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Spalling Prevention of High Performance Concrete at High Temperatures

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<http://dx.doi.org/10.5772/64551>

Abstract

In recent year, the use of high performance concrete (HPC) has significantly increased in applications such as prestressed concrete structures, bridges, large-span roof structures, and containers for hazardous fluids or nuclear wastes due to its outstanding structural performance and higher durability. However, its fire resistance performance remains a concern, especially in relation to explosive spalling in a fire. Therefore, it is essential to understand the spalling properties (mechanism, influencing factors, and prevention measures, etc.) of high performance concrete exposed to high temperature, so that the safety of a structural fire design involving HPC can be ensured. This report presents a state-of-the-art review for the prevention measures and explosive spalling of high performance concrete under fire situations.

Keywords: high performance concrete, fire, explosive spalling, mechanism, spalling prevention, PP fiber, thermal barrier

1. Introduction

Recently, high performance concrete (HPC), as it can satisfy the expectations for excellent mechanical properties and a long service life, is increasingly applied in various structures such as bridges, tunnels, high-rise buildings, and large-span infrastructures. HPC is now well established as a very dense homogeneous concrete microstructure, especially in the interface region between hydrated paste and aggregate [1]. This is generally achieved through the use of low w/c ratio (0.2~0.3) with the help of superplasticizers that can produce slumps ranging from 75 to 125 mm [1]. Additional densification and homogeneity of the interfacial region are achieved through the inclusion of mineral admixtures such as fly ash, silica fume,

etc. However, this beneficial microstructure, ironically, causes a critical problem exposure to a fire, especially in relation to explosive spalling, which is defined as the violent breaking off of layers or pieces of concrete from the surface of a structural element when exposed to high and rapidly rising temperature under fire conditions [2]. Some investigations have shown that HPC is more vulnerable to explosive spalling under high temperatures compared to normal strength concrete (NSC), which seriously jeopardizes the safety of HPC applications. The experience of Madrid Windsor Tower fire in Spain (2005), explosive spalling of HPC, has highlighted a serious social problems in the public's mind, as shown in **Figure 1**. Thus, solving of the spalling problem is now a primary requirement in any new structures design. However, there is a lack of data on design and performance of HPC, especially under fire situations.

Figure 1. Damage of concrete and reinforcement after Madrid Windsor Tower fire (Spain, 2005).

This report presents a state-of-the-art review of the phenomenon of the spalling of HPC in general and explosive spalling in particular. The mechanisms and the factors of explosive spalling are discussed.

2. Spalling of high performance concrete

2.1. Definition and types of spalling

As the most typical form, spalling is defined as the violent or nonviolent breaking off of layers or pieces of concrete from the surface of a structural element when exposed to high and rapidly

rising temperature under fire conditions [3]. Gary [4] suggested that spalling could be grouped into four categories: (a) aggregate spalling, (b) corner spalling, (c) surface spalling, and (d) explosive spalling. As shown in **Figure 2**, aggregate spalling, surface spalling, and explosive spalling occur during the first 7–30 minutes in a fire, accompanied by popping sounds (aggregate spalling) or violent explosions (surface and explosive spalling) [5]. Spalling may also occur nonviolently (corner spalling) later in a fire when the concrete has so weakened after a period of heating of 30–90 minutes that cracks develop and pieces fall off its surface [5]. The most important of these is explosive spalling, which occurs violently and results in serious loss of material.

Figure 2. Time of occurrence of different types of spalling in a fire [5].

2.2. Mechanisms of explosive spalling

The most recent theories of the causes of explosive spalling indicate that three factors play a crucial role, i.e., (a) the build-up of pore pressure, (b) thermal stresses, and (c) combined high pore pressure and thermal stress in the concrete when exposed to a rapidly increasing temperature. The first hypothesis supposes that heating produces water vapor in concrete and as the permeability of HPC is low, which limits the ability of vapor to escape, a build-up of vapor pressure results. The second possibility is thermal stresses close to the heated surface due to preload or a high temperature gradient caused by a high heating rate. Third, a combination of both phenomena is also possible. These different mechanisms may act individually or on combination depending upon the moisture content, the section size, and the material.

