibers, which are 3.2 times more frequent in concrete. The results also show that panel comprising 1.0kg / m3 of 32μm diameter fiber produced slightly better outcomes than those comprising the 18μm diameter fiber higher dose of 1.5kg / m3. The number of fibers in the concrete is a success factor but obviously it's not the major factor.

Together with in-house work at propex concrete systems in poured concrete and shotcrete [38], this research supports Sullivan and others' view that it is the extension of the melted PP fiber that causes the microcracks to build a channel for steam pressure relief; This is the predominant mechanism for the provision of destructive concrete spilling resistance. The important requirement is that the microcracks have to be generated before any system can exploit the pressure alleviating benefits. By using a 32μm diameter fiber rather than a smaller diameter fiber, including an 18μm diameter fiber, this process is preferred.

Similarly, a fiber of 12 mm length will increase the amount of individual fibers and encourage the development of microcracks in a fire, more than a 6 mm long fiber, while also providing adequate numbers of fibers (approx. 120 million / kg) will create the system needed to dissipate steam vapour. While a 6 mm fiber will function at a high level, a 12 mm fiber would be more efficient, especially under serious conditions where the highest performance degree is needed and discrepancies between fibers can be seen. In contrast to the length of the fiber diameter, there are other essential criteria to integrate fibers into concrete to achieve a functional, viable fiber to avoid destructive spalling.

For example, the various parties concerned can have different demands. The consumer needs a fire-resistant, robust structure, quick installation, minimal servicing repairs, low service loss during repair, decreased insurance rates and a price-effective solution. The designer / engineer needs approved potential for destructive spalling resistance, performance guaranteed materials, no adverse effects on other concrete assets, ease of use in building and an efficient solution. The technician / concrete manufacturer needs a cost-effective approach, ease of adding to concrete, and no issues about mixing and concrete delivery. Obviously, the overall best requirement would be a fiber that offers the optimal balance among established explosive spalling resistance, convenience (trouble-free use) and cost-effectiveness – a fiber that meets all of the stakeholder needs.

PP microfibers are compliant with steel fibers and chemical admixtures, combining, distributing, pouring and casting / wet spraying close to unreinforced concrete / shotcrete. The fine quality of PP fibres has been noticed not to be consistent with the dry shotcrete framework [30].

Practical considerations: There have been many instances of works where fibers have been solely chosen for spalling outcomes from tiny-scale lab testing and then, when complete-scale site development has started, engineers and contractors have seen that certain fiber materials have a significantly negative effect on the concrete-especially the workability, air quality and compressive strength. Adjustments to the mix configuration were then made to counteract these negative results, and the fire test data were essentially made void. Thus, it is important that designers take into account the impact of the fibers on concrete workability, air quality, and strength during selection for PP microfibres.

Effect on workability: The effectiveness of all fiber reinforcing depends on achieving a uniform fiber distribution throughout the concrete, its contact with the cement matrix, and the capacity of the concrete to cast or spray effectively. Basically, to have some value in the concrete, each single fiber needs to be covered with cement paste. Users of fiber reinforced concrete will understand that adding more fibers to concrete, especially with a very limited diameter, would have a larger negative impact on workability and the need for improvements in the design of mixtures. Because the average surface area of very small diameter fibers is much higher (for example, 18µm diameter fibers have a surface area 77 per cent greater than 32µm diameter fibres). This additional demand on the cement paste, unless changed by adding more water and cement or alloying elements (and thus the costs), would ultimately have a drastic impact on the concrete's workability, especially if the dose is above 1kg/m3. Kompen [39] recorded Norway experience that ultrafine fibers in wet shotcrete have an impact on the mix's water request and that the fibers were extracted from the shotcrete filters and jammed air filters on the spray machines.

Effect on air content: A practical thing to consider in the choice of PP microfibers is that it is more difficult to disperse packets of very small diameter fibers in the concrete, and it is known to carry more air into the concrete. Relative site tests have shown that the higher air content for concrete with 18µm diameter fibers was about 5-8 percent opposed to about 1.0 percent for a fiber with a diameter of 32µm. This rise has a negative impact on concrete strength which in basement structures is not attractive. Few works using 18µm diameter fibers have made use of deforming products to reduce the air content. This will ultimately affect the concrete's in-place costs and put a period on the validity of any fire tests conducted to determine the destructive spalling efficiency of the initial concrete / fibre mix.