2.2.1. Pore pressure spalling

This mechanism is proposed by Shorter and Harmathy [6], Meyer-Ottens [7], and Aktarruz-zaman et al. [8]. The hypothesis is that the spalling is due to the build-up of very high pore pressures within the concrete as a result of the liquid-vapor transition of the capillary pore water as well as that bound in the cement paste component of the concrete (so-called moisture clog spalling) [6, 7]. As shown in **Figure 3**, heating on the surface of concrete results in a temperature gradient, which forces moisture into the internal of the concrete as well as out of the surface. Then, three moisture zones develop with depth from heated surface of concrete: a dry zone near the heated surface (a), an evaporation intermediate zone (b), and a moisture saturated zone (c), which could contain more moisture than the initial moisture content. As a result, pore pressures build-up to reach a maximum level at a distance from the surface depending upon the permeability of the concrete and contribute to explosive spalling. The maximum pore pressure is greater in HPC (or HSC: high strength concrete) and develops nearer the surface than in NSC. The pore pressure spalling, therefore, introduces that HPC has dense microstructure and many disconnected pores, which significantly prevents water vapor from free transport and escapes in the matrix when exposed to elevated temperature. The explosive spalling occurs when the pore pressure in the matrix accumulates to a threshold exceeding their tensile strength [9, 10].

Figure 3. Changes in temperature (T), vapor pressure (P), and moisture content (u) in moist concrete heated from one face [10].

2.2.2. Thermal stress spalling

This mechanism is proposed by Saito [11] and Dougill [12]. Thermal stresses will occur inside the concrete due to temperature gradients from the heated surface toward the inner, cooler sections of the concrete, as shown in **Figures 4** and **5**. These gradients will increase with rapid heating rates. Different strains due to the thermal gradient are deemed to cause tensile and

compressive stresses, depending on the thermal and mechanical properties of the concrete. Hindered expansion, loads, and restraints as well as the heating rate are mentioned as further parameters [13]. Failure due to spalling is considered to exceed the compressive strength of the concrete close to the heated surface. The compressive stresses due to the thermal gradient also lead to tensile stresses in the cooler sections of the concrete. Moisture migration is not considered with spalling due to thermal stresses [14] and spalling of HPC or of NSC with high moisture content cannot be explained by thermal stress spalling. Explosive spalling only due to thermal stresses is relatively a rare occurrence [14].

Figure 4. Mechanism of thermal stress spalling [11].

Figure 5. Typical temperature distribution in concrete at 60 minutes of heating in BS476 fire [13].

2.2.3. Combined pore pressure and thermal stress-induced explosive spalling

This mechanism is proposed by Zhukov [15], Sertmehetoglu [16], and Connelly [17]. According to the Zhukov's model, the stresses developed within a heated concrete member may be

superimposed upon each other and their summation compared to the material strength of concrete. He considered that the stresses acting could be categorized as load-induced stresses, thermal stresses, and pore pressures. Based on Zhukov’s ideas, Khoury [13] presented a general sketch of combined thermal stress and pore pressure-induced explosive spalling, as shown in **Figure 6**. Generally, high performance concrete tends to undergo the multiple spalling (combined pore pressure and thermal stress spalling) of thinner sections as experienced in the great Belt tunnel fire in Denmark (1994).

Figure 6. Explosive spalling caused by combined thermal stresses and pore pressure by Khoury based on Zhukov [13].

Although theoretical modeling for the various spalling forms has been attempted in the past, it is recently that significant development has been made in this field. The complex combined nature of the influences of moisture content, pore pressures, and thermal stresses in the heterogeneous concrete material with complex pore structure, which varies markedly with temperature during first heating, does not lend themselves easily to analytical modeling [15].

2.3. Factors influencing spalling

Based on the spalling mechanisms, the main factors leading to the explosive spalling of concrete at high temperatures are heating rate, permeability of concrete, moisture content, presence of reinforcement, and level of external applied load, but more factors have been identified in the literature review as influencing on the risk and extent of spalling [18, 19]. The factors influencing to the explosive spalling of concrete can be classified into three categories as follows:

- a. Material-related factors.
- b. Structural or mechanical factors.
- c. Heating characteristics.

However, some of these factors would fit into more than one category.

2.3.1. Material-related factors

The research on concrete spalling at high temperatures identifies several material-related parameters with a big influence on spalling. **Table 1** shows a brief overview on these governing parameters in relation to the concrete mix design or the selection of materials used for the concrete.

Factors	Risk of spalling	Influences
Moisture content	Very high	Higher moisture content (mainly free water) significantly increases the risk of explosive spalling due to high vapor pressure, but it is depending on the permeability of the concrete.
Silica fume	Very high	Silica fume decrease the permeability and increases the possibility of explosive spalling due to the reduced release of high vapor pressure.
Permeability of concrete	High	Low permeability and insufficient temperature-dependent increase in permeability increases the risk of spalling due to insufficient release of pore pressure.
Cement content	High	High cement content increases the total amount of water added to the concrete, even with low w/c ratios.
Compressive strength	High	Higher strength grade usually increases risk of explosive spalling, mainly due to the lower w/c ratio and permeability
Quartzite aggregates	High	Can increase the risk of spalling due to a change in the quartzite phase at 573°C.
Limestone filler	High	Lowers permeability, similar behavior compared to silica fume.
Aggregate size	Moderate	Larger aggregates increase the risk of explosive spalling due to a poor surface to mass ratio.
Internal cracks	Variable	Two opposite effects. Small cracks might promote the release of high pressure and reduce the risk of spalling. However, parallel cracking close to the heated surface due to loads might increase the risk of spalling.
Concrete age	Variable	Young concrete has a high amount of free water, which increases the risk of spalling. This effect decreases with HPC and UHPC due to the low permeability.
Lightweight aggregates	Variable	Higher porosity and permeability enables the release of high pore pressure and decreases the risk of spalling. The higher moisture content of lightweight aggregates promotes the risk of spalling.

Table 1. Material-related factors with an influence on spalling.

2.3.2. Heating characteristics

Among the factors associated with heating characteristics, the heating rate and temperature gradients have a strong influence on explosive spalling. **Table 2** summarizes the governing factors depending on the heating characteristics that influence spalling in general.

Factors	Risk of spalling	Influences
Heating rate	Very high	Higher heating rates usually lead to explosive spalling with HPC mixes.
Temperature gradient	High	Temperature gradient is closely related to the heating rate. Higher temperature gradients promote the risk of explosive spalling due to thermal stresses.
Exposure on multiple surface	High	Heat exposure on more than one side increases the risk of corner or explosive spalling due to higher temperature gradients and thermal stresses
Absolute temperature	Moderate	Explosive spalling might occur with temperatures of less than 300-350°C. Very high temperatures $T > 1000^{\circ}\text{C}$ increase the risk of postcooling spalling.

Table 2. The governing factors depending on the heating characteristics with an influence on spalling.

2.3.3. Structural or mechanical factors

The main structural or mechanical factors with a significant influence on spalling are presented in **Table 3**. It is difficult to distinguish between pure material and pure structural or mechanical factors leading to spalling in some cases, since some factors can be attributed to both categories.

Factors	Risk of spalling	Influences
Applied load (compressive stress and restraint)	High	The risk of spalling increases with applied higher load levels. High compressive stresses caused by restraint to expansion develop when the rate of heating is such that the stresses cannot be relieved by creep quickly enough.
Cross section geometry (section size and shape)	High	Round cross section, rounded corners, sufficient reinforcement cover and spacing and modified tie design lowers the likelihood of spalling or increases the remaining load bearing capacity of concrete members after spalling.
Thermal expansion	High	Fixed ends as boundary conditions, eccentric load or bending increases risk.
Tensile strength	Low	A high tensile strength is considered as lowering the risk of explosive spalling since it offers a higher resistance.

Table 3. Structural or mechanical factors with an influence on spalling.

3. Design against explosive spalling

3.1. Preventive measures

Today, the explosive spalling of concrete is an important requisite to consider in fire safety design of RC structures. Various preventive measures against explosive spalling of concrete

under fire attack have been studied and discussed by many researchers for a long period of time. However, the available standards for the protection of structures against explosive spalling are insufficient. In the BS 8110: Part 2: 1985 [20], the standard adds that “In any method of determining fire resistance where loss of cover can endanger the structural element, measures should be taken to avoid its occurrence.” As the fire-proof design recommendations according to the European design standard EN 1992-1-2 [21], the possible use and effectiveness of steel fiber and polypropylene (PP) fiber are discussed in addition to general thoughts on the use of a protective lining and changes to the structural design of concrete members. Several measures based on the factors influencing the spalling of concrete have been suggested to eliminate spalling or to reduce the damage (**Table 4**). These measures can be employed singly or in combinations.

Factors influencing spalling	Basic measures	Specific measures
Concrete conditions	- Thermal barrier	- Use of fire resistive materials
- High performance concrete	- Control of temperature rise in concrete surface layer	- Coating of fire-proof paints
- Light-weight concrete	- Reduction of temperature gradient	- Plastering of fire-proof mortars
- Thermal properties	- Relief & reduction of vapor pressure	- Covering of concrete by steel pipe etc.
- Moisture contents		- Addition of synthetic fiber (Polypropylene fiber, etc.)
- Materials		- Forced-drying of structural members
		- Installation of moisture eliminatory tubes
Fire behavior & conditions	- Prevention of temperature rise	- Elimination of inflammable materials in building
- High heating rate		- Make noncombustible of Materials
- Fire exposure time		- Expansion of fire prevention facilities
Structural member conditions	- Fire safety design	
- Section size & shape		
- Concrete depth		

Table 4. Preventive measures response to the factors causing spalling [22].