The use of ultrafine microfibers will result in a very loss of concrete strength with a 6 percent reduction in compressive strength for every 1 percent increase in air content. In an attempt to divert focus from the adverse effects these very fine diameter fibers have on workability and air quality, it was proposed that lower dosages be the solution. Although this may be viewed as an fascinating commercial strategy for contractors and ready-mixed concrete suppliers whose goal is to provide a lower cost solution, this recommendation increases the level of destructive spalling resistance and should not be endorsed on the grounds of tiny panel lab testing of concrete with elevated air volume. This rise in air content does not present a shotcrete issue as the air is forced during blasting, but if the fiber output for a shotcrete mix is measured on a cast concrete stand, The raised air content that cover the fiber's coaching ability to overcome incendiary spalling when used in the actual shotcrete as it enhances the likelihood of completing a fire test concrete board.

Addition and mixing of PP fibres: Adding PP monofilament microfibers to concrete is a fairly simple method which depends on the project size. Normally, fibers specially designed for concrete reinforcing are supplied in entirely recyclable paper wrapping, which allows the required dose per unit volume to be easily applied directly to the concrete truck or pan mix. The wrapping is meant to break down easily, enabling the fibers to be evenly spread through the concrete. This is also the most efficient approach to implement in comparatively small ventures, with labeling accessible in 1 kg bags or 2 kg bags.

Where works require substantial amounts of PP microfibres, contractors and ready mixed suppliers frequently suggest using more advanced, standardized ways of applying fibers to the concrete. Fiber dose machines maintain an accurate measurement and automatic delivery to the concrete mixer of the appropriate amount of fibres. While using very fine fibres, they risk sticking together in packets, being coated in cement paste and not uniformly spread in the concrete. This was see during fibre washing out experiments when fiber clumps were found. This is clearly inappropriate as security towards destructive spalling is not distributed evenly in the concrete. This was not a concern with the fibers with a diameter of 32µm, which also performed well in automated fiber administering and distribution systems.

3. Fibers role

As per [40], the inclusion of long fibers (lf > 10 mm) has a structural-level effect, which helps to increase the material's deformability. Fibers are slowly employed shortly after cracking, resulting in a multi-cracking cycle (pseudo-hardening phase) and crack translation (softening behaviour).At the other hand, the introduction of short and microfibers (a few mm long) has an effect on the level of the material, helping to increase the tensile strength correlated with the pseudo-elastic domain. Instantly after concrete microcracking the microfibers are enabled, contributing to a concrete behavior defined by a longer elastic period (elastic + pseudo-elastic).Owing to their high strength, high resistance in alkaline environment and high elasticity modulus, steel fibers (twisted, hooked-end, straight long and short) are used regularly in UHPFRC mixtures.It really is worth noting that in a fire situation, polypropylene fibers (PP) can be inserted into the concrete mix to prevent destructive spalling. In this case, melt of PP fibers, about 180oC, results in an increase in permeability, removing the vapor pressure within the matrix.The different types of fibers are shown in Figure 4.

Figure 4. Synthetic and steel fibers used in concrete formulations

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3.1Orientation and alignment of fibres

The size of the sample, boundary conditions (wall effect), mixture workability, fiber thickness and compaction procedures affect the distribution and alignment of fibres.Experimental experiments carried out on round panels[41] using X-ray computed tomography and tests of electrical resistivity showed that the better results in terms of strength capability were obtained by pouring concrete from the core.The movement of concrete inward from the middle of the panel contributed to the fibers being preferentially aligned, parallel to the panel length, expanding the number of fibers trying to bridge the cracks.

4. CONCLUSION

- High temperature penetration contributes to a marked reduction in UHPC's mechanical properties due to physical-chemical transformations (free water evaporation, CSH dehydration, and microcracking). In addition, despite its compact microstructure, UHPC is susceptible to violent spalling. Research on this region has shown that a small amount of PP fibers integrated in the mix can reduce spalling triggering and even avoid it.

- The introduction of polypropylene fibers has proven to be an amazing method for minimizing the explosive spalling of RPC when subjected to temperatures of up to 800 ° C due to the melting of polypropylene fibers and instead leaving vacuum for vapor injection.

- If fibers are to be used to provide explosive spreading resistance in shotcrete or cast in-place concrete, two key requirements should be met: a proven ability to withstand explosive spalling along with no adverse side effects in concrete. The best way to meet these requirements was to use a fiber made of 32µm diameter and 12 mm long polypropylene monofilament manufactured to and in line with ISO 9001 and EN14889-2 specifications.

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