As the most effective methods to reduce the risk of explosive spalling, the addition of polypropylene fibers and the use of a thermal barrier are recommended. The risk of explosive spalling, which can occur during the first 7–30 minutes of a fire attack, is also weakened by reducing the moisture content of the concrete to less than 5% by volume, by avoiding thin sections and rapid changes in shape, and by limiting the compressive stress.

3.2. Reduction in the high vapor pressure

A major recent development in the prevention of explosive spalling has been in the use of synthetic fibers in the concrete mix, especially polypropylene fibers. Polypropylene fibers melt at about 170°C, thus it could reduce the build-up of high pore pressure within the concrete due to creating channels for vapor to escape easily, as shown in **Figure 7**. This measure was first reported in Japan [23] and subsequently studied by Diederichs [24] and Connelly [17]. Connelly [17] reported that the addition of 0.05% by weight of fibers in concrete (w/c = 0.4, 10 mm aggregate) completely eliminated spalling in fire (heating rate 25°C/min), while 83% of similar specimens without fibers was broken explosively. It is clearly shown that the addition

Figure 7. Melting of PP fibers in concrete at about 170°C [22].

Figure 8. Fire resistance performance of the concrete with PP fibers of 0.9 kg/m³ [22]. (a) Without PP fibers; and (b) addition of PP fibers (0.9 kg/m³).

of polypropylene fibers is an effective means of preventing explosive spalling, as shown in **Figure 8**. The Euro Code 2 (Design of Concrete Structures, Part 1-2: Structural Fire Design, 1993) [25] also suggests PP fiber content of at least 2.0 kg/m³ for effectively preventing the explosive spalling of HSC. However, more recent studies have reported that this fiber content in ultra-high-strength concrete (UHSC) of more than 150 N/mm² such as reactive powder concrete (RPC) was not enough for preventing explosive spalling in a fire, although they were found to be beneficial when used with HSC of 60~110 N/mm² [26]. Hence, the use of such fibers is more effective in lower strength concrete.

Meanwhile, in recent decades, different synthetic fibers have been tested in terms of melting characteristics, workability, and overall performance with the aim of reducing the risk of spalling. **Table 5** gives a brief overview of various fibers available to prevent explosive spalling of concrete.

Type of fibers	Effectiveness
Polypropylene fiber	<ul style="list-style-type: none"> - Melting (170°C) of PP fibers within concrete, increases permeability of concrete and releases high pore pressure. - Fibers might have negative influence on workability, in particular very thin fibers. - Fiber contents of 2~3 kg/m³ seems to be most effective in spalling protection.
Nylon fiber	<ul style="list-style-type: none"> - A rather high melting temperature of 200°C, which might be too high for some mixes.
PVC	<ul style="list-style-type: none"> - Releases hazardous chlorides, should not be used with concrete.
Polyethylene fiber	<ul style="list-style-type: none"> - Low melting temperature of 90°C, but high viscosity of molten fibers minimizes the increase in permeability (less applicable).
Steel fiber	<ul style="list-style-type: none"> - Increases ductility of HPC and increases spalling resistance of columns with narrow spacing between the ties. - However, no noticeable increase in resistance with other structures was observed in tests.

Table 5. Use of various fibers to prevent the explosive spalling of concrete.

3.3. Thermal barrier

Thermal barriers usually limit the temperature increase and the maximum temperature at the surface of the concrete and thus reduce the risk of explosive spalling as well as loss of mechanical strength. Their layer thickness has to keep these temperatures below a critical level for spalling of concrete. However, critical temperatures leading to spalling are not generally available because they change with each individual concrete mix. Thermal barrier measures could be classified as two categories: (a) materials methods and (b) construction methods. In materials methods, the protective coating on the surface of the concrete by high fire resistive materials is usually used, as shown in **Figure 9**. In construction methods, the covering methods concrete with a steel pipe, the use of the metal-lath, or confinement steel reinforcement against spalling (**Figure 10**), and the surrounding methods concrete with a fire-proof board are presented as protective measure of spalling.

Figure 9. Fire resistance performance of the concrete coated with high fire resistive materials.

Figure 10. Fire resistance performance of the concrete with the confinement steel reinforcement against spalling. **(a)** Use of the confinement steel and **(b)** surface of the concrete after fire test.

In terms of the reduction of the peak temperatures within the concrete, these measures are the very effective method (PP fibers do not reduce that). However, there are two potential drawbacks: (1) the cost of the insulation is likely to be more than that of the fibers and (2) with some of the manufacturers there has been a problem with delamination during normal service conditions. In general, the design criteria are to apply a sufficient thickness of coating so as to

reduce the maximum temperature at the surface of the concrete to below about 300°C and the maximum temperature at the steel rebar to about 250°C within 2 hours of the fire [13]. It should be noted that experience indicates that while 25 mm of coating may be adequate for concrete strength up to about $f_c = 60 \text{ N/mm}^2$, but a coating thickness of 35 mm may be required for high strength concrete to avoid explosive spalling [13].

3.4. Spalling control techniques in the field

3.4.1. Advanced fire resistance (AFR) concrete

Advanced fire resistance concrete is manufactured with the polypropylene fibers (diameter: 0.012–0.2 mm, length: 5–20 mm) of 0.1–0.35% by volume and practically used in the HSC of 80–120 N/mm². In this concrete, the addition of polypropylene fibers is derived to prevent explosive spalling on the surface of concrete by the release of high vapor pressure and thermal expansions due to the melting of the PP fibers at about 160°C, which resulted in channels for water vapor to escape within the concrete. **Figure 11** shows the fire resistance performance of the column specimens applied in the ARF concrete [22].

Figure 11. Fire resistance performance of the column specimens applied on the ARF concrete.

3.4.2. Fire performance concrete (FPC) method

Fire performance concrete method is to apply the PP powder instead of PP fibers in high strength concrete. The melting point of the PP powder is 165°C, the density is 0.9 g/cm³, and it is usually used in the addition contents of 1–3 kg/m³ by weight. Especially, PP powder has the excellent dispersibility and reduces the difficulty such as fiber ball when mixing it. **Figure 12** shows the fire resistance performance of the column specimen applied in the FPC method [8].

Figure 12. Fire resistance performance of the column specimen applied in the FPC method. (a) Plain concrete and (b) FPC method.

Figure 13. Fire resistance performance of the column specimen applied the FRCC method. (a) Plain concrete and (b) FRCC method.

3.4.3. Fire reinforced concrete column (FRCC) method

Fire reinforced concrete column method is to apply the protective coating on the surface of concrete by high fire resistive materials. As the high fire resistive materials, the calcium silicate board with fibers, the ceramic fire-proof mortars, the mortars mixed cellulose fibers, etc. are usually used. This is a thermal barrier method to limit the temperature increase and the maximum temperature at the surface of concrete in order to reduce the risk of explosive spalling. Their layer thickness has to keep more than 20 mm for the HSC of 80–120 N/mm² to

avoid explosive spalling, in general [22]. **Figure 13** shows the fire resistance performance of the column specimen applied in the FRCC method.

4. Conclusions

Explosive spalling is a very violent form of spalling, which is characterized by the breaking off of layers or pieces of concrete from the surface of a structural element, accompanied a typically loud explosive noise when exposed to high and rapidly rising temperature under fire conditions. It normally occurs within the first 7–30 minutes in a fire. The most recent theories of the causes of explosive spalling indicate that three factors play a crucial role: (a) the build-up of pore pressure, (b) thermal stresses, and (c) combined phenomena in the concrete when exposed to a rapidly increasing temperature. Explosive spalling generally occurs singly or on combination depending upon the moisture content, the section size, and the material. It is noticed that the high performance concrete tends to experience multiple spalling (combined pore pressure and thermal stress spalling) of thinner sections. In fact, a large number factors influence explosive spalling of concrete. Based on the mechanisms, the major factors leading to explosive spalling are heating rate, permeability of concrete, moisture content, presence of reinforcement, and level of external applied load. The factors can be classified into three categories: material-related factors, structural or mechanical factors, and heating characteristics. The majority of these factors can be directly associated with explosive spalling. However, some are also related to other types, and a clear separation between individual parameters is difficult to match. As the most effective methods to reduce the risk of explosive spalling, the addition of polypropylene fibers and the use of a thermal barrier are recommended. The risk of explosive spalling is also weakened by reducing the moisture content of the concrete to less than 5% by volume, by avoiding thin sections and rapid changes in shape, and by limiting the compressive stress.

